BETTER SHELTER: A Virginia Beach Bus Evacuation Simulation for the Vulnerable in a Flooding Disaster

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CAPSTONE PROJECT REPORT

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Abstract

The city of Virginia Beach is cited as one of the top 10 flood-risk regions in Virginia [Amodeo, M., et al., 2020]. During a flood related disaster, a large portion of Virginia Beach's population of 450,000 will evacuate the area. However, approximately 49,000 people of the city's population are considered to have access and functional needs and some of this vulnerable population may not have the means to relocate themselves once an evacuation order is issued. Using Virginia Beach's current protocols and resources, the modeling of transportation routes for the disabled population of Virginia Beach was simulated. From these findings, we compared the city's current protocols to our results to establish recommendations and a way forward for optimizations in regard to evacuation planning.

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1 Introduction

1.1 Background

Natural disasters and lack of reaction plans have caused billions of dollars in damages and countless lives in the recent years [NOAA, 2022]. Worldwide, floods are notorious killers in coastal cities and islands. In the United States, floods account for 90% of all natural disasters [Kansas Department of Agriculture, 2010]. Floods are America's most frequent and expensive natural disaster [NOAA, 2022]. Flooding events are becoming more severe. In the Eastern U.S., there are up to 70% more heavy downpours each year [Dourte, D. R., et al., 2015]. Due to this increase, many cities which encounter frequent natural disasters have created or updated their disaster response plans [Sterling, B., 2022].

Virginia Beach is a coastal city in southeastern Virginia which has experienced harsh floods from hurricanes, heavy rains, and tropical storms. The National Weather Service, [National Weather Service, 2016], reports that hurricanes are of particular concern to the area since Virginia Beach has historically experienced tragedy from hurricanes, including the disasters of Hurricane Sandy (2012) and Hurricane Matthew (2016). Hurricanes are graded by intensity from Category 1 (sustained winds of 74-98 mph) to Category 5 (sustained winds of 157mph or higher) [VDEM, undated]. Eastern Virginia is projected to experience increased flood risk over the next 30 years [FloodFactor.com, 2022]. Due to this, Virginia Beach has evacuation plans and sheltering protocols in place to curb disaster costs and save lives [VDEM, undated].

In situations where an evacuation is declared, the portion of the population with access and functional needs is one of the highest risk groups for bad outcomes, and often is the group unable to make it to a safe location during an evacuation [Norman Oliver, M., et al., 2020]. There is a lack of planning and protocols to transport this segment of the population to safety. This report will address the current protocols and simulate a solution to transport those with access and functional needs to a safe sheltering location. For the purposes of this project, we will hereby refer to individuals with access and functional needs with a variety of respectful terminology including AFNs, the vulnerable population, and the disabled population [National Youth Leadership Network, 2006].

1.1.1 Virginia Beach Evacuation Overview

All hurricanes are assigned to a severity category based wind speed as defined by the Saffir-Simpson Hurricane Scale with a tropical storm being the least severe, and category 5 being the most severe as seen in Table 1 below:

Table 1: Hurricane Category Overview [NOAA, 2012]

Hurricane Category	Wind Speed
Tropical Storm	39-73 mph
1	74-95 mph
2	96-110 mph
3	111-129 mph
4	130-156 mph
5	157 mph or higher

Decisions to issue an evacuation order for the city of Virginia beach are at discretion of the local emergency management departments, and are based on the forecasted severity of the storm.

The city has defined a detailed response plan for all residents in the case of an evacuation order. This city, along with 22 other localities in this region, utilizes a tiered evacuation plan in the event of a disaster, “Know Your Zone” [W.A.V.Y., 2019]. This is an “awareness initiative that applies to roughly 1.25 million residents” within 23 localities along Coastal Virginia [VDEM, undated]. In this plan, all addresses are designated to one of four evacuation zones, A through D. These zones are designated based on flood risk in each zone according to historical flood maps. Zone A has the highest flood risk, followed by B, C, and D sequentially. Figure 1 below depicts the geographic location of each Evacuation zone.

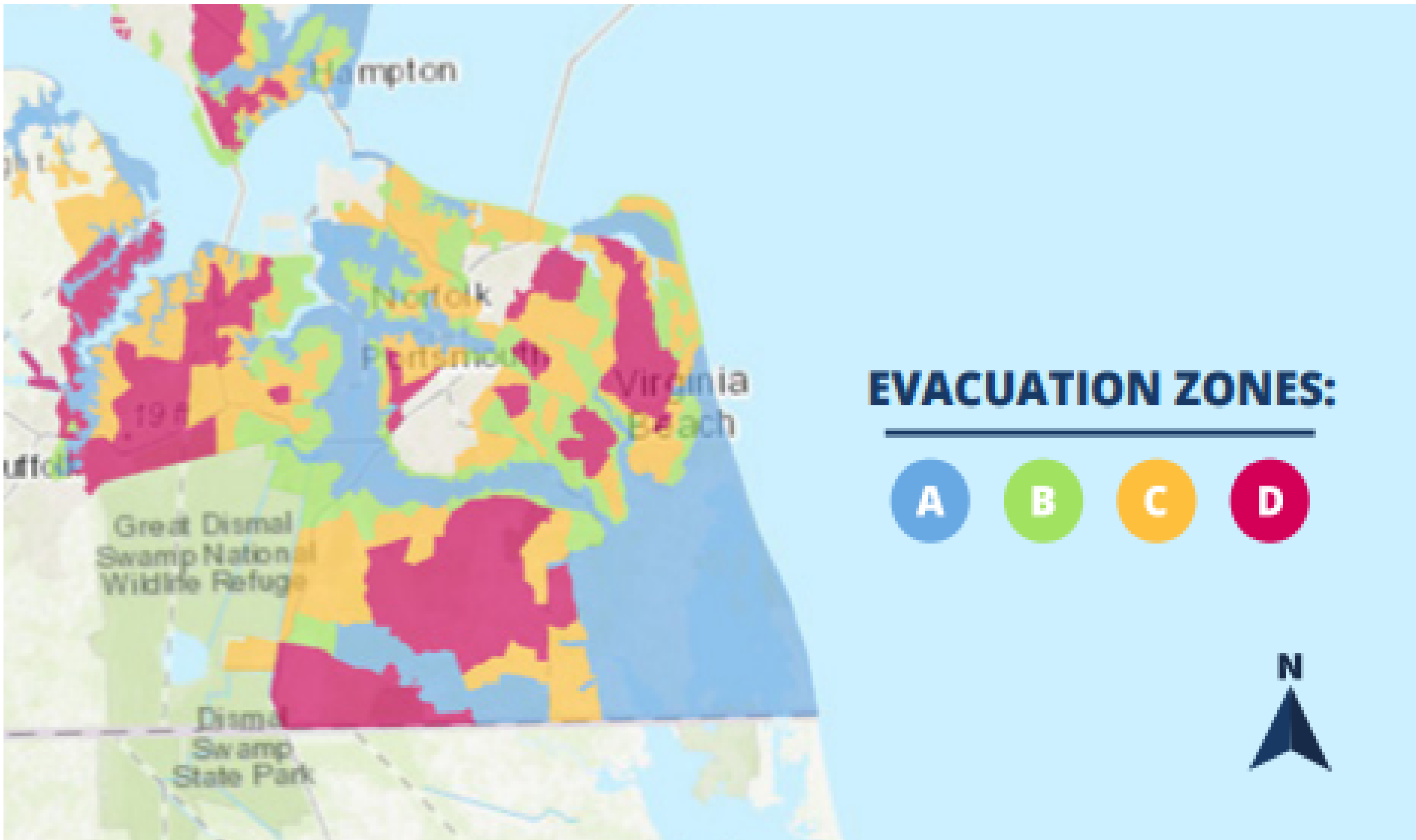


Figure 1. Evacuation Zones of Virginia Beach [VDEM, undated]

An evacuation order will be given prior to the forecasted landfall of tropical storm force winds for a particular zone. Tropical-storm force winds are identified as sustained winds greater than 39 mph [NOAA, 2012]. Once the evacuation order is given for a particular zone, residents of that zone need to go at least as far as the next zone to be safe from the flood risk. For example, "if Zone A is evacuated then residents would only need to go as far as Zone B" [Sterling, B., 2022]. This is because Zone A is more likely to be flooded than Zone B, and Zone B more than Zone C.

The Virginia Department of Emergency Management has defined scenarios for zone evacuation based on the forecasted category of the storm on which local emergency management can base their decisions to issue an evacuation order. In general, only Zone A and/or B will be evacuated for a category 1 or 2 storm. Zone C will be evacuated for a Category 3 storm and Zone D will be evacuated for a Category 4-5 storm [VDEM Hurricane Evacuation Scenarios, 2021].

VDEM also uses "clearance times" as a metric for successful evacuation. "Clearance Time" is defined as the time it takes from when the evacuation order is issued to the time when all individuals in that zone have safely exited the risk area (evacuation zone). Each zone has

Clearance Time goals as indicated below.

Table 2: Zone Clearance Times [VDEM, 2021]

Zone	Clearance Time
A	28 Hours
B	45 Hours
C	58 Hours
D	67 Hours

When an evacuation order has been issued, VDEM has designated specific routes for which those evacuating the area should take. The routes in Figure 2 are to be utilized in an ordered evacuation. As shown, the only authorized evacuation routes for the Virginia Beach area are I-64 and I-264 west.

Figure 2: Evacuation Routes of Virginia Beach [VDEM, undated]

1.1.2 Virginia Beach Shelter Overview

In the case of an evacuation, there will also be a subset of the population that is either unable or unwilling to evacuate. For these individuals, the city has identified 9 general population shelters that can be utilized for this purpose [Spach, D., 2022]. These general population shelters and their respective capacities can be seen in the table below. The total of the shelter capacities is 7,288 people.

Table 3: Virginia Beach Evacuation Shelters [Spach, D., 2022]

Shelter	Capacity	Tier
Kellam High School	1564	1
Landstown High School	1232	1
Old Donation School	611	1
College Park Elementary School	293	2
Corporate Landing Middle School	500	2
Great Neck Middle School	935	2
Larkspur Middle School	1094	3
Renaissance Academy	559	3
Virginia Beach Middle School	500	3

These general population shelters are each designated to a tier, 1-3, and are opened based on this designation. Tier 1 shelters are opened first, and once they reach capacity, the Virginia Beach Emergency Management department will begin to open the Tier 2 shelters. All shelter tiers will be stocked with food, water, and general hygiene items (shower supplies, etc.), but individuals are required to bring sleeping supplies and any other necessary items (medicine, clothes, etc.).

These shelters have limited medical support including a nurse available for general needs such as first aid. The city may also, at the discretion of the emergency management department, may also open a designated Medical Friendly Shelters (MFS) for those with more severe medical needs. It is important to note that the MFS will not be open during all evacuation events [Spach, D., 2022]. These medical friendly shelters and their capacity are given in Table 4 below:

Table 4: Virginia Beach Medical Friendly Shelters [Spach, D., 2022]

Shelter	Capacity	Tier
Kellam High School	50	MFS
Virginia Beach Fieldhouse	1300	MFS

It is important to note that Kellam High School is also a Tier 1 general population shelter, but may open a section with a capacity of 50 as a medical friendly shelter. This is at the discretion of Virginia Beach Emergency Management, and the MFS portion of this location may not always open concurrently with the Tier 1 general population shelter. Virginia Beach Emergency Management utilizes Virginia Beach Fieldhouse as a dedicated medical friendly shelter and is not considered a general population shelter.

The MFS will have additional support for those with specific medical needs, such as:

> "...people who, during periods of evacuation or emergency, require sheltering assistance due to physical, mental or cognitive impairment, or a sensory disability that exceeds the basic level of care provided at a general population shelter, but does not require the level of care provided at a skilled medical facility. This includes helping with administering medication, personal hygiene assistance with activities of daily living (washing, dressing and eating). The MFS is not for people who have significant medical problems, injuries or illnesses and/or that require total dependence on others for care. Examples: bedridden, have NG tubes for feeding, require monitoring and pain management after recent injury, recovering from surgery, or who are contagious. " [City of Virginia Beach, 2020].

Opening these shelters during an evacuation event is at the discretion of Virginia Beach Emergency Management and is only required for a category 2 storm or greater [Spach, D., 2022]. Those individuals who do not meet the criteria above are required to proceed to a hospital or an emergency medical facility.

1.1.3 Virginia Beach Population Overview

The city of Virginia Beach has a full-time population of approximately 450,000, and of this population, approximately 49,000 make up the noninstitutionalized vulnerable population (also referred to as people with "access or functional needs") based on the US Census data [United States Census, 2020]. This refers to the population with specific needs who are not in a nursing home, long-term hospice care, or mental hospital [United States Census Glossary, undated] This population is broken down as follows:

Table 5. Population Breakdown of Disability Types in Virginia Beach [United States Census, 2020]

Category	Number of Individuals
With a Hearing Difficulty	13,231
With a Vision Difficulty	9,095
With a Cognitive Difficulty	17,685
With an Ambulatory Difficulty	23,186
With an Independent Living Difficulty	15,805

The given categories can be defined as follows:

- Hearing difficulty: deaf or having serious difficulty hearing (DEAR).
- Vision difficulty: blind or having serious difficulty seeing, even when wearing glasses (DEYE).
- Cognitive difficulty: Because of a physical, mental, or emotional problem, having difficulty remembering, concentrating, or making decisions (DREM).
- Ambulatory difficulty: Having serious difficulty walking or climbing stairs (DPHY).
- Self-care difficulty: Having difficulty bathing or dressing (DDRS).
- Independent living difficulty: Because of a physical, mental, or emotional problem, having difficulty doing errands alone such as visiting a doctor's office or shopping (DOUT).

A disabled individual may be included in one or more of the categories in Table 5. Based on 2020 U.S. Census data, Figure 3 below portrays the distribution of the disabled population within the census tracts of Virginia Beach. The region of blue gradients depicts the Virginia Beach city limits, which includes 112 different census tracts. The legend on the leftmost side provides data for how many census tracts belong to that color, along with the range of number of disabled individuals within each tract.

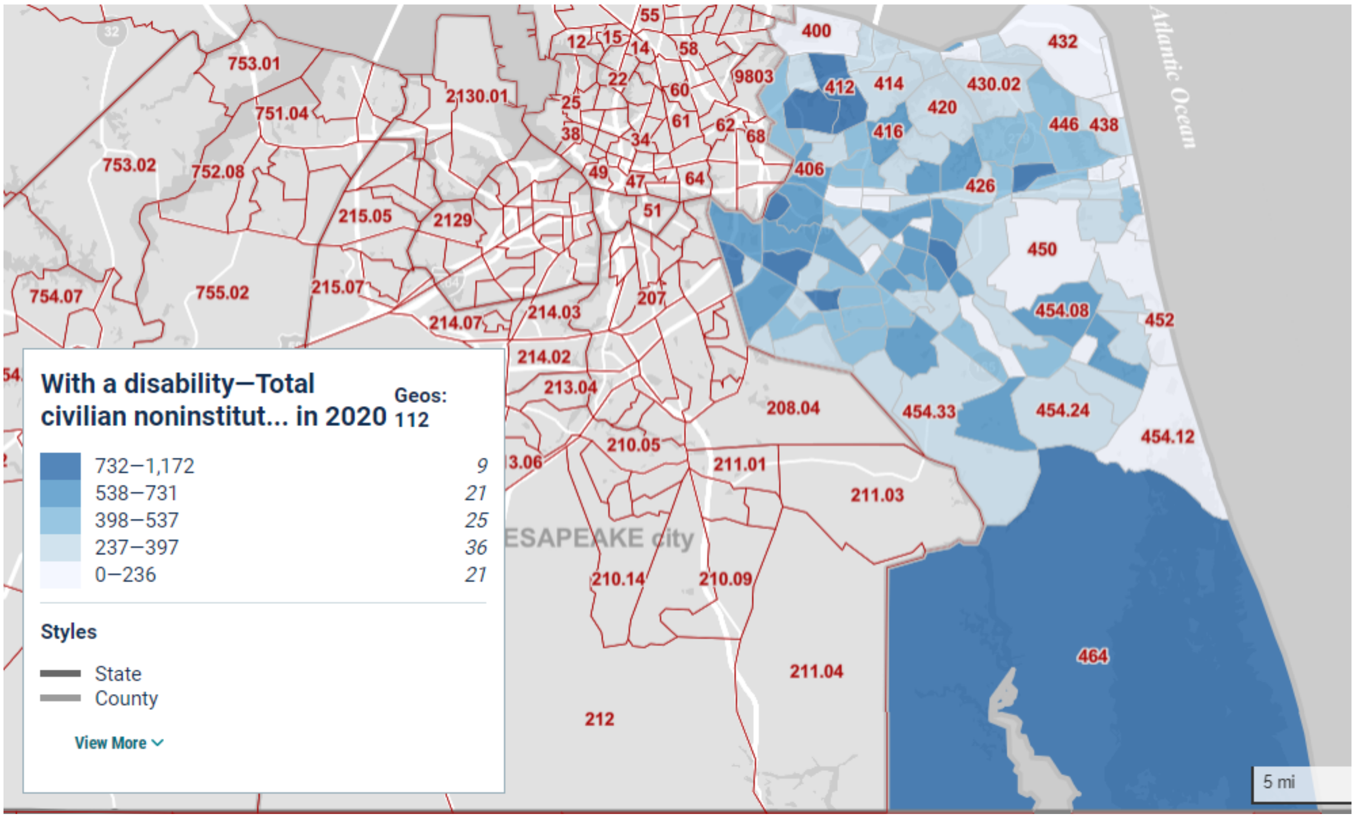


Figure 3. Virginia Beach Disabled Population Distribution [United States Census, 2020]

The population distribution depicted above includes all individuals in Virginia Beach living independently with access and functional needs that do not require emergency or hospice care. This population accounts for 48,643 individuals. This spread of data, along with geographic flood zone data, allows us to visualize which areas in the city have an increased need for shelter and transportation resources.

1.1.4 Estimates for Population to Seek Shelter

The VDEM assumes that 80% of the population in the risk area (the zone in which an evacuation order has been issued) will either evacuate or seek shelter during an evacuation event for their evacuation scenarios, the other 20% is assumed to take no action (i.e. remain at home and wait out the storm) [B. Sterling, 2022]. This applies both to the general population and the portion of the population with access and functional needs. This is referred to as the “medium participation rate”. The VDEM also assumes that of the 80% that participates in the evacuation, 8% will seek shelter while the remaining 72% of this subset will completely evacuate the risk area. We also assume that each member of the vulnerable population that will utilize a shelter during an evacuation event will have one caregiver with them.

The total AFN population plus caregivers obtained through the summation of the Virginia Beach census tracts in Figure 3 can be seen below in Table 4:

Table 6. Virginia Beach AFN Population to Seek Shelter

Total Population:	48,643.00
Assume 80% * 8% Sheltering	3,113
Vulnerable Population Including Care Givers	**6,226**

The city of Virginia Beach notes that both the general population shelters and the MFS should be used as “a measure of last resort — a place to go if it is unsafe to stay at home to ride out a storm and there are no other options available to you” [City of Virginia Beach, 2020]. Based on this, it can be assumed that those most likely to utilize the shelters are AFN’s and their caregivers. It can also be assumed that based on the definition for a MFS, vulnerable people that can otherwise live on their own can be accommodated at a general population shelter, and do not need to utilize a MFS in the case of an evacuation event.

1.1.5 Transportation to Shelters

There currently is no transportation system in place to assist individuals in either evacuating the Virginia Beach area or getting to a shelter. The only assistance the city provides is the capability to transport an individual from a general population shelter to a MFS if a MFS has been opened and the individual has arrived at a general population shelter and proper medical care is unavailable. In this scenario, the city will provide transportation from the general population shelter to the MFS [Spach, D., 2022].

The region has a public transportation system, the Hampton Roads Transit (HRT), that provides buses for local routes within the Virginia Beach area [HRT Routes, Virginia Beach, 2022]. The HRT serves seven cities in the coastal Virginia region, and has approximately 240 buses [Hampton Roads Bus Service, 2022]. During hurricane events, HRT service will likely be suspended [HRT Inclement Weather Plan, 2022] due to high winds and flooding. Because of this, public transportation in the region is not a reliable solution to assist in ensuring the population with AFN’s safely evacuates the area or to a shelter during a hurricane event. There is a possibility to utilize the HRT’s resources to model a transportation system.

1.2 Problem Need

During a hurricane evacuation order, a portion of the vulnerable population will have the ability to evacuate either on their own or with their families. However, there is a portion of the vulnerable population that will be unable to evacuate. This population may not have the means to relocate themselves once an evacuation order is issued. These individuals will either utilize a designated hurricane shelter or a MFS, and there is currently no transportation system in place to address this issue. Our model will address this need by utilizing the shelter locations, evacuation zones,and population densities to minimize evacuation completion time for the population of Virginia Beach identified in Figure 3.

1.3 Stakeholders

The stakeholders are the vulnerable population of the city, their families, the staff/volunteers at the shelters, and the City of Virginia Beach Government, the Virginia Beach population, the transportation system, and the education system. As well as the project sponsors, Dr. Gregory Tagonan and Ateneo de Manila University. Extended stakeholders include statewide and national emergency management centers and the military that may be required to supply shelter locations, distribute food and other necessary supplies and also transport some of the population.

1.4 Bus Evacuation Problem in Literature

The logistical problem of evacuating populations who rely on public transportation systems has been studied extensively in literature, and has resulted in a number of modeling and simulation approaches. These approaches typically address the location and operation of shelter facilities; the placement of bus stops or pick-up points; the routing and operation of buses; and the allocation of bus resources. We have organized these studies according to their overall objective.

- Total evacuation time
- Total number of evacuees transported to a shelter
- Safety (or threat exposure)
- Operational costs
- Other assessed benefits

1.4.1 Minimize Total Evacuation Time

In [Zhang, X., et al., 2014], the authors propose a transit-based evacuation model for metropolitan areas to help determine pick-up locations and flexible bus routes that minimize the overall evacuation time. The model considers variable demand at pick-up points, and generates flexible bus routes using optimization. The authors apply this model to a scenario set in Baltimore, Maryland. How the authors handle the topics of arrival distributions, experiment design, and key parameters serves partially as a basis for our own project, which will relate the maximum waiting time threshold to the required number of buses. Another model described in [Deghdak, K., et al., 2014], deals with post-disaster bus evacuation and implements large-scale optimization of the bus evacuation problem with time-indexing. A third model [Lu, W., et al., 2020], integrates pedestrian routes, bus stops, and bus routes using nonlinear optimization methods and GAMS software. The authors use a "one-one-one" evacuation constraint which is used as a starting point in our own model. This constraint states that every demand origin node is linked to one pickup node, which is linked to one shelter. The exploration of pedestrian routes as it relates to the design of bus networks is a helpful resource for any future studies on this topic.

Another study [Esposito, A., et al., 2021], proposes a two-stage optimization model to find shelter locations, bus stops, and routes that minimize evacuation completion time for a given population demand. The first stage involves optimal planning without knowledge of disruptions, whereas the second stage deals with ongoing disruptions. This study is a potential resource for integrating a bus evacuation model with a car based evacuation including contraflow lanes.

1.4.2 Maximize the Number of Evacuees Moved

A bus evacuation case study set in Miami-Dade county [Margulis, L., et al., 2006] proposes an optimization model in which buses are dispatched from shelters on routes to a single pickup location before returning to the same shelter again. This model allocates buses to variable routes to maximize the total number of evacuees from given pick-up points over a given time period. Given that demand at pick-up points will be highly uncertain, the authors also examined literature that deals with varying demand over time and the concept of flexible bus route optimization [Qazi, A.N., et al., 2017].

1.4.3 Maximize the Overall Safety of Population

All of the studies mentioned so far are bus evacuation problems which handle the decision-making process for pickup locations and routing. A study [Li, M., et al., 2018] investigates risk-based optimization, and the notion of minimizing risk for different alternatives in an evolving, hazardous environment. This study models a dynamic bus schedule problem under no-notice evacuation with disaster dynamics taken into consideration. This is a particularly helpful resource for follow-on work in risk analysis of bus evacuations.

1.4.4 Minimize Operating Costs via Efficient Resource Allocation

An important aspect of a bus evacuation plan is the operation of shelter facilities. These facilities are often school buildings, and there is a quantifiable cost associated with displacing their intended purpose of education. Planners should minimize the financial burden on these institutions during a disaster; one of the ways to cut costs is to design an efficient plan to close out the sheltering operations and send people home. One study [Hitoshi, S., et al., 2022], proposes various optimization approaches (Sequential Facility Location Problem, No

Move Model, and Bin-Packing Model) to explore ways to control and transfer shelter occupancy across multiple shelters in a disaster event. This study is relevant to our own project which measures shelter occupancy over time across a multi-tiered sheltering system. It also forms a helpful starting point for follow-on work on the topic of facility location and operation.

1.4.5 Maximize Assessed Benefit of a Bus Network

A study on evacuating special needs populations using bus transit [Kaisar, S. 2022] stands out in that it provides a methodology for determining bus stop benefits based on population size, demographics, region size, and weighted stakeholder inputs. The model seeks to maximize the total "benefit" by choosing optimal bus stop locations.

From these studies on bus evacuation optimization and evacuation networking, it is clear there are many aspects to consider in regard to the logistics of an evacuation plan. Figure 4 portrays numerous components and factors that affect their increase and decrease of the component's relative unit (ie. time, availability, number, etc) within an evacuation transportation system for the City of Virginia Beach.

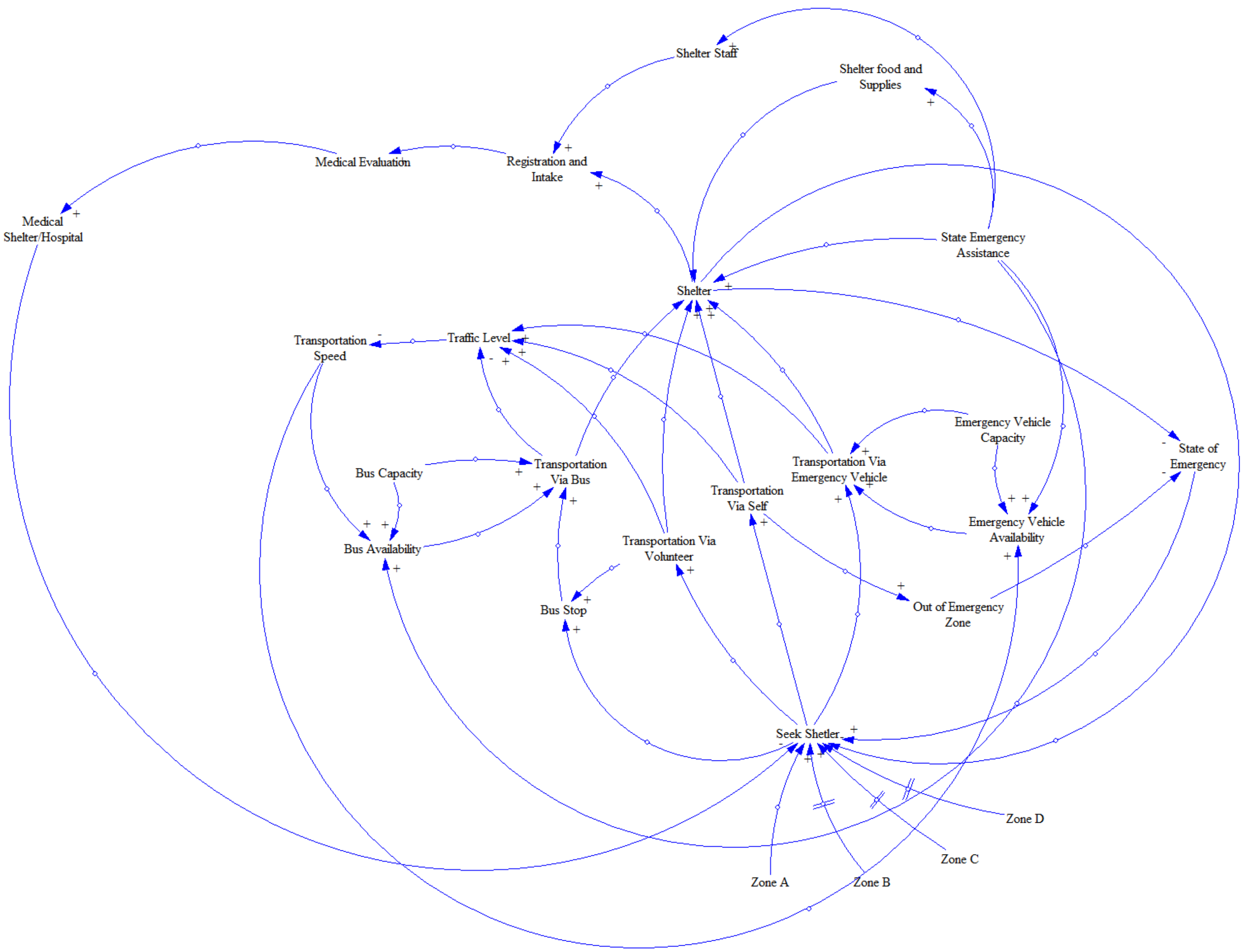


Figure 4. Causal Loop Diagram

2 Problem Statement

The city of Virginia Beach is cited as one of the top 10 flood-risk regions in Virginia [Amodeo, M., et al., 2020]. Virginia Beach has been affected by major flooding events due to rainstorm, hurricane, and tropical storms, and the risk is projected to increase over the next 30 years [FloodFactor.com, 2022]. There is also a highly vulnerable population in the area [United States Census, 2020], and giving sufficient attention to this population is important to saving lives in a natural disaster [Hammad, A., et al., 2022]. The team will model the logistics of a shelter network for the disabled population under uncertainty and constrained resources, such as a lack of buses or a shelter at capacity. The objective will be to minimize the time associated with an evacuation effort focused on vulnerable populations during a flooding event. This project will utilize established safe zones (i.e. areas outside of predicted flooding regions) and safe shelter facilities to model a transportation system that moves the disabled populations, within an affected zone, to shelters during a flooding event. Safe zones will be defined as the next zone tier from the evacuated zone in the Know Your Zone protocol, with Zone D being the highest tier [VDEM, undated]. A Zone D evacuation is considered out of scope for this project because the city of Virginia Beach will require assistance from VDEM for this type of event. Some key parameters will include population size and distribution, flooding time advance notice, flooding extent, and number of vehicles available.

3 Scope

3.1 Scope Tree

Evacuation protocols involve a large number of components and dependencies that would take more time and manpower to factor in. For the purposes of this project, we will exclude the population that evacuates, shelter staffing and supplies logistics, the non-disabled population, and volunteer, emergency, and personal vehicles that may be used for transportation to the shelters. The non-disabled population can be considered out of scope since we are prioritizing the vulnerable populations to seek shelter first, before the general population. We are specifically including the individuals with AFNs utilizing bus transportation to seek shelter. The scope of our project can be visualized in the Scope Diagram given below.

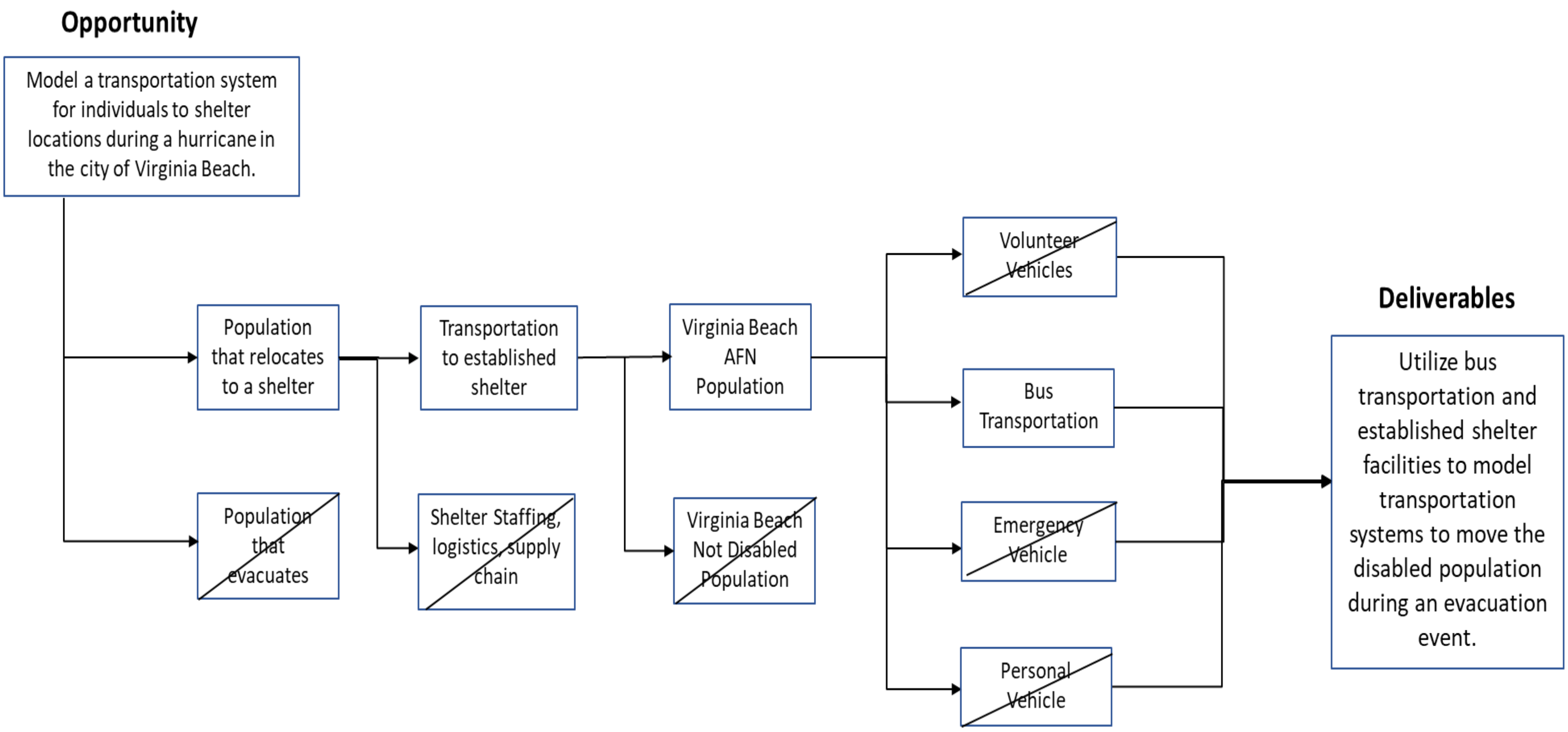


Figure 5. Project Scope Diagram of Inclusions and Exclusions

3.2 Assumptions

- Assume the population with access and functional needs will be prioritized in an evacuation event due to the fact that they are more vulnerable to the consequences of staying in place during a hurricane. This assumption is critical as the non-vulnerable population will not be factored into shelter capacity until those with AFN's are all transported. Referring to Figure 5, the non-vulnerable population will be out of scope for the model.
- Assume the population that is being modeled in this study, that is the vulnerable population (those with access or functional needs) are utilizing general population shelters, not a Medical Friendly Shelter. Transportation from a general population shelter to a MFS is out of scope since this transportation plan is separate and already in place.
- Assume a Zone D evacuation will require VDEM state level assistance and will be out of scope for this model due to Zone D being the zone at least risk, and therefore if the zone needs to evacuate the state will have to provide aid.
- Assume evacuation route roads will be busy and therefore will not be used in the simulation [VDEM, 2022].

- ➢ Assume That local buses will be available (unconstrained) during an evacuation for the transportation of persons with AFNs to shelters
- ➢ Assume the evacuation to shelters will be based on the “Know Your Zone” protocol.
- ➢ Assume a zone will not be partially evacuated. An evacuation order will be issued for a zone in its entireity.
- ➢ Assume a zone evacuation order includes all higher-risk zones as well. For Example, a Zone C evacuation order will always include Zones A and B. [VDEM, 2021].
- ➢ Assume a shelter’s internal resource/staffing needs are out of scope.
- ➢ Assume the vulnerable population of Virginia Beach to be approximately 49,000 persons as defined by the US Census ACS 5 year estimates. [United States Census, 2020]
- ➢ Assume only the full-time population of Virginia Beach and not the seasonal/tourism population will utilize the transportation model.
- ➢ Assume shelters admit the population with access and functional needs prior to accepting the general population and may reach capacity before the general population arrives.
- ➢ Assume the “risk area” is the Evacuation Zone or Zones for which an evacuation order has been issued.
- ➢ Assume that during a hurricane evacuation, 80% of the population in the risk area will either evacuate or seek shelter [Sterling, B., 2022]. The remaining 20% will do nothing (i.e. stay at home).
- ➢ Assume that 8% of the population that will either seek shelter or evacuate will seek shelter [Sterling, B., 2022]. The remaining 72% of this subset will evacuate the area.
- ➢ Assume that the percentage of the disabled population that will evacuate, seek shelter, or do neither is analogous to the general population [Sterling, B., 2022].
- ➢ Assume 100% of the disabled population that proceeds to a shelter will have a caregiver with them [Sterling, B., 2022]. This brings the total population to mobilize to 6,226 people.
- ➢ Assume only the schools listed in Table 3 are authorized shelters during the disaster and will be utilized for this model.
- ➢ Assume the model will reroute from one shelter to the next nearest shelter if the closest shelter’s capacity has been reached.
- ➢ Assume clearance times for each Zone are as follows: Zone A- 28 hours, Zone B - 45 hours, Zone C - 58 hours, Zone D - 67 hours [Sterling, B., 2022].
- ➢ Assume persons with access and functional needs that are in a hospice, nursing and/or assisted living facilities, or in hospitals will not utilize the transportation system. Any movement of this more infirmed population is out of scope for this model [Spach, D., 2022].
- ➢ Assume 70 city buses are available for transit each with a 20 person capacity.

➢ Assume shelters are opened and functional by the time an evacuation order is given [Sterling, B., 2022].

3.3 Data

The data used for the modeling and simulation of sheltering will include the disabled population statistics, shelter locations, evacuation routes, and zoning data as described in section 1.1.1 and 1.1.2. We will also use bus stops, vehicle routes, vehicle availability, vehicle capacity, and capacity of a shelter data that is provided by the Virginia Emergency Management Office. The gathered input data can be adjusted to any locality. The input data we will be using for Virginia Beach can be found here: [Virginia Beach Model Input Data]. The tables below illustrate a summary of the input and output data formats for the model.

Table 7. Input Data Overview

Input	General Unit(s)	Resource	Data Type	How it may Change Over Time
Population	# of People	United States Census Bureau, 2020 Arrival Distribution	Deterministic	Change would occur based on population growth/decline
Shelters	# of Locations Location Address Shelter Capacity	VDEM, 2022	Deterministic	Shelters may be added or dismantled based on disaster frequency and population change
Bus Stops	# of Stops Stop Address	United States Census Bureau, 2022 and Manual Inputs	Deterministic	Location may change based on integrity of stop during disaster and population movement across neighborhoods
Routes	Address of Origin Address of Destination	VDEM, 2022 and Manual Inputs	Deterministic	Change would occur based on disaster location and regions of flooding
Vehicles	# of Available Vehicles Vehicle Capacity	VDEM, 2022	Deterministic	Vehicles may be added or dismantled based on volunteered vehicles, vehicle breakdown, or

				population change
Arrival Distribution to Bus Stop	Distribution Type	Manual Inputs	Stochastic	Change would occur based on predicted distribution by modeler or available data
Clearance Time	Time(hrs)	Clearance Times, VDEM, 2022	Stochastic	Changes based on Zone, may change if evacuation order is given sooner/later
Loading Times	Time(minutes)	% of population in wheelchairs	Deterministic or Stochastic	Change based on number of the population requiring extra time to load onto buses

Table 8. Output Data Overview

Output	**General Unit(s)**	**Resource**	**Data Type**	**How it may Change Over Time**
People Moved	# of People	Input Population	Stochastic	Change would occur based on vehicle availability, capacity, clearance times, and route openness
People Remaining	# of People	Input Population - People Moved	Stochastic	Change would occur based on people moved
Total Evacuation Time	Time(hrs)	Bus route data, population, shelter data, and Loading times	Stochastic	Change depends on Population, Bus Route times and Shelter locations and capacities
Number of Buses Required	# of Buses Utilized	Optimization	Deterministic	Change depends on the wait times for each bus route

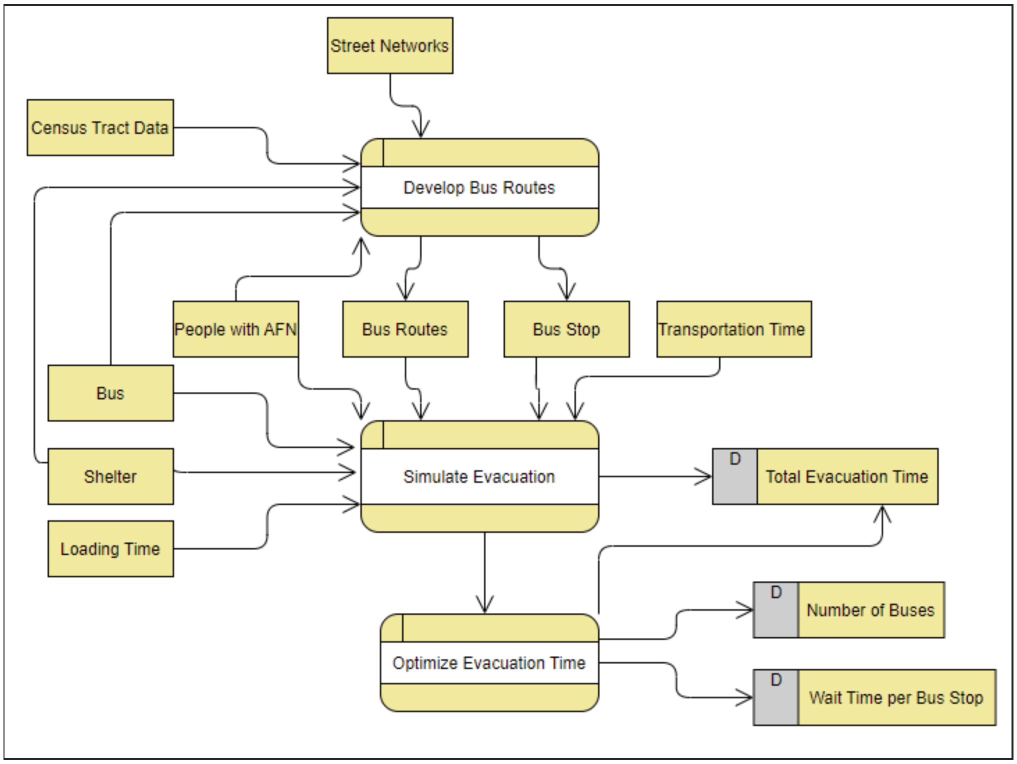


Figure 6: Level 0 Data Flow Diagram

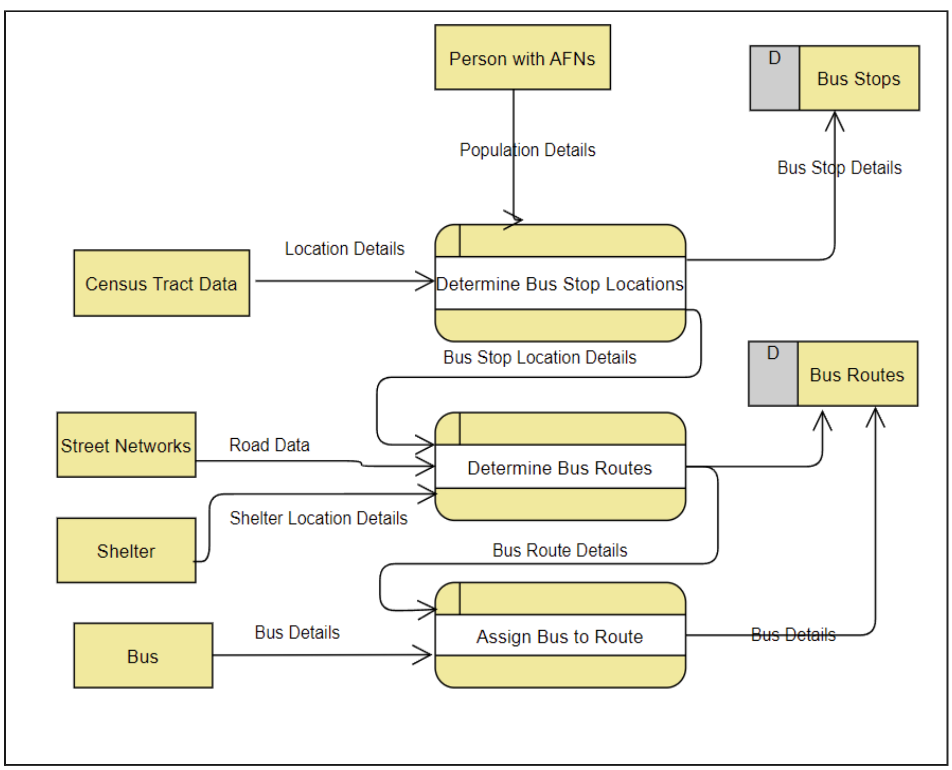


Figure 7: Bus Routing Data Flow Diagram

4 Requirements

4.1 Functional Requirements

1. The system shall utilize published data to model the transportation system.

   1.1 The system shall utilize evacuation times provided from VDEM as clearance times for each zone. Each zone shall be evacuated within the clearance time.

   1.2 The system shall utilize established shelter locations as an input provided by Virginia Beach Emergency Management Department.

   1.3 The system shall utilize and adhere to existing shelter capacities as provided by Virginia Beach Emergency Management.

   1.4 The system shall utilize and adhere to established shelter tiers as established by Virginia Beach Emergency Management.

   1.5 The system shall utilize established "Know Your Zone" protocols and prioritization.

2. The system shall model the transportation of the portion of the population with access and functional needs that does not evacuate.

   2.1 The system shall utilize most recent census data to estimate the number of individuals with access and functional needs.

      *2.1.1 The system shall model transportation to a shelter for 80% * 8% of the population with access and functional needs plus a caregiver for each disabled person based on the US Census data.*

      2.1.2 The system shall model identity locations based on census tract population density data for individuals with AFN's.

   2.2 The system shall utilize the "Know Your Zone" evacuation process for hurricane evacuation events.

      2.2.1 The system shall model a Zone A evacuation to evacuate individuals with AFN's living within Zone A based on the census tract data plus a caregiver.

      2.2.2 The system shall model a Zone B evacuation to evacuate individuals with AFN's living within Zone A and Zone B based on the census tract data plus a caregiver.

      2.2.3 The system shall model a Zone C evacuation to evacuate individuals with AFN's living within Zone A, Zone B, and Zone C based on the census tract data plus a caregiver.

2.3 The system shall model transportation of disabled persons to the nearest shelter location from the identified pickup location.

2.3.1 The system shall not utilize identified evacuation routes identified in Figure 2.

2.3.2 The system shall identify a pickup location for each census tract.

2.3.3 The system shall model transportation of the specified proportion of the population for each census tract to the nearest shelter over time.

2.3.4 The system shall utilize a maximum 60 minute wait time at a pickup location for each individual as a constraint. Individuals shall not wait longer than 60 minutes at a pickup location.

2.3.5 The system shall re-route to the next-nearest shelter location if the nearest shelter has reached capacity.

2.3.6 The system shall allow a user to input the number of buses available and model routing based on this constraint.

3. The system shall output metrics from a pickup point to the nearest shelter.

3.1 The system shall output shelter occupancy following the simulation for each shelter.

3.2 The system shall output a map of pickup points and routes to each shelter.

3.3 The system shall determine mean, minimum, maximum, and standard deviation for total time taken to evacuate all individuals from the risk zone to a shelter.

3.4 The system shall indicate whether the evacuation was completed within VDEM's indicated clearance time.

3.5 The system shall report a mean wait time for individuals at a pickup point before a bus arrives.

4.2 Non-Functional Requirements

1. The system shall be accessible to emergency planners.

1.1 The system shall be accessible for Windows OS.

1.2 The system shall operate on free, open-source Python packages.

1.3 The system shall require moderate knowledge of coding in order to run the model.

1.4 The system shall have a Microsoft Excel input file.

1.5 The system shall run a simulation of one iteration in under 20 seconds.

1.6 The system shall have the ability to adapt to different scenarios and localities, assuming that all data requirements are met.

2. The system shall include instructions for how to operate the tool.

2.1 There shall be instructions to download the necessary software to run the tool.

2.2 There shall be instructions to configure the necessary software.

2.3 There shall be instructions where to find and input the required data.

2.4 There shall be instructions for running the tool.

4.3 Modeling Requirements

The key metrics and modeling objectives of the model are as follows:

Table 9. Model Key Metrics and Requirements

Metric	**Type**	**Modeling Objective**
Total clearance time	Output	Stay within specified time limits
Evacuee wait times	Output	Do not exceed 60 minutes
Number of individuals	Input	Fixed number
Number of buses	Input	Variable case parameter
Number of shelters	Input	Begin with Tier 1 shelters; Open additional shelters as necessary; Specify capacity

5 Scenarios

5.1 Use Cases

5.1.1 Use Case 1: Evacuation of Zone A

Characteristic Information:

- Goal In Context: This use case is intended for the scenario in which an individual with access and functional needs, along with a caregiver, resides in Zone A and an evacuation order for Zone A is issued.
- Scope: The use of the evacuation transportation system by individuals with access and functional needs and their caregivers.
- Level: Primary
- Pre-Condition: An evacuation order must be issued for Zone A and available shelters established outside of Zone A.
- Evacuation Time Period Goal: Individuals with access and functional needs reach the shelter within a 28 hour clearance time.

- Primary Actors: Individuals with access and functional needs, Caregivers, Bus Driver, Emergency Manager
- Trigger Event: Evacuation order is issued for Zone A and shelters are opened.

Main Success Scenario:

Step	Actor	Action Description
Step 1	Emergency Manager	Emergency manager activates evacuation order of Zone A.
Step 2	Disabled Individuals & Caregivers	Individuals with access and functional needs and caregivers locate the nearest pickup location.
Step 3	Disabled Individuals & Caregivers	Individuals with access and functional needs and caregivers make their way to the nearest pickup location.
Step 4	Bus Drivers	Bus driver makes way to pickup location
Step 5	Disabled Individuals & Caregivers/Bus Driver	Bus driver picks up caregivers and individuals with access and functional needs at pickup location
Step 6	Disabled Individuals & Caregivers/Bus Driver	Bus driver transports caregivers and individuals with access and functional needs to nearest shelter location outside of Zone A

Scenario Extensions

Step	Condition	Action Description
3a	Individuals with access and functional needs are unable to make it to the nearest pickup location.	Individuals with access and functional needs are to call 911 to request emergency services.
3b	Individuals with access and functional needs travel to separate pick up location with caregivers	The bus destined for that pick up point will transport individuals and caregivers to shelter.
6a	Nearest shelter location is at capacity	The bus reroutes to transport individuals to the next closest shelter.

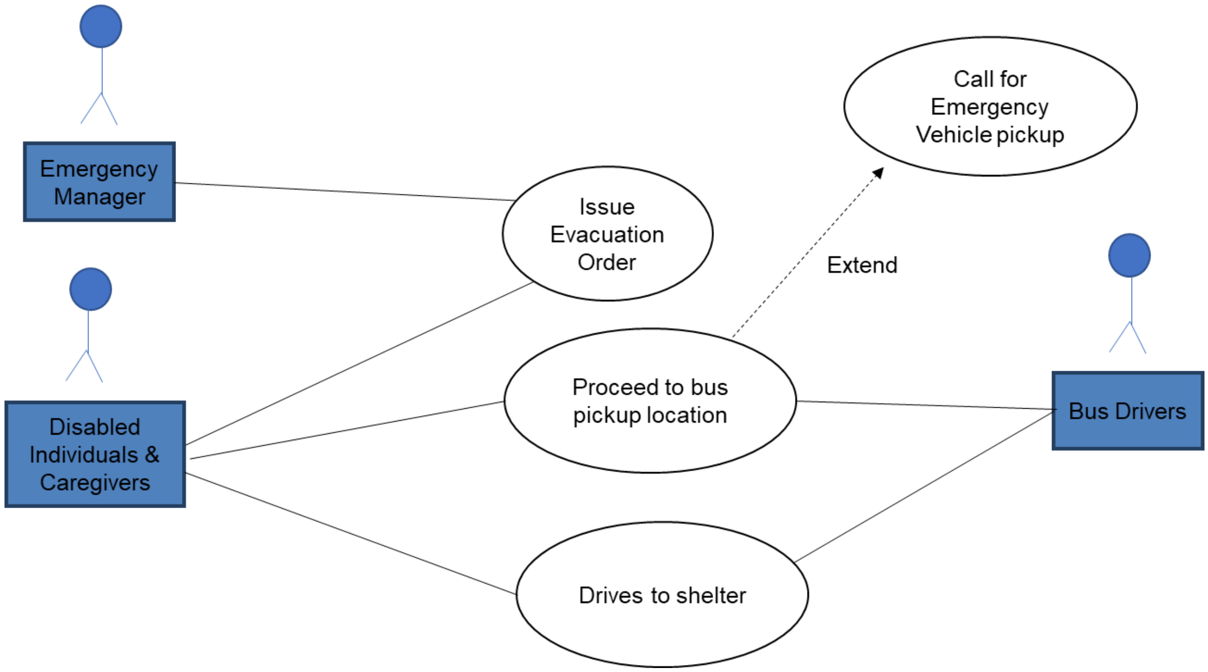


Figure 8. Evacuation of Zone A Use Case Diagram

5.1.2 Use Case 2: Evacuation of Zone B

Characteristic Information:

- Goal In Context: This use case is intended for the scenario in which an individual with access and functional needs, along with a caregiver, resides in Zone A or B and an evacuation order for Zone B is issued.
- Scope: The use of the evacuation transportation system by individuals with access and functional needs and their caregivers.
- Level: Primary
- Pre-Condition: An evacuation order must be issued for Zone B and available shelters established outside of Zone B.
- Evacuation Time Period Goal: Individual with access and functional needs reaches the shelter within a 45 hour clearance time.
- Primary Actors: Individuals with access and functional needs, Caregivers, Bus Driver, Emergency Manager
- Trigger Event: Evacuation order is issued for Zone B and shelters are opened.

Main Success Scenario:

Step	Actor	Action Description

Step 1	Emergency Manager	Emergency manager activates evacuation order of Zone B.
Step 2	Disabled Individuals & Caregivers	Individual with access and functional needs and caregiver locate nearest pickup location.
Step 3	Disabled Individuals & Caregivers	Individual with access and functional needs and caregiver make their way to the nearest pickup location.
Step 4	Bus Drivers	Bus driver makes way to pickup location
Step 5	Disabled Individuals & Caregivers/Bus Driver	Bus driver picks up caregiver and individual with access and functional needs at pickup location
Step 6	Disabled Individuals & Caregivers/Bus Driver	Bus driver transports caregiver and individual with access and functional needs to nearest shelter location outside of Zone B

Scenario Extensions

Step	Condition	Action Description
3a	Individuals with access and functional needs are unable to make it to the nearest pickup location.	Individuals with access and functional needs are to call 911 to request emergency services.
3b	Individuals with access and functional needs travel to separate pick up location with caregivers	The bus destined for that pick up point will transport individuals and caregivers to shelter.
6a	Nearest shelter location is at capacity	The bus reroutes to transport individuals to the next closest shelter.

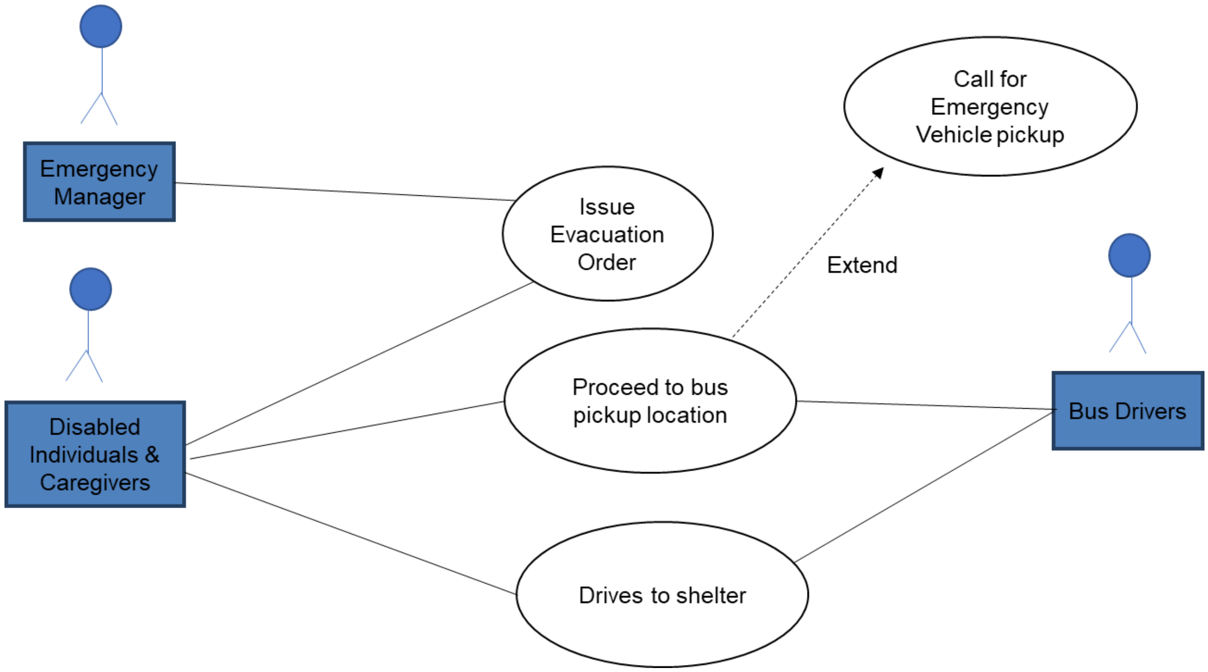


Figure 9. Evacuation of Zone A-B Use Case Diagram

5.1.3 Use Case 3: Evacuation of Zone C

Characteristic Information:

- Goal In Context: This use case is intended for the scenario in which an individual with access and functional needs, along with a caregiver, resides in Zone A, B, or C and an evacuation order for Zone C is issued.
- Scope: The use of the evacuation transportation system by individuals with access and functional needs and their caregivers.
- Level: Primary
- Pre-Condition: An evacuation order must be issued for Zone C and available shelters established outside of Zone C.
- Evacuation Time Period Goal: Individuals with access and functional needs reach the shelter within a 58 hour clearance time.
- Primary Actors: Individuals with access and functional needs, Caregivers, Bus Driver, Emergency Manager
- Trigger Event: Evacuation order is issued for Zone C and shelters are opened.

Main Success Scenario:

Step	Actor	Action Description
Step 1	Emergency Manager	Emergency manager activates evacuation order of Zone C.

Step 2	Disabled Individuals & Caregivers	Individuals with access and functional needs and caregivers locate the nearest pickup location.
Step 3	Disabled Individuals & Caregivers	Individuals with access and functional needs and caregivers make their way to the nearest pickup location.
Step 4	Bus Drivers	Bus driver makes way to pickup location
Step 5	Disabled Individuals & Caregivers/Bus Driver	Bus driver picks up caregivers and individuals with access and functional needs at pickup location
Step 6	Disabled Individuals & Caregivers/Bus Driver	Bus driver takes caregivers and individuals with access and functional needs to the nearest shelter location outside of Zone C

Scenario Extensions

Step	Condition	Action Description
3a	Individuals with access and functional needs are unable to make it to the nearest pickup location.	Individuals with access and functional needs are to call 911 to request emergency services.
3b	Individuals with access and functional needs travel to separate pick up location with caregivers	The bus destined for that pick up point will transport individuals and caregivers to shelter.
6a	Nearest shelter location is at capacity	The bus reroutes to transport individuals to the next closest shelter.

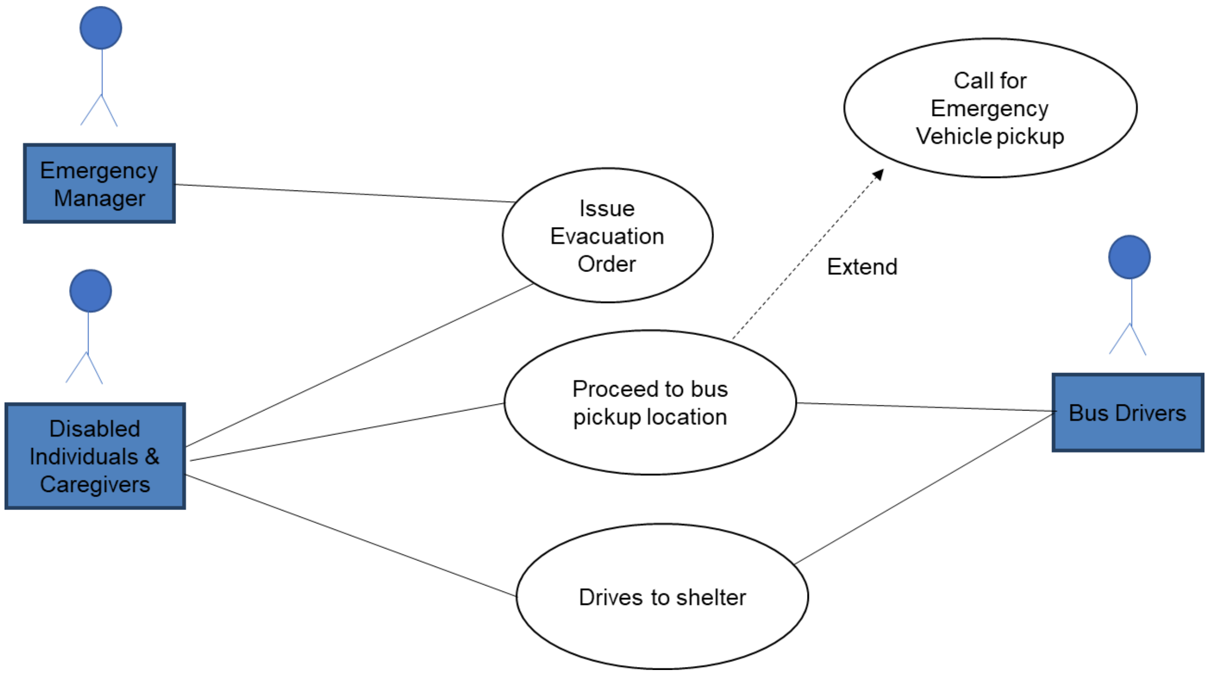


Figure 9. Evacuation of Zone A-C Use Case Diagram

5.1.4 Use Case 4: Evacuation of Zone D

Characteristic Information:

- Goal In Context: This use case is intended for the scenario in which an individual with access and functional needs, along with a caregiver, resides in Zone A, B, C, or D and an evacuation order for Zone D is issued.
- Scope: The use of the evacuation transportation system by individuals with access and functional needs and their caregivers.
- Level: Primary
- Pre-Condition: An evacuation order must be issued for Zone D and available shelters within Zone D, or another region.
- Evacuation Time Period Goal: Individuals with access and functional needs reach the shelter within a 67 hour clearance time.
- Primary Actors: Emergency Manager, Individuals with access and functional needs, Caregivers, VDEM representative
- Trigger Event: Evacuation order is issued for Zone D.

Main Success Scenario:

Step	Actor	Action Description

Step 1	Emergency Manager	Emergency manager activates evacuation order of Zone D.
Step 2	VDEM Representative	VDEM Representative provides guidance for evacuation.
Step 3	Disabled Individuals & Caregivers	Individuals with access and functional needs and caregivers adhere to guidance from VDEM representatives.

Scenario Extensions: N/A

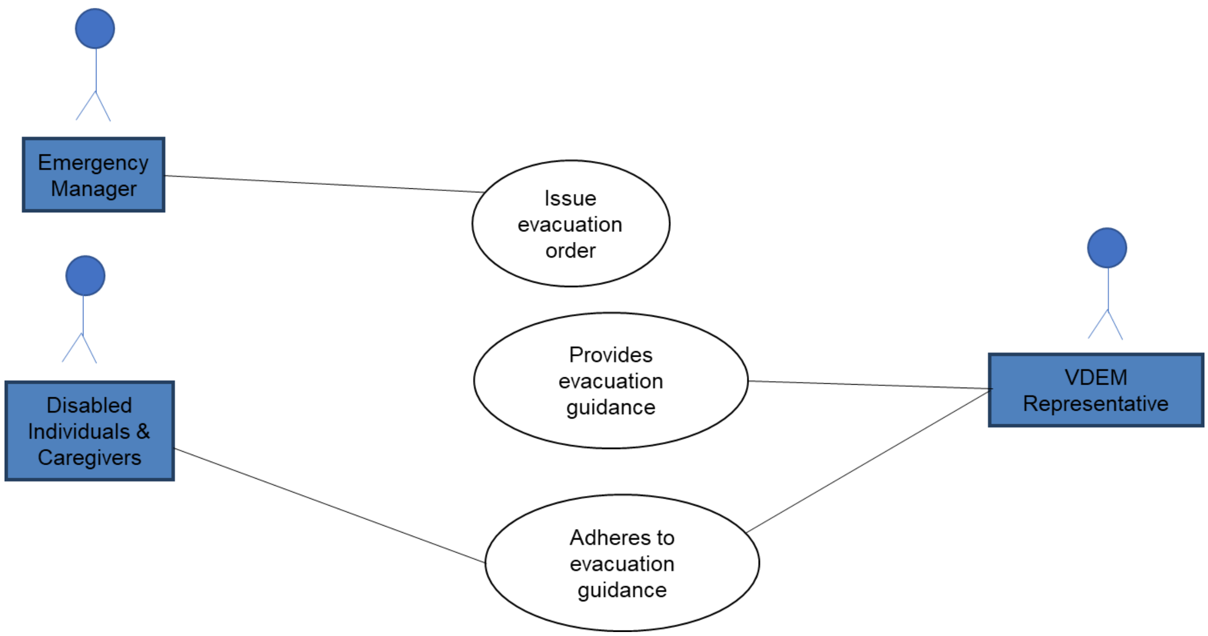


Figure 10. Evacuation of Zone A-D Use Case Diagram

6 Modeling and Simulation

The concept for this bus evacuation system draws elements from two hurricane evacuation decision-support models using public transit [Margulis, L., et al., 2006] and [Swamy, R., 2016]. Both models include shelters and buses which make trips to pick-up locations until the given population is moved to shelter. Margulis, et al, proposes a single-stop approach in which buses make a fixed number of trips to different stops, returning to shelter after each stop. Swamy, et al, proposes a more comprehensive approach to shelter, pickup, and route location that involves both optimization and simulation. The key issues addressed in these studies are the identification of pickup locations, assignment to shelters, and the design of routes that minimize overall travel burden. The objective of these studies is to either maximize the number of people evacuated or to minimize the overall clearance time for a given population. The authors each propose heuristic approaches to solving these problems. The efficiency and scalability of these approaches is particularly useful for large problem scenarios such as metropolitan areas with dense populations, constrained resources, and too many decision variables to effectively process without computing power.

6.1 Methodology

Our modeling intent is to evacuate a known population concentrated into multiple nodes located across Virginia Beach within an acceptable timeframe and with acceptable evacuee wait times per the system requirements. Each node carries a known and fixed number of individuals needing evacuation. Our model will evacuate 100% of these individuals.

Buses will travel radially from shelters to pickup locations in order to move evacuees to shelters. Buses are allowed to stop at up to two locations. This number was chosen to limit modeling complexity for the scope of this project, while allowing greater flexibility than only one stop per bus. The problem of deciding facility locations is considered out of scope and unnecessary for our project requirements. Both shelter and census tract population centroid points are given from Virginia Beach planning data. Pickup locations are by default located on the population points, and are intended to be representative of a stop placed somewhere within the census boundaries.

Our model employs a blend of deterministic routing heuristics and agent-based simulation to model the bus network. Uncertainty caused by evacuee arrival times at pickup locations is a major driver of both clearance time and wait times. The model therefore provides a way to test different routing models in a stochastic environment.

The scope and design of this model is as follows:

- *Population:* Population demand and location is a user input consisting of a set of known, discrete points on the map: each with a quantity of people requiring evacuation and a flood zone designation (A, B, C, or D).

- *Shelter location:* Shelter facility location is not decided by this model. These are considered an input and will include their respective names, locations, capacity, and tier levels. The tier-based approach means that Tier 1 shelters fill first in an evacuation, then Tier 2, and finally Tier 3. When a tier opens, all shelters categorized within that tier are considered to be "open" as well.
- *Pickup location:* Although pickup locations are by default located directly on population points, it is not necessary to do so. The model is able to accept as inputs any number of potential pickup locations and match them to population points based solely on driving proximity. A maximum threshold may be set which prevents populations from traveling too far to a given bus stop. The primary intent for this feature is to allow clusters of population points to assemble at a single, proposed bus stop. This may be desirable from a consistency standpoint to keep the set of population points constant, while assessing the benefit of adding new bus stop locations. Pickup arrivals are governed based on a distribution function such as the Rayleigh distribution [Duanmu, et al., 2010]. However, if a pickup location exists some non-zero distance from a population point, the time to transit from that point to the pickup location may also be considered. In our modeling scenario this is assumed to be zero.
- *Shelter assignment:* Each pickup is initially assigned one shelter. This assignment heuristic takes on one of two forms: closest-proximity linkage (simple) or least-overall-transit-distance (heuristic search method).
    - The first approach assumes no knowledge of pickup demand at each stop, and simply links each pickup with the closest shelter. The simulation dynamically re-routes buses and opens additional tiers as necessitated by shelter capacity.
    - The second approach was devised as a means to reduce trip lengths for some buses when their assigned shelter became filled. It makes two major assumptions: that the knowledge of pickup demand is known, and that if the demand is sufficient, multiple tiers of shelters may be opened simultaneously. It reduces transit burden by creating an efficient allocation strategy from the very beginning. The heuristic used in this approach is a tabu search with swapping improvements of an initial feasible solution. The objective is to minimize the distance traveled for each unit of demand. The search ends when no improving solution can be found within a certain number of steps.
- *Number of buses:* The number of buses is a user input for the model.
- *Route assignment:* Once a number of buses has been determined, the model determines which routes buses will take to cover each pickup location. A bus route will always include the same pickup locations for the duration of the simulation, even if the shelter is changed. The two approaches taken by the model are as follows:

- The first approach simply assigns one bus per pickup-shelter link. This number may be increased depending on simulation results to achieve a desired result. Routes will dynamically shift to the next closest shelter if the present shelter is filled (as discussed).
- The second approach allows up to two stops per route, using greedy heuristics to achieve a desired amount of "bus coverage" at each pickup location. Bus coverage is additive and occurs in increments of 0.5, which corresponds to a bus visiting the pickup on a two-stop route. The desired bus coverage is determined mathematically using a combination of transit time, demand, and a calibration parameter. The heuristic searches feasible routes (consistent with allocation plan) and adds the one that brings the coverage closest to the desired level at the least transit cost. Once an initial route assignment solution has been generated, a second heuristic performs swaps to ensure any uncovered pickup locations are covered by at least 0.5. Additional buses may be added iteratively to whichever pickup location has the highest wait time in the simulation. For two-stop routes, buses will alternate directions for each trip during simulation.

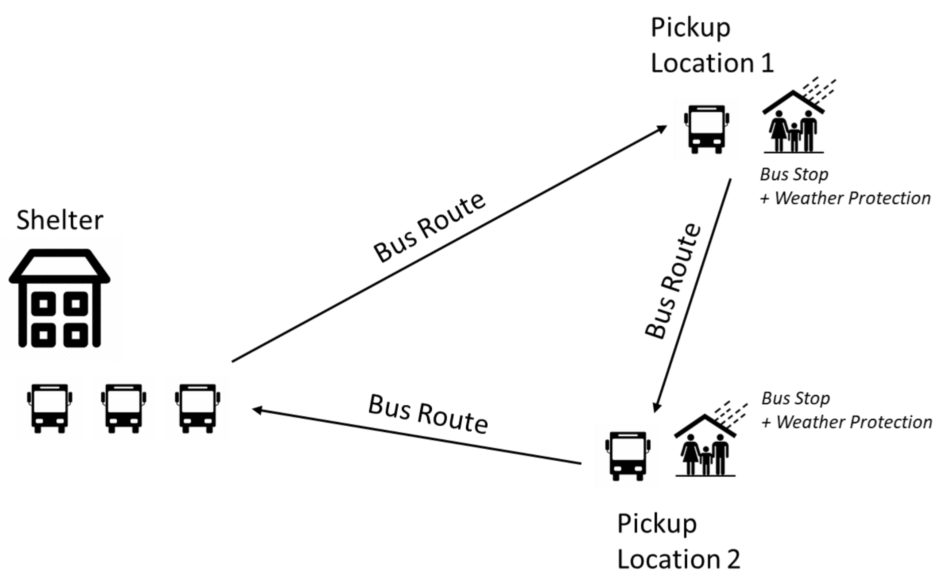


Figure 10. Pickup Point to Shelter Relations Example Diagram

The modeling choice of using stationary routing assignments is again based on the fact that demand is considered to be known (regardless of whether shelter capacity is taken into account). It poses the potential, real-life benefit of familiarity for bus drivers and increased reliability. However, as a topic for future study, dynamic routing should be investigated in terms of its ability to better adapt to unknown population demands. For instance, if trained personnel are positioned at every pickup location with counters to measure queue lengths and wait times, it would be possible for coordinators to send routing assignments on a dynamic basis during an evacuation. Additionally, many-stop routes should be considered for large regions with low population densities.

The agent-based simulation will measure the flow of evacuees into shelters over time, as well as the wait times experienced by evacuees at pickup locations and in the bus during transit. From the resulting data, we will recommend the number of buses to achieve a desired outcome for different evacuation cases. We will compare the findings with the city's current protocols to create recommendations. High-level, analytical questions we will investigate include:

- How many buses are needed?
- How does arrival distribution influence clearance time and waiting time?
- What factors should be considered in designing a routing strategy?

The model is built as a Python project directory. Python has a variety of open-source packages that we have used. The packages OSMNx, Mesa, Networkx, and Folium were most instrumental: Mesa is an agent-based simulation package; OSMNx connects to OpenStreetMaps and produces street networks and speed limit information; Networkx provides efficient routing between points; and Folium provides high-quality mapping.

Table 10. Data Input Descriptions

Inputs	**Fields**	**Notes**
Census Data	ID, location, number of people	Centroid of census tracts
Shelters	Name, location, capacity, tier	
Flood Zones	Mapping polygons	Flood Zones A, B, and C
Number of buses	Model determines initial number of buses based on logic rules	Variable Input
Bus Capacity	Max number of individuals	20 seats
Load/Unload Time	Time to load/unload one agent	30 seconds per agent/caregiver pair 4+ minutes to load wheelchair
Bus Interval	Minimum arrival interval; Maximum arrival interval	Future modeling should change this to departure intervals
Caregivers	Number of caregivers per agent	1 caregiver for every agent
Percent sheltered	Percent of census data who will evacuate and go to shelters	(80%)(8%) = 6.4% of total disabled population

Arrival Distribution	Arrival distribution for evacuees at pickup locations	Rayleigh distribution

We define a population node as a point identified from census data that includes the number of people with access or functional disabilities who will be evacuated. For the purposes of this analysis, our assumption is that a single bus stop is placed directly on each population node, regardless of exact location. This is intended to be an initial approximation of the actual system, and should be refined in detail in follow-on work.

Driving times are calculated in Python using the OpenStreetMaps “OSMNx” package assuming standard, free-flow traffic conditions. A Poisson distribution used to generate random variations in driving times.

For bus capacity, assume each bus carries up to 20 individuals, or 10 agents total. For loading and unloading times, we assume a fixed 30-second loading time per agent (includes person with access or functional disabilities + 1 companion). As a case study, we will also include the ~29% of the population with ambulatory difficulties from Table 5 and assume that each individual takes 4 minutes to load and offload.

A “bus interval time” is counted from the time the first bus arrives to the time the second bus “arrives,” since the second bus is “idling” at the pickup and has not opened its doors yet. The loading time is therefore added onto the end of the interval for P4 and P5. P6 arrives too late to be picked up. Future modeling efforts should refine this assumption to allow loading to occur during idling.

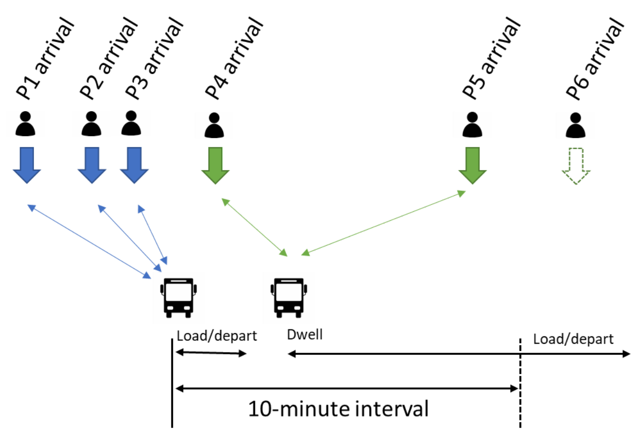


Figure 11. Loading, Dwell, and Departure Concept

Table 11. Basic Simulation Steps

Step	Description	Outcome

1	**Compile inputs**	Inputs and parameters loaded into data structures; Initialize mapping
2	**Generate routes & buses**	Collection of buses and assigned routes
3	**Simulate evacuee and bus agent movement**	Agent activity data vs. time
4	**Generate outputs and plots**	Evacuee wait times, Shelter occupancy, Activity log (CSV), Queue lengths, Map

The detailed steps to running the simulation are as follows (see Table 11 for basic overview):

1. Load inputs and parameters
2. Initialize map
3. Generate initial allocation and routing (see Table 13 for more details)
    a. *Allocation Model 1: Match pickups to nearest Tier 1 shelter regardless of demand or shelter capacity. If shelter is filled during simulation, buses must reroute to another shelter, resulting in potential delays.
    b. *Allocation Model 2: Solve capacitated facility allocation problem to reduce overall travel distance. The initial allocation plan will include multiple tiers of shelters if necessary.
        i. Tabu search heuristic: Minimal-cost allocation of demand to capacitated facilities; perform improving swaps; all demand from a pickup must go to the same shelter.
    c. Routing Model
        i. Calibration: Scale the fractional bus coverage objective for pickups based on pickup demand, distance to shelter, and a calibration value which will be varied until the desired number of buses is reached across all pickups.
        ii. Greedy heuristic: Generation and assignment of pickup routes to buses to minimize the shortfall of actual bus coverage vs. objective amount.
        iii. Final step: If necessary, modify routes to ensure all pickup locations are covered. If a bus covers one pickup, it is capable of expanding its route to cover another pickup that is in need of a bus. This must adhere to shelter allocation rules. If multiple, feasible route expansions are identified, the one yielding the smallest overall travel time is chosen.
4. Initialize agent-based simulation
5. Run simulation
    a. Evacuees arrive at pickups on some specified distribution schedule
    b. Buses are assumed to be at pickup locations at start of simulation

c. Bus agents travel continuously between shelter and pickups, stopping only to load or offload evacuees. If shelter capacity has been reached at any point, the bus reroutes to the nearest, available shelter. The bus continues serving the same pickup location for the duration of the simulation, even if it changes shelters.
d. At each stop, bus takes the time necessary to load as many people as possible
e. If nobody is present, the bus continues moving along its route
f. If shelter fills, bus reroutes to closest available shelter

6. Generate outputs
    a. Line plot of shelter occupancy over time
    b. Box-whisker plot of evacuee wait times at pickups
    c. Box-whisker plots of both 80% and 100% clearance times for a given run
    d. Box-whisker plots of overall evacuee wait times across all pickups
    e. Histogram plot of arrival distribution at pickups and at shelters
    f. Activity log to CSV file
    g. HTML map with routes, locations, and interactive markers
7. Repeat Steps 3-6 with until satisfied
    a. Once an initial run is performed with N buses, the model may add a bus to any route that covers a pickup location experiencing the highest wait time. This may be repeated iteratively for any number of buses.
    b. Evacuee wait times should be within the required range
    c. Clearance time should be within the required range

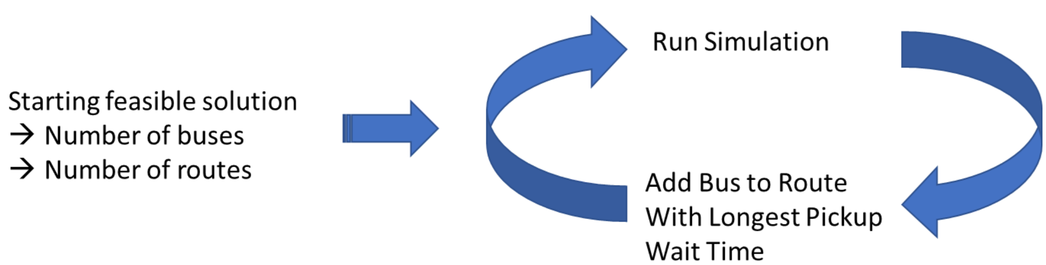
Table 12. Pickup-Shelter Allocation Schemes

Allocation Scheme #1 (Single-Tier Sheltering)	- Match pickup locations to the nearest shelter - Works best when all of demand fits within one tier of shelters - Requires no knowledge or planning in terms of shelter capacity or demand size - Buses will reroute automatically during the simulation whenever shelter capacity is exhausted. This may result in extra travel burden for the bus network, hence why it works best when demand does not exceed tier shelter capacity. - All demand from a given pickup must go to one shelter, i.e., a pickup cannot link to multiple shelters unless that shelter capacity is exhausted during simulation.
Allocation Scheme #2 (Multi-Tier Sheltering)	- Minimize overall transit distance across multiple tiers of shelters. - Works best when demand exceeds the remaining capacity of the current shelter tier level, and must expand to the next tier. - Assumes some knowledge about what the demand will be and

	what the shelter capacity is. - Tabu search heuristic allocates demand from pickups to capacitated shelters with minimal travel volume cost - Improving swaps of demand between pickup locations and shelters are performed until no improvements can be found. Stopping conditions occur after the solution stalls (fails to find an improving swap) for some number of turns. - Opens multiple tiers of shelters from the start (if necessary) to cover the total demand - All demand from a given pickup must go to one shelter (under same conditions as Single-Tier Allocation Scheme)

Table 13. Bus Routing Heuristic

Step 1	**Estimate bus coverage needed per pickup demand** Inputs: Desired number of bus routes Outputs: How many buses to generate from each shelter; how much fractional bus coverage is needed at each pickup. A mathematical formula is used to estimate the amount of bus coverage across all pickup locations. Although formulated with several variables, the end result is simply a calibration factor scaled by the amount of demand and travel time between the pickup and shelter. $t_{trip} = 2 \cdot t_{transit} + t_{load} + t_{unload}$ $N_{trips} = \frac{demand}{bus\ capacity}$ $T_{clearance} = \frac{N_{trips} \cdot t_{trip}}{N_{buses}}$ $\Rightarrow N_{buses} = \frac{t_{trip} \cdot demand}{T_{clearance} \cdot bus\ capacity} = C_{parameter} \cdot t_{transit} \cdot demand$ This estimate is intended to address the problem of disproportionate wait times at stops with higher demand volume and distance. Calibration allows easy scaling of the number of bus coverage needed. The algorithm iterates $C_{parameter}$ by some small increment (0.01), generating a set $N_{buses, pickup} = \{N_{buses, P1}, N_{buses, P2}, ..., N_{buses, PN}\}$, rounds off the numbers to

	the nearest whole integer (min=1), and sums the result to return the total number of buses across the set. Once this number equals the desired amount, the calibration is complete and the appropriate number of buses is generated at each shelter.
Step 2	**Assign bus routes to meet demand coverage requirement** <u>Inputs</u>: Results from Step 1 <u>Outputs</u>: 1- or 2-stop routes assigned to every bus <u>Metric</u>: Fractional bus coverage per pickup Greedy heuristic assigns routes to buses of up to 2 stops each until the coverage per pickup is as close to $\{N_{buses,\,p}\}$ as possible. A bus that visits two stops is assumed to contribute 0.5 to each stop. The simulation alternates route directions with every trip. The choice of routes must adhere to the demand allocation rules produced by the first heuristic, i.e., a route cannot be assigned that delivers people to the wrong shelter. Once a feasible set of routes is assembled, the one with the minimal traveling distance is chosen. If, at the end of Step 2, a feasible solution could not be reached and a pickup location is left uncovered, the model may allow a route with one stop to expand its coverage to the uncovered pickup.
Step 3	**Simulate** The result of Steps 1-2 is a set of buses, each with designated routes that it will repeat until all evacuees are moved to shelters. Simulation will reveal how well the heuristics performed in terms of both clearance time and evacuee waiting times. If either metric is excessively large, then buses may be added sequentially to existing routes to target high-wait pickups. In particular, an iterative feedback loop is used for most simulation results in this project, in which an initial starting point is chosen using calibration, followed by successive simulation runs and assignment of buses to routes with pickups experiencing the longest wait time. 

6.2 Simulation Case Overview

The scenario used across all simulations consists of census tract data for Virginia Beach, which concentrates populations into individual nodes located at the centroid of each tract. These nodes are binned into flood zones based on our own approximation of Virginia Beach's flood zone map. Although the census tract centroids are positioned using official data from www.census.gov, the exact boundaries of flood zones from the Virginia Beach website had to be approximated, and consequently the populations listed below represent our best estimate of how the census data would be binned into Virginia Beach flood zones.

Table 14. Binning of Virginia Beach Census Data

	Total Number of People with Disabilities	**Number who would shelter (80%*8%), plus caregivers**
Virginia Beach	48,643	6,226
Flood Zone A	3,777	484
Flood Zone B	14,595	1,870
Flood Zone C	15,400	1,972
Flood Zone D	12,639	1,618
No Zone	2,232	286

The following map forms the basis for how populations are binned into zones and counted in our modeling and simulation. Red indicates Zone A, orange is Zone B, yellow is Zone C, and blue is Zone D.

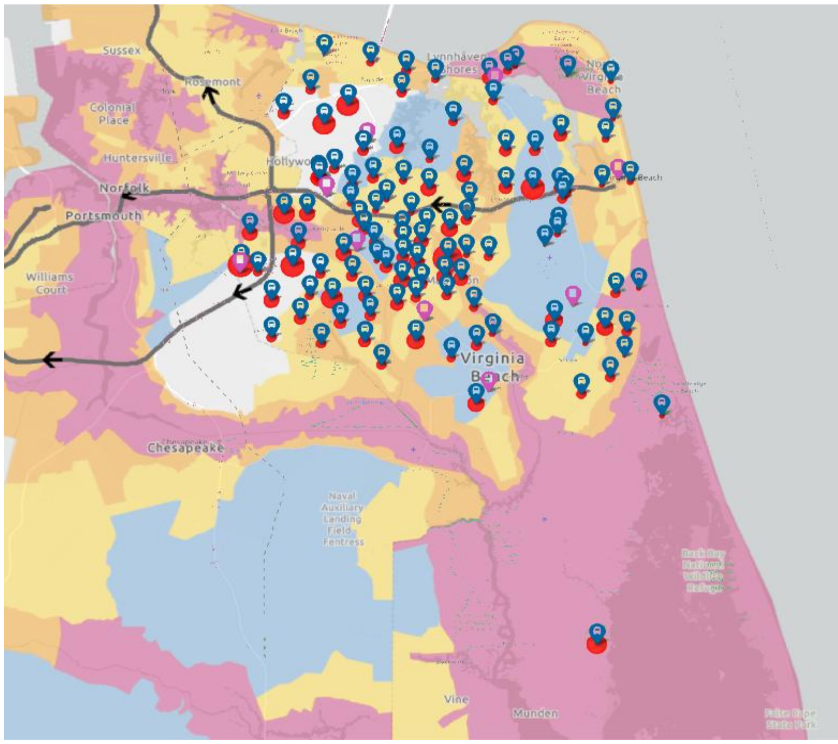


Figure 12. Virginia Beach Population Node Distribution

6.3 Experiments and Results

As described in the previous section, it is possible to generate a solution for any number of buses. An iterative approach was suggested in the previous section as a way to decrease wait times by adding buses to routes with maximal wait times at pickups. This approach therefore does not increase or modify the routes, but instead adds buses to existing routes.

The point at which the model switches to this iterative mode will be referred to as a "branching point." It is generally sufficient to choose a branching point at the first feasible solution, but an "optimal" branching point can be chosen to improve the results even further. Figures 13 and 14 show the impact of which branching point yields the best results.

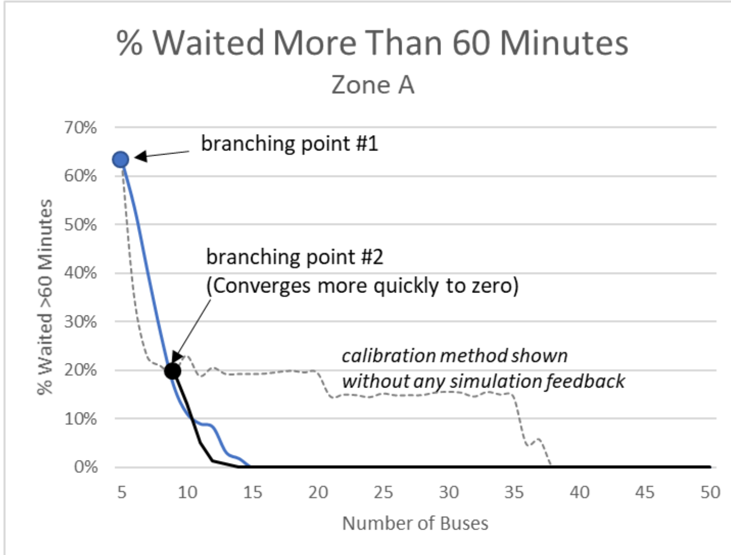


Figure 13. Choosing a Starting point: Impact on Waiting Time

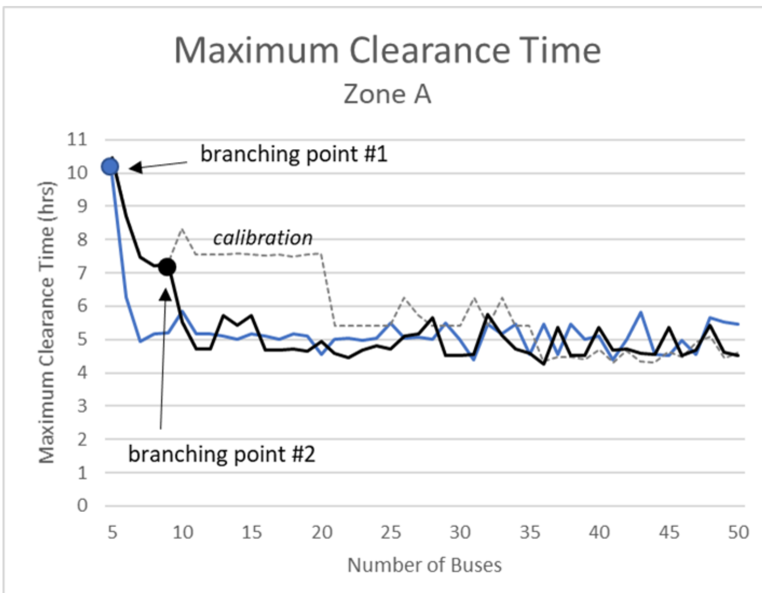


Figure 14. Choosing a Starting Point: Impact on Clearance Time

If waiting times are more important than clearance times, then it may be desirable to branch at a point that yields better waiting times, as shown in Figure 13.

The procedure used for determining the best runs in this project is therefore as follows:

1. Do a calibration sweep across some feasible range of bus numbers
2. Branch at the first point (first feasible solution) and use simulation feedback to

generate additional buses
3. Branch at later points until the resulting solution ceases to improve

Experiment 1: Bus Intervals, Wait Times, and Time Spent on Bus

One issue that arises in the simulation is that multiple buses traveling along the same route are dispatched simultaneously and tend to travel as a group to each pickup location. Unless the pickup is saturated with demand, the benefit of having multiple buses is diminished by the fact that anyone who arrives just after the group of buses leave must wait for the next round-trip. This results in wait times such as those shown in Figure 14, which shows the amount of waiting that occurs on arrival at some time during a Zone A evacuation. Anyone who arrives just after 45 minutes must wait an hour for the next pickup at around 110 minutes.

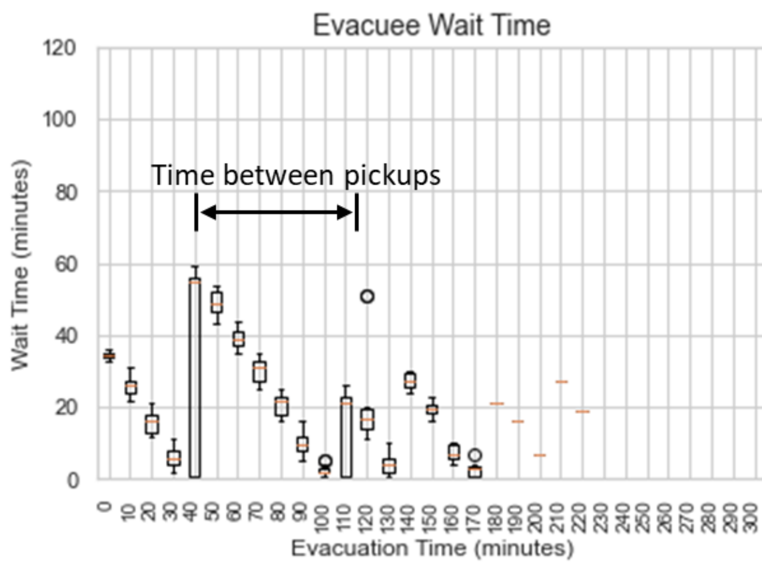


Figure 15. Waiting Times at a Sample Pickup Location, No Bus Dwell Time

Although the system requirements state 60 minutes as the waiting threshold, it is worthwhile to assess how easy or difficult it is to reduce the wait time further. Figure 15 shows the relationship between the number of buses and the percentage of people who ended up waiting longer than the threshold amount. The problem is apparent that it is not possible without a very large number of buses to reduce the waiting times for anything under 60 minutes.

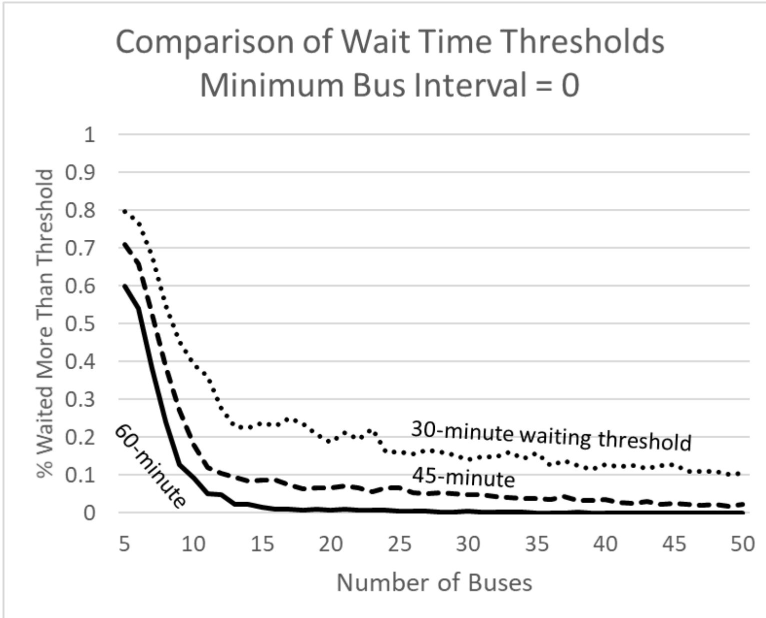


Figure 16. Percentage Over Threshold, No Minimum Bus Interval

The answer to this problem is that both shorter and more consistent wait times can be generated easily by adding minimum visit intervals for buses at a given pickup. A minimum interval refers to the minimum amount of time between bus arrivals. Figure 16 shows the result of setting the minimum bus interval to 10 minutes. It is possible to maintain shorter wait times with fewer buses.

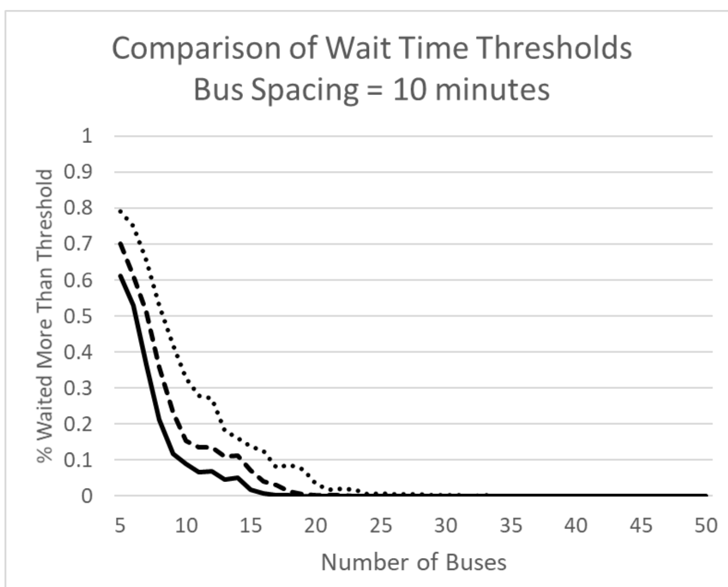


Figure 17. Percentage Over Threshold, 10-Minute Minimum Bus Interval

Figure 18 summarizes the benefit of different intervals in terms of the number of buses required to stay entirely within the wait time threshold (30, 45, or 60 minutes). The best interval in this case of Zone A is 10 minutes.

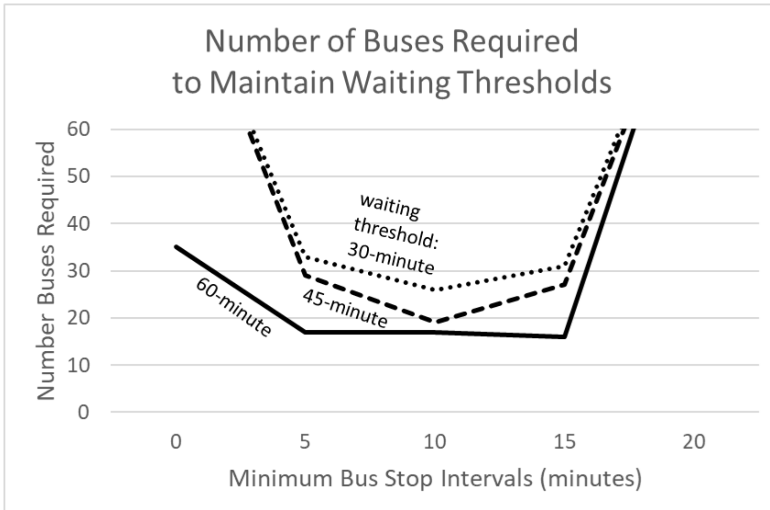


Figure 18. The Impact of Different Bus Intervals and Waiting Thresholds

Finally, to revisit the first plot which shows wait times as a function of arrival times for a given pickup, we rerun the same case using a 10-minute minimum bus interval with 28 buses and a 30-minute wait time threshold. The results are shown in Figure 19.

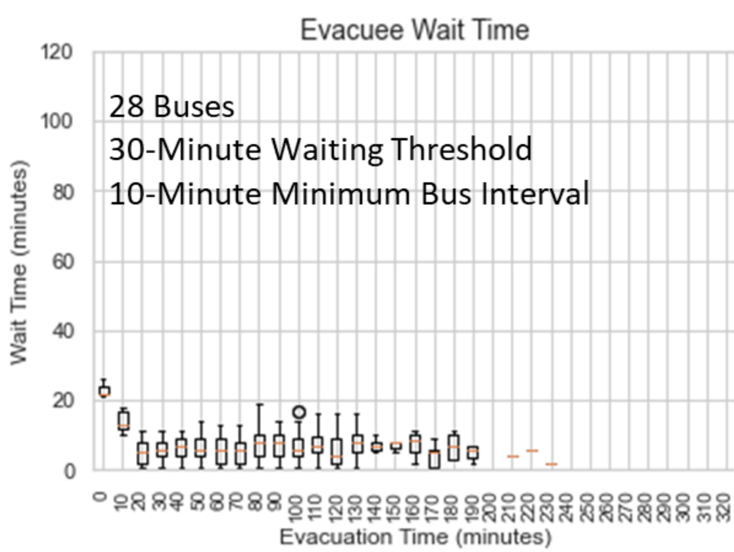


Figure 19. Mitigated Wait Times Using 10-Minute Bus Interval

The time people spend in buses is also important to consider. Figure 20 shows the time spent riding in a bus for different cases.

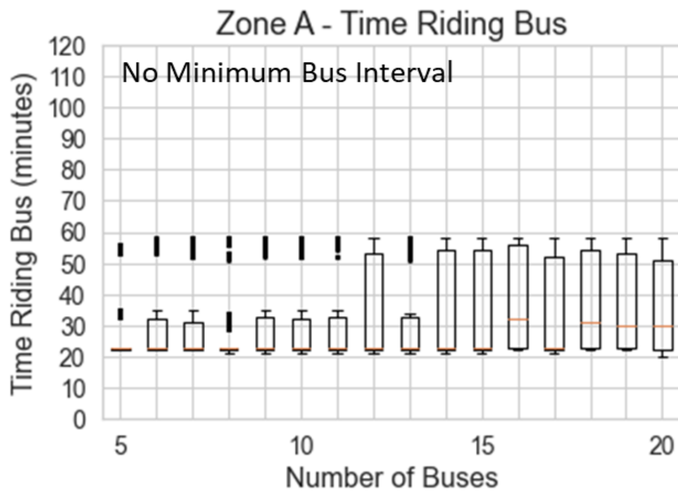


Figure 20. Time Spent on Bus, No Minimum Bus Interval

If buses are spending longer on routes because of this minimum interval, the amount of time people spend on buses may also increase. Figure 21 shows the time spent waiting in the bus, assuming a minimum 10-minute bus interval. The time an evacuee spends on a bus is assumed to begin when they depart the pickup location, and end when the bus arrives at a shelter.

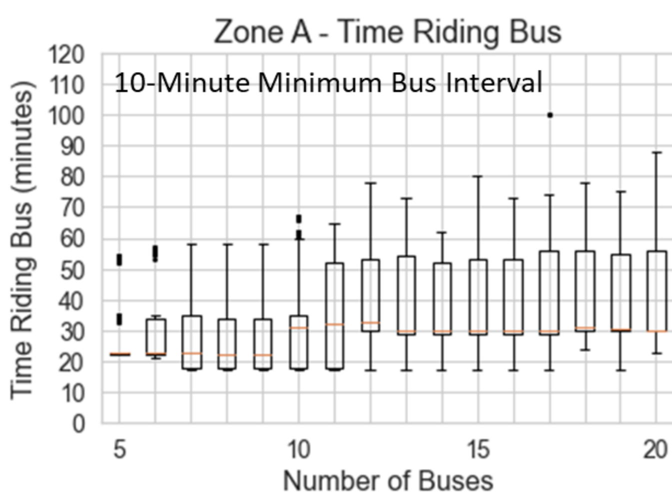


Figure 21. Time Spent on Bus, 10-Minute Bus Interval

The amount of time buses spend waiting at a pickup location due to the minimum bus interval is shown in Figure 22. To illustrate, if 3 buses arrive at the same pickup at the same time, the third bus will dwell for 30 minutes plus loading time before proceeding. Future modeling should take into account that loading may occur during dwell time.

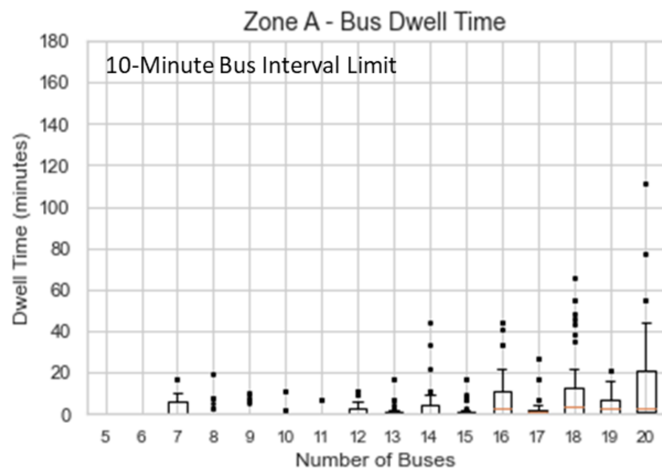


Figure 22. Bus Dwell Time

As expected, there is some correlation between the amount of time buses spend idling at pickup locations and the amount of time people wait on buses, since during some of that idling time there may be passengers aboard from the first pickup location. Additionally, having a bus idle for an hour or longer may be unacceptable, and a better use may be found for the bus during that hour.

In conclusion, the following questions should be addressed in follow-on modeling:

1. What should the bus interval be?
2. What is an acceptable amount of passenger time spent inside a bus?
3. Should bus idling time be limited?

Experiment 2: Sensitivity to longer load times due to mobility impaired individuals

The impact of individuals who require wheelchair, walkers, or other forms of assistance is an important factor in modeling a bus system for people with AFN's. This impact will be measured in terms of increased onloading and offloading times for a percentage of the sheltered population. From the census data in Table 5, we calculate 29% of the passengers require some form of mobility assistance. This will be modeled as a fixed value ranging from 30 seconds to 4 minutes. The scenario used in this experiment is Zone C.

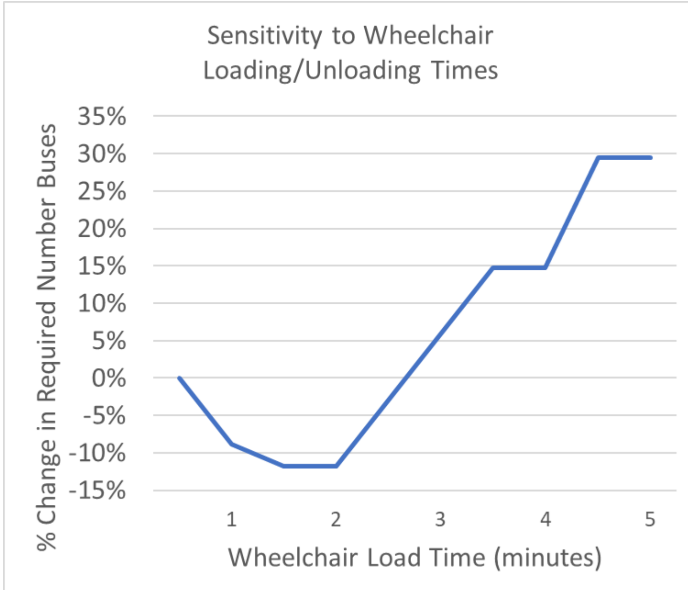


Figure 23. Bus Dwell Time

Analysis of Figure 23 shows that a 4-minute loading and unloading time increases the bus requirement by 15% to maintain <60-minute wait times at pickup locations. The “dip” between 1-3 minutes occurs because of the bus interval issue in Experiment 1. A 10-minute minimum interval was chosen in Experiment 1 for modeling, but that was based off of Zone A; it is apparent from this analysis that additional tuning may be needed for individual scenarios. Future modeling should focus on finding optimal bus intervals and operational rules. However, the conclusion of this experiment is that an increase in loading time due to wheelchairs does not always result in a linear increase in overall waiting times and consequently the bus requirement. Thus, the key take-aways from Experiment 1 are:

1. Bus idling intervals should be optimized for every, individual scenario
2. Additional loading times due to wheelchairs does not necessarily drive up the number of buses required to maintain waiting times of less than 60 minutes
3. Bus idling time can be used to “absorb” some of the loading time by allowing passengers to board early

Case Study 1: Evacuee surge conditions, 60-minute waiting threshold

The first set of experiments assumes most evacuees will arrive over a period of about two hours, following a Rayleigh distribution with peak arrival at 1 hour. This is an extreme situation that may be the “best” case in terms of clearance time (if the bus system can handle the demand), but the most difficult case in terms of wait times. The purpose of this set of experiments is to get a sense of how the bus system may be stressed in terms of maintaining reasonable waiting times, which may be of great importance during inclement weather.

Because Zones A-B do not exceed Tier 1 shelter capacity, the Single-Tier Allocation method will be used to achieve minimal transit times. This means that each pickup will simply be routed to the closest shelter.

Another key assumption of these first experiments is that the evacuation of each zone occurs simultaneously across all pickups within that zone. This means that the pickups are not organized into groups with scheduled pickup windows, but rather all evacuated at once. The expected outcome is that the clearance time will be shorter, but the wait times will be higher. The end result is that more buses will be required.

The metric used to assess wait times is the percentage of evacuees who waited longer than 60 minutes before being picked up by a bus. Buses are pre-positioned at pickup locations at the start of simulation, so the initial transit time from shelters to pickups does not weigh into this metric. Another key metric is both the 100% and 80% clearance times across all simulations.

The following plots show the outcome of the Zone A evacuation of 484 individuals to Tier 1 shelters using the Simple Allocation and Improved Allocation approaches. The results show that in both cases, 15 buses is sufficient to keep wait times below 60 minutes. The maximum clearance time as well as 80% clearance time are also shown to flatten out after 15 buses.

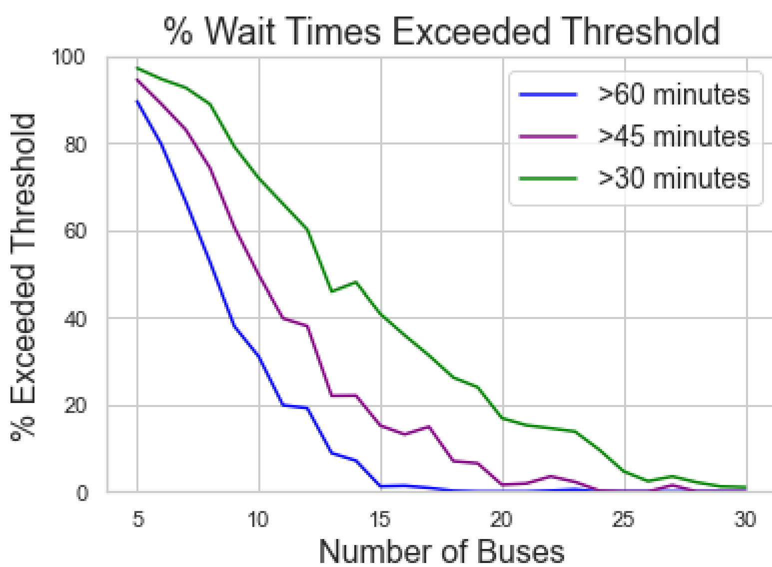


Figure 24. Zone A: Evacuee Wait Time Percentages

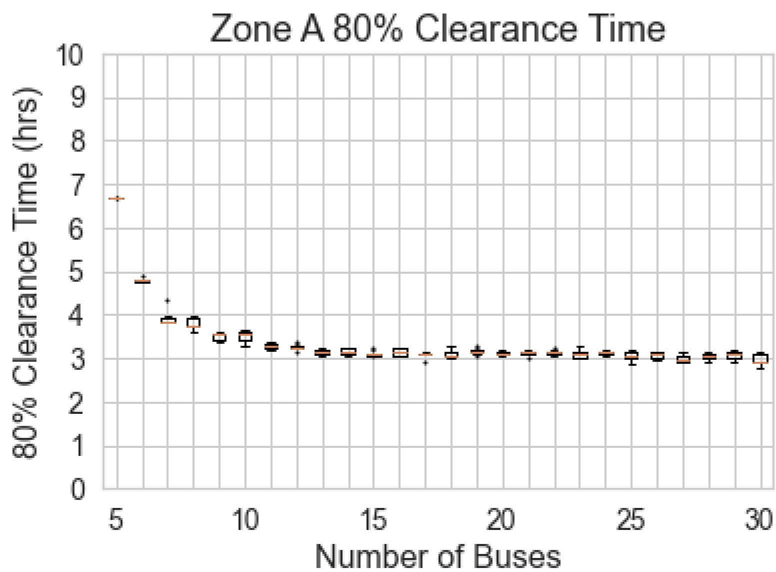


Figure 25. Zone A: Clearance Time for 80% of Population

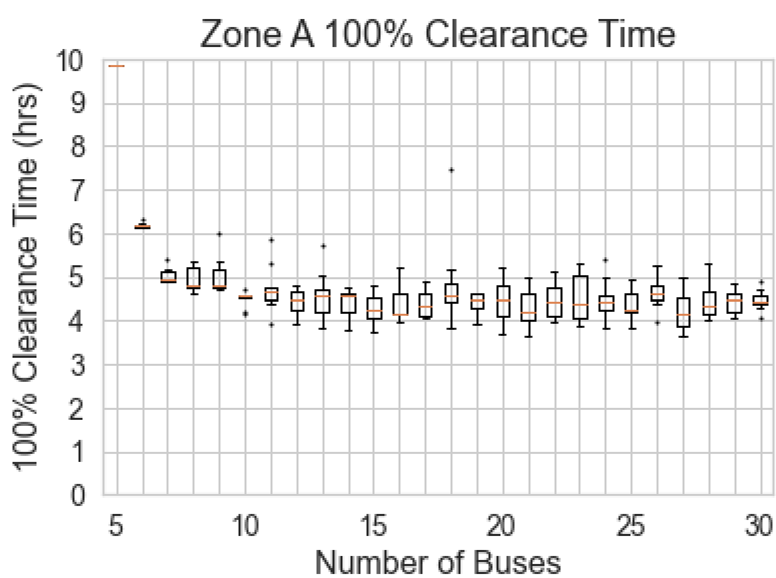


Figure 26. Zone A: Clearance Time for 100% of Population

The occupancy in each shelter after Zone A evacuates is:

- Tier 1 - Kellam High School: 48
- Tier 1 - Landstown High School: 184

- Tier 1 - Old Donation School: 254

Zone B evacuation is treated as an independent event except that shelters assume capacity of Zone A individuals as listed above. A total of 1,870 individuals are evacuated to Tier 1 shelters. The results show that with 40 buses, evacuee wait times are reduced to the threshold value of 60 minutes with a 1% margin of error.

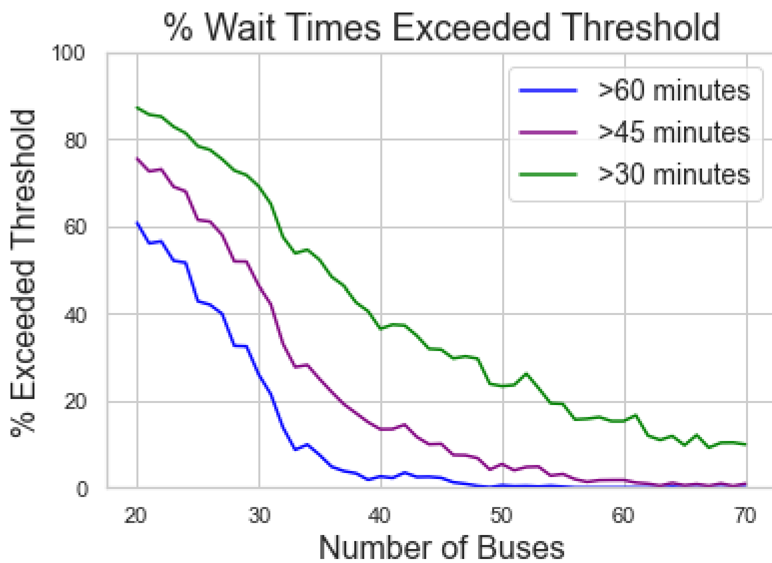


Figure 27. Zone B: Evacuee Wait Time Percentages

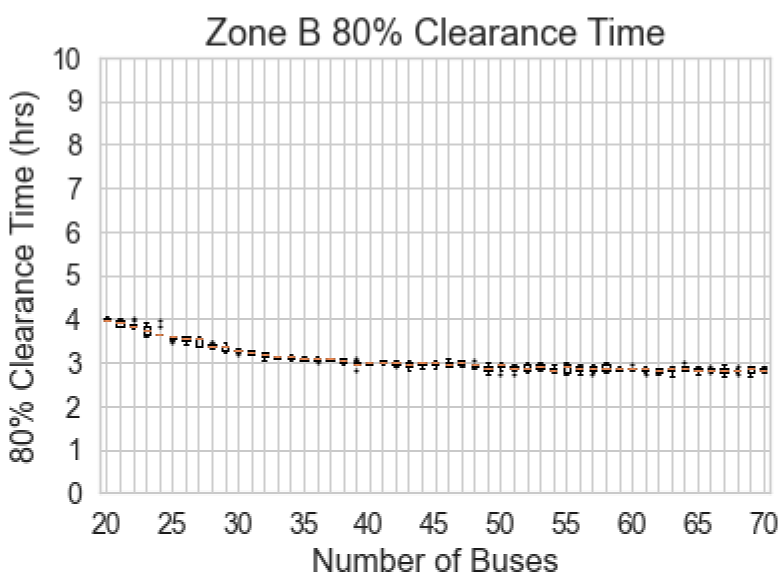


Figure 28. Zone B: Clearance Time at 80%

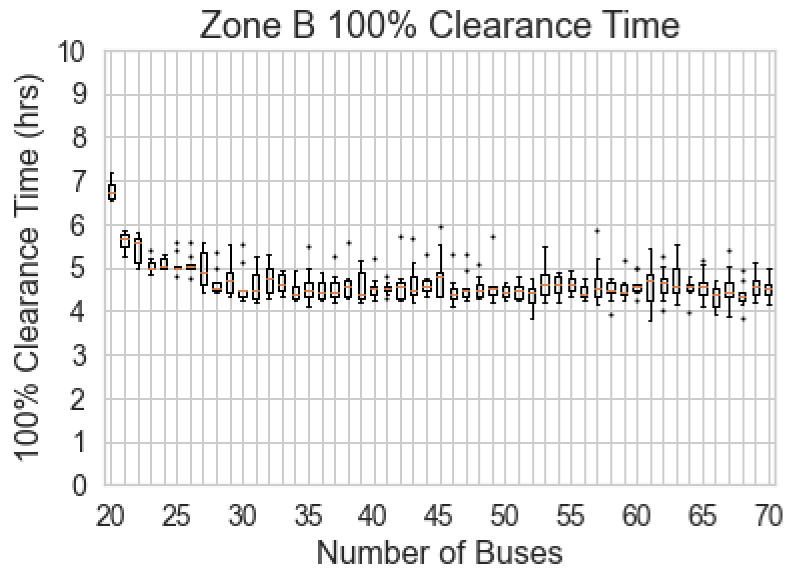


Figure 29. Zone B: Clearance Time at 100%

The occupancy in each shelter after Zone A and B evacuate is:

- Tier 1 - Kellam High School: 604
- Tier 1 - Landstown High School: 1,142
- Tier 1 - Old Donation School: 610

Zone C evacuation assumes shelter occupancy from zones A through B as listed above. A total of 1,972 individuals from Zone C will be evacuated to Tier 1 and 2 shelters. The results show that with 50 buses, fewer than 1% of the evacuees will wait more than 60 minutes. Figure 30 shows the benefit of using the Multi-Tier Allocation approach, which preemptively opens Tiers 1-2 shelters to accommodate the total demand, and routes to minimize overall transit time. In Figure 30, the minimum number of buses required to keep wait times below the 60-minute threshold are significantly lower than in Figure 29.

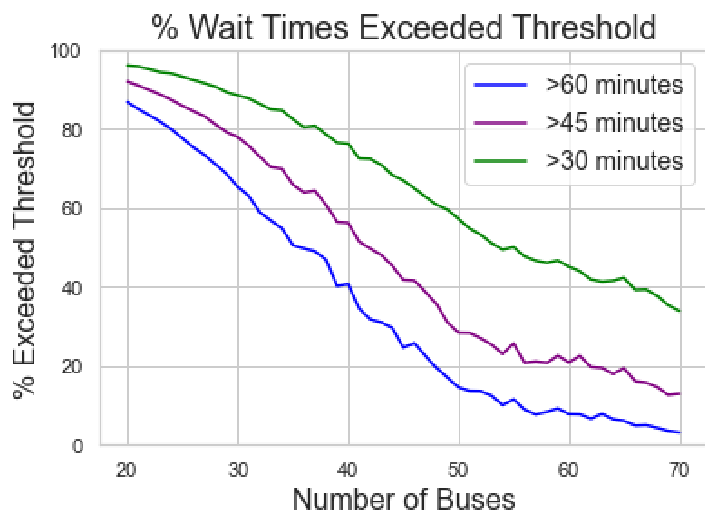


Figure 30. Zone C: Single-Tier Demand Allocation

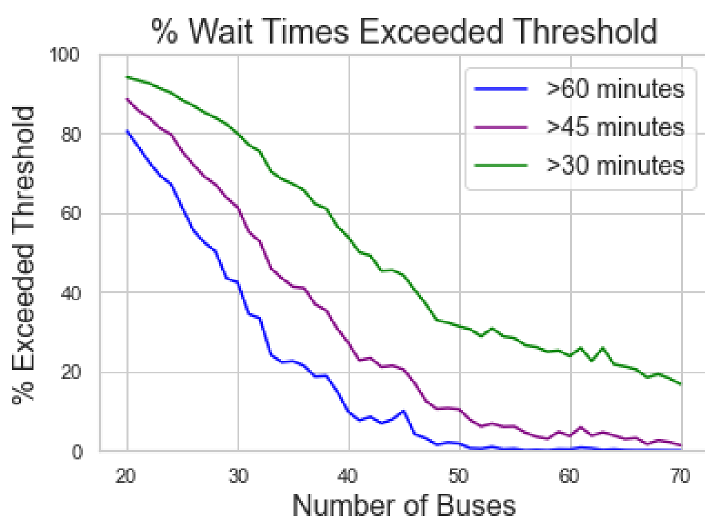


Figure 31. Zone C: Multi-Tier Demand Allocation

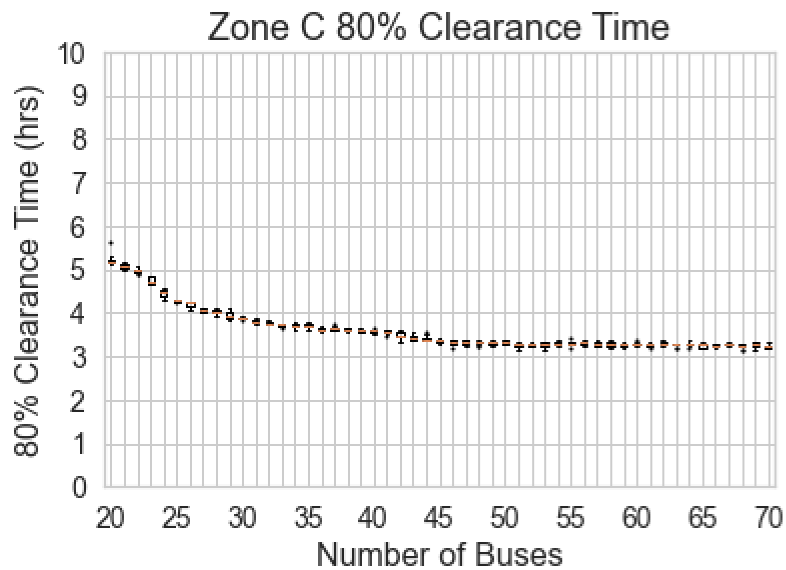


Figure 32. Zone C: Clearance Time at 80%

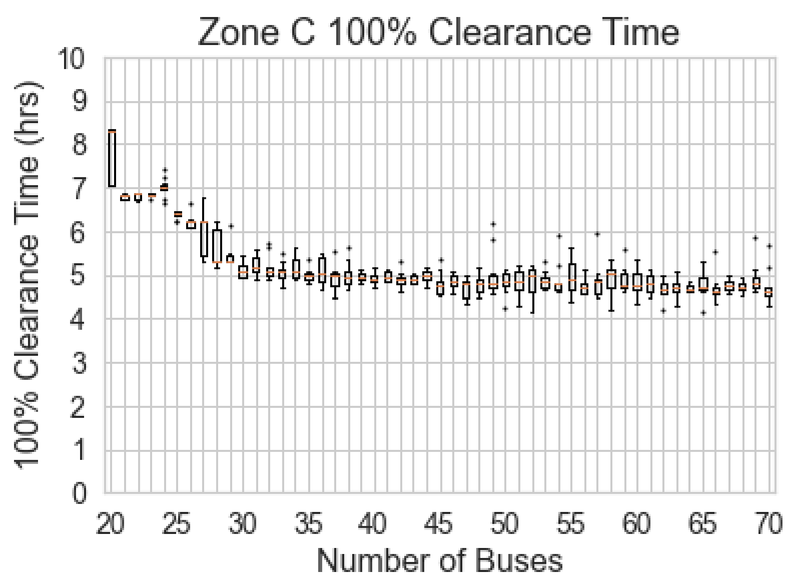


Figure 33. Zone C: Clearance Time at 100%

In summary, we have demonstrated that finding the smallest number of buses that yield wait times within the 60-minute threshold (with 1% margin of error) yields a requirement of 15 buses for Zone A, 40 buses for Zone B, and ~50 buses for Zone C. The measured clearance time is shown to be short, as expected. Finally, the benefit of the Multi-Tier Allocation approach is shown for Zone C which exceeds Tier 1 capacity.

Figures 34-36 show the arrival distributions at both pickup locations and shelters for select numbers of buses. The shelter arrival distribution, which reflects overall clearance time, converges to a shape similar to that of the pickup arrivals, but is offset by the mean travel time of routes (~30 minutes). The shelter arrivals fluctuate due to the fact that buses dispatch at the same time, resulting in "groups" of pickups at similar times.

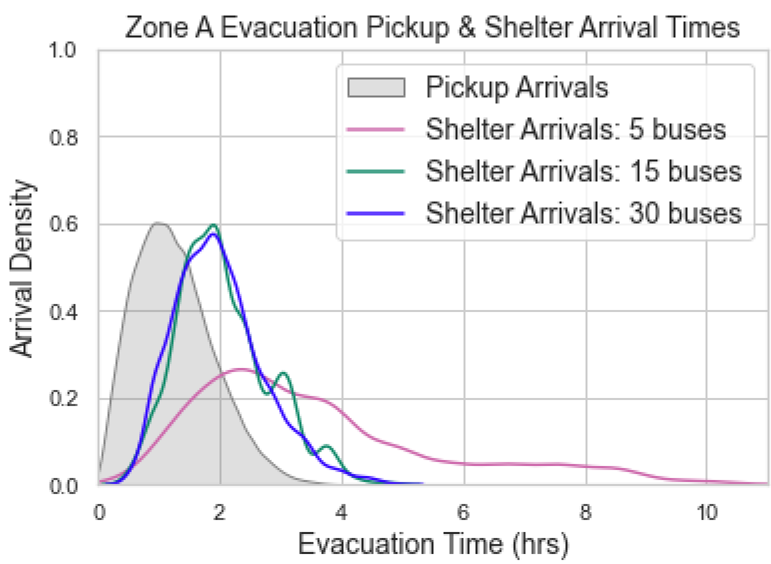


Figure 34. Zone A: Arrival Density vs Evacuation Time

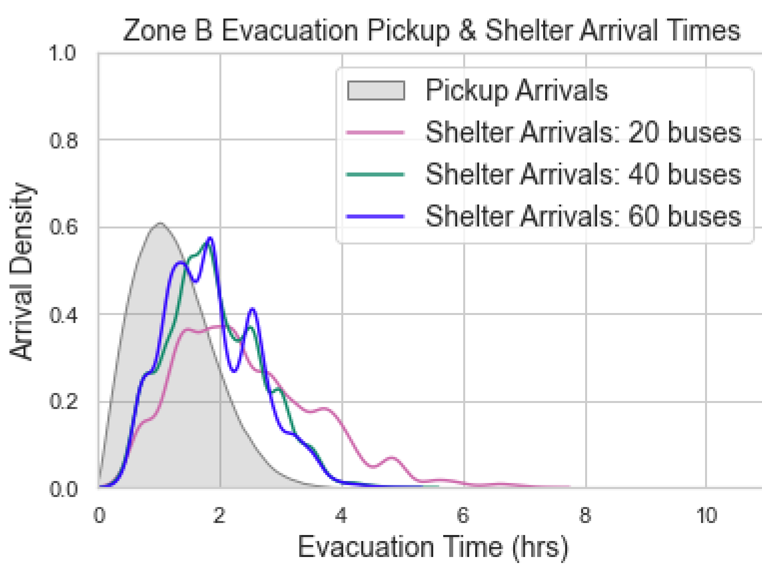


Figure 35. Zone B: Arrival Density vs Evacuation Time

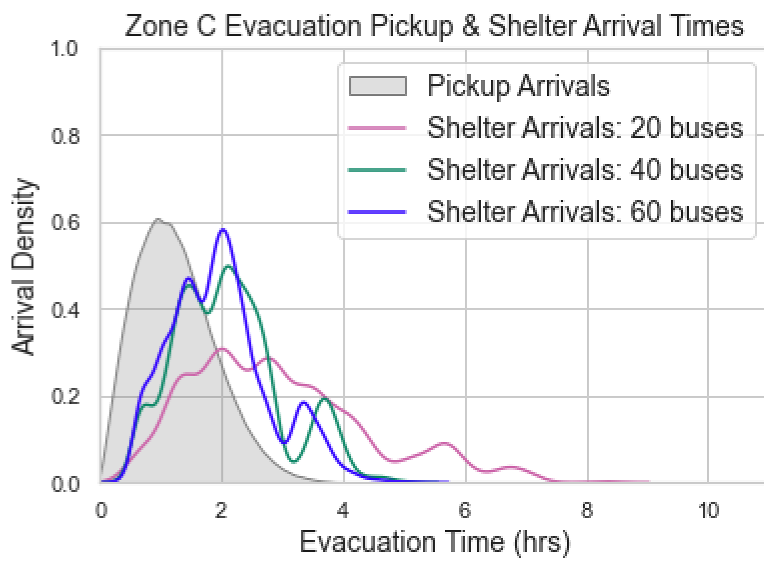


Figure 36. Zone C: Arrival Density vs Evacuation Time

Case Study 2: A phased approach to evacuating Zone A with 5 buses

In this next section, we explore having only 5 buses to effectively service all pickup locations in Zone A. A phased evacuation is proposed in which pickup locations are clustered into groups. The purpose of this case study is to demonstrate how a phased evacuation plan can in theory be approached. It is assumed that arrivals occur uniformly during a 4-hour window, and bus operations are to occur in 5-hour windows allowing an extra hour for picking up those who arrive towards the end, and for repositioning for the next pickup window.

Table 15. Zone A: Group 1 Results

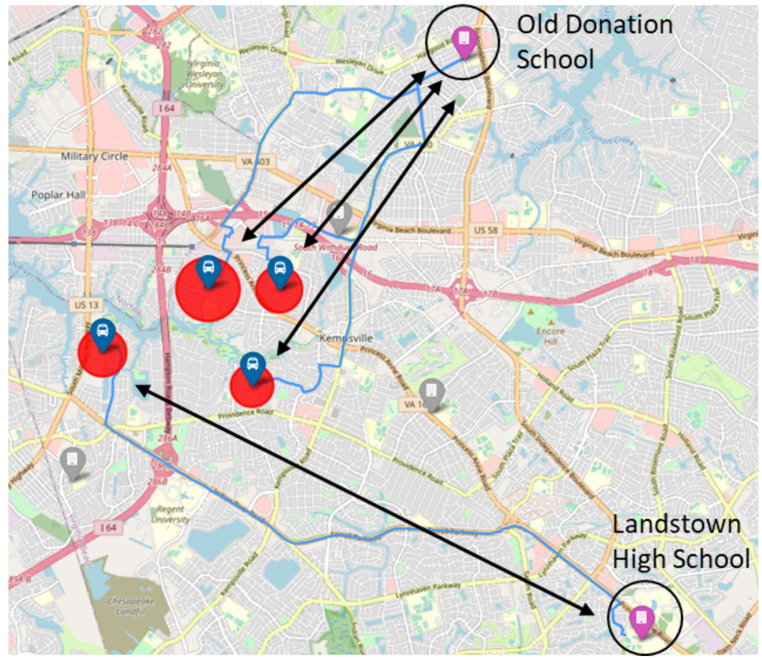
Zone A: Group 1

Starting at 07:00, dispatch 3 buses from Old Donation School to P82, P84, and P85. Due to wait times exceeding 1 hour, it is recommended to dispatch an additional bus to P85, or as an on-call bus for pickup locations in need of extra assistance.

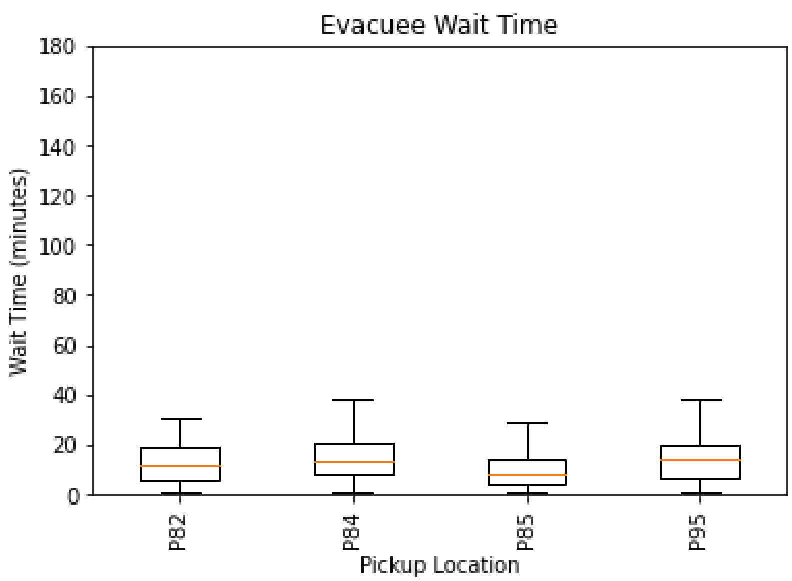
Dispatch 1 bus from Landstown High School to P95.

Total Evacuation Time (hrs)

mean	**4.52**
std	0.11
min	4.35
max	4.68



The evacuee wait times are maintained below the 60-minute system requirement.



Shelter occupancy fills at a steady pace for uniform arrival patterns.

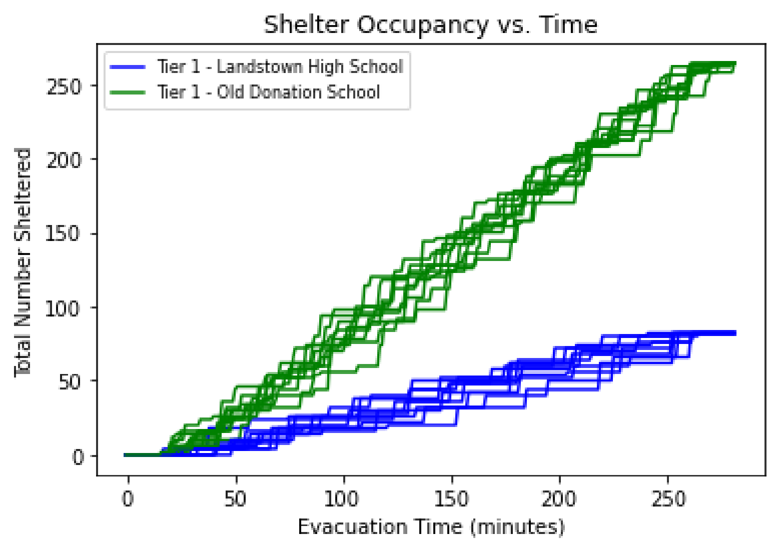


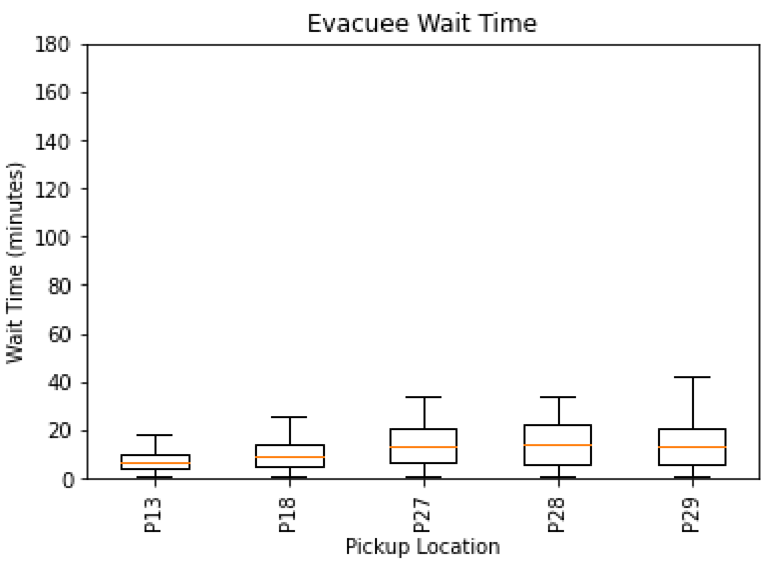
Table 16. Zone A: Group 2 Results

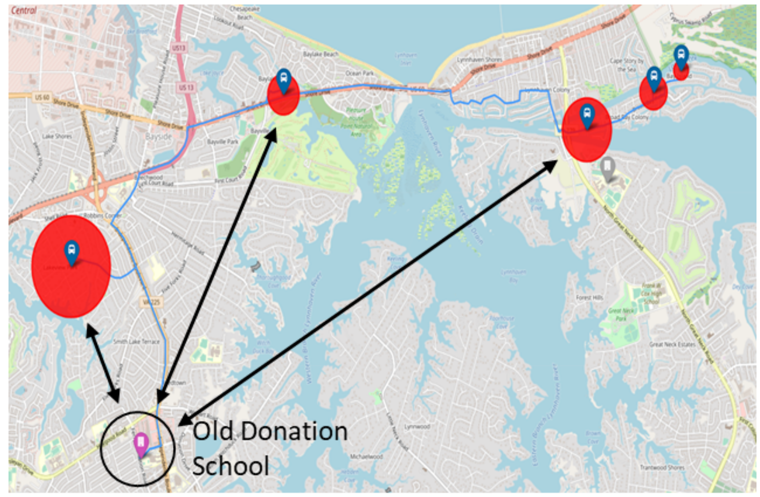
<u>Zone A: Group 2</u>

Starting at 12:00, dispatch 5 buses from Old Donation School to P13, P18, P27, P28, and P29. Efficiency may be gained by routing empty buses to other stops on return journeys.

Total Evacuation Time (hrs)	
mean	4.48
std	0.09
min	4.32
max	4.58

The evacuee wait times are maintained below the 60-minute system requirement.





Shelter occupancy at Old Donation School increase by the following amount during Group 2 evacuation.

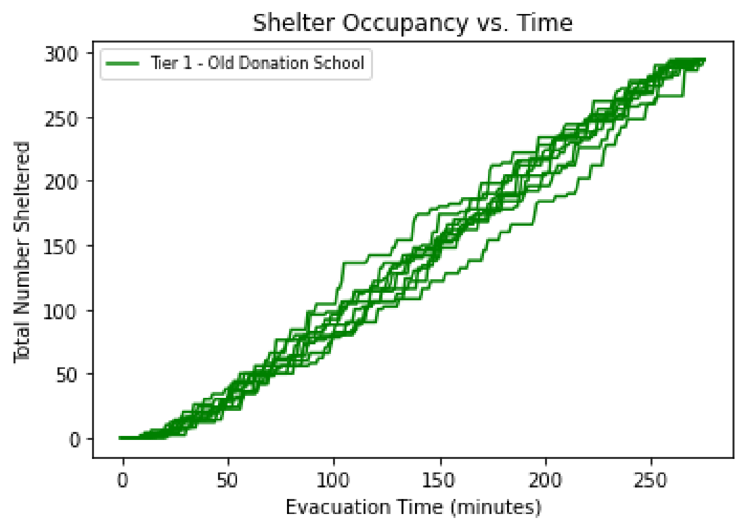
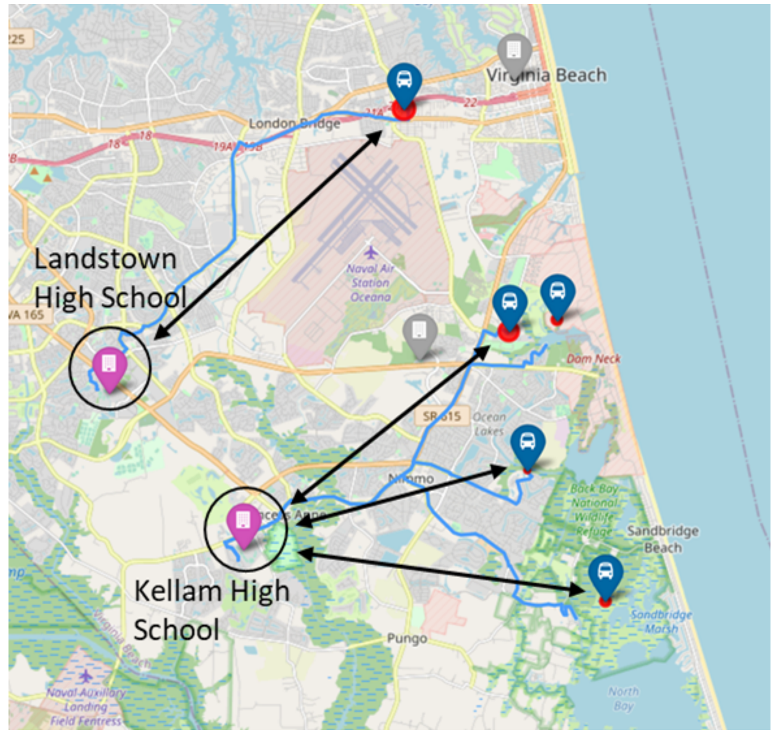


Table 17. Zone A: Group 3 Results

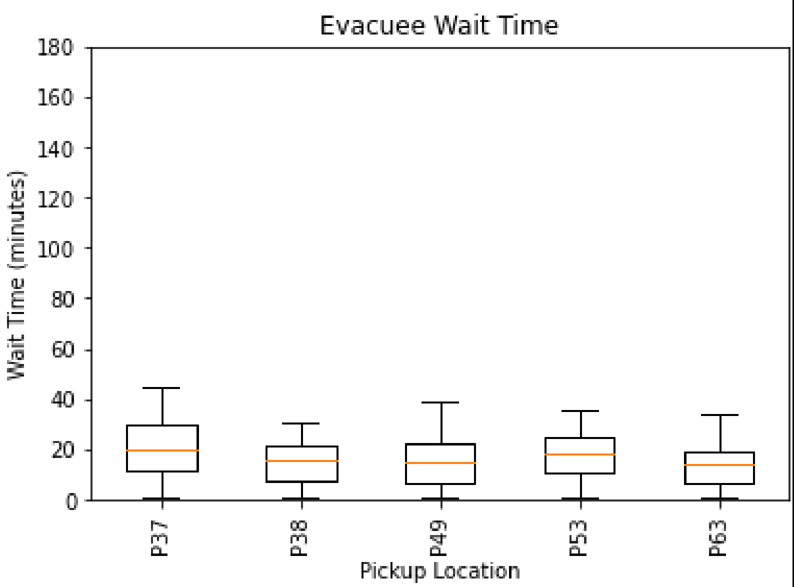
Zone A: Group 3

Starting at 17:00, dispatch 1 bus from Landstown High School to P37. Dispatch 4 buses from Kellam High School to P38, P49, P53, and P63. Efficiency may be gained by combining P49 and P63 due to their close proximity.

Total Evacuation Time (hrs)	
mean	4.53
std	0.20
min	4.27
max	4.90



The evacuee wait times are maintained below the 60-minute system requirement.



Kellam High School and Landstown High School increase by the following amount during Group 3.

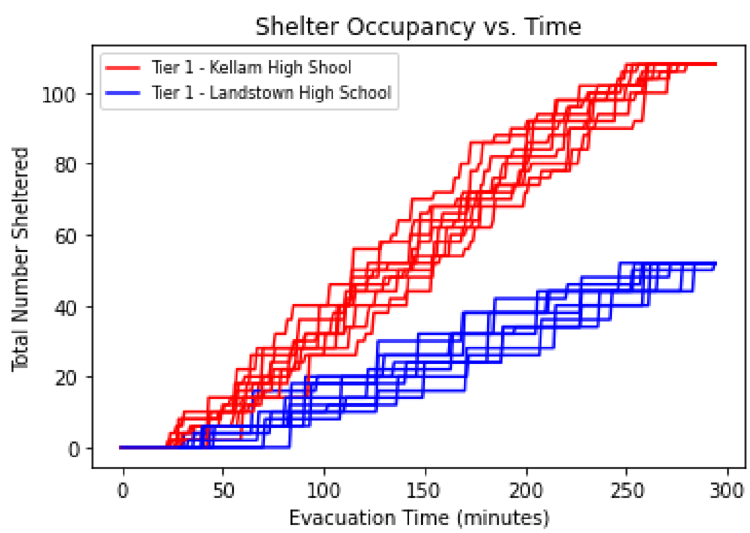


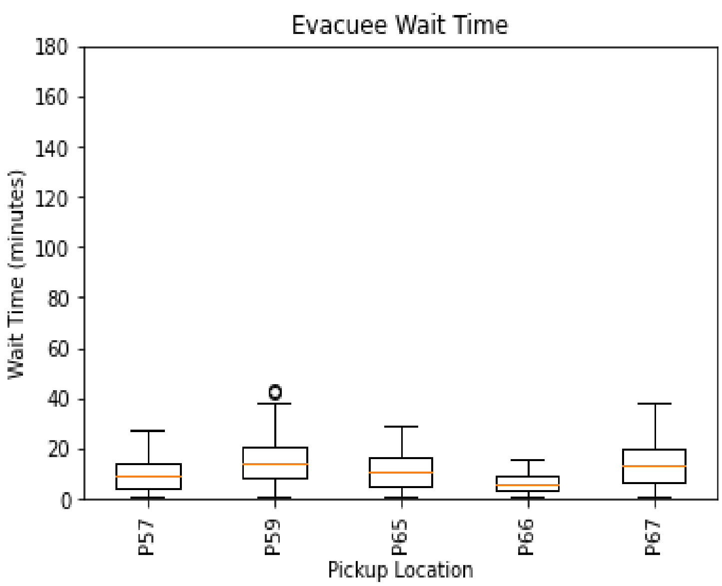
Table 18. Zone A: Group 4 Results

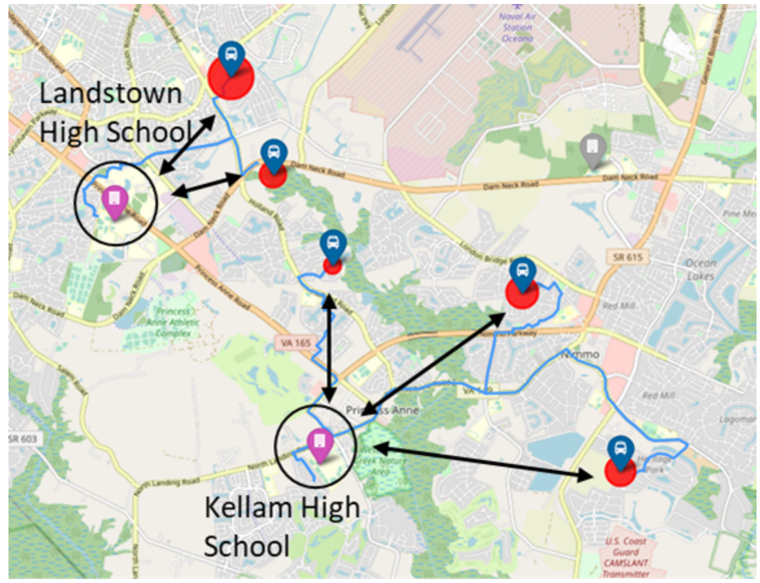
<u>Zone A: Group 4</u>

Starting at 07:00 on Day 2, dispatch 2 buses from Landstown High School to pick-up points P65 and P66. Dispatch 3 buses from Kellam High School to pick-up points P57, P59, and P69.

Total Evacuation Time (hrs)	
mean	4.50
std	0.12
min	4.35
max	4.72

The evacuee wait times are maintained below the 60-minute system requirement.





Graph of evacuees moved to shelter over time (does not track overall shelter occupancy)

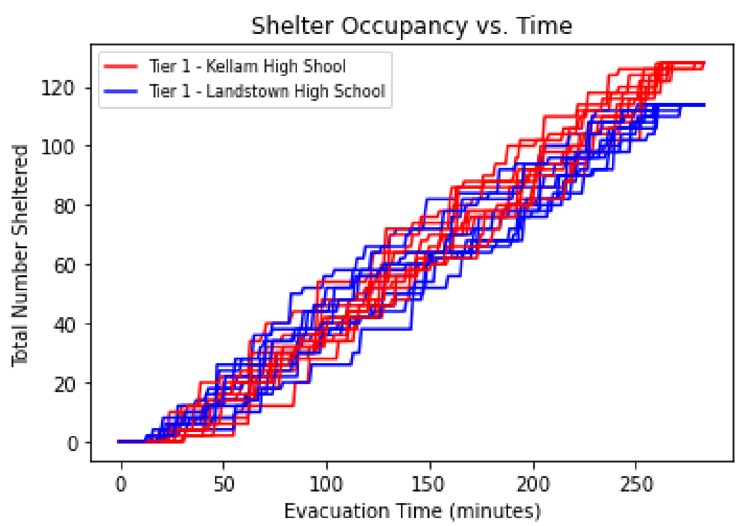


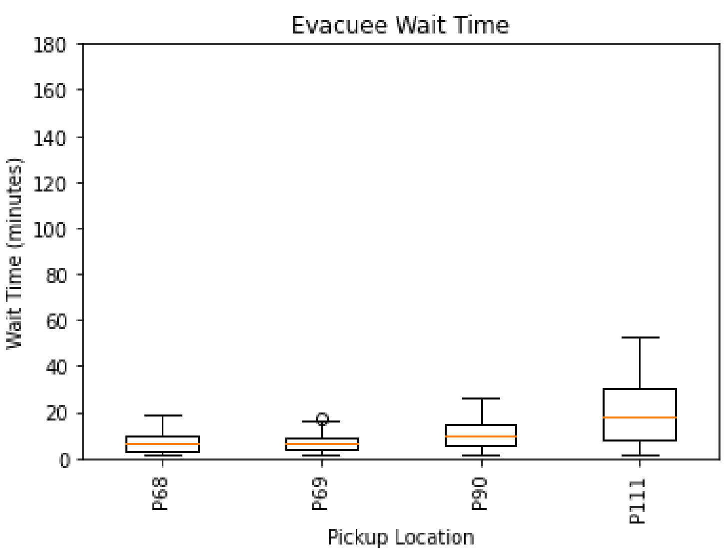
Table 19. Zone A: Group 5 Results

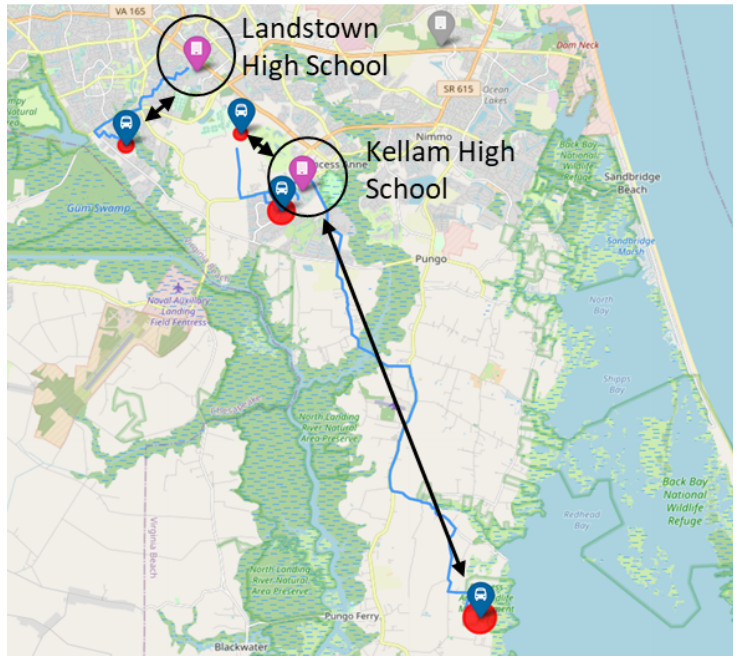
<u>Zone A: Group 5</u>

Starting at 12:00 (Day 2), dispatch 1 bus from Landstown High School to P90. From Kellam High School dispatch 1 bus each to P68 and P69, combining stops if necessary. Also dispatch 2 buses to P111, which is a long distance away and may require extra resources to evacuate in a timely manner. Expect to finish by 17:00.

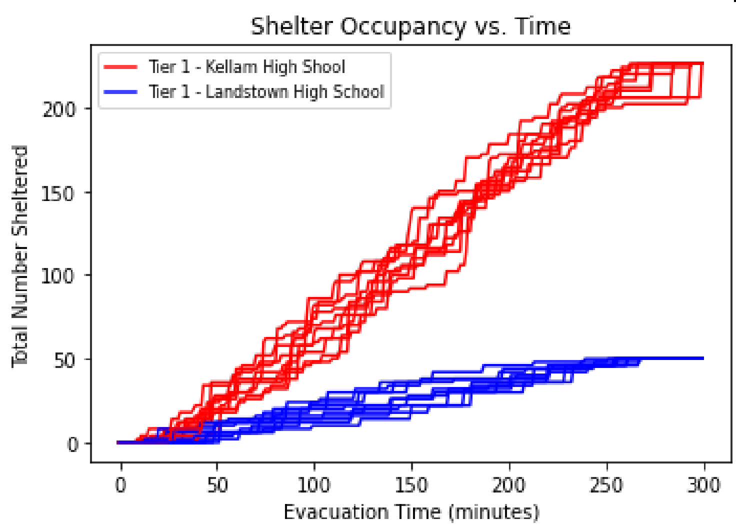
Total Evacuation Time (hrs)	
mean	4.66
std	0.22
min	4.38
max	4.98

The evacuee wait times are maintained below the 60-minute system requirement, but P111 should be closely monitored to ensure the threshold is not crossed. Additional bus stops may be added along the P111 route to help cover the large service area.





Graph of evacuees moved to shelter over time (does not track overall shelter occupancy)



In summary, we have created a bus evacuation plan for a given population in Zone A. This plan involves five buses, five groups of 3-5 pickup spots each, and spans 2 days (34 hours, including 27 hours of bus operation, all during hours from 7:00 AM to midnight).

The evacuation arrival windows are publicized as 4-hour increments during which all evacuees must arrive in order to be picked up. Assuming a uniform arrival distribution, we can expect buses to operate for an additional 30-60 minutes after the window ends, hence accounting for 5 hours total per group.

This case study is unsatisfactory in terms of meeting system requirements for 28-hour Zone A clearance time, and should be modified. Reducing the arrival windows to 3 hours instead of 4 would reduce the overall clearance time by only 2 hours, since Day 2 only has two groups (10 hours of operation) that begin at 7AM. It also does not provide any buffer in case evacuees arrive late in the window. In order to build in more buffer space, pickup groups should be either evacuated in pairs using 5 buses each (total estimated clearance time: 15 hours from 7AM to 10PM on Day 1).

Case Study 3: Assume 4-minute wheelchair load time, and range of arrival distributions
The same methodology of Case Study 2 is applied in this study, using waiting times as the primary metric by which the required number of buses is chosen. This time, a 4-minute wheelchair loading time is assumed, and we expect an increase in buses on the order of 30% based on the results of Experiment 2.

The Rayleigh distribution is scaled four different ways, with peak times occurring at the first, second, third, or fourth hour following t=0. Because the arrival tail tapers towards the end of the day, we assume operations will shift over to an as-needed basis, and we ignore this part of the evacuation effort by measuring the 80% clearance time.

Note that Zone C contains two columns, the first of which utilizes all three Tier-2 shelters as well as a capacitated facility allocation scheme to find improved routing. The purpose of showing these alternative routing and sheltering schemes is to demonstrate the potential benefits of such strategies during large-scale evacuations with multiple shelters opening in a tiered approach. Future studies should focus on exploring ways to employ these strategies.

Table 20. Buses verus Wait Times

Arrival Distribution (Peak Time)	80% Clearance Time	Zone A (3 shelters)	Zone B (3 shelters)	Zone C (6 shelters)	Zone C (4 shelters)
		# Buses Required to keep wait times < 60 minutes			
1-hr peak	3-4 hrs	21	38	62	80
2-hr peak	5-6 hrs	19	30	46	72
3-hr peak	7-8 hrs	17	28	42	68
4-hr peak	9-10 hrs	15	28	40	65

6.4 Discussion

Both clearance times and waiting times experienced by evacuees at pickup locations play a major role in driving the number of buses and evacuation time windows. Clearance time is not necessarily the limiting factor in deciding the routes and number of buses needed to move a certain population; waiting times are important, especially during inclement weather. Planners should determine an appropriate threshold. In this project, we chose 60 minutes: if waiting times exceed the required threshold of 60 minutes, then planners should consider the following mitigations:

- Increase the number of buses serving pickup locations with high wait times
- Design routing and shelter location strategy to reduce overall transit costs (Case Study 3)
- Organize groups of locations that will be evacuated in sequence (Case Study 2)
- Change operating patterns of buses (such as dwell time and dynamic routing; see Experiments 1 & 2)

Based on the results, we have determined an extreme case in which most evacuees from a given zone mostly arrive during a 2-hour window, with peak arrivals at 1 hour. If all pickup locations from each zone are evacuated in a single stage (with all buses operating simultaneously at all pickup locations and arrivals following the pattern described above), then at least 21 buses are required when evacuating the AFNs population living in Zone A, 38 buses if evacuating through Zone B, and 62 buses if evacuating through Zone C. This number will prevent waiting times from exceeding 60 minutes. However, if arrivals follow the distribution in Case Study 3, with peak at 4 hours and 80% clearance time between 9-10 hours, then the bus requirement is reduced to 15, 28, and 40, respectively. This assumes the benefits of using a capacitated facility allocation routing strategy and opening all Tier-2 shelters to improve overall routing efficiency.

In case of a Zone C evacuation, the recommended approach to satisfying the Virginia Beach clearance time requirements (28 hours for Zone A, 45 hours for Zone B, and 58 hours for Zone C) is to evacuate zones A and B simultaneously, followed by Zone C. In order for this bus evacuation system to function properly, the city of Virginia Beach would be responsible for maintaining 62 wheelchair-friendly buses and work to build infrastructure around bus evacuation routes and stops.

Future modeling and simulation efforts should focus on the following areas:

- Designing optimal routing for multiple stops
- Add the ability for buses to dynamically reroute to increase efficiency
- Perform sensitivity analysis for each zone regarding bus capacity, wheelchair loading times, and bus intervals

7 Schedule

7.1 Project Plan

Our team originally planned to complete the project endeavor with a 4-phase implementation, as shown in the Figure below. Although the completion of tasking was delayed for phase 2 specifically due to challenges addressed in section 7.4, each team member's role in the project remained consistent as described in section 7.2. An enlarged version of the Gantt Chart below is given in the Appendix.

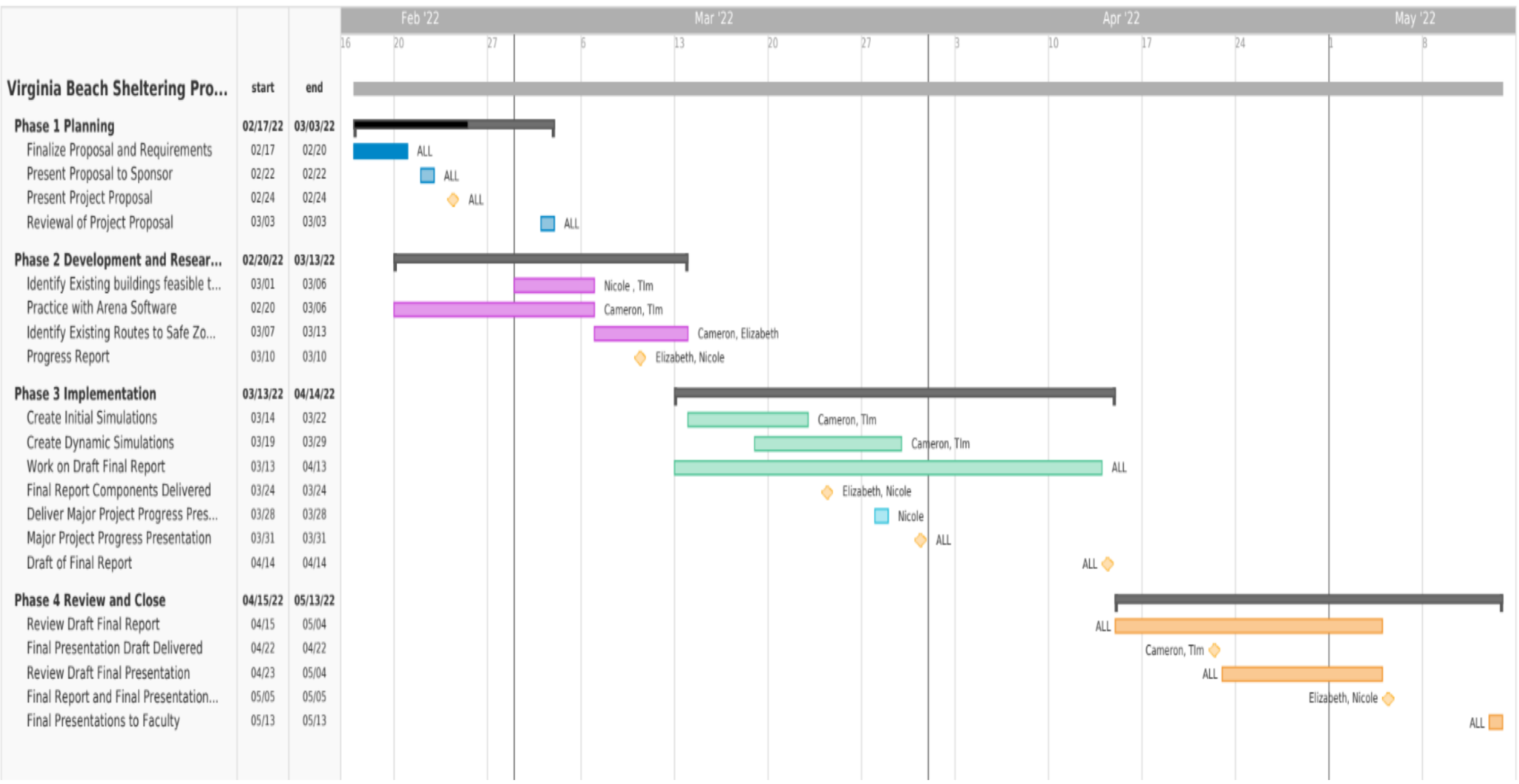


Figure 37. Team Gantt Chart

7.1.1 Team Roles

Cameron - *Project Manager and Simulation Engineer* - Cameron's duties include the designation of project tasking and decision making, and the creation of evacuation simulations. He aligns the necessary parameters and examines the simulation progress and effectiveness. He assists with optimization and supports the team as a whole with tasking.

Tim - *Lead Integrator and Optimization Engineer* - Tim's duties include the processing of requirements and background into fundamental requirements met by the simulation, and finding ways to optimize the simulation. He evaluates parameter and constraint impact, and adjusts the simulations and project expectations as needed. He integrates the simulation with the optimization and relays the findings back, he supports the team as a whole with tasking as well.

Nicole - *Lead Documentor and Quality Assurance Engineer* - Nicole's duties include the upkeep of project rework and progress, monitoring of deadlines, and revision of deliverables. She also vets the techniques, resources, and simulations for meeting the requirements of our proposed project, and she supports the team as a whole with tasking.

Liz - *Lead Researcher and Customer Engineer* - Liz's duties include gathering literature and extrapolating the needed information, keeping in touch with our customer, and finding relevant software and methodologies to implement. She ensures the project holds foundations in reality and is comparable to the current methods of evacuation in society. She interacts with the customer and checks that our project is in line with his expectations, she as well as supports the team as a whole with tasking.

7.1.2 Project Deliverables

Major deliverables and their submission dates are as follows:
3/28 - Deliver Major Project Progress Presentation to Professor
3/31 - Major Project Progress Presentation
4/14 - Draft of Final Report
4/21 - Final Presentation Draft Delivered
5/5 - User Manual (software installation and data requirements found in Section 11.2)
5/5 - Final Report and Final Presentation Delivered
5/9 - Complete Project Website
5/13 - Final Presentations to Faculty

7.2 Project Tasking

Our team completed many tasks in order to put together our final deliverable. We had setbacks within our schedule due to needing to rescope and detail our original proposal, which included requesting data from VDEM and VBDEM. Initially, we did not plan on reaching out to them but VDEM and VBDEM have been a wealth of information and feedback that has been essential to our project success. The table below examines the tasks completed to visualize our team's progress and project engagements.

Table 21. Project Tasking and Assignments

Start Date	Task	Assignee
2/14	Create Proposal and Requirements	ALL
2/22	Create Proposal Presentation	Nicole, Liz
2/22	Confirm Proposal with Sponsor	ALL
3/1	Identify Virginia Beach Shelters and Zoning	Cameron, Liz
3/1	Methodology Background Research	ALL
3/2	Determine Model Approach	Tim, Cameron
3/2	Determine Questions to Ask VA emergency management	Nicole, Liz
3/3	Obtain Information/Data from Emergency Planning Staff of Virginia and Virginia Beach	Liz
3/3	Practice with Software	Cameron, TIm
3/3	Finalize Requirements	Nicole, Liz
3/5	Identify Existing Bus Stops and Routes to Shelters	Cameron
3/5	Complete List of Data Inputs	Nicole, Liz
3/10	Create Preliminary Simulation	Tim
3/10	Write Progress Report	Nicole
3/11	Create Final Report Components	Nicole, Cameron
3/14	Weekly Team SYNC Meeting	ALL
3/15	Documentation of Final Report Components	Nicole, Liz

	(Introduction)	
3/15	Causal Loop Diagram	Cameron
3/15	Initial ArcGis Mapping	Liz,Tim
3/15	Create Simulations with Data List	Tim
3/15	Analyze Results and Create Recommendations	Cameron, Tim
3/21	Weekly Team SYNC Meeting	ALL
3/22	Interview VA emergency Management	Liz
3/24	Meeting with Dr. Hoffman	ALL
3/24	Requirements and Use Cases	Liz, Nicole
3/25	Create Final Report Presentation	Nicole
3/28	Simulation Work and Report	Cameron, Tim
3/28	Weekly Team SYNC Meeting	ALL
3/28	Work on Project Update Class Presentation	Nicole, Liz
3/30	Practice Project Update Class Presentation	ALL
3/31	Major Update Class Presentation	ALL
4/1	Review FeedBack	ALL
4/1	Examine Presentation Feedback	ALL
4/4	Weekly Team SYNC Meeting	ALL
4/2	Finalize Simulation	Tim, Cameron
4/7	Meeting with Dr. Hoffman	ALL

4/2	Work on Final Report	Liz, Nicole
4/2	Work on Final Presentation	Nicole, Liz
4/11	Weekly Team SYNC Meeting	ALL
4/14	Dry Run Final Presentation	ALL
4/17	Weekly Team SYNC Meeting	ALL
4/24	Weekly Team SYNC Meeting	ALL
4/28	Final Presentation to Class	ALL
5/13	Final Presentation to Faculty	ALL

7.3 Earned Value Management (EVM)

Based on the Schedule Performance Index (SPI) as of week 10, we are slightly behind Schedule since the SPI for this project is 0.899 because the Planned Value (PV) is greater than the Earned Value (EV). The Cost Performance Index of this project is 1.03 which means that we are correctly budgeting our actual cost of hours on the project. Since we are about a week behind and we only have two weeks left, we need to work on this project 80hrs per week in order to complete the analyses of the simulation, finalize the report and presentation.

7.4 Challenges

Several challenges have been addressed and caused setbacks within the timeline of our project. These challenges include having to rework the scope of the project, delayed communication by the project team with VDEM to obtain information of current Virginia Beach disaster protocols, and conflicting expectations and feedback from sponsors. These challenges were addressed through several weeks of rework on our project proposal, extensive literature review, interviews with managers of Virginia and Virginia Beach Emergency Management centers, and sponsor meetings and communications, respectively.

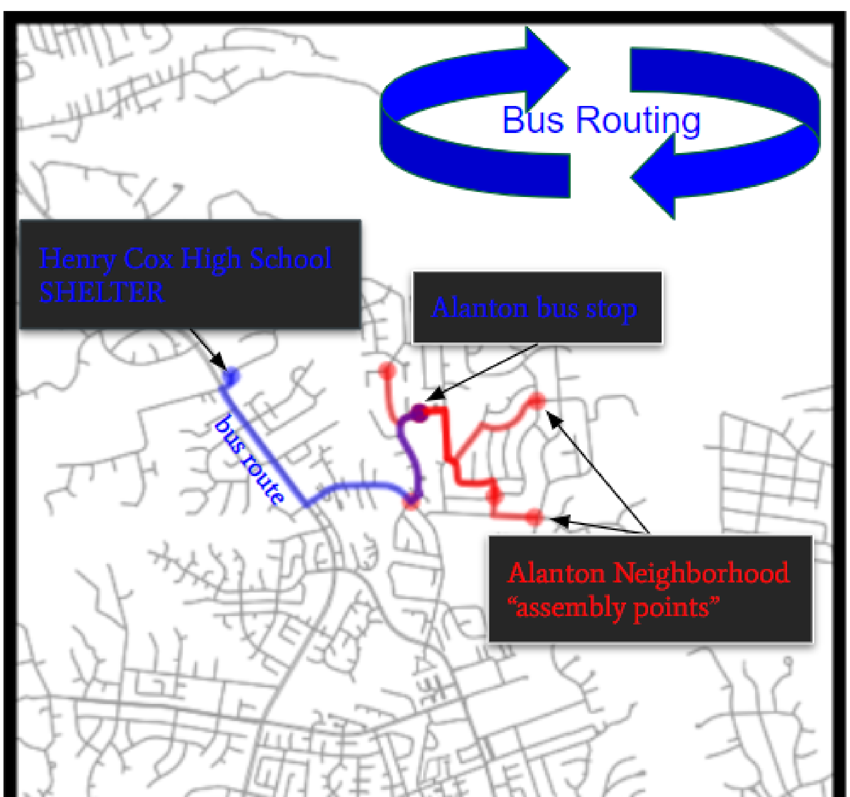
7.5 Future Work

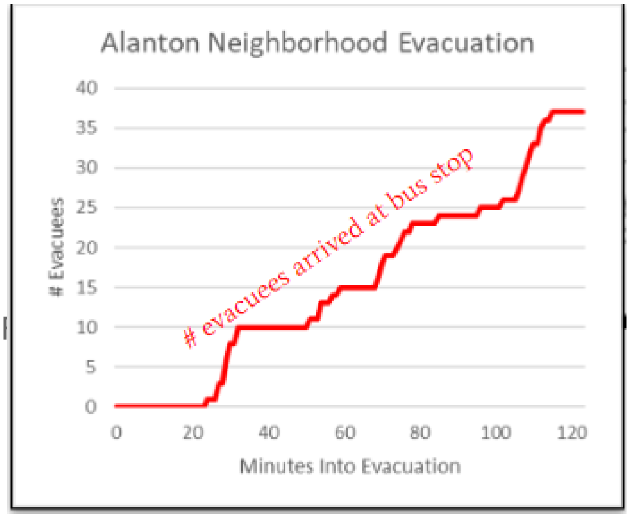
The work that our team has done this semester focused on only one small part of a much larger transportation system. As we mentioned in our scope, there are many different avenues for this project to explore. One future topic to explore is the actual logistics of the evacuation transportation system. This can include determining potential civic organizations that can assist in the transportation system, real time tracking of buses and evacuees, and ways to build community trust in this transportation system. There is plenty of work to be done with the shelters including determining more potential shelters, evaluating the current shelters, and developing a system to provision the shelters with resources. To continue work on this model, the team has provided a user manual for software installation and model use that can be found in Section 11.2. We suggest that future teams continue work on this model by specifying evacuee flow to the pick up points. Evacuee flow to the pick up points would provide a more accurate time measurement for evacuation time, as well as provide a basis as to when residents should be alerted to make their way to the pickup points. The following modeling example can be utilized for an initial future study of the evacuee flow to pick up points.

QUESTION: How do evacuees get from home to the pick-up?
LOGIC:

1. Assume volunteers go to homes and help evacuees to designated spots (5 red nodes on map)
2. Assume evacuees are assembled to nodes and depart as a group in 20(+/-5) minute intervals
3. Once gathered at one of the nodes, they go (transported at ~ 5 km/h) to bus stop
4. Once at bus stop, evacuees wait for pick-up

SOFTWARE: The following example is computed using Agent Based Simulation package "mesa" in Python 3.9.12. All road distances/times computed using OSMnx and Networkx packages.
INPUTS: lat/lon positions, time intervals for gathering evacuees





Other avenues of future work to branch from our model include:

1. Scheduling of regional pick-up windows to reduce the number of buses required while maintaining reasonable wait times
2. Designing routes with multiple stops, especially for low-population-density areas
3. Allocation of more buses to higher-demand areas
4. Consideration of shuttle transportation between residential areas and bus stops

8 Recommendations

From the information gathered, there are a few recommendations we suggest for the current Virginia Beach evacuation plan. One recommendation would be to provide more accessibility to detailed VA Beach evacuation information. There seems to be a lack of detailed evacuation and transportation information specifically for the Virginia Beach area currently available and easily accessible to the public. However, once the team got into contact with Subject-matter experts within VBDEM and VDEM, they were able to provide a wealth of information and feedback on assumptions and the model. Another recommendation, is that the shelters that Virginia beach utilizes for evacuations need to be reevaluated if a bus transportation system were to be implemented. The Shelters are reported to withstand up to a Category 2 hurricane and two of the shelters are in Zone B. Therefore, if an evacuation order of Zone C or Category 3 hurricane or higher were to occur, the shelters will not be safe and must be evacuated which would limit the total capacity of the shelters. This could cause a massive strain on the transportation system and emergency responders. Another problem with the shelters is the lack of capacity. The current model only captures the AFNs population who are living in Zone A-C and that fills more than half the total capacity of the shelters. In order to provide shelter to the non-vulnerable population, we recommend that more shelter locations with a large capacity capability should be established to increase total capacity and reduce strain on the bus evacuation system. Also in order to adhere to new social distancing protocols, the required space for one individual has changed from 20sqft to 113sqft. This severely limits the capacity of shelters and current shelter capacities may need to be reevaluated if they haven't already. Another important recommendation is to acquire more accurate information about the vulnerable population including their location, transportation and medical needs (i.e., # of people requiring wheelchair accessibility). This will allow for a more accurate model/simulation and will better define the amount of need required in shelters and buses. The final recommendation is for VBDEM to plan practice evacuations to ensure current shelter, transportation and emergency infrastructure is sufficient. Also by practicing evacuations, we can build the communities trust and resilience to the evacuation and transportation system.

9 Conclusion

The purpose of this project was to model and simulate a bus transportation system for the most vulnerable in Virginia Beach during a major flooding event. By utilizing Systems Engineering and Operational Research methods learned at George Mason University, our team has researched and developed a functional bus evacuation simulation to model the city's current protocols. The simulation was implemented for the population with AFNs living within the City of Virginia Beach. Through this work, we completed an initial task to continue an evacuation planning network for Virginia Beach and other cities. The information that we gathered in this project will be essential to policy makers and emergency management offices in developing more comprehensive evacuation transportation systems. This project is just the step to a full transportation system, there are a number of questions that still need to be answered and plenty of future work to continue to expand on the project.

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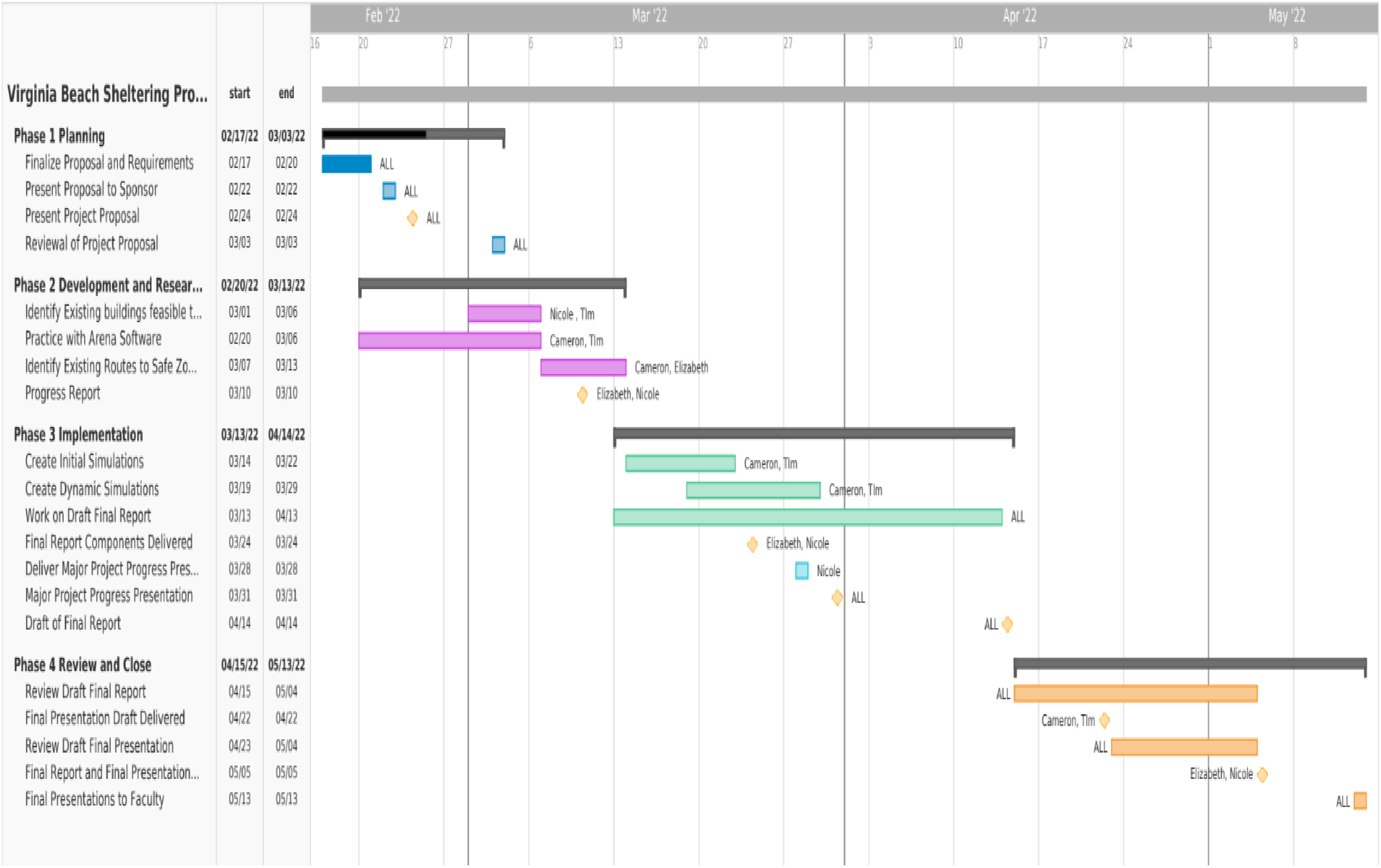
11 APPENDIX

11.1 Earned Value Management (EVM) and Gantt Chart

Planned Value (PV)
PV = Total project cost * % of planned work
PV = 840hrs * 90% = 756 hrs
Actual Costs (AC) at the end of 10 weeks is 650hrs
Earned Value (EV)
Total project cost * % of actual work
EV= 840hrs * 80% = 672hrs
Schedule Variance (SV)
SV = EV − PV
SV = 672 - 756 = -84hrs
SV% = (SV/PV) *100
SV% = (-84/756) *100 = -11%
Cost Variance (CV)
CV = EV – AC
CV = 672 - 650 = 22hrs
Schedule Performance Index (SPI)
SPI = EV/PV
SPI = 672/756 = 0.889
Cost Performance Index (CPI)
CPI = EV/AC
CPI = 672/650 = 1.03



Virginia Beach Sheltering Pro...
start
end
Feb '22
Mar '22
Apr '22
May '22
16
20
27
6
13
20
27
3
10
17
24
1
8
Phase 1 Planning 02/17/22 03/03/22
Finalize Proposal and Requirements 02/17 02/20 ALL
Present Proposal to Sponsor 02/22 02/22 ALL
Present Project Proposal 02/24 02/24 ALL
Reviewal of Project Proposal 03/03 03/03 ALL
Phase 2 Development and Resear... 02/20/22 03/13/22
Identify Existing buildings feasible t... 03/01 03/06 Nicole , Tim
Practice with Arena Software 02/20 03/06 Cameron, Tim
Identify Existing Routes to Safe Zo... 03/07 03/13 Cameron, Elizabeth
Progress Report 03/10 03/10 Elizabeth, Nicole
Phase 3 Implementation 03/13/22 04/14/22
Create Initial Simulations 03/14 03/22 Cameron, Tim
Create Dynamic Simulations 03/19 03/29 Cameron, Tim
Work on Draft Final Report 03/13 04/13 ALL
Final Report Components Delivered 03/24 03/24 Elizabeth, Nicole
Deliver Major Project Progress Pres... 03/28 03/28 Nicole
Major Project Progress Presentation 03/31 03/31 ALL
Draft of Final Report 04/14 04/14 ALL
Phase 4 Review and Close 04/15/22 05/13/22
Review Draft Final Report 04/15 05/04 ALL
Final Presentation Draft Delivered 04/22 04/22 Cameron, Tim
Review Draft Final Presentation 04/23 05/04 ALL
Final Report and Final Presentation... 05/05 05/05 Elizabeth, Nicole
Final Presentations to Faculty 05/13 05/13 ALL

11.2 Python Installation Notes

Python 3.9.12 (Release Date March 23, 2022)

Anaconda Distribution for Windows 10 (64-bit) and Python 3.9

Download Sypder:

```
conda install –c anaconda spyder
```

Ensure matplotlib was installed in the python base library. Open Anaconda prompt and type:

```
conda install matplotlib
```

For the remaining packages, create a new anaconda environment called “evacuation”

```
conda create –n evacuation

conda activate evacuation
```

It may be necessary to copy python.exe from its base installation path to the evacuation environment within the folder called “Scripts.” Search “python.exe” in Windows Explorer. After copying python.exe from its default location to anaconda3\envs\evacuation\python.exe, open Spyder, navigate to Tools>Preferences>Python Interpreter, and set the default path to the path of python.exe described above. Restart Spyder. On reopening Spyder, the kernel may show an alert to install spyder-kernels. In this case, open the evacuation environment in anaconda prompt and type:

```
conda install spyder-kernels=2.2
```

Restart Spyder after installation.

Install geospatial libraries together to ensure compatibility:

```
conda install –c conda-forge fiona python=3.9 fiona
shapely rasterio pyproj pandas jupyterlab geopandas osmnx
mesa seaborn
```

11.3 Sample Activity Log: Bus Agent

time	entity_name	location	amount	activity
0	B12	SH11	1	initialized
35	B12	P63	0	picked up
68	B12	P111	2	picked up
92	B12	SH11	2	dropped off
122	B12	P111	2	picked up
176	B12	P63	2	picked up
188	B12	SH11	4	dropped off
209	B12	P63	0	picked up
265	B12	P111	2	picked up
289	B12	SH11	2	dropped off
320	B12	P111	4	picked up
362	B12	P63	4	picked up
374	B12	SH11	8	dropped off
419	B12	P63	0	picked up
456	B12	P111	2	picked up
480	B12	SH11	2	dropped off
508	B12	P111	0	picked up
540	B12	P63	0	picked up
552	B12	SH11	0	dropped off
575	B12	P63	0	picked up
631	B12	P111	2	picked up
655	B12	SH11	2	dropped off
712	B12	P111	0	picked up
770	B12	P63	0	picked up
782	B12	SH11	0	dropped off
827	B12	P63	0	picked up
867	B12	P111	0	picked up
891	B12	SH11	0	dropped off
929	B12	P111	0	picked up
958	B12	P63	0	picked up
970	B12	SH11	0	dropped off

Sample Activity Log: Shelter Facility

time	entity_id	entity_name	location	amount	capacity	activity
25	SH11	Kellam High Shool	SH11	0	1564	shelter capacity used
67	SH11	Kellam High Shool	SH11	2	1564	shelter capacity used
68	SH11	Kellam High Shool	SH11	6	1564	shelter capacity used
78	SH11	Kellam High Shool	SH11	8	1564	shelter capacity used
86	SH11	Kellam High Shool	SH11	10	1564	shelter capacity used
91	SH11	Kellam High Shool	SH11	14	1564	shelter capacity used
92	SH11	Kellam High Shool	SH11	16	1564	shelter capacity used
92	SH11	Kellam High Shool	SH11	18	1564	shelter capacity used
95	SH11	Kellam High Shool	SH11	20	1564	shelter capacity used
117	SH11	Kellam High Shool	SH11	22	1564	shelter capacity used
137	SH11	Kellam High Shool	SH11	24	1564	shelter capacity used
164	SH11	Kellam High Shool	SH11	26	1564	shelter capacity used
167	SH11	Kellam High Shool	SH11	28	1564	shelter capacity used
170	SH11	Kellam High Shool	SH11	30	1564	shelter capacity used
175	SH11	Kellam High Shool	SH11	32	1564	shelter capacity used
181	SH11	Kellam High Shool	SH11	34	1564	shelter capacity used
182	SH11	Kellam High Shool	SH11	38	1564	shelter capacity used
186	SH11	Kellam High Shool	SH11	44	1564	shelter capacity used
188	SH11	Kellam High Shool	SH11	48	1564	shelter capacity used
189	SH11	Kellam High Shool	SH11	50	1564	shelter capacity used