Modeling Battery Electric Vehicle Disaster Evacuations Utilizing a Design Science Approach

by

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Abstract

Battery-powered electric vehicles (BEVs) are becoming a popular means of transportation throughout the United States. However, the sudden rise in BEV market share comes with obstacles that must be surmounted. Evacuating from natural disasters, such as forest fires and hurricanes, using BEVs presents an increasing challenge for governments and evacuees. To ensure efficient and effective evacuation, it is crucial to understand the limits of the charging infrastructure along evacuation routes, determine the optimal locations for new charging stations, and plan for additions to the infrastructure as needed. My research takes a design science approach to build a model that simulates BEVs during a disaster evacuation, providing organizations with a tool to answer these questions. The model is created by using the GAMA platform and validated through a hypothetical hurricane evacuation case study in Mobile, Alabama.

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1. Introduction

Battery Electric vehicles (BEVs) are becoming increasingly popular as a primary means of transportation worldwide (Nickischer, 2020). Unlike other vehicles, BEVs rely solely on battery power for energy (Yong et al., 2015). While this increased adoption of BEVs is generally considered a positive development due to their lack of tailpipe emissions (Nickischer et al., 2020), it also exposes issues in BEV infrastructure that need to be addressed. Charging infrastructure can be underdeveloped or lacking, leaving BEV owners particularly vulnerable during a disaster evacuation (Ahmad et al., 2022; Adderly et al., 2018). To address these issues related to charging infrastructure for battery electric vehicles (BEVs), it is critical that governments and relevant organizations have a comprehensive understanding of charging infrastructure under their jurisdiction, particularly along evacuation routes. Additionally, they must be informed of the most effective solutions to serve evacuating residents.

Importantly, the goal of this research is not to provide a comprehensive disaster planning recommendation for a particular city. Instead, this thesis aims to develop a tool that municipalities, highway departments, emergency planners, and other organizations can utilize to find the solution(s) to these pressing disaster evacuation issues. To this end, this thesis utilizes the design science methodology to design and develop a simulation artifact that simulates disaster evacuations. The simulation tool focuses on BEVs and how their evacuations are affected by current charging infrastructure and defined solutions. The simulation model is created using the GAMA platform, a powerful tool for large-scale agent-based simulations (Drogoul et al., 2013). Finally, an evacuation from a hypothetical hurricane in Mobile, Alabama, is presented as a case study to validate the model. The number of vehicles estimated to leave along evacuation routes in the simulation is compared to traffic sensor data along the same roads during Hurricane Sandy to validate the artifact.

2. Literature Review

2.1 Battery Electric Vehicle Evacuations

The adoption of BEVs has been increasing rapidly, with many countries setting ambitious targets to entirely phase out gasoline-powered vehicles. This means that the number of BEVs on the road during disaster evacuations is likely to increase, making understanding the impact this will have on power grid capacity and charging infrastructure essential (MacDonald et al., 2021; Adderly et al., 2018; Peterson et al., 2020).

First, power grid capacity is an essential factor that must be considered during disaster evacuations. In the case of a natural disaster or another emergency, the electricity demand can be overwhelming. If there are too many BEVs attempting to charge simultaneously, it could cause a strain on the power grid, leading to blackouts and other issues that could further complicate the evacuation process (Feng et al., 2020; Peterson et al., 2021). Therefore, researchers must study the capacity of the power grid and how it can be improved to accommodate the needs of BEVs during disaster evacuations.

Feng et al. studied grid capacity during the evacuation of Hurricane Irma in Florida (2020). They found that if the BEV population were greater than 45 percent of the total vehicles on the road, the grid would suffer from a lack of power. Feng et al. suggested longer-lasting batteries and tailored evacuation strategies as possible solutions. Similarly, Peterson et al. discuss the infrastructure requirements for evacuating BEVs during natural disasters (2021). They focus on Santa Rosa, California, amid evacuations caused by earthquakes and wildfires. Peterson et al. found that an increase in DC fast chargers (referred to as Level 3 chargers), the fastest available charger type ("Developing Infrastructure to Charge"), would allow for the minimum number of chargers to be added to evacuate every BEV safely. However, they find that DC fast chargers place a much greater strain on the power grid than Level 2 chargers. In the event of a power grid failure, neither BEVs nor petroleum-based vehicles could refuel, leaving all vehicles in danger of being stranded during an evacuation.

Second, the availability of charging infrastructure is a critical factor that affects the success of disaster evacuations involving BEVs. If there are not enough charging stations along evacuation routes, BEVs may run out of charge, leading to delays and increased risk. During disaster evacuations, charging infrastructure for battery electric vehicles (BEVs) is often insufficient, as highlighted in studies conducted by MacDonald et al. (2021), Purba et al. (2021), Dickerson (2022), Adderly et al. (2018), and Li et al. (2022). Purba et al. found that BEVs must take alternate evacuation routes to reach charging stations, which leads to longer evacuation times. They suggest that improving the accessibility of charging stations would decrease these evacuation times. Li et al. used the evacuation of the state of Florida as a case study and constructed a model to identify the best disaster evacuation routes. They found that charging stations are mainly concentrated in urban areas where most people begin their evacuation, resulting in minimal usage during an evacuation. This also highlights the need for charging stations along evacuation routes where BEVs will likely run low on charge.

MacDonald et al. studied the capacity of charging infrastructure during a hypothetical short-notice evacuation of Prince George, British Columbia (2021). They find the current charging facilities inadequate to charge every vehicle and recommend adding more charging stations as an effective solution. Several studies have simulated BEV evacuation from areas offering a single evacuation route (Dickerson, 2022; Adderly et al., 2018). Dickerson studied simulated disaster evacuations from two rural towns in California (2022). She looked specifically at the required number and type of chargers and the ideal placement of a second charging facility along the exit route. Dickerson concludes that rural towns should invest in DC fast chargers as an increase in one DC fast charger does more to decrease evacuation times than two Level 2 chargers. Adderly et al. studied the effects of BEVs on evacuating the Florida Keys (2018). Researchers agree that there is a need for more charging stations to be placed along evacuation routes (Adderly et al., 2018, Dickerson, 2022, Purba et al., 2021). Additionally, the researchers recommend that these new stations be fast-charging stations to allow BEVs to reach a safety zone.

Researchers vary many variables when developing a model to determine power grid capacity or charging infrastructure availability during a disaster evacuation (Erskine et al., 2022, Adderly et al., 2018). The type and severity of the natural disaster are considered in determining evacuation zones and grid stability (Erskine et al., 2022).

Further, papers focusing on charger types do so by customizing charging speed and availability to determine an optimal infrastructure makeup (MacDonald et al., 2021; Dickerson, 2022; Adderly et al., 2018). BEV market saturation, charge times, and driving range also influence evacuation times (Erskine et al., 2022, Adderly et al., 2018). In their research, Adderly et al. assumed a ten percent BEV makeup and a single electric vehicle type (2018). These assumptions are not rigid, and differing values for BEV concentration, charging, and range specifications are expected in different locales and across time (Erskine et al., 2022). Finally, researchers consider the actual evacuation times of populations (Whitehead et al., 2000). For example, while the government may release an evacuation mandate for specific zones, individuals from other zones may also decide to evacuate. These people are known as “shadow evacuees,” and they can further congest evacuation routes (Erskine et al., 2022). While many studies have simulated the evacuation of BEVs, no known study to date has developed a simulation tool that models the evacuation of BEVs from varying locations to determine weaknesses in charging infrastructure and to test possible solutions.

2.2 GAMA Platform

The GAMA platform is a powerful tool used for agent-based modeling in spatially explicit environments (Drogoul et al., 2013; GAMA Platform website). It specializes in large, complex models built with a high-level modeling language called GAML (Taillandier et al., 2019; Drogoul et al., 2013). GAMA is utilized for solving spatial problems, including predicting urban growth, modeling land use, and simulating traffic flow (Tsagkis et al., 2018; Mejean et al., 2021; Taillandier et al., 2018).

2.3 Design Science

Design science is a research methodology that looks to add to the existing knowledge base through the creation of artifacts (vom Brocke et al., 2020). An artifact can be physical or abstract (Gregor et al., 2013). Nonetheless, artifacts are generally understood to be something that can be converted into a model, instantiation, software, or method (Gregor et al., 2013). Unlike more theoretical forms of research, design science looks to create solutions to practical problems (Johannesson et al., 2014).

Design science is used heavily in many disciplines, including Information Systems, Engineering, and Economics (March et al., 2008). Hevner et al. (2004) state that design science is considered the foundation of the Information Systems discipline. The results of design science research have been shown to have significant effects on the economy and society (March et al., 2008). Evaluation of design science research is critical for creating artifacts that will have such impacts (Peffers et al., 2012). Peffers et al. suggest determining how well the created artifact helps solve the presented problem through case studies, simulation, or controlled experiments (2012).

Design science has been increasingly used to create artifacts contributing to the disaster science body of research (Horita et al., 2013). Horita et al. found that one-third of the papers published in this area utilized the design science methodology (2013).

Multiple studies have focused on creating artifacts that aid disaster evacuations (Magnusson et al., 2018; Leelawat et al., 2018, Roßnagel et al., 2011). Magnusson et al. explored crisis training and how design science artifacts could improve the disaster training status quo (2018). Leelawat et al. utilized design science to build a mobile application to improve tsunami evacuations (2018). Finally, Roßnagel et al. created an artifact design that uses mobile social media to better emergency support (2011).

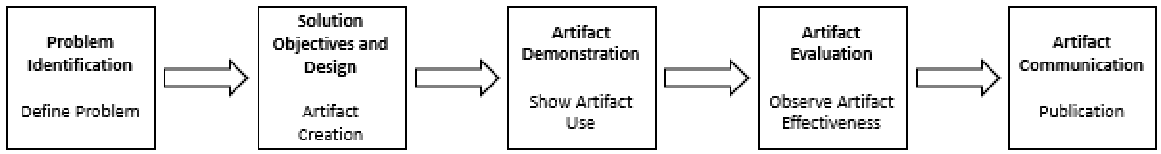
3. Methodology

3.1 Design Science Process

Once a problem has been defined, the design science research process is completed through five main steps. These steps were created to standardize this research process and ensure that the artifact is an adequate solution to an existing problem (Peffers et al., 2007). These steps are shown in Figure 1. Importantly, this process has the researcher lay out the features that would be necessary for the artifact to be a successful solution to the problem area. Next, the researcher designs the artifact to fulfill the stated specifications and demonstrates how the artifact works. The artifact is then evaluated to determine the efficacy of the solution. Finally, the research is communicated to stakeholders through the publication of the thesis.

Figure 1:

Design Science Research Process



Note. Figure adapted from Peffers et al. (2007). The figure has been simplified to highlight the artifact creation steps.

The Introduction and Literature Review identifies the problem and demonstrates that it has yet to be solved by extant research. The methodology will outline the solution objectives and design as well as demonstrate the use of the created artifact. The artifact will be evaluated through a case study of an evacuation of Mobile County in the state of Alabama. Artifact communication will occur when this thesis is published, thereby completing the design science process.

3.2 Solution Requirements

There are multiple variables that must be considered when determining the required charging infrastructure and placement. These variables fall under three main categories: the Evacuating Vehicles, the Disaster, and the Charging Infrastructure. These categories must be further broken down to model these variables properly.

The Evacuating Vehicles category can be further broken down into two subsections: battery electric vehicles (BEVs) and vehicles with an internal combustion engine. All vehicles must be able to drive and respond to other drivers in a realistic manner. However, key differences include the range of a BEV versus a petrol-fueled vehicle, the number of chargers versus fuel pumps, and the time it takes to charge a BEV as opposed to petrol-based vehicles. Considering these differences ensures that possible solutions drawn from simulation results can be relied upon to work similarly upon implementation.

BEVs must also keep track of other variables exclusive to their engine type. BEVs contain batteries with differing capacities, ranges, and charge times. Table 1 shows a sample of the more common vehicles, their associated battery data, and their recharge rates based on different charger types. Much like drivers of petrol vehicles that watch their fuel gauge, drivers of BEVs must keep track of their remaining charge to determine if they are required to visit a charging station to successfully complete their evacuation. We expect these variables to differ based on the make, model, and year of the BEVs, and we should consider these differences. Furthermore, BEVs will likely begin their evacuations with differing charges due to varying circumstances occurring before the evacuation. For example, a BEV owner may have left their vehicle plugged in until the evacuation, allowing them to take advantage of a full charge. On the other hand, the BEV owner may have been utilizing their BEV to collect supplies, leaving their vehicle at a lower state of charge when they begin their evacuation.

Table 1:

Sample BEV Battery Data (U.S. Market)

EV	Battery Capacity	Range	Charge Times (Based on Charger Type)
2022 Tesla Model Y	75 kWh	303-330 Miles	110V[a] 33 h DCFC[b] 220V[a] 7 h 20 min
2022 Tesla Model 3	50-82 kWh	272-358 Miles	110V 33 h DCFC 220V 7 h 30 min
2022 Chevrolet Bolt	65 kWh	102 Miles	110V 55 h DCFC 220V 7.5 h 1 h
2022 Ford Mustang Mach–E	91 kWh	305 Miles	110V 95 h DCFC 220V 15 h 45 min
2021 Volkswagen ID.4	82 kWh	240-260 Miles	110V 36 h DCFC 220V 8 h 30 min
2022 Nissan Leaf	62 kWh	239 Miles	110V 27 h DCFC 220V 10 h 30 min
2022 Audi e-tron	95 kWh	249 Miles	110V 42 h DCFC 220V 9 h 30 min
2021 Hyundai Kona	39-64 kWh	258 Miles	110V 9 h DCFC 220V 1.5 h 40 min
2021 Porsche Taycan	79.2 kWh	254 Miles	110V 35 h DCFC 220V 7 h 20 min

2022 Hyundai Ioniq	38.3 kWh	193 Miles	110V 17 h 220V 6 h	DCFC 30 min

Note. Table adapted from Erskine et al. (2022).

[a]Level 1 and Level 2 chargers are not discrete but, instead, exist on a continuous range. Two voltages for each level (110V for Level 1 and 220V for Level 2) are shown. [b]DCFC refers to DC fast chargers. The difference between DC fast chargers and Level 1 and Level 2 chargers is discussed later in the research.

While the primary focus of a model would concern evacuating BEVs, consideration of vehicles with internal combustion engines is necessary as they affect the evacuation. BEVs have been shown to consume a negligible amount of charge when idling in traffic. Nonetheless, more vehicles on the road, regardless of engine type, can limit the speed of travel and increase the time it takes for all vehicles to reach their chosen safety zone.

Natural disasters cover a plethora of different events that can cause evacuations. Wildfires, floods, and hurricanes are particular types of natural disasters in that they cause sudden, mass evacuations from large areas. There are many ways of measuring the intensity of the disaster. Furthermore, the disaster intensity determines which subsets of the population are affected and will need to evacuate to a safe location. Different disasters may require evacuees to utilize different road networks to reach safe zones. A proposed solution to modeling charging infrastructure needs must account for this variation in determining which geographic areas will join the evacuation and which routes evacuees must utilize.

Charging infrastructure solutions must allow for two different customizations. First, charging stations must be able to be placed at different locations to locate the optimum placement along the evacuation routes. The simulation must support the simulation of a baseline evacuation that represents the status quo. As chargers are added, the simulation must indicate how the charging requirements of evacuees are also changing to allow for easy testing of the proposed placement solution. Second, the simulation must allow for variation in charger type to determine the charger type makeup that best expedites evacuations. There are currently three different categories of chargers: AC Level 1, AC Level 2, and DC Fast Charge. All charger categories have a kilowatt (kW) range they can provide under varying circumstances. These ranges can increase or decrease the time it takes for vehicles to recharge. DC fast chargers are occasionally referred to as Level 3 chargers, but they are an altogether different charging type that can provide faster charging times by bypassing the converter in the BEV.

3.3 Artifact Design

The design of the artifact relies on several assumptions that result due to the complicated nature of disaster evacuations. First, the model assumes that everyone within an evacuation zone evacuates at the same designated time. Realistically, individuals living within evacuation zones sometimes choose not to evacuate. Furthermore, some individuals choose to evacuate early or from zones that have not been advised to evacuate. These evacuees are known as shadow evacuees (Erskine et al., 2022) and they are difficult to predict. Second, this artifact assumes that there are no traffic impediments, such as accidents, during the evacuation. This research focuses on the distance that BEVs need to travel and the additional time that specific charging solutions would require during the evacuation rather than the time spent in traffic where BEVs consume a negligible amount of charge. Depending on the infrastructure of the evacuating location, some evacuees may utilize trains or other such means of transportation instead of utilizing their personal vehicles. It is, thus, also assumed that every household will evacuate using at least one of their personal vehicles. Finally, the charging stations are assumed to have access to as much power as needed and the electric grid powering the stations will not suffer under a lack of power. While this assumption is necessary for the overall model, petroleum-based vehicles would likewise be unable to refuel their vehicles in the event of a power outage. This makes ensuring power grid sufficiency necessary for evacuating all vehicles, not just BEVs. Thus, the artifact takes a simplified view of disaster evacuations while properly determining weaknesses in charging infrastructure and accurately testing possible solutions.

The GAMA platform will be used to build a simulation tool that fulfills the solution requirements. GAMA is an open-source tool that is used to build models and simulations that are spatially explicit and agent-based (Drogoul et al., 2013). It also offers native GIS support and utilizes the GAML programming language to build robust, large-scale models that can be applied to real-world data.

The simulation tool will take advantage of an object-oriented approach to development. GAML allows researchers to utilize classes to create the simulation. Each class contains attributes that the associated agent tracks and manipulates as required by the simulation. Classes also have reflexes which are a series of actions that classes perform. Reflexes can be fine-tuned to only be performed given certain statuses. Skills are another aspect of classes that GAML offers. There are multiple skills that are built into GAML that allow users to give their classes advanced actions and attributes. Finally, classes created as children of a parent class inherit the parent's attributes, reflexes, and skills. The artifact utilizes four primary classes to create simulations. These classes are defined as the Vehicle class, the BEV class, the Road class, and the Node class.

The Vehicle class utilizes the Advanced Driving skill and three reflexes. Agents utilizing the Advanced Driving skill are able to move along roads, adjust speed and the current lane, navigate traffic, and obey traffic laws in a way that accurately portrays real drivers (Taillandier, 2014). Vehicle agents' three reflexes allow them to move along the road network and utilize actions from the Advanced Driving skill. Vehicles begin at a specific location and select a final target. Once a predetermined time to vacate has been reached, they drive along the shortest path to reach the target. Upon reaching the goal, the vehicle is removed from the simulation.

The BEV class is a child of the vehicle class. This means that it inherits the Advanced Driving skill and all the Vehicle class's reflexes and attributes. Like Vehicle agents, BEV agents can move from a starting location to a target before being removed from the simulation. However, to monitor their available charge, BEV agents need additional functionality. To do this, the BEV class also includes the FIPA skill and adds other reflexes. BEV agents monitor the distance they can travel based on their remaining charge. If the remaining distance they can cover is less than what is needed to reach their destination, they will search for a charging station along their evacuation route. When the BEV agent enters a charging station, it will use the FIPA skill to communicate with the charging station and ascertain the time needed to reach a full charge. FIPA stands for The Foundation for Intelligent Physical Agents, which is an organization that defines standards for sending and receiving information between heterogeneous agents. The FIPA skill simply acts as a way for different classes to share information while applying codified communication standards. After completing the charging process, the BEV agent will proceed toward its destination with a full charge. If a BEV agent exhausts its charge before reaching a charging station or its destination, its location will be noted on the graph. The presence of numerous BEVs without charge may indicate insufficient charging infrastructure along the evacuation route.

Evacuation road networks are defined using the Road class. The simulation takes in a shapefile containing the road network and relevant attribute data. The Road class uses three attributes: the number of lanes, whether or not the road allows only one-way traffic, and the speed limit. These attributes are utilized by the Skill Road skill that is attached to this class. This skill works in tandem with the classes that use the Advanced Driving skill. The Skill Road skill allows roads to have a queue system for the Vehicle and BEV classes that are on that road. This informs these classes of their location and the traffic situation so they can adjust their driving as needed.

The last main class is the Node class. The Node class includes the Skill Road Node skill that works with both the Advanced Driving and Skill Road skills. This skill allows drivers to interact with, and drive through, these nodes. Nodes are created through a shapefile supplied by the user. The shapefile contains the nodes and their locations, as well as attribute data associated with each node. The Node class offers many different uses within this simulation and an attribute defines their possible actions. First, nodes can function as the starting location for members of the Vehicle and BEV classes. These starting locations represent cities, towns, census tracts, or other such locations with varying levels of granularity where Vehicle and BEV agents will begin their evacuation. Second, members of the Node class can be defined as a possible final target for the Vehicle and BEV classes. These nodes are located at the end of evacuation routes given to the simulation and do not necessarily represent the end of the evacuation for evacuees. Neither the starting location nor the final target Node agents have any reflex actions. The third Node type is the charging station. Charging stations are what members of the BEV class communicate with to recharge their batteries. As such, the communication skill, FIPA, is also utilized by these nodes. BEV agents that reach a charging station Node agent and communicate the need for charging are brought into the charging station. These BEV agents are added to the charging queue. The length of time needed to traverse the queue is dependent on the number of chargers and the charge rate of the chargers. These attributes will be discussed later in the research. Once they reach the front of the queue and finish charging, they are released back onto the road. Finally, some nodes do not have any expressed purpose and only serve to connect roads along the route.

While the previous discussion has centered around how the simulation operates, nothing thus far allows the user to manipulate the simulation to fit different data and real-world scenarios. This manipulation is done in the initialization of the simulation. Here, there are a large number of parameters that the user can modify to fit the requirements of the problem. Users begin by supplying the program with files for the Node and Road classes as well as the file that represents the boundary in which the simulation will be contained. After this is done, users can make multiple changes to different parameters to determine problem areas and identify possible solutions. Users can choose not to include any charging stations in the simulation, to discover weak points in the current charging infrastructure, or include them to test predefined solutions. Additionally, the number of chargers at each station as well as the rate of charge can be edited. Vehicle (and BEV) attributes can be manipulated as well. These include speed and acceleration parameters and vehicle lengths. Evacuees may be more or less likely to choose to evacuate to the closest safe zone or to some specific city instead of to a safe zone that is farther away or offers fewer amenities. To accommodate this, a parameter is included that allows users to provide the odds that evacuees will choose their closest evacuation zone (or other supplied zone) over any of the other safe zones. The number of evacuees may differ from what was initially expected. A parameter to adjust the total percentage of vehicles that evacuate is also included. As BEV battery ranges change frequently, the battery range minimum and maximum parameters allow users to choose ranges that are in line with BEVs currently on the market or popular in the simulation's target area. Another aspect of BEVs that is constantly changing is the market share that they hold. As time progresses or different locations are considered, varying percentages of evacuating vehicles will be BEVs. A parameter is included that allows users to test evacuation models under different ratios of evacuees using BEVs versus vehicles powered by combustion engines. Finally, the intensity of the disaster can be changed by the user to force different subsets of the focused area to evacuate. The inclusion of these parameters allows the simulation tool to remain relevant in an environment that is rapidly evolving.

The simulation is initialized by taking in the data from these parameters. Starting zones are initialized based on which areas are within the disaster's affected area; this is affected by the disaster intensity parameter. The roads are also created, with each road being weighted based on their speed limits. The model prefers roads with higher speed limits as they allow agents (the simulated BEVs) to evacuate more quickly. The user can decide if they wish to initialize charging stations in the model. Once configured, the user can start the simulation.

Users can observe the simulation through the visualization suite. A display window shows the road network available to evacuees. The nodes are also visualized and color-coded in a way that makes it easy for users to identify starting zones, possible final targets, and charging stations. Finally, the display window shows Vehicle and BEV agents as they evacuate. BEV agents that run out of charge are highlighted to show problem areas in the evacuation network.

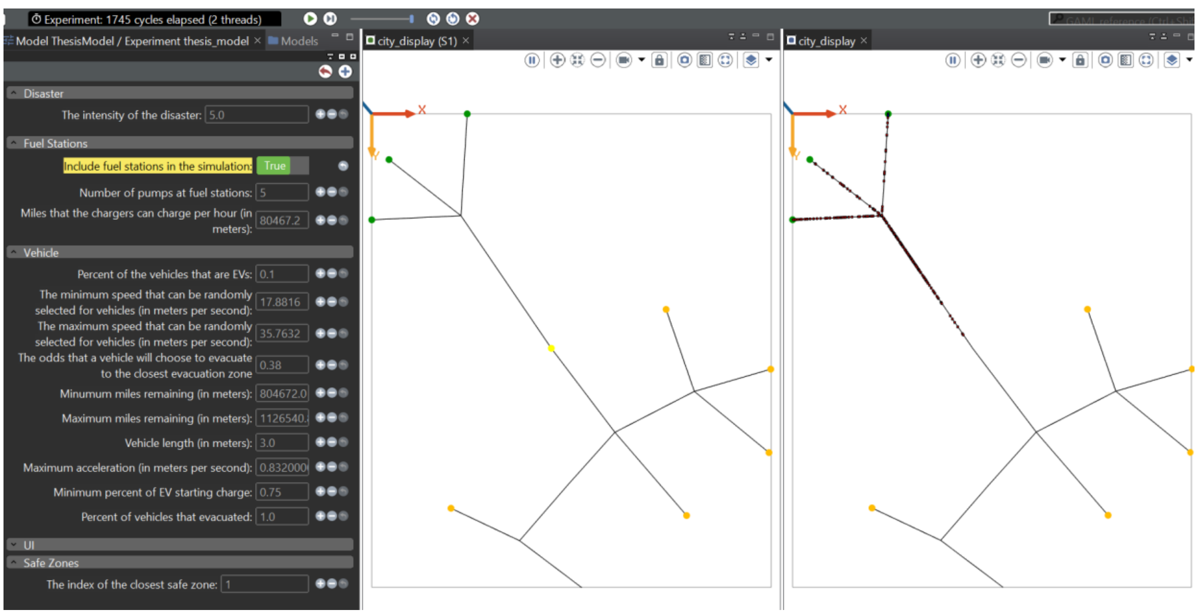
This artifact design properly considers the three categories mentioned in the solution requirements (3.2). Vehicles (including BEVs) have realistic driving habits to allow the simulation to model their evacuation properly. Further, BEV agents have different fuel tank sizes and starting charges; they keep track of these values throughout the evacuation process and determine when they need to visit a charging station. For natural disasters, users can modify the intensity of the natural disaster which will affect which areas will evacuate. The last category is charging infrastructure. The artifact allows users to consider the status quo and place hypothetical charging stations at locations along the evacuation route to test solutions. The artifact also allows the number of pumps at the fuel stations as well as the chargers' charging rate to be changed. For the artifact to remain relevant in a rapidly changing BEV marketplace, the artifact requires users to input value ranges for vehicles and pumps. That way, as new BEVs offer increased ranges and charger options include different charging rates, users simply input the values that are currently available. Thus, all three solution requirements are met by the artifact design.

3.4 Artifact Demonstration

A run of the simulation artifact is shown in Figure 2 using a hypothetical road network. On the left side of the figure, the user can make changes to the parameters of the simulation. These parameters include the disaster, fuel station, and vehicle parameters, as well as the shapefiles that represent the evacuation network. On the right side of Figure 2, two different viewer panels show the results of a simulation run. The user can choose to make changes to the parameters and add a new simulation viewer that utilizes those changed parameters. This allows users to identify weak points in charging infrastructure and compare possible solutions. The circles on the graph represent the nodes. The locations that the nodes represent are as follows: orange nodes represent evacuation zones, green nodes represent safe zones, and yellow nodes represent charging stations. The red agents indicated on the right viewer pane are the BEVs that have exhausted their battery charge. The viewer panes update after each cycle (each cycle representing a oneminute interval) to show the current evacuation status of the evacuees. The top portion of Figure 2 shows the run button and a slider that allows the user to change the speed at which the cycles occur. It also shows the amount of time that the current evacuation has taken.

Figure 2:

Simulation Artifact Example Demonstration



For the simulation run shown in Figure 2, the right panel represents the original state of the evacuation route. Importantly, no charging infrastructure has been built along the hypothetical evacuation route. This has caused evacuating BEVs to become stranded. In the left viewer, a single charging station has been added to the route as a potential solution. This solution was found to evacuate all BEVs successfully. However, the time it took to complete the evacuation under the proposed solution was about 29 hours. This lengthy evacuation duration may need to be shortened. This could be done by increasing the number of charging pumps at the single proposed charging station or by increasing the charge that each pump can output, thereby increasing charging speed.

4. Validation

The artifact must be validated to determine its applicability to empirical population and spatial data and to ensure that the insights that users glean from it are accurate to the real world. To achieve this, I simulated a hypothetical hurricane in Mobile, Alabama. Mobile (shown in Figure 3) is the southernmost county in Alabama. Below Mobile County is the Gulf of Mexico, where many hurricanes have originated. From 2019 to 2021, five hurricanes impacted the Mobile/Pensacola area (Weather Forecast Office). Thus, this chosen area offers a wealth of data from which to draw for validation. It is important to note that while Mobile County is utilized to validate the simulation created, this thesis aims not to use Mobile data to provide potential solutions to BEV evacuations from this area.

Figure 3:

Mobile Alabama

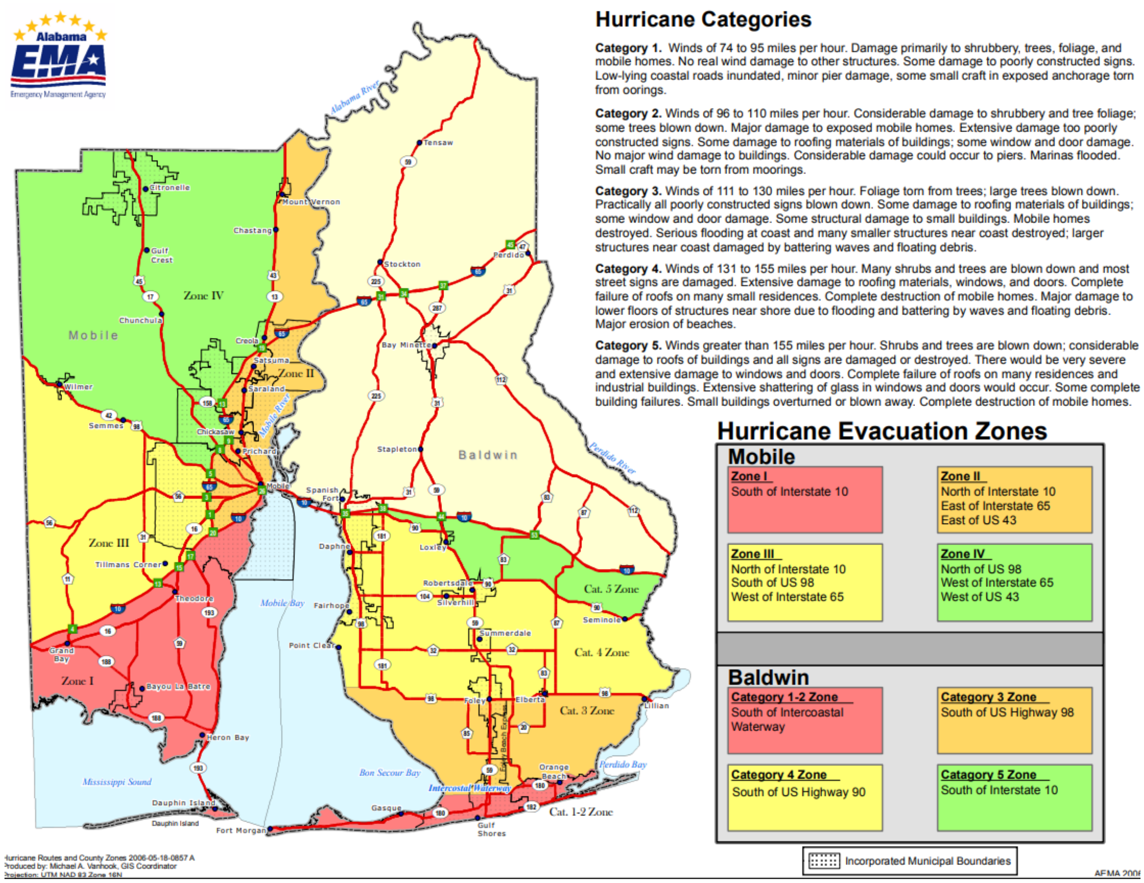
Note. Sourced from "Mobile County Map," Encyclopedia of Alabama.

While much data can be used for validation, validating proposed solutions offers some difficulties since the proposed solutions have not yet been implemented. As such, this thesis approaches validation by comparing the number of evacuees in the simulation to those that have evacuated just before a hurricane makes landfall in the area studied. Traffic sensor data along predefined evacuation routes were collected to perform this comparison.

Depending on the intensity of the hurricane, Mobile has several different evacuation zones. Figure 4 outlines the location of the zones and when they would evacuate. Notably, four zones are evacuated depending on the intensity of the hurricane. Households in Zone I (shown in red) evacuate if there are category one or two hurricanes. Zone II (in orange) evacuates when there is a category three hurricane. Zones III (in yellow) and IV (in green) evacuate when category four and five hurricanes occur, respectively. For the evacuating zones, Mobile offers three evacuation routes ("EVACUATION ROUTES"). Highway 45 North and 43 North are shown in Figure 4 to evacuate directly north of the county. Highway 45 North bisects Zone IV on its way out of the county. Highway 43 North acts as the dividing line between Zone II and Zone IV as it exits the county to the north. The third route, I-65 North (shown in Figure 4), evacuates north and to the east, crossing over Highway 43 North before exiting into Baldwin County.

Figure 4:

Mobile Evacuation Zones



Note. Sourced from "Evacuation Zones," Mobile County Emergency Management Agency.

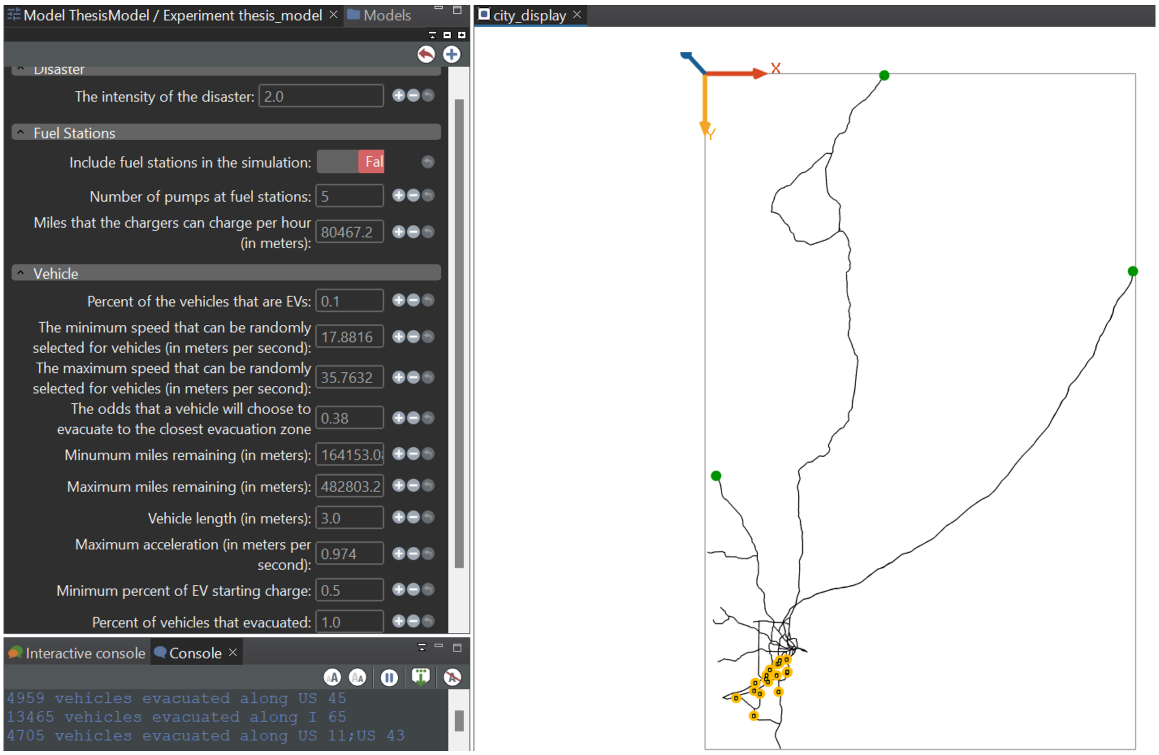
The data for modeling the evacuation comes from Open Street Maps under the Open Database License (OpenStreetMap contributors, 2015) and from Government census data ("TIGER/Line Shapefiles," 2022; "Census Bureau Data"). The data from Open Street Maps relate to road data. This data includes attributes on the speed limits, whether the road allows only one-way traffic, and the road type (e.g., highway, arterial, residential). The collected census data captured the census tracts in Mobile. The census tract boundaries and the number of available vehicles in each tract are taken from this data.

Because the simulation works with graphs that are composed of nodes and edges, the available vehicle field from the census data was first joined to edges. This was done by first finding the centroid of each vertex. The road is composed of nodes located at the beginning and end of each road edge. Once the centroid is found, the data is joined to the road nodes by determining the closest road node to each centroid. These road nodes were considered the starting evacuation points for the simulation and were labeled as starting zones.

Additionally, the final nodes at the end of evacuation routes were labeled as safe zones. These nodes are what evacuating vehicles target as the destination (final) point in the simulated evacuation. During this stage, I also identified potential charging stations. The prepared data was added to the simulation. Figure 5 shows the simulation results.

Figure 5:

Mobile Evacuation Simulation



The hypothetical hurricane used was a category two hurricane to best match the data collected from the evacuation of Hurricane Sandy (also a category two hurricane). As such, only the census tracts located in Zone I were required to evacuate. Orange nodes represented these census tracts in Figure 5. The three roads branching from the more congested road system and terminating with green nodes are the three predefined evacuation routes.

The simulation utilized the settings displayed in the leftmost side of Figure 5. The following number of evacuees used each road: 4,705 for Highway 43 North, 4,959 for

Highway 45 North, and 13,465 for I-65 North. To validate these results, I compared the numbers to traffic sensor data collected from the evacuation of Hurricane Sandy in 2020. Hurricane Sandy was a category two hurricane that made landfall on the coast of Alabama on September 16 of that year. Only two roads offer traffic sensor data for this period: Highway 43 North and I-65 North. The four days of outbound traffic – starting two days before the hurricane hit – were used to determine the number of evacuees using each evacuation route. I selected a four-day time frame as there was a noticeable uptick in northbound traffic along the evacuation routes compared to the same days in different weeks. For I-65 North, the total number of vehicles was 44,641; for Highway 43 North, the number was 15,936. The numbers resulting from the simulation are much smaller. The observed phenomenon of high traffic volume in the evacuation zone before Hurricane Sandy's landfall could be attributed to a large number of shadow evacuees leaving the area. For example, there might have been an influx of tourists to the area during this time. As the census data does not include non-residents, my model did not account for tourists. Considering these concerns, I used a parameter available to simulation users (rather than modifying the source code) to update the number of evacuating vehicles and incorporate these factors into the simulation. The number of evacuees for the updated simulation along Highway I-65 North and Highway 43 North is 43,873 and 15,653 respectively. These new numbers accurately reflect the traffic sensor data to within less than ten percent of the actual evacuation numbers.

5. Discussion and Conclusions

In 2022, over three million adults were required to evacuate their homes in the United States (Frank, 2023). As the average number of natural disasters has continued to increase (NOAA National Centers for Environmental Information, 2023), preparations for evacuations must remain sufficient. Currently, BEV owners are at a distinct disadvantage when evacuating. BEVs' decreased range and increased charge time leave them vulnerable to losing all their charge while attempting to evacuate. Implementing sufficient charging infrastructure is necessary to ensure the safety of BEV evacuees.

Through utilizing a design science approach, I designed and developed an artifact that simulates disaster evacuations to determine weak points in the current charging infrastructure and to test possible solutions. Following this, I validated the artifact in accordance with design science methodology through a case study of Mobile, Alabama. The artifact was accurate within less than ten percentage points of traffic sensor data taken along evacuation routes during the Hurricane Sandy evacuation.

5.1 Discussion of Design Science Methodology

This thesis utilized the design science process outlined by Peffers et al. (2007) to design, develop, and validate the simulation artifact. The design science research methodology ensures that the artifact created follows a standardized process that results in an artifact that accurately solves the problem. The practical nature of disaster evacuations offers a good fit for the design science process which focuses on solving practical problems.

5.2 Practical Contributions

Design science research focuses on practical solutions, and the artifact provides several valuable contributions to disaster evacuation preparedness. Relevant organizations, including governments, can use the simulation artifact to address concerns about the sufficiency of charging infrastructure along evacuation routes. Those responsible for managing long evacuation routes can strategically determine the optimal placement and type of chargers installed in new charging stations to meet the evacuation time limit requirements.

5.3 Limitations

Given the nature of building a simulation that models a complex real-world process, there are multiple limitations that the artifact possesses. The simulation assumes a complete evacuation from evacuation zones at a specified time. However, people may anticipate the evacuation order and evacuate early. Furthermore, some individuals choose not to evacuate and decide to stay despite being given an evacuation order. Residents from other zones may opt to evacuate voluntarily, adding more vehicles to the evacuation routes, even though they have not received an official evacuation order. Those who do decide to evacuate their zones may choose to take another form of transportation. This model does not account for residents who use other transportation options, including airplanes or trains. Some residents who prefer to evacuate by BEV may opt for alternate (non-designated) routes, which can reduce the number of vehicles that pass through charging stations along the designated evacuation routes.

Additionally, visitors to the region will evacuate with residents. The census data does not include such evacuees. The limitations listed are not exhaustive but offer situations that may cause the model to become inaccurate. Further refining of the artifact to consider these and other areas will help to eliminate inaccuracies within the artifact.

5.4 Next Steps

The limitations presented offer a surfeit of areas where researchers could apply and improve the model to consider a broader range of human behaviors. On top of this, giving the user better control of the simulation through more parameter controls can increase usability. Finally, testing the model under different disaster and evacuation scenarios will further validate the artifact, exposing potential weaknesses and increasing its credibility. I encourage future researchers to apply my model to wildfire evacuation scenarios in California and Norway (areas with comparatively large BEV concentrations). Validating the model under these varying scenarios will further ensure that the model can be accurately applied to a plethora of unique disaster situations.

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