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

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Sponsor: Dr. Gregory Tangonan, Ateneo de Manila University

Problem Development

- GMU in partnership with Ateneo de Manila University in Manila, Philippines collaborates on disaster and evacuation planning. Worldwide, natural disasters are becoming more frequent and intense. Evacuation planning has never been more imperative for cities.

- Floods are America's most frequent and expensive disaster based on NOAA's National Centers for Environmental Information. Flooding events are becoming more severe. In the Eastern U.S., there are up to 70% more heavy downpours each year according to Climate Risk Management.

- Virginia Beach is a coastal city in southeastern Virginia which is ranked in the top 10 Virginian cities at risk for flooding according to the First National Flood Risk Assessment of 2020. Due to the fact that a full scale evacuation has not hit Virginia Beach since 1933, the residents of Virginia Beach tend to be complacent, despite the high vulnerable population in the area.

Problem Statement

The city of Virginia Beach is cited as one of the **top 10 flood-risk regions** in Virginia. Virginia Beach has been affected by major flooding events and the risk is projected to **increase over the next 30 years**. There is also a highly vulnerable population in the area, and giving sufficient attention to this population is important to saving lives in a natural disaster. 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 capacity saturation at shelters.** The objective will be to minimize the time and risk associated with an evacuation effort focused on vulnerable populations during a flooding event.

The team will model a transportation system for the vulnerable population to established shelter facilities during a flooding event.

Stakeholders

- VA beach population (full time and tourists)
- Vulnerable population of the city and their families
- Shelter staff/volunteers
- VA Beach Local Government
- VA Beach Department of Emergency Management
- VA Beach school system
- VA Beach transportation system
- VA Department of Emergency Management
- Ateneo de Manila University, Dr. Gregory Tangonan

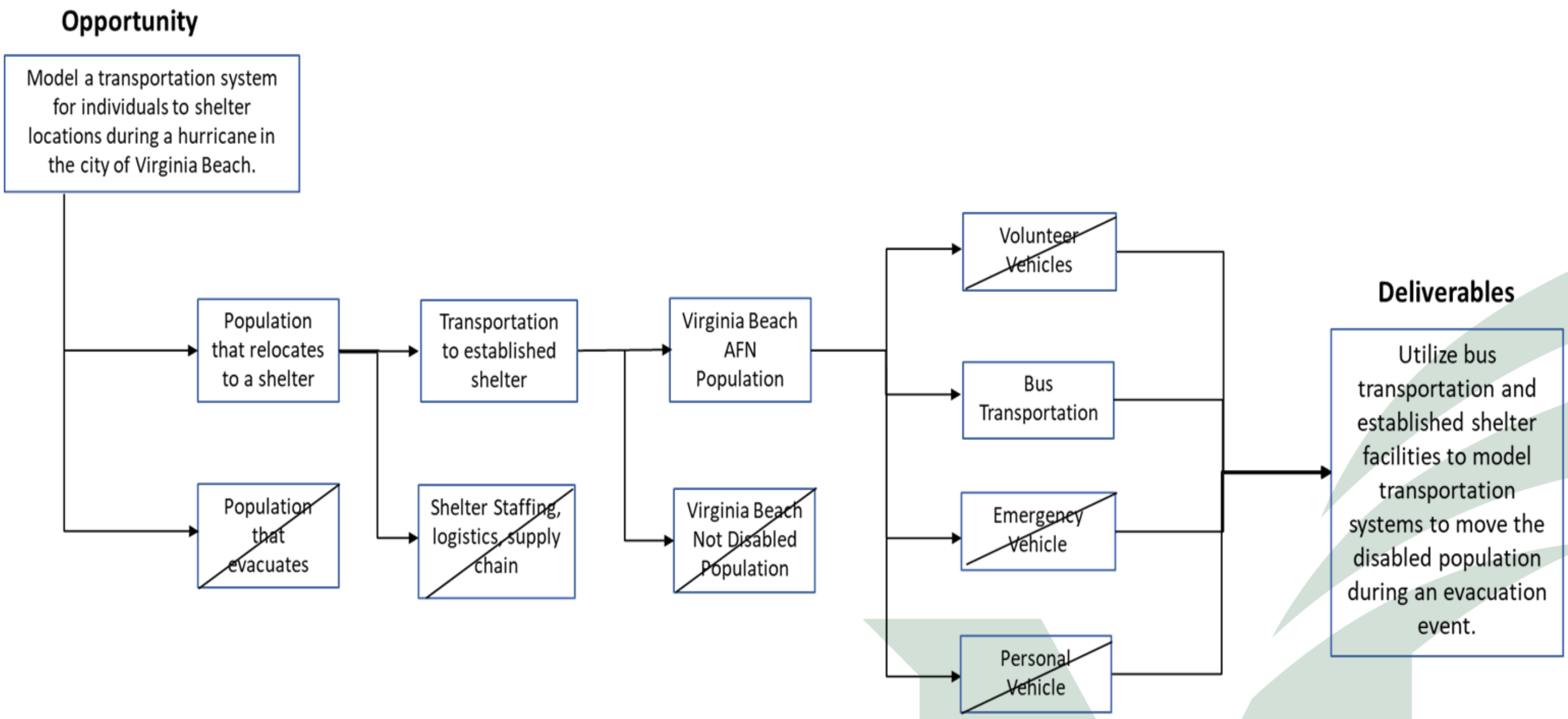
Problem Need

- Virginia Beach has evacuation plans and sheltering protocols in place. These plans:
  - **Do not include evacuation transportation**
  - **Are rarely implemented**
  - **Have a gap in planning how the vulnerable population will arrive at shelters**
- Zone based evacuation orders in Virginia Beach have clearance times within 28-67 hours

Problem Approach

- Components of this Access and Functional Needs (AFN) bus evacuation system:
  - **Strategically located shelters**
  - **Temporary bus stops for pick ups**
  - **Efficient bus routes**

Scope



***AFN = "Access and Functional Needs"**

Virginia Department of Emergency Management (VDEM) & Virginia Beach Emergency Management (VABEM) Current Protocols

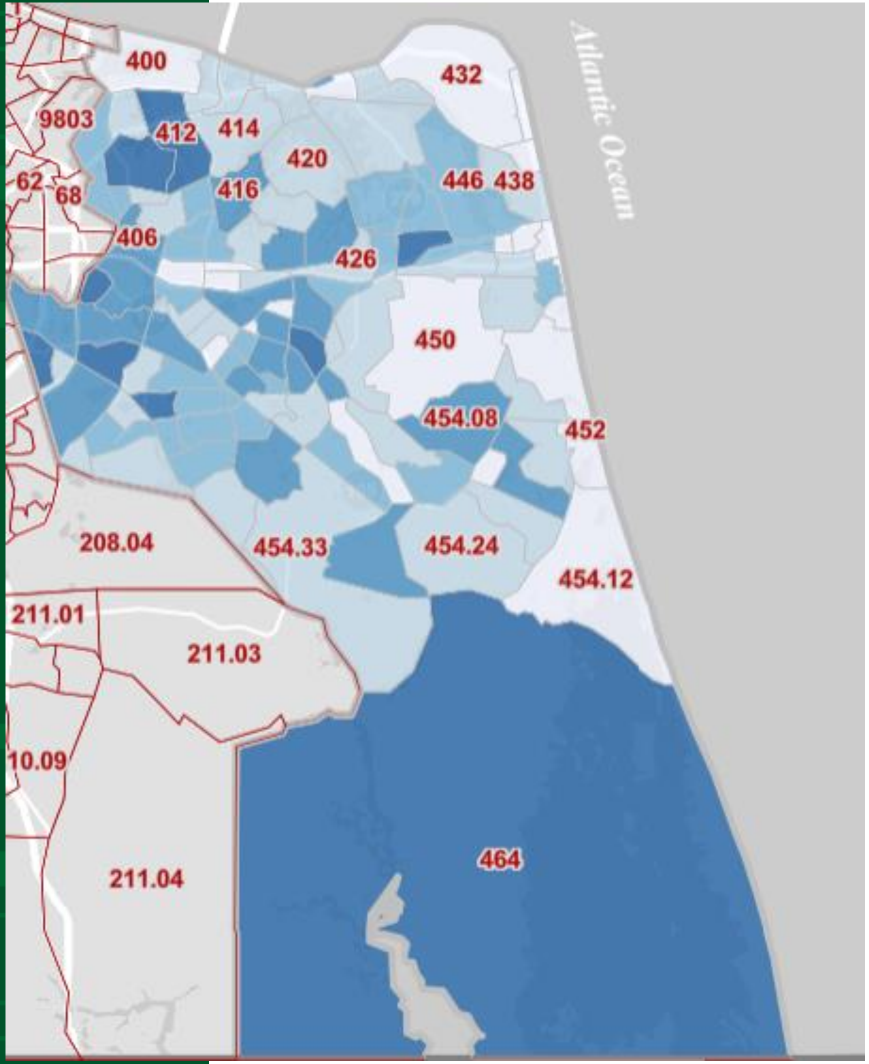
Virginia Department of Emergency Management

- VABEM will activate general population shelters during a hurricane event at their own discretion

- Standard Shelter Criteria:
    - Designated by tier level
    - Activated on a tiered basis (Tiers 1-3) based on storm severity
    - Americans with Disabilities Act (ADA) compliant

- VDEM may activate additional shelters once local established shelters exceed capacity

- VDEM is coordinating with FEMA to develop a transportation system for individuals that do not have access to evacuation means during a disaster



VA Beach Population Overview

- ❑ The City has a full-time population of approximately 450,000, ~10% of which is considered disabled.
- ❑ Population density determined by Census Tracts

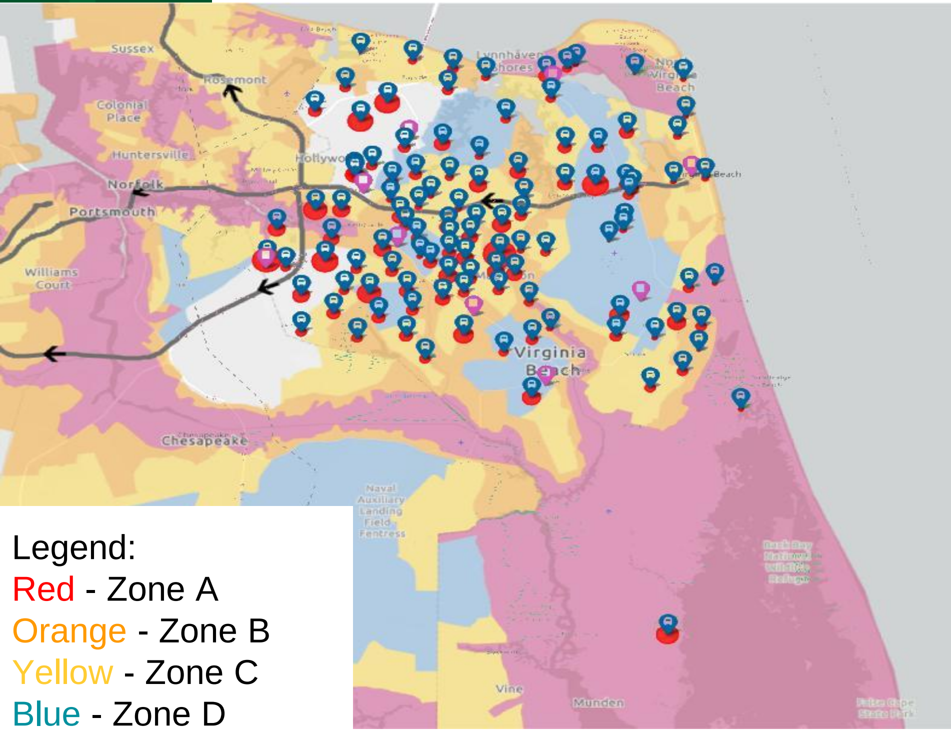
Legend:

Darker Blue = Higher Density of Disabled

Lighter Blue = Lower Density of Disabled

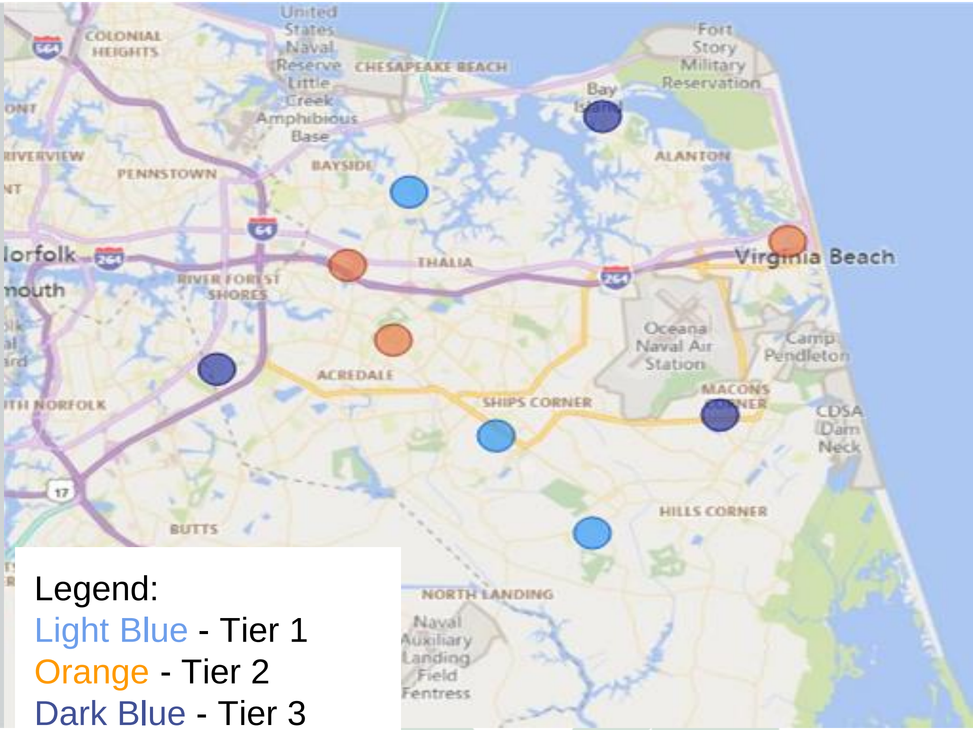
Flood Zones, Shelters, and Evacuation Routes

Flood Zones with Pickup Points



Legend:
Red - Zone A
Orange - Zone B
Yellow - Zone C
Blue - Zone D
Black - Evac. Routes

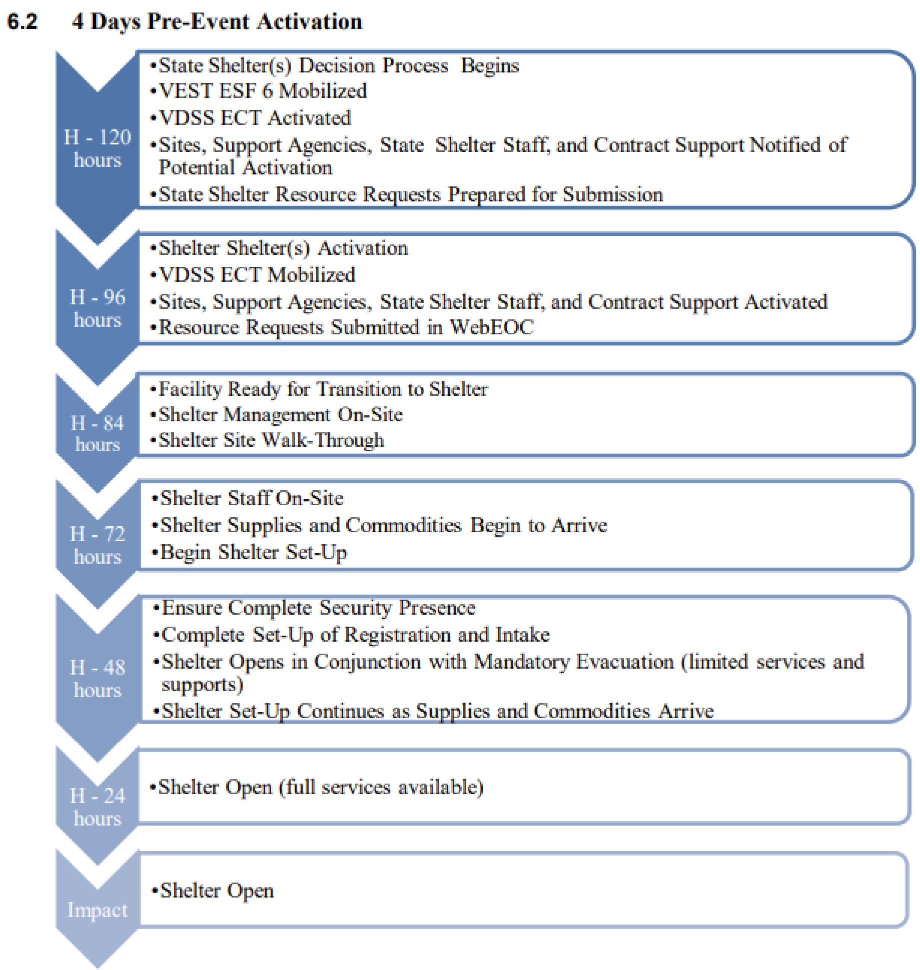
Established Shelters



Legend:
Light Blue - Tier 1
Orange - Tier 2
Dark Blue - Tier 3
Purple - Evac. Routes

Virginia State Coordinated Regional Shelter Plan

Evacuation Timeline


6.2 4 Days Pre-Event Activation

H - 120 hours
- State Shelter(s) Decision Process Begins
- VEST ESF 6 Mobilized
- VDSS ECT Activated
- Sites, Support Agencies, State Shelter Staff, and Contract Support Notified of Potential Activation
- State Shelter Resource Requests Prepared for Submission

H - 96 hours
- Shelter Shelter(s) Activation
- VDSS ECT Mobilized
- Sites, Support Agencies, State Shelter Staff, and Contract Support Activated
- Resource Requests Submitted in WebEOC

H - 84 hours
- Facility Ready for Transition to Shelter
- Shelter Management On-Site
- Shelter Site Walk-Through

H - 72 hours
- Shelter Staff On-Site
- Shelter Supplies and Commodities Begin to Arrive
- Begin Shelter Set-Up

H - 48 hours
- Ensure Complete Security Presence
- Complete Set-Up of Registration and Intake
- Shelter Opens in Conjunction with Mandatory Evacuation (limited services and supports)
- Shelter Set-Up Continues as Supplies and Commodities Arrive

H - 24 hours
- Shelter Open (full services available)

Impact
- Shelter Open

- ❑ Depending on the zone, the decision to evacuate will be made early with limited information
- ❑ Zone evacuation can occur concurrently or separately
- ❑ Shelters are opened when the evacuation starts
- ❑ Impact is defined as when storm force winds begin

Key Assumptions:

- **Population with an AFN will be prioritized in an evacuation event and may fill shelters to capacity prior to general population arrival at shelters. This simulation will only model the transportation of the disabled population to shelters.**

- Based on VDEM assumptions, 80% of the entire population in a risk area will participate when an evacuation order is issued, 8% of this population will seek shelter

- Each person with AFN will have one caregiver accompanying them

- A Zone D evacuation is an extreme event, and likely to exceed the City of Virginia Beach’s resources. This is out of scope for our project.

- The model will transport from one shelter to the next nearest shelter if the closest shelter’s capacity has been reached.

- That local school buses will be available (unconstrained) during an evacuation for the transportation of persons with AFNs to shelters.

Logistics Overview

Shelter Capacity by Tier

Shelter	Capacity	Tier
Kellam High Shool	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
Total	**7288**	

Population Transported to Shelter

Total Disabled Population	48,643
Assume 80% * 8% Sheltering	3,113
Disabled Population Including Caregivers (Total to be Transported by Model)	**6,226**

The model will prioritize the 6,226 disabled plus a caregiver to occupy shelters prior to accommodating the general population.

Simulation Overview

Python 3.9 packages
Mesa = Agent Based Modeling
OSMnx = OpenStreetMap
Folium = HTML Maps
Networkx = travel distance

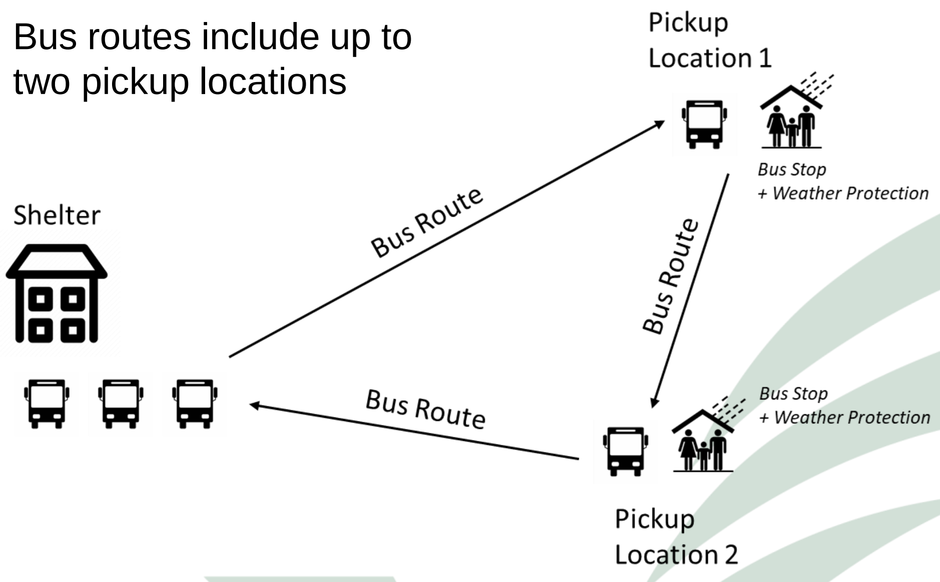
Bus evacuation planning tool helps design efficient bus routing and pickup locations.

Measure clearance time by simulating agent transportation from pickups to shelters.

Minimize overall transit time by using capacitated shelter allocation plan.

Minimize waiting times with appropriate bus schedule and operations.

Bus routes include up to two pickup locations



Key Parameters

Driving times: Calculated from OpenStreetMaps using standard, free-flow traffic conditions. Poisson distribution used to generate random variations in driving times.

Loading times: Assume a fixed **30-second loading/unloading time** for passengers, with a **4-minute time for wheelchairs** (assume 29% of passengers based on census data).

Bus capacity: Assume each bus carries up to **20 individuals**.

Bus operation: Bus travels continuous circuit, stopping only to load, unload, or idle (10-minute inter-departure time required for multiple buses traveling on same route to avoid “bunching”)

Arrival distribution of evacuees to pick-up locations: A Rayleigh distribution was chosen from evacuation literature. The peak arrival time may be varied.

Simulation Methodology

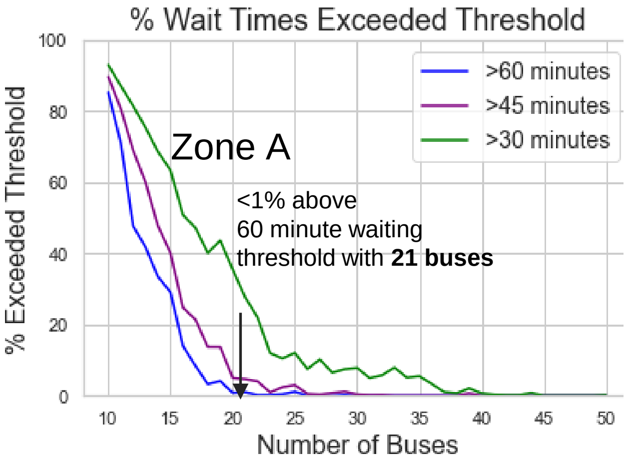
Step 1: Generate Routes

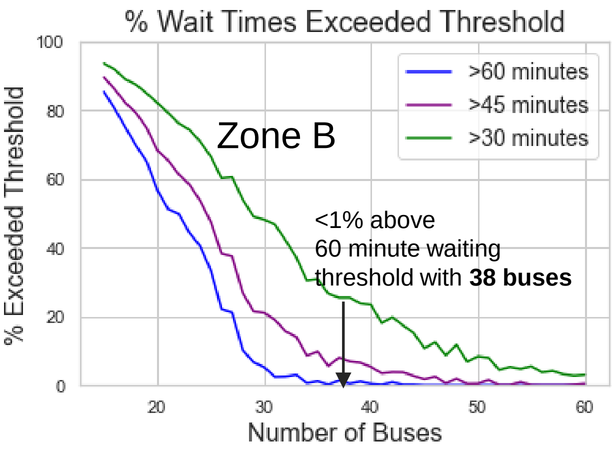
Step 2: Generate Buses & Assign to Routes

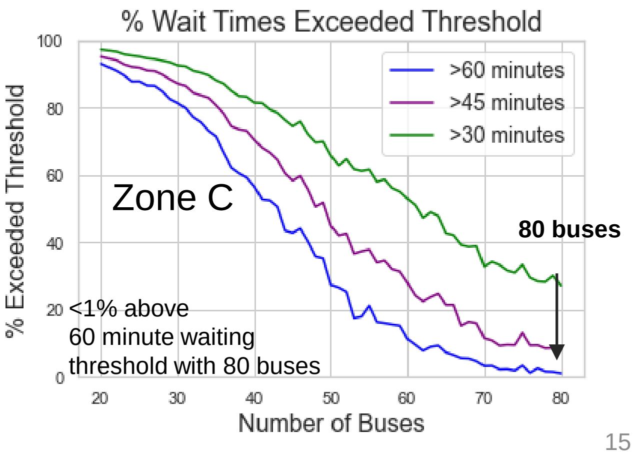
Step 3: Simulate

Step 4: Add buses to routes with longest wait times

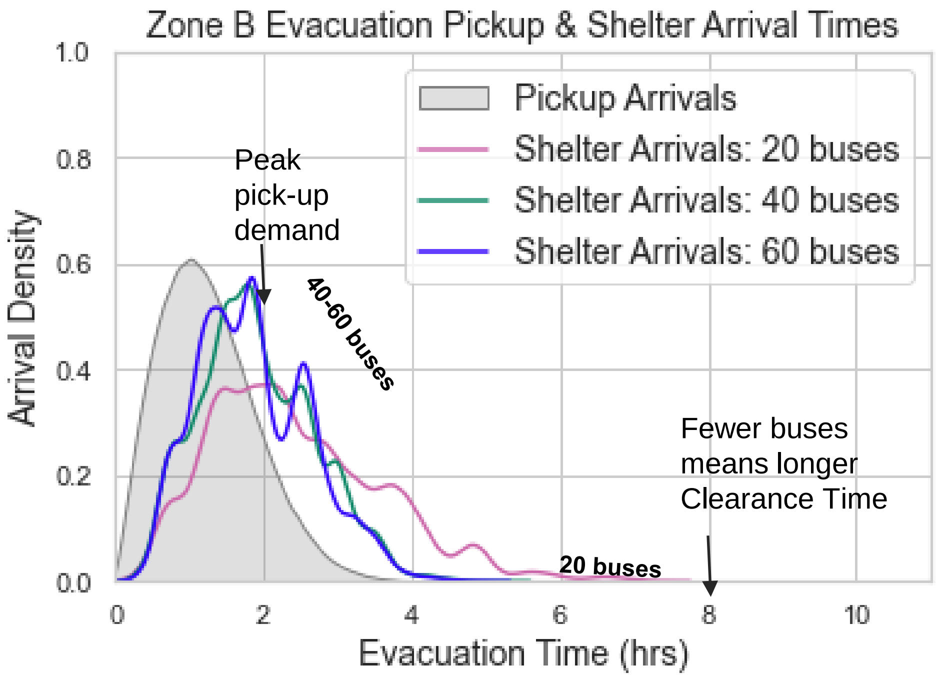
When is a solution “good enough”?
→ All wait times must be < 60 minutes
(within 1% margin of error)

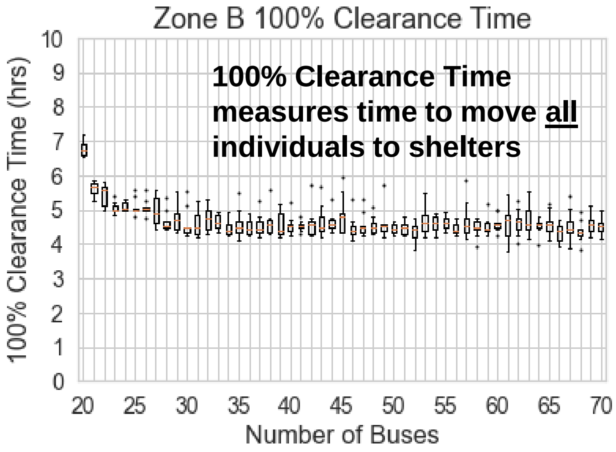


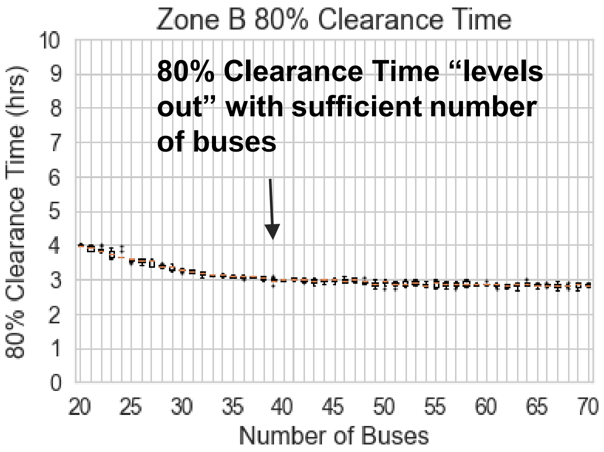




Measuring Clearance Time





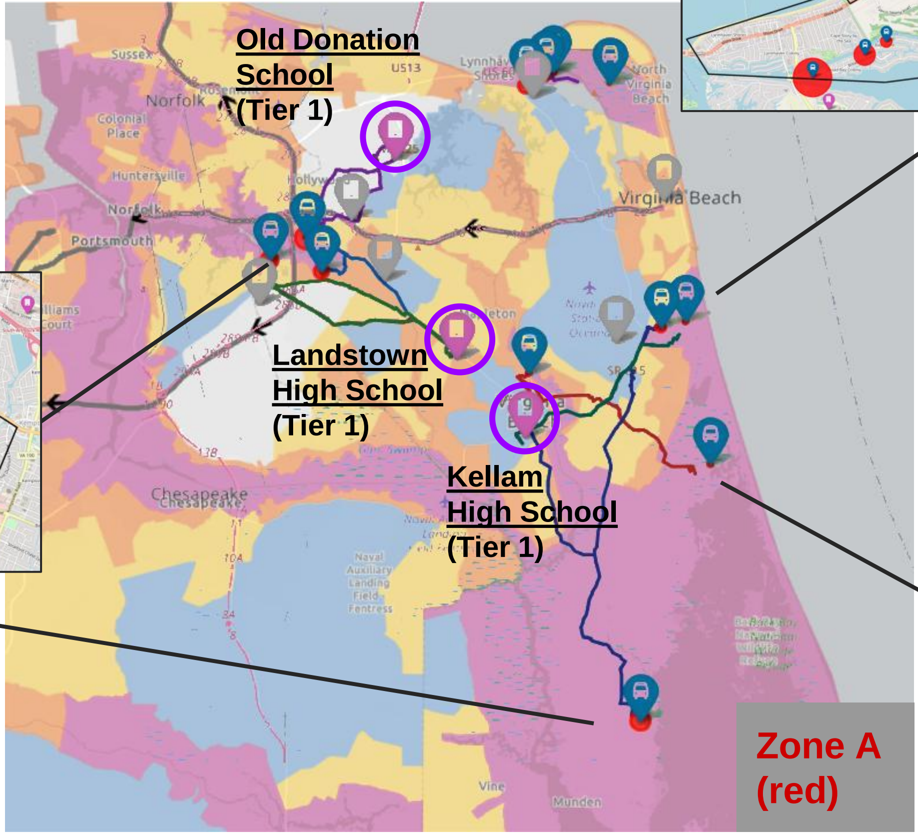


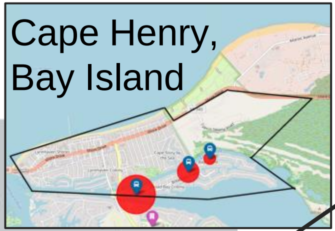
Zone A - Evacuation

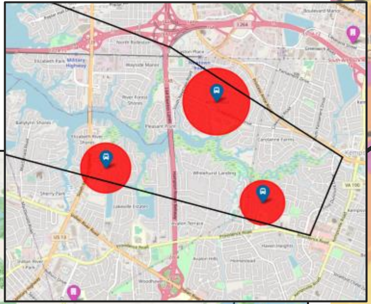
Sheltered: 484

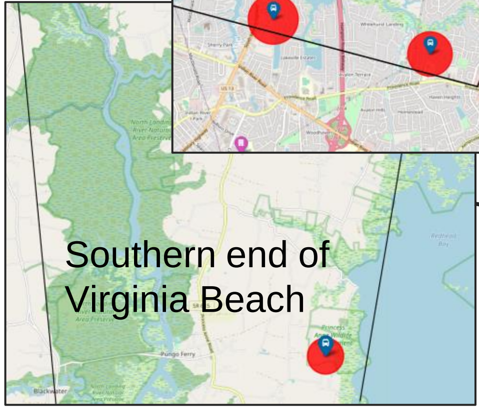
Pickup Locations: 12

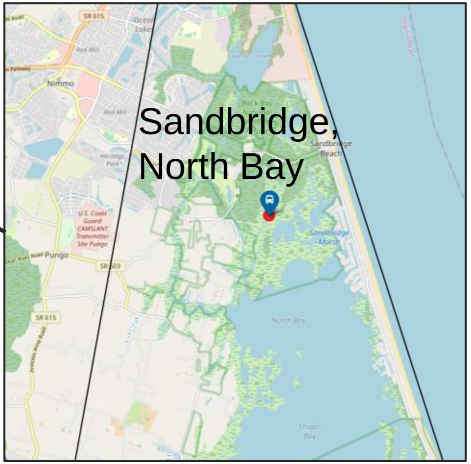
Bus Routes: 10









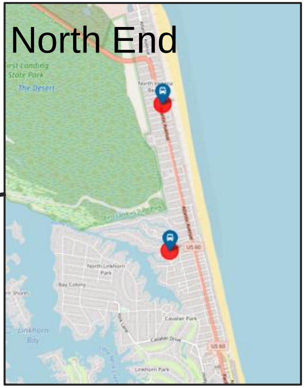


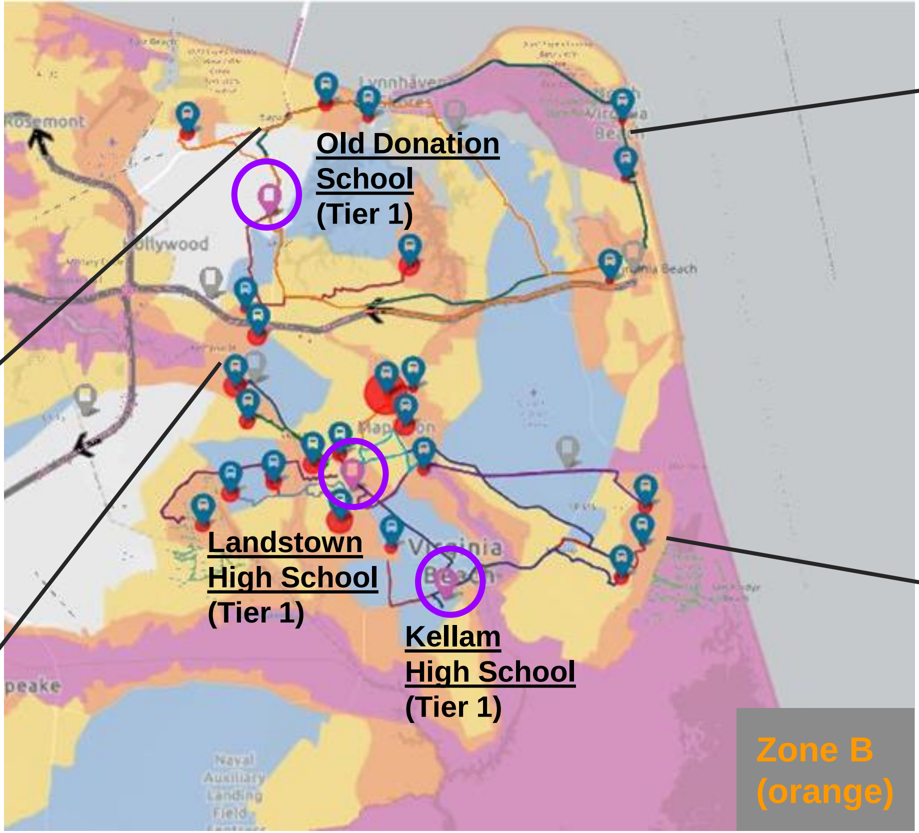
Zone B - Evacuation

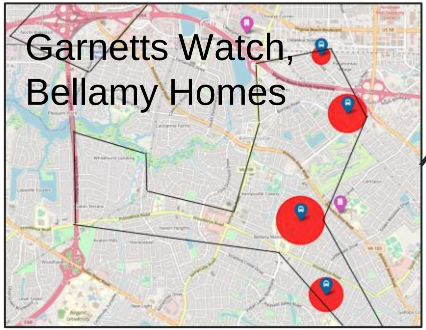
Sheltered: 1,870

Pickup Locations: 25

Bus Routes: 15





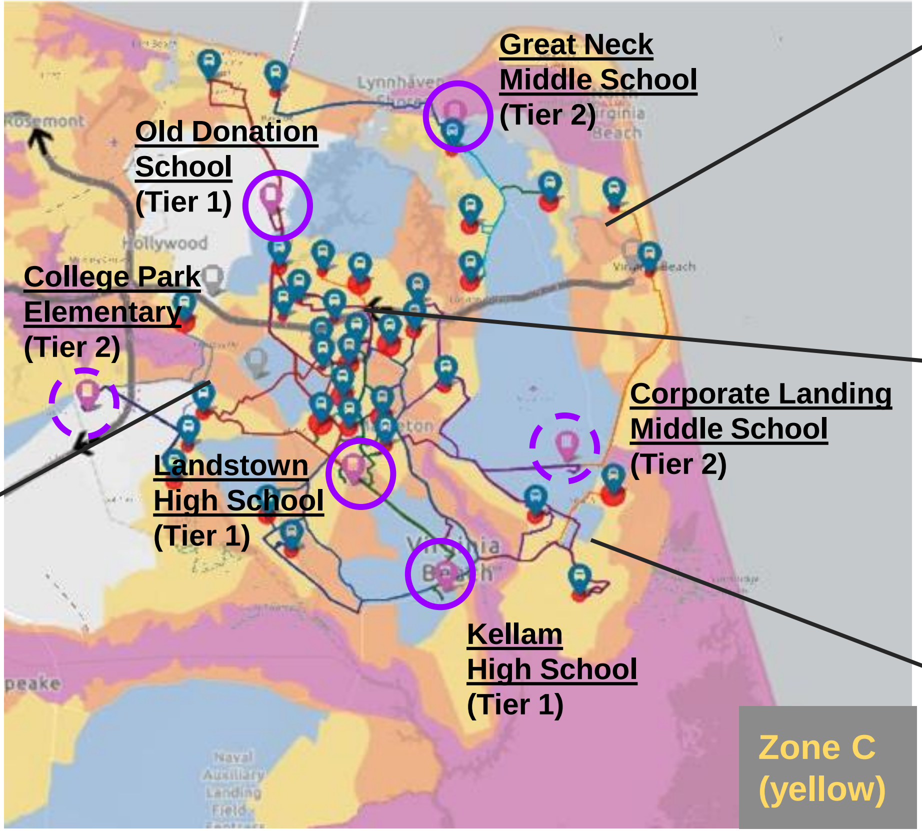


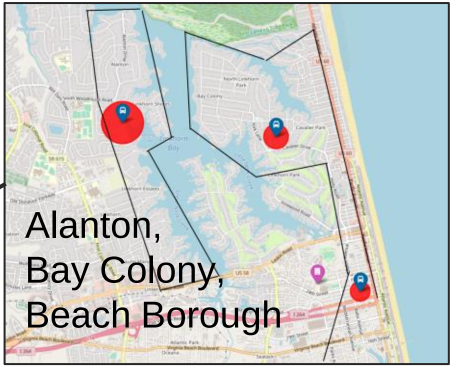
Zone C - Evacuation

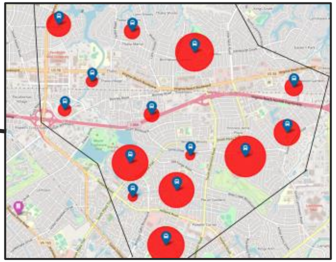
Sheltered: 1,972

Pickup Locations: 35

Bus Routes: 20







Improved routing strategy
+College Park Elementary
+Corporate Landing Middle

Required Number of Buses

Rayleigh Arrival Distribution (Peak Time)	80% Clearance Time	Zone A (Tier 1)	Zone B (Tier 1)	Zone C (Tier 1-2; 6 total)	Zone C (Tier 1-2; 4 total)
		# 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

Discussion -Overall clearance time is heavily affected by arrival patterns of evacuees-

Waiting times experienced by evacuees at pickup locations plays a major role in the number of buses and evacuation time windows. Planners should consider the following mitigations:

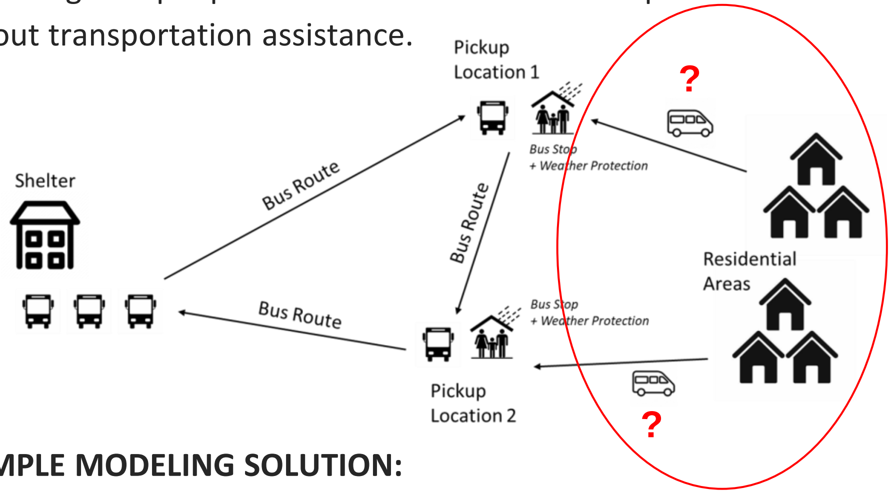
- Increase the number of buses
- Increase bus coverage for pickup locations with more demand/distance from shelter
- Design routing to minimize overall transit cost (Consider opening multiple Tiers simultaneously)
- Organize groups of pickup locations that will be evacuated in sequence
- Change operating patterns of buses (such as dwell time and dynamic routing)

Focuses for future work could also include:

- Supply needs (types and quantities) at a variety of different sized and function shelters.
- Expand the Scope of the model(i.e., different populations and transportation methods)
- Expand the functionality of the model

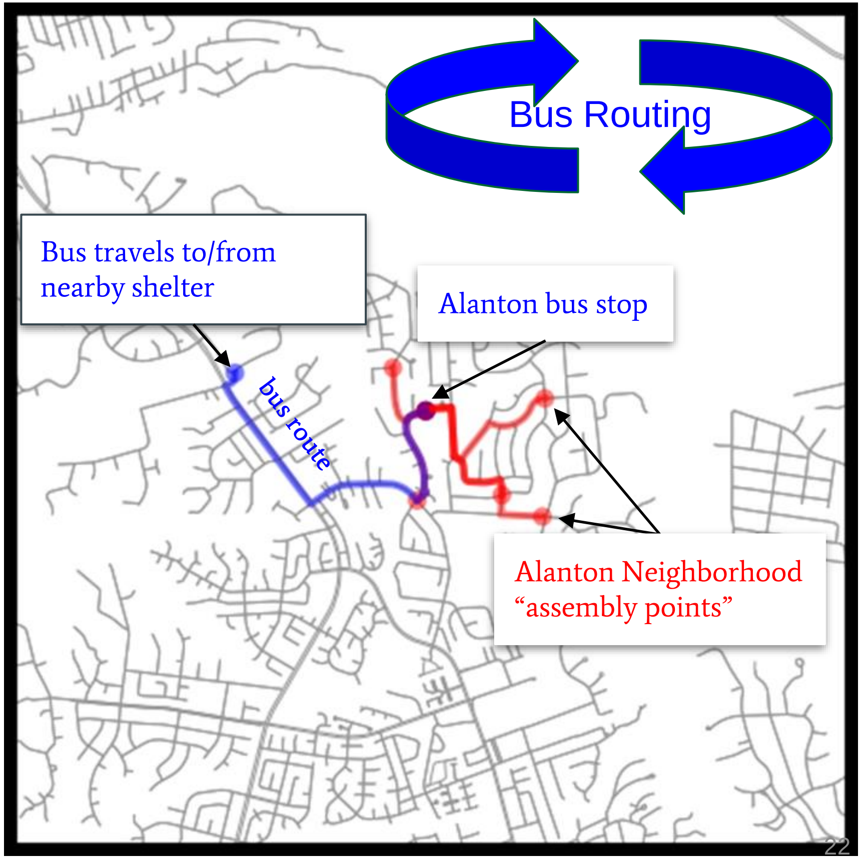
Future Work Focus: Evacuee Flow to Pick-Up Points

PROBLEM: The area served by a single pickup location may be too large for people with AFN's to reach the stop without transportation assistance.



EXAMPLE MODELING SOLUTION:

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



Recommendations

- Revaluation of shelter locations, capacities, and capabilities.
- Potential utilization of current School Bus Routes
- Acquire more accurate information about the vulnerable population including their location, transportation and medical needs (i.e., # of people requiring wheelchair accessibility).
- Re-run the model using the data acquired above.
- Accessibility to VA Beach evacuation information.
- Plan practice evacuations to ensure current shelter, transportation and emergency infrastructure is sufficient and to build community resilience and trust.

Conclusion

By utilizing **Systems Engineering and Operational Research methods**, we have developed a prototype model of the **evacuation of vulnerable populations** to already-determined shelter locations. The model **can be expanded** by future classes.

This type of modeling is not only **useful to Virginia Beach**, but to other Coastal locations in the U.S., as well as those living in the Philippines and elsewhere.

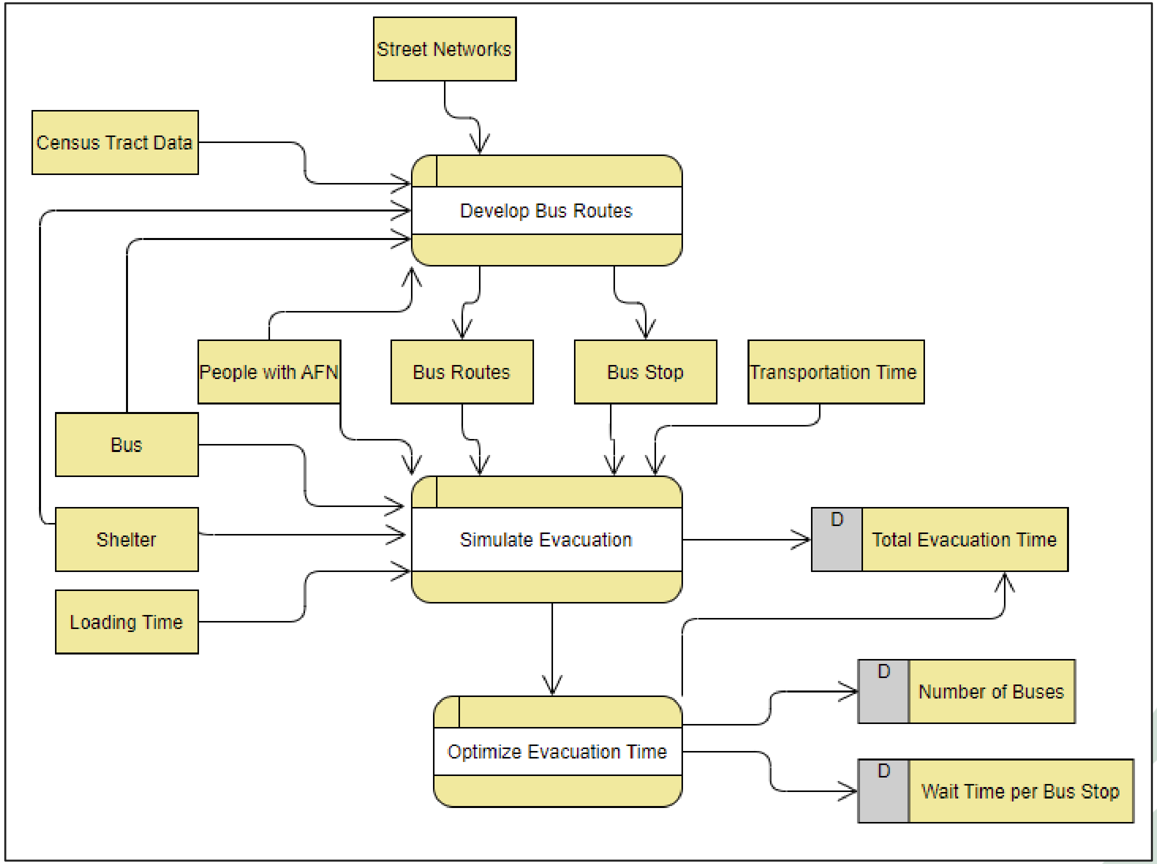
Thank You!
Any Questions?

Special Thanks:
Dr. Gregory Tangonan, Ateneo de Manila University,
Bruce Sterling and all those with VDEM,
Danielle Spach with VBDEM,
Dr. Karla Hoffman and Dr. Xu from GMU

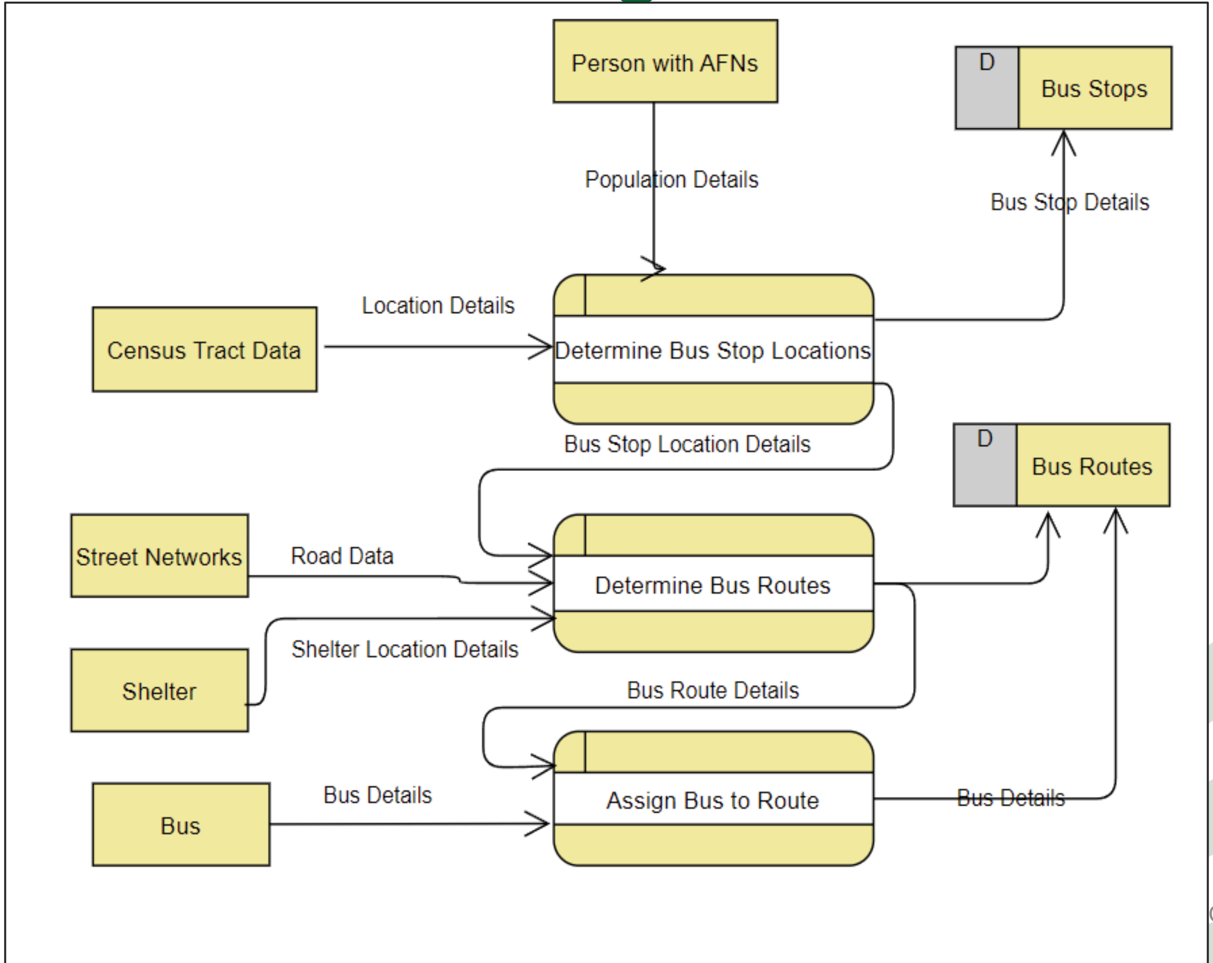
Department of Systems Engineering and Operations Research (SEOR)

Backup Material

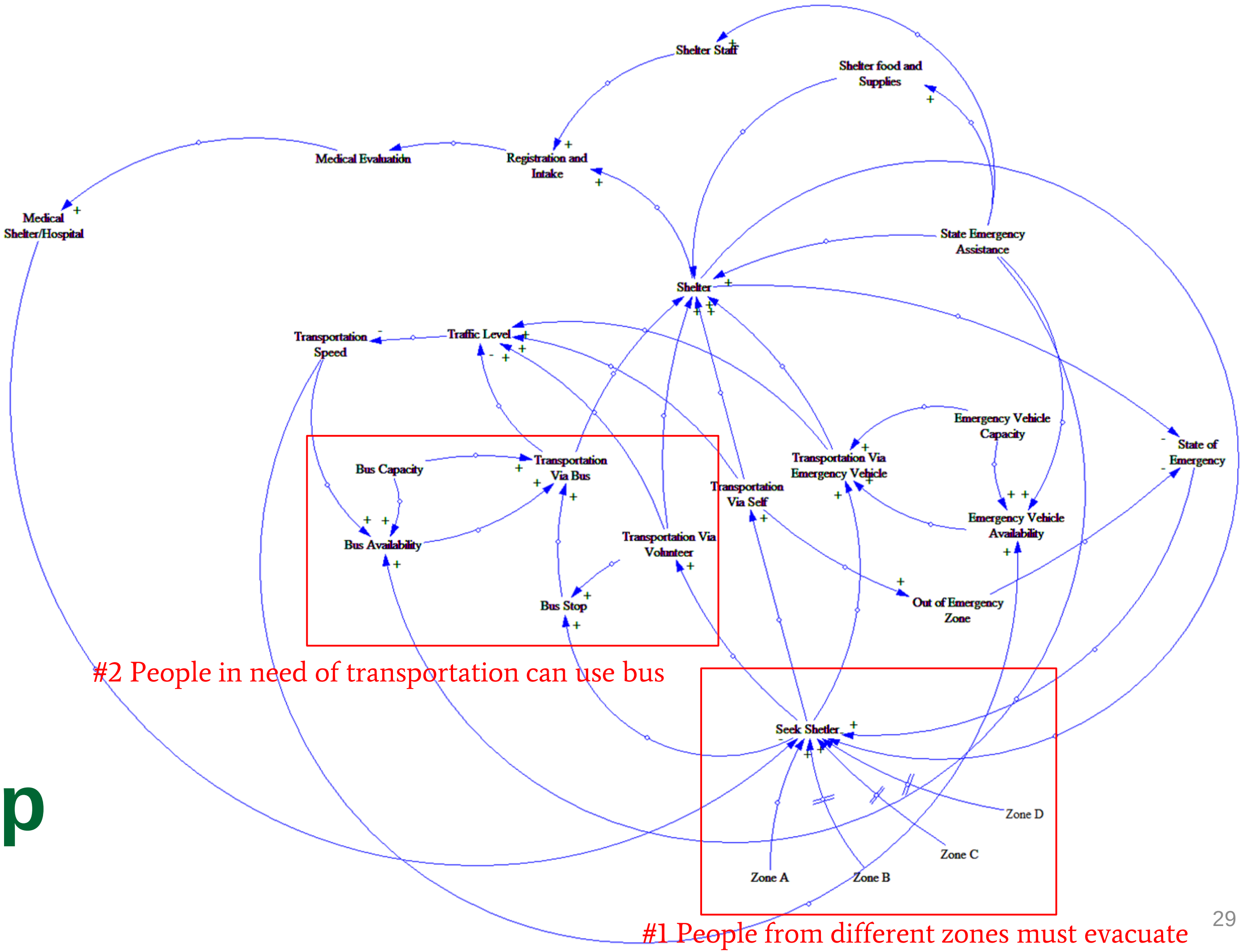
Data Flow Diagram



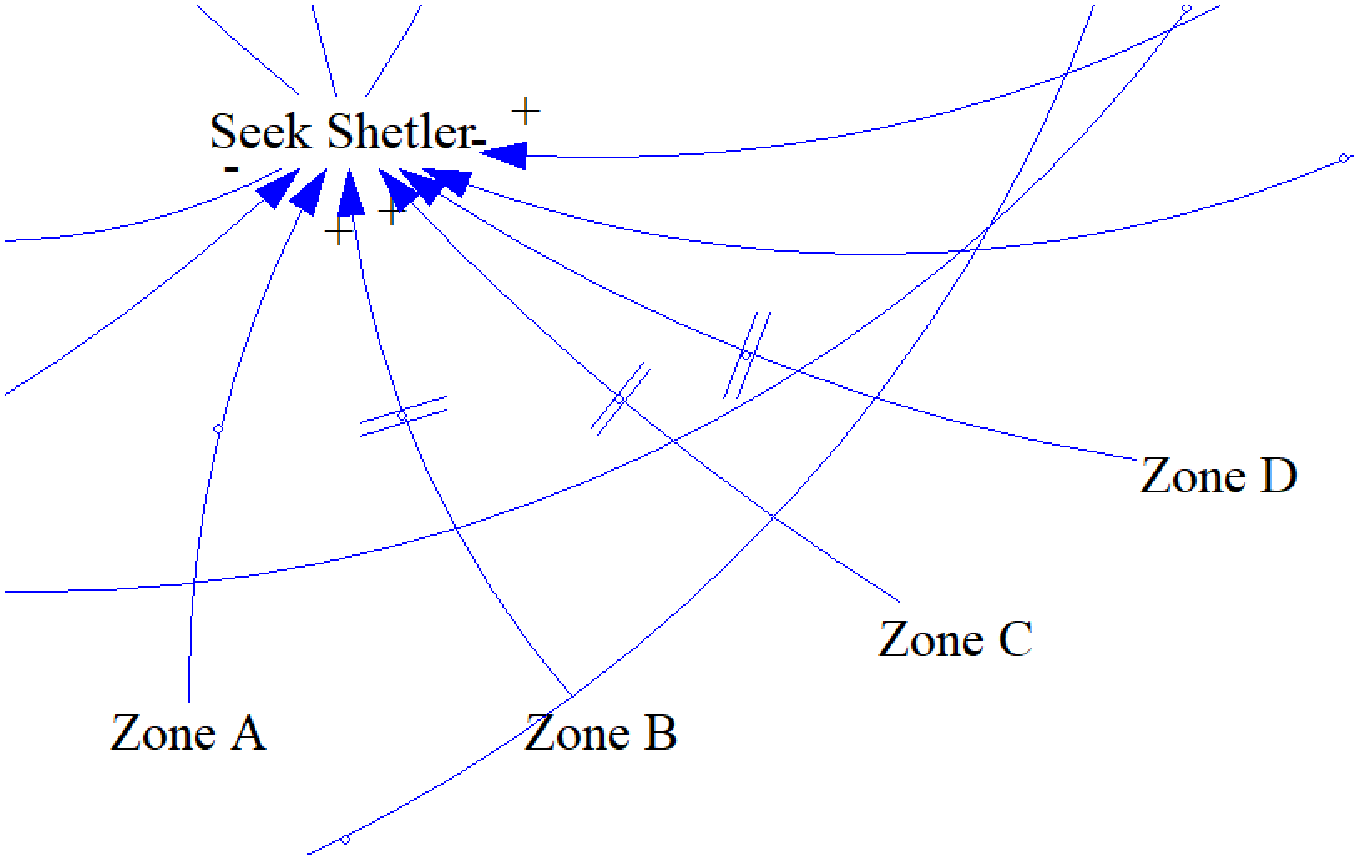
Data Flow Diagram



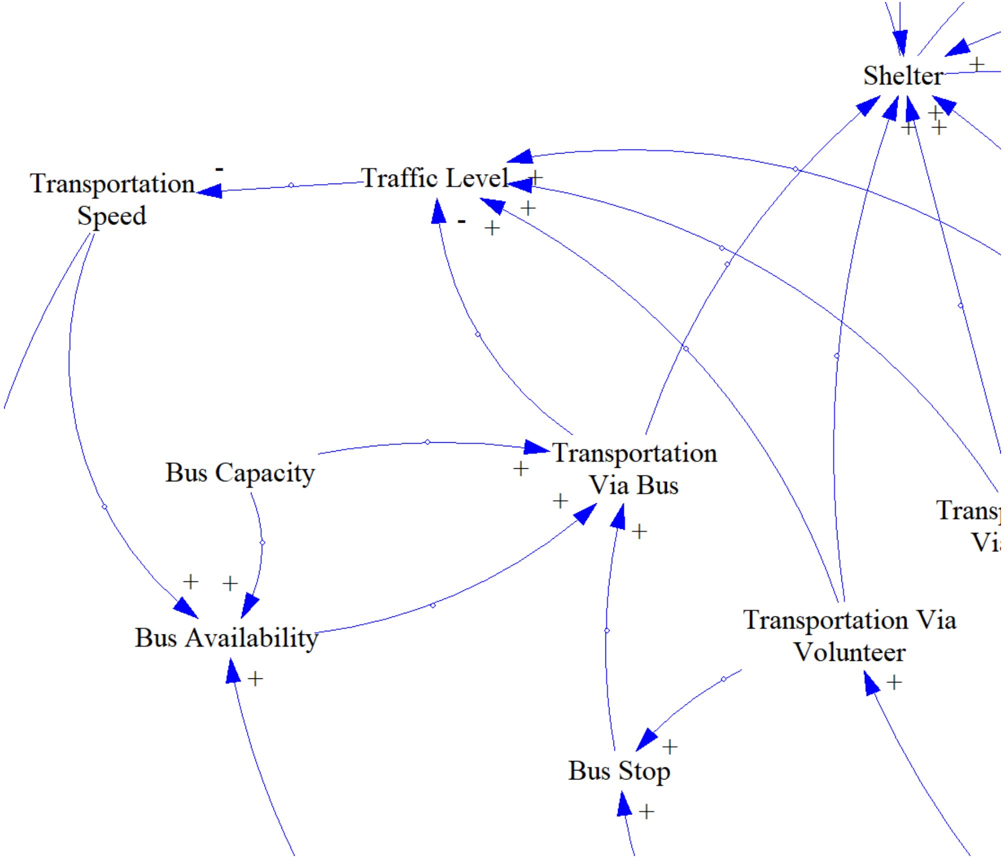
Evacuation System Causal Loop Diagram



#1 People from different zones must evacuate

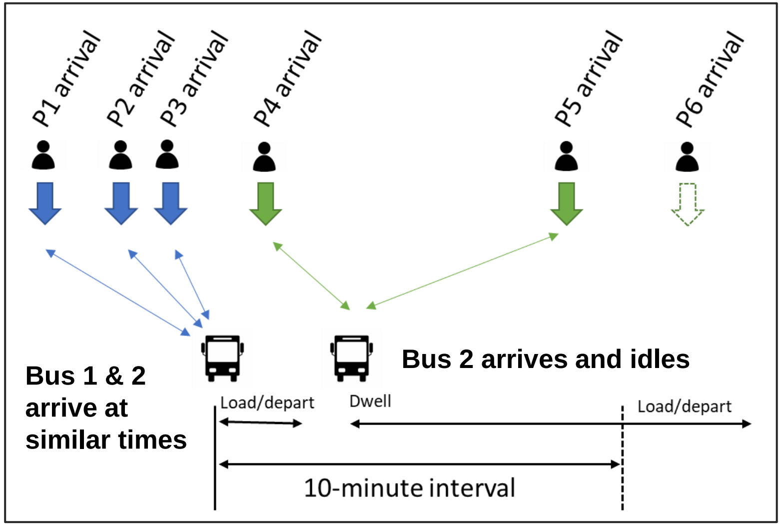


#2 People in need of transportation can use bus



Simulation Overview

Modeling the interaction of bus and evacuee agents at pickup locations



Planning Considerations for Bus Operators

1. People spend too long at pickup locations.
   → **Add more buses to route**

1. Multiple buses on same route “bunch” at pickup locations, producing disparity in waiting times.
   → **Set minimum departure intervals: “idling”**

1. People spend too long riding on buses.
   → **Limit route length**
   → **Limit idle time at pickups**

Data Requirements

Input	General Unit(s)	Resource	Data Type	How it may Change
Population	# of People with AFNs	United States Census Bureau, 2020	Stochastic	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	Stochastic	Change would occur based on disaster location and regions of flooding
Vehicles	# of Available Vehicles Vehicle Capacity	VDEM, 2022	Stochastic	Vehicles may be added or removed based on volunteered vehicles, vehicle breakdown, or population change

Evaluation

Key modeling questions:

- ❑ **Can the evacuation be completed in time?**
- ❑ **Are wait times at pickup locations maintained below a reasonable threshold?**
  - ❑Current threshold is set at max 60 minutes
- ❑ **How/when do evacuees arrive at pickup locations?**
  - ❑ Number of traveling companions
  - ❑ Arrival distribution
- ❑ **How should buses operate? What capacity?**
  - ❑ Assignment of pickups to shelters
  - ❑ Bus routes and number of stops (max=2 in our model)
  - ❑ How many buses per route

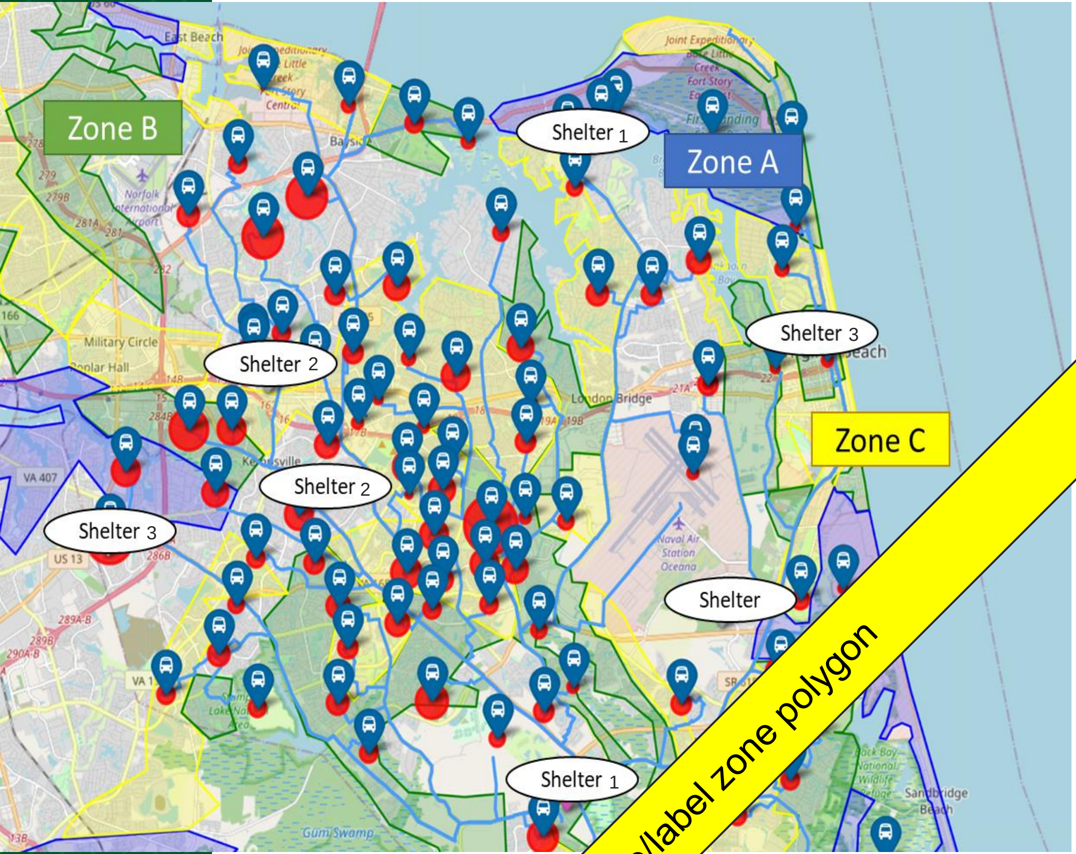
Evaluation Parameters:

1. Clearance time
2. Time spent waiting at bus stop
3. Number of buses
4. Number of bus stops

Model Methodology Overview

Step	Description	Notes
Build Baseline Scenario	Locate population nodes, shelters, and bus stops	Census Data, Flood map, Virginia Beach emergency planning,
Build Routes	Route populations to nearest pick-up location Route buses to nearest available shelter	Python packages: OSMNx, Networkx
Simulate	Agent-Based Simulation models flow of evacuees from population nodes to bus stops to shelters. Evacuee wait times (at bus stop), transit time, total # evacuated to shelters in allotted time	Python packages: Mesa, Geopandas, Folium
Evaluate	Primary objective: minimize clearance time Secondary objective: minimize wait times Limited resources: # of buses, # of bus stops	Subject matter inputs

Simulated Bus Evacuation Map



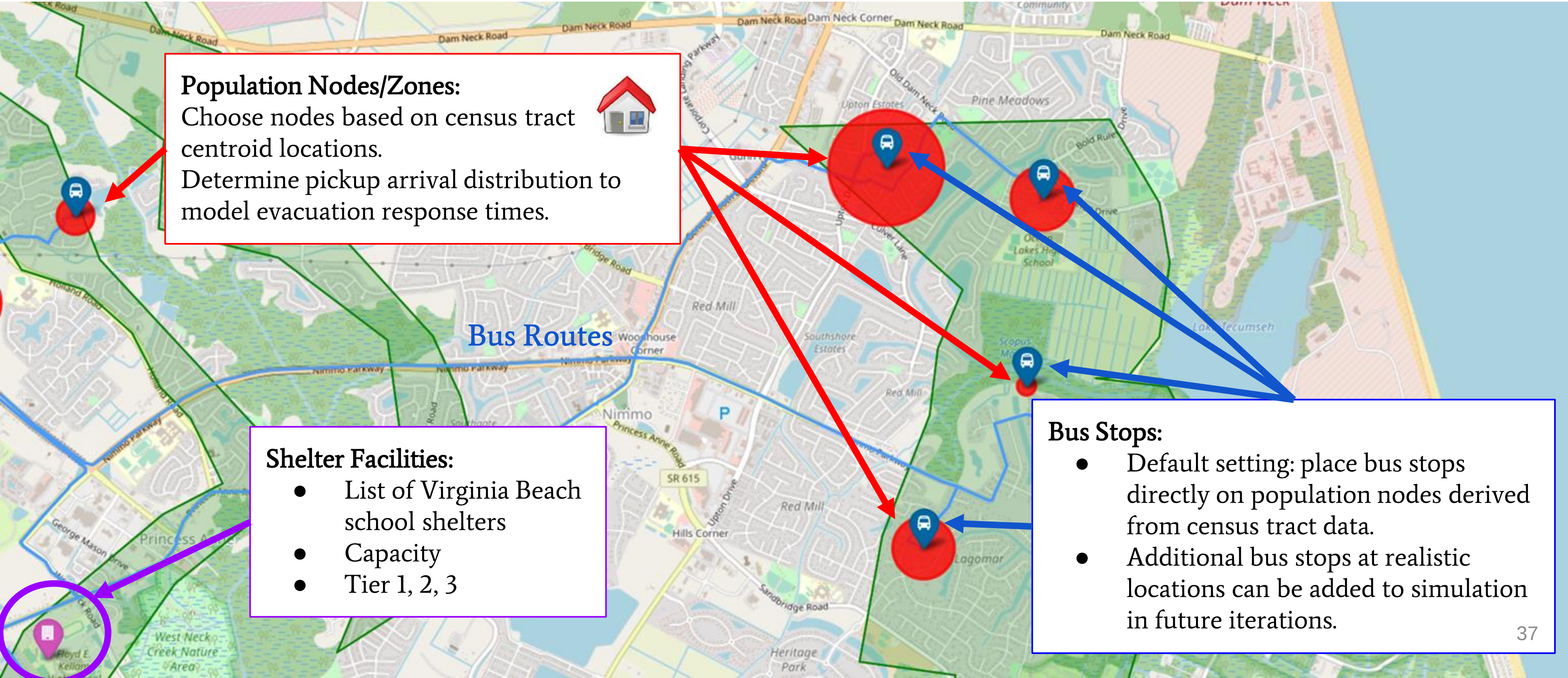
Update/label zone polygon

Map … nia Beach:

1. …ownload census data for people with functional and access needs; plotted latitude/longitude positions on map
2. Overlay flood zone polygons
3. Match census nodes to flood zones A, B, and C
4. Assume pickup locations at every census data node
5. Add Virginia Beach public school shelters

Simulation Overview

Python 3.9 packages
Mesa = Agent Based Modeling
OSMnx = OpenStreetMap
Folium = HTML Maps
Networkx = travel distance



Population Nodes/Zones:
Choose nodes based on census tract centroid locations.
Determine pickup arrival distribution to model evacuation response times.

Shelter Facilities:

- List of Virginia Beach school shelters
- Capacity
- Tier 1, 2, 3

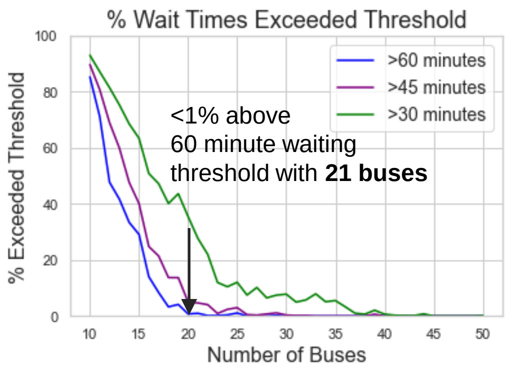
Bus Stops:

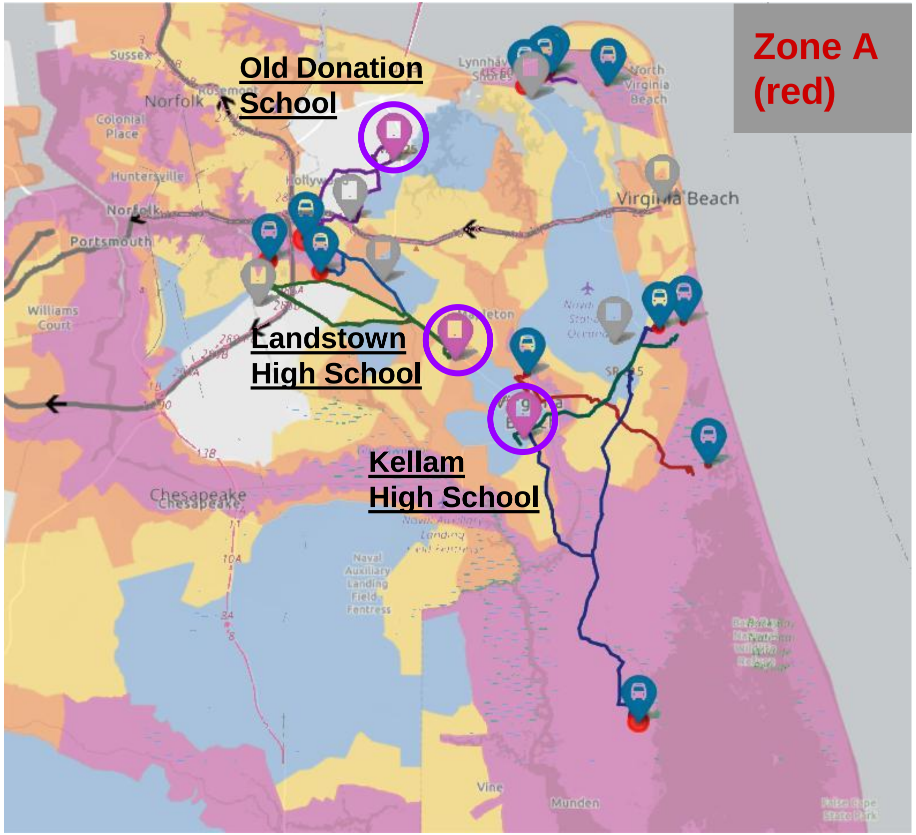
- Default setting: place bus stops directly on population nodes derived from census tract data.
- Additional bus stops at realistic locations can be added to simulation in future iterations.

Zone A Evacuation:

PROPOSED SYSTEM UNDER SURGE CONDITIONS:
3 shelters, 12 pickups, 10 routes, 21 buses
Arrival pattern: Surge conditions, peak at 1 hr
Max simulated clearance time: 4 hrs 54 minutes

Passengers with wheelchairs: 29%
Time to load/offload wheelchairs: 4 minutes
Time to load/offload other passengers: 30 sec
Dwell time for multiple-bus routes: 10-30 min

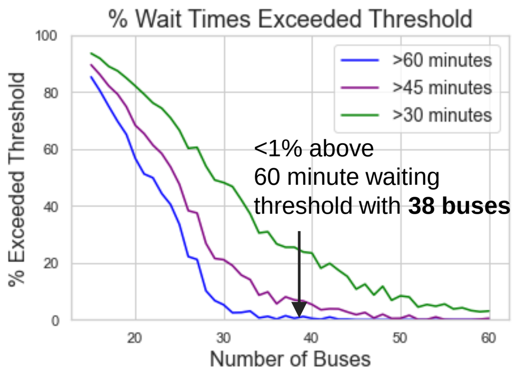


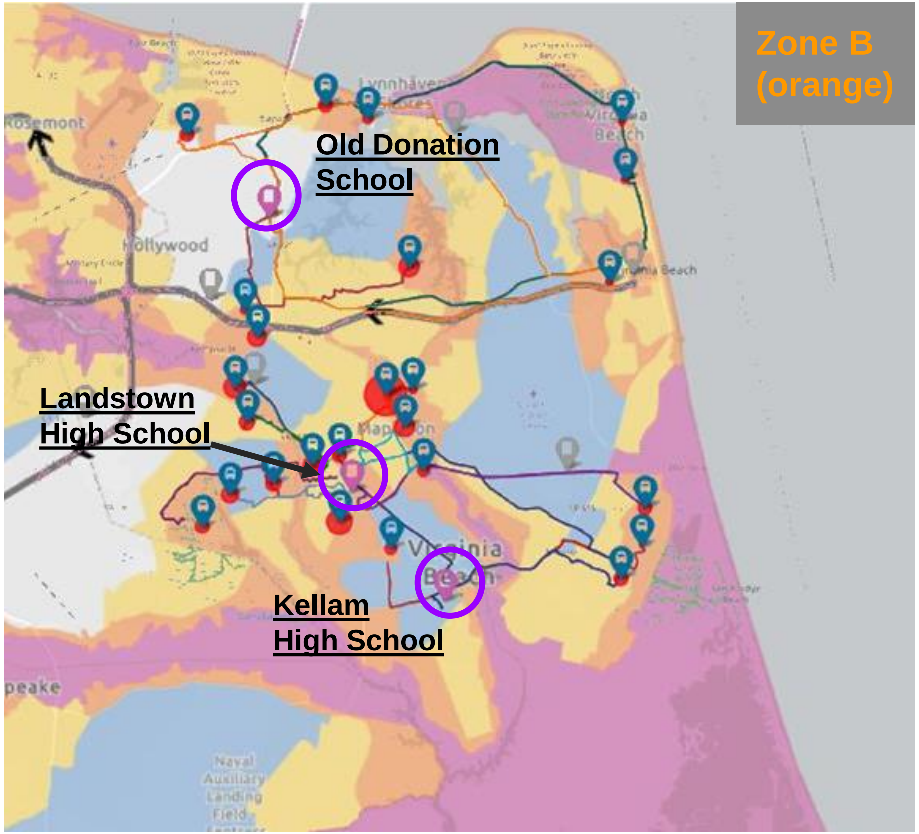


Zone B Evacuation:

PROPOSED SOLUTION:
3 shelters, 25 pickups, 15 routes, 38 buses
Arrival pattern: Surge conditions, peak at 1 hr
Max simulated clearance time: 4 hrs 30 minutes

Passengers with wheelchairs: 29%
Time to load/offload wheelchairs: 4 minutes
Time to load/offload other passengers: 30 sec
Dwell time for multiple-bus routes: 10-30 min





Zone C Evacuation:

PROPOSED SOLUTION

(1) Simple routing (use 4 shelters):

4 shelters, 35 pickups, 20 routes, 80 buses

Arrival pattern: Surge conditions, peak at 1 hr

Max simulated clearance time: 5 hrs 10 minutes

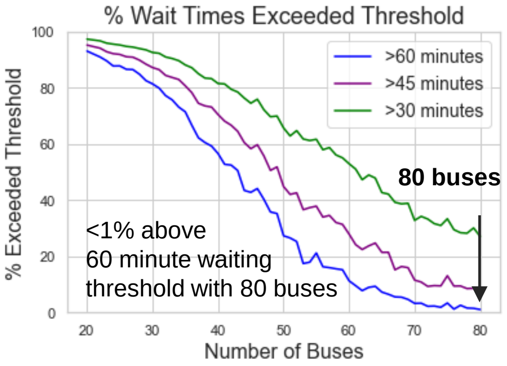
(1) “Improved” routing (use 6 shelters):

6 shelters, 35 pickups, 20 routes, 62 buses

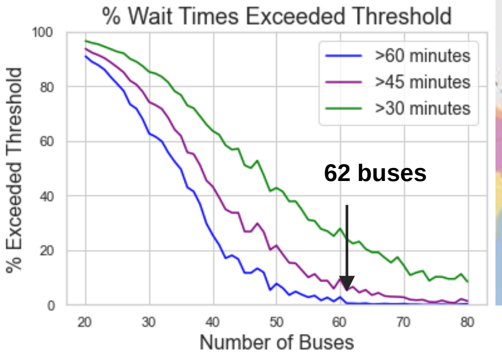
Arrival pattern: Surge conditions, peak at 1 hr

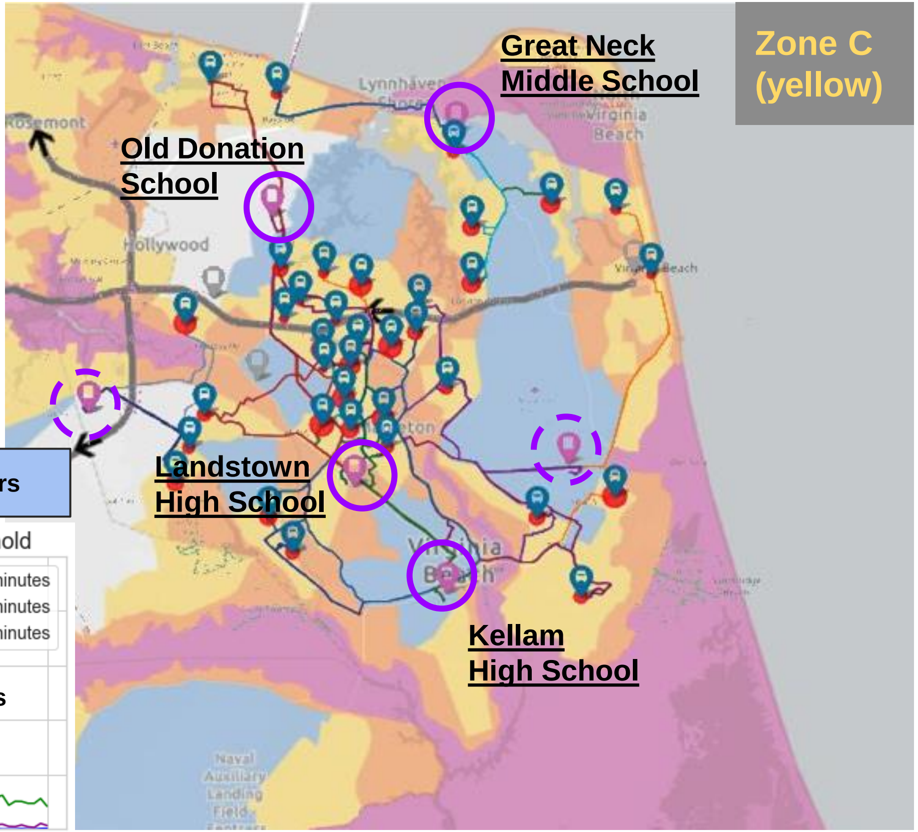
Max simulated clearance time: 5 hrs 4 minutes

Simple Routing, Fewer Shelters

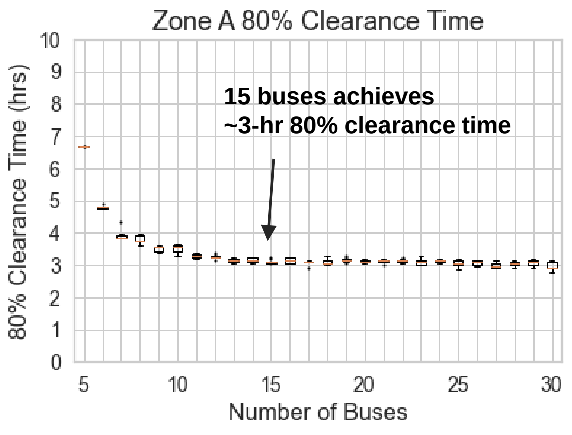


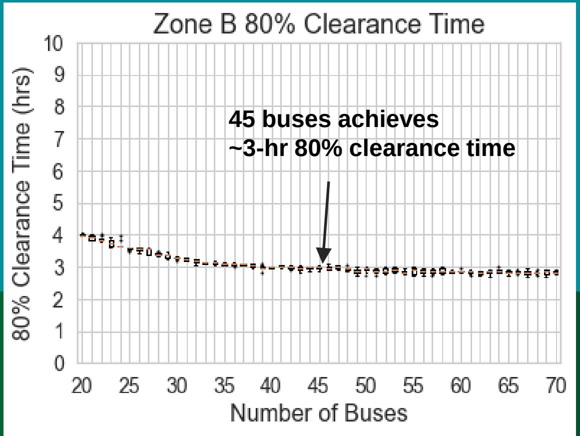
Improved Routing, More Shelters

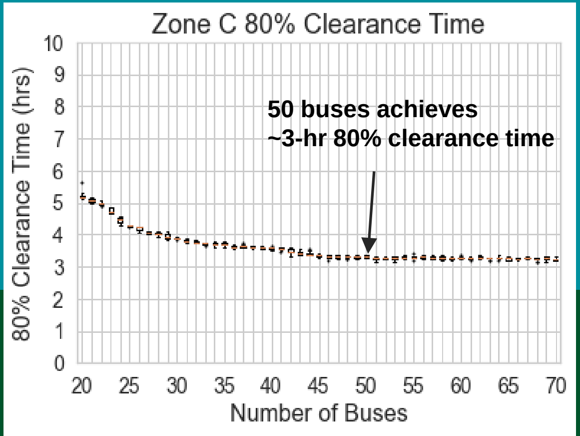




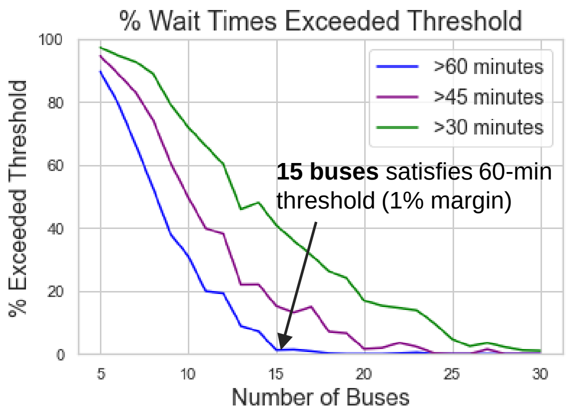
Determining Number of Buses Required



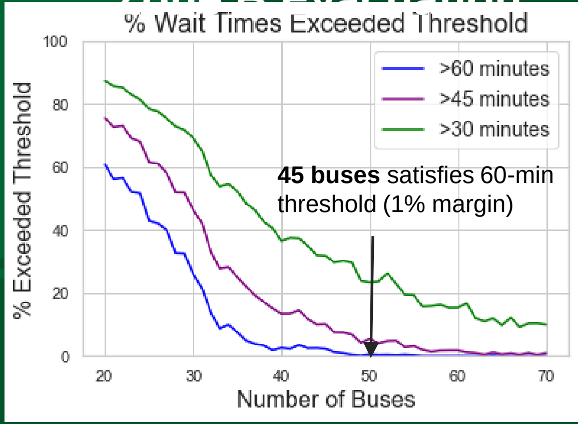




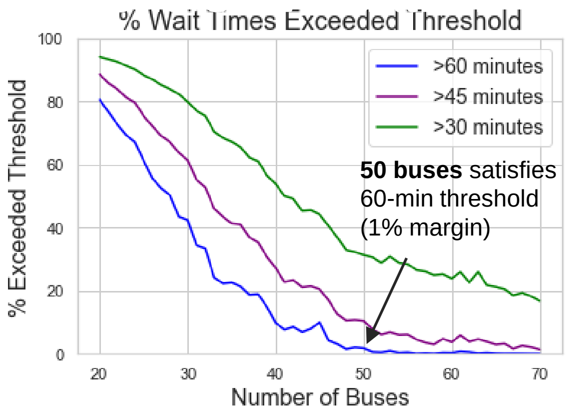
Zone A Evacuation



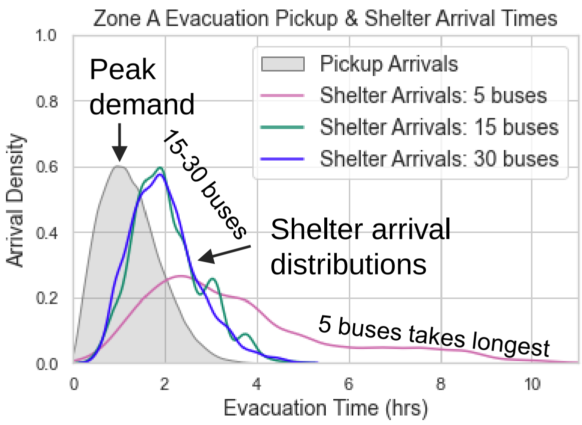
Zone B Evacuation



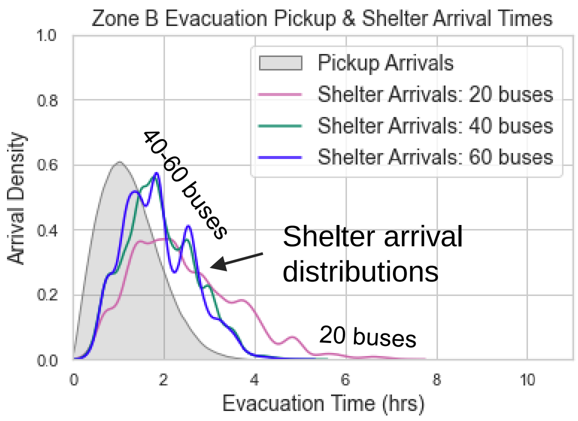
Zone C Evacuation



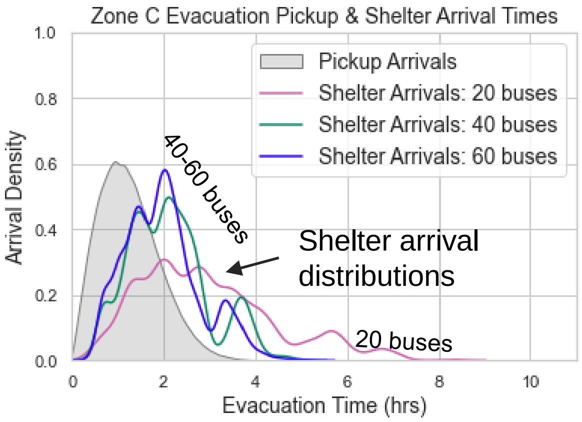
Measuring Clearance Time



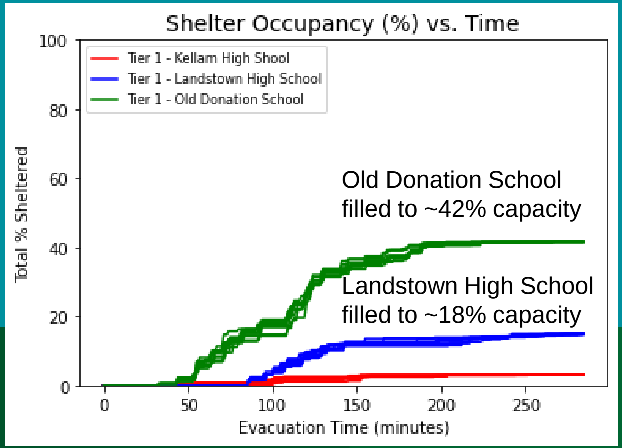
Zone A Evacuation

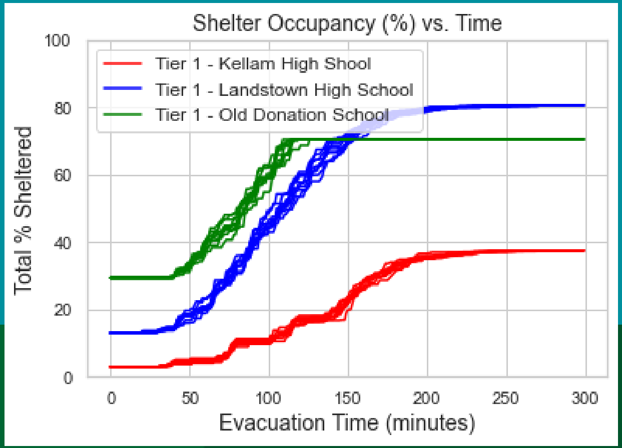


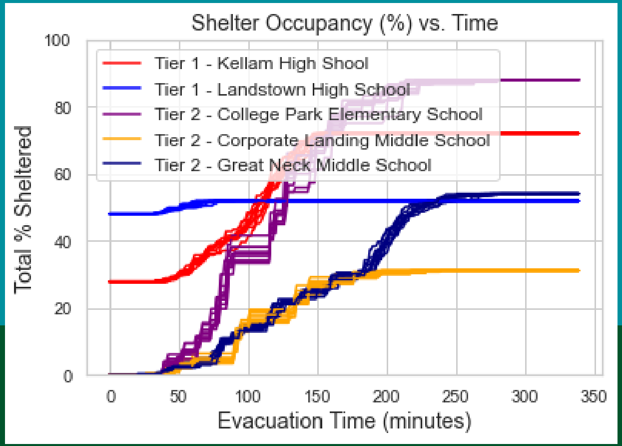
Zone B Evacuation



Zone C Evacuation







Zone A Evacuation

Sheltered: 484

- Tier 1 - Kellam High School
- Tier 1 - Landstown High School
- Tier 1 - Old Donation School

Zone B Evacuation

Sheltered: 484 + 1,870

- Tier 1 - Kellam High School
- Tier 1 - Landstown High School
- Tier 1 - Old Donation School

Zone C Evacuation

Sheltered: 484 + 1,870 + 1,972

- Tier 1 - Kellam High School
- Tier 1 - Landstown High School
- Tier 1 - Old Donation School
- Tier 2 - College Park Elementary School
- Tier 2 - Corporate Landing Middle School
- Tier 2 - Great Neck Middle School

Shelter Occupancy (%)