SIMULATING TRAFFIC FLOW FOR EMERGENCY EVACUATION IN MANHATTAN, KS USING ROCKWELL ARENA

by

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B.S., Kansas State University, 2010

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Industrial and Manufacturing Systems Engineering
College of Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2010

Approved by:

Major Professor
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Abstract

The community of Manhattan, Kansas was recently chosen as the future site of the National Bio- and Agro-Defense Facility (NBAF). At this site, research of agricultural and animal diseases and pathogens will take place. Due to the fact that the site will be in close proximity to a university, as well as many residents, a risk assessment must be completed to determine whether or not the current road infrastructure would be sufficient for evacuating the city in the event of an emergency. It should be noted that while NBAF is a large concern for this report, risk management is important in other scenarios as well, such as natural disasters or chemical spills, and this information can be applied to such events.

This paper discusses the creation and analysis of a discrete-event simulation using ARENA software. The simulation described several scenarios. They were a base case scenario with only campus traffic evacuating; a scenario in which campus and outside traffic evacuate; a case with increased outside traffic; a case in which a vehicle breaks down; a case which includes guardians of children attending campus childcare are re-routed to pick up their children before evacuating; a case which accounts for reduced traveling speeds due to cell phone usage; and a case which closes a direction outside of Manhattan due to wind direction. Such simulations are an ideal performance measure of traffic flow under certain conditions due to the fact that physical resources are not needed to make a realistic comparison between each of them.

Each of the situations described above were compared based on percentage of traffic leaving Manhattan and arriving at a defined safe zone each hour. Based on the findings, those involved with disaster management planning can determine if the percentages of vehicles leaving the system per hour are acceptable. They should be evaluated against potential spread rates of diseases to ensure that all residents may evacuate without the danger of becoming infected. For applications outside of NBAF, the results give insight into the degree of change in evacuation percentage that changes within the system may cause, and change any routing accordingly.

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CHAPTER 1 - Introduction

Manhattan, Kansas was recently chosen as the future site of the National Bio- and Agro-Defense Facility (NBAF). The facility will continue to research several highly infectious BSL-4 viruses including rift valley fever (RVF) and foot and mouth disease (FMD) (U.S. Department of Homeland Security, 2009). While the facility will be designed to contain all hazardous agents, safety and security is always a concern. Additionally, because NBAF will be located within a community, necessary precautions should be taken to ensure that all residents remain unharmed.

Aside from the concerns present when planning for such a facility to be added to a community, there are other conditions inherent in the community that should be addressed as additional reasons to plan for an emergency evacuation. Chemical spills on campus and in industrial settings could force a temporary evacuation. In addition, an active nuclear reactor sits on the Kansas State University campus, in the midst of nearly 23,000 students and 1,300 faculty members. Although unlikely, an evacuation could be forced due to radioactive material being leaked into the atmosphere, putting students, faculty, and community members at risk of being penetrated by cancer-causing subatomic particles.

Finally, along with the NBAF research facility, two other research facilities will also be added to the community. The two facilities are the U.S. Department of Agriculture's Arthropod-Borne Animal Disease Research Unit and the Department of Homeland Security's national Center of Excellence for Emerging and Zoonotic Animal Diseases (Schulz, 2010). Research taking place at each of these facilities is also targeted toward animal and agricultural diseases that could affect the community in much the same ways that the pathogens at NBAF could. The integration of these facilities into the community strengthens the need for emergency action planning.

In order to illustrate an emergency evacuation of the Kansas State University campus and surrounding areas, a simulation was created to determine how many vehicles may be evacuated from the area in a given time period using the current road structures. Additionally, the model will be used to perform sensitivity analyses to determine what traffic rules should be applied if an emergency evacuation does need to be carried out.

1.1 Rift Valley Fever

Emergency management is a priority when planning for the arrival of NBAF in Manhattan. The most concerning virus that will be handled in the facility is rift valley fever (RVF). RVF affects many different species of animals, including cattle, sheep, and goats. It also may be transmitted to humans.

Transmission of RVF within animal species occurs through direct contact with body fluids of infected animals; the slaughtering of RVF-infected animals through herding and animal husbandry; the ingestion of raw milk from RVF-infected animals; and via necropsies or contact with contaminated laboratory specimens. It is important to note that because the state of Kansas is a heavy provider of beef to the country, RVF-infected cattle would severely damage the state's economy, and could harm anyone ingesting infected beef. This also presents a concern regarding the quarantine of infected animals, which will be discussed in the Future Work section of this report.

The virus remains viable under the following conditions:

- 23°C at 50-80% humidity after one hour will retain 25% of the initial infectivitiy of aerosols
- 27°C within a 6.9 to 7.3 pH level buffered solution for at least one day
- 25°C for 14 months in whole blood
- 4°C for several months in serum
- Below 0°C for 18 years

As seen above, RVF is not only transmittable, but when stored under the proper conditions, may still be active. It should be noted that while the virus is viable at the above conditions, it is inactive at temperatures at or above 56°C.

RVF in humans results in flu-like signs and symptoms. In Egypt in 1977, an estimated 200,000 people contracted the disease. Of the 18,000 reported cases, 598 died. In more recent years, fatality rates of 23% in Kenya, 45% in Somalia, and 40% in Tanzania have been reported. While there are treatments for RVF available, there is no cure. It should also be noted that human-to-human contraction of RVF has not been documented.

Due to the dense population in the Kansas State University campus area, contraction of this and other diseases is a concern. Although the facility will be designed to contain the pathogens it holds, a terrorist attack or natural disaster cannot be predicted. Therefore, it is necessary to determine an action plan in the event that an emergency evacuation is required (Kansas State University, 2007).

1.2 Definitions

1.2.1 Emergency Evacuation

There are two types of evacuation: precautionary and mandatory. Precautionary evacuation is used to describe a situation in which evacuation is recommended for residents within a certain perimeter of an incident. It is typically short-term, and may only require evacuees to travel one block. It should be noted that in an evacuation, movement is typically round-trip (Quarantelli, 1980).

Mandatory evacuation occurs when residents of an area absolutely must evacuate, typically on a larger scale and for a longer period of time.

Based on the definitions above, an emergency evacuation is a mandatory evacuation. To expand the definition of emergency evacuation, one could say that in an emergency evacuation situation, a large movement of people and their possessions takes place, moving from a disaster area to a safe area (Liu et al, 2007). In this report, the evacuation situation described will be a variation of an emergency evacuation, the difference being that it will be assumed that community members evacuating will take only possessions that they have with them at the moment an evacuation is issued, and will not make trips to their residences to pick up other belongings.

CHAPTER 2 - Literature Review

Emergency evacuation plans have been thoroughly researched over the years, particularly in the case of evacuations due to natural disasters. In each case researched, certain assumptions and variables were collected before either simulating or calculating the flow of traffic to determine the average length of time before each vehicle arrives in a safe zone.

The same concept may be applied to the community of Manhattan, Kansas, where it has been proposed the National Bio- and Agro-Defense Facility (NBAF) be built. NBAF has been the target of both positive and negative publicity since being approved for construction in Manhattan.

Arguments in favor of NBAF being added to the community include the fact that its research facility will produce 2,000 new jobs in the community; worldwide notoriety as a top-notch agricultural research facility; and economic stimulus as a result of an increase in population and visitors.

Arguments opposing the construction of NBAF in Manhattan include concerns of accidental or intentional release of pathogens into the community.

Though NBAF brings concern to the community, other situations inherent to communities and educational facilities also warrant evacuation planning. Some of these are chemical or nuclear warfare, natural disasters, and safety concerns, such as bomb threats.

Some notable disasters that required large or small-scale evacuations include the following:

- Chernobyl Nuclear Power Plant in Ukraine, in which the power plant exploded, prompting the evacuation of over 336,000 people in Ukraine, Russia, and Belarus. The explosion killed 56 people and left 600,000 highly exposed to radiation from the reactor (Jaworowski, n.d.).
- Arguably the most influential disaster of the decade, Hurricane Katrina prompted mandatory or elective evacuation of over 1.2 million Gulf Coast residents in 2005 (U.S. Department of Transportation, 2006).
- Hurricane Rita, which devastated the Gulf Coast in 2005, was said to have the largest evacuation in U.S. history with over 3 million Gulf residents evacuating prior to the storm hitting the coast (Associated Press, 2005).

- Many Aboriginal tribes in Indonesia made use of evacuation routes to get to higher ground when an earthquake, which resulted in a tsunami, occurred in 2004 (British Red Cross, 2009).

In addition to validating the importance of evacuation planning from the cases referenced above, emergency planning becomes essential for transportation agencies to fulfill their necessary duties regarding their role in the National Incident Management System (NIMS). NIMS provides “a consistent nationwide approach for federal, state, tribal, and local governments to work effectively and efficiently together to prepare for, prevent, respond to, and recover from domestic incidents, regardless of cause, size, or complexity” (Hutton and Graham, 2009). However, after a study done by Hutton and Graham in which several state emergency operations plans (SEOPs) were reviewed, it was found that few plans contained information or reference to traffic control in the event of an emergency. Those plans that did make mention of traffic control being the responsibility of local officials gave no details about how the plan should operate.

2.1 Modeling Emergency Evacuation Systems

Emergency evacuation systems have become more necessary, particularly since the destruction caused by Hurricane Katrina. Researchers have concentrated on modeling evacuations using network flow modeling and simulation modeling.

Simulation models have been used in many studies, especially concerning evacuating an area following a natural disaster, such as a tornado or hurricane. The flexibility of simulation allows a researcher to modify variables and attributes in the model to determine the best routes resulting in the quickest evacuation time, greatest number of people evacuated, or to determine whether or not the current road network is sufficient for evacuating a specific population in a desired time frame.

Most of the models that have been developed have some of the same assumptions and rules. For example, designs for simulating an evacuation often consider the daily traffic rates at specific times throughout the day under normal conditions.

2.1.1 Network Flow Modeling

Time of evacuation may be calculated given certain inputs. McLean and his research partners simulated this process for a region surrounding a nuclear power plant in 1983. The model was known as CLEAR, or Calculates Logical Evacuation and Response.

To begin the process, the area was divided into eight zones at 45-degree angles from the central nuclear power plant. Each of the eight zones was then divided into three sections different distances from the reactor site. Inputs for the model include length of each road segment along the evacuation route, number of lanes on the segment, flow of traffic under normal circumstances, vehicle position relative to the reactor, the segment of road on which the vehicle will be traveling next, and any intersections that will be crossed. Each vehicle is assigned its own evacuation direction and each road segment is assigned a number of outbound lanes.

After the above information and data are collected, evacuation trees are determined. Evacuation trees include all roads that interact with one another, whether the road segments are from the same zone or different zones. To begin the evacuation process, each vehicle is randomly assigned to a road segment. The distance between each vehicle can be calculated by dividing the road segment length by the number of vehicles occupying the road segment. This information will provide insight into whether or not a vehicle can enter a road segment to continue with the evacuation.

To begin the flow of the evacuation, the model first determines whether or not the starting road segment has been loaded. According to the model, vehicles cannot be set into motion until the road segment has been loaded. If the segment has not been loaded, the maximum departure time is compared to the elapsed time. If the elapsed time is greater than the maximum departure time it is assumed that all vehicles have been loaded, and the vehicles waiting in the queue may be transferred to a loading queue.

The loading queue contains all vehicles not yet on a road segment that is in motion. Therefore, vehicles will experience a delay. Another queue that causes delays is the back-up queue. If the total length of a vehicle being added to a road segment exceeds the capacity of the road segment, the vehicle is sent to the back-up queue where it is held until adequate space frees up for it to join the road segment. This test is completed using decision logic. While both the loading and back-up queue are considered delays, the loading queue has priority over the back-up queue.

The maximum allowable density for any link is defined as the number of vehicles per hour per traffic lane where the minimum velocity allowed is equal to 15 miles per hour. The maximum allowable density for a road segment depends on how much actual space a vehicle occupies. The program defines this as 46.59 feet, or the density that vehicles begin to line up at the minimum speed.

To determine the total evacuation time, the system uses a simple equation that sums the total time it takes for residents to hear and react to a notice that an evacuation must take place (notification time), time to prepare to evacuate, including gathering belongings if time permits (preparation time), and time to arrive at the destination (response time).

After running the CLEAR model, McLean found that it approximates total evacuation time slightly lower than other models due to the fact that the model requires hypothetical values for current traffic flow parameters. Another finding included the fact that certain parameters have more of an effect on evacuation time. Some of these include time to notify residents of an evacuation, time to prepare to evacuate, free flow speed, and capacity of each segment of roadway. While McLean was able to pinpoint the most dependent parameters, he concluded that further research must be conducted in order to more accurately determine values for inputting into the model (McLean et al., 1983).

2.1.2 Microscopic Agent-Based Simulation Models

Microscopic simulation models use object-oriented, autonomous decision making entities as agents. The powerful tool allows for each individual vehicle, in this case, to be modeled independently, thus, each vehicle makes decisions based on its own characteristics and interactions with other agents. Microscopic simulation differs from macroscopic simulation in that microscopic simulations have the ability to track each individual agent in a certain situation (Chen, 2008).

Research and examples of microscopic simulation models have increased since the 1990s due to the fact that modeling in this manner requires a large amount of computing power that was not readily available. Sinuany-Stern and Stern provided an early example of a microscopic simulation in 1989, in which they incorporated dissemination of evacuation instructions, evacuation preparation time, and total evacuation time into their model. Since this time, simulations have become more advanced.

A model produced by Chen in 2008 explored the differences in evacuating a small city using simultaneous evacuation strategies versus staged evacuation in which one region of the area was evacuated at a time. Using agent-based simulation, Chen found that when the population density increased, staged evacuation was quickest in the case of the road network being in a grid formation since there will likely be less congestion. However, he found that in the case of a ring network and a real road network in San Marcos, Texas, there are no significant differences in evacuation times between simultaneous evacuation and staged evacuation (Chen, 2008). Examples of grid, ring, and real road network structures with zone definitions are shown respectively below in Figure 2-1.

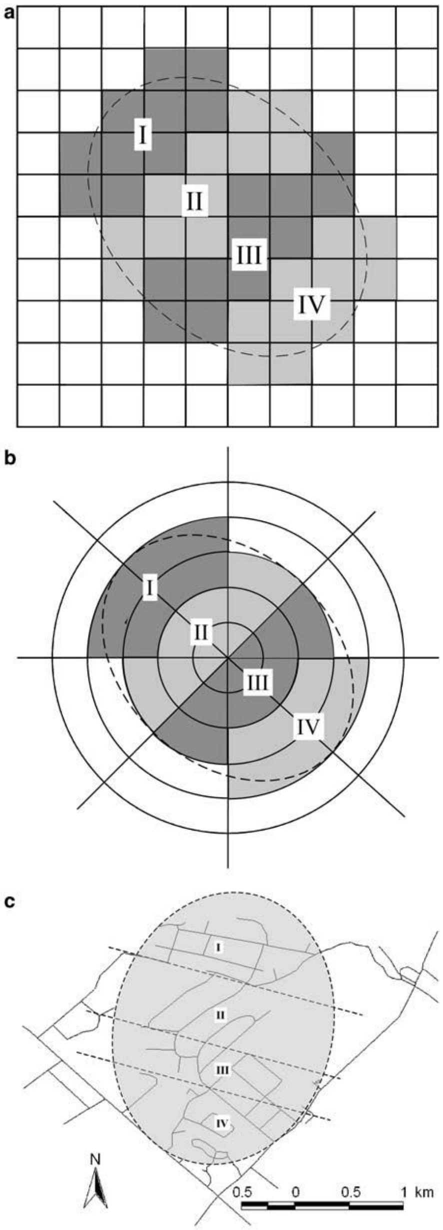


Figure 2-1 Road Structure Examples (Chen, 2008).

In summary, Chen found that the evacuation time under staged evacuation is dependent on the road network, and that if there is little congestion on the road, simultaneous evacuation is ideal.

A simulation for evacuating Ocean City, Maryland was conducted using microscopic simulation (Zou et al., 2005). Prior to simulating, the team gathered information, including the area of the region, population during peak and off-peak seasons, population distribution of specific regions, safe zone definitions, and what highways and interstates were available for use surrounding the area.

The plan included six different scenarios. The first was to evacuate the city keeping the road network structure in its current state. The next five included variations of converting one or two highway lanes to additional right turn lanes, and reversing one lane of traffic on a different highway. The team found that reversing a lane of traffic from Ocean City to an outbound highway increasing the number of vehicles that could be evacuated in a 10 hour period by more than 30,000 (Zou et al., 2005).

While most emergency evacuation simulations are modeled after natural disasters, the Center for Study of Preparedness and Catastrophic Event Response (PACER), supported by the U.S. Department of Homeland Security, completed research and a simulation following a chemical disaster in Baltimore, Maryland. In this scenario, a train carrying hazardous chlorine derailed, and, as a result of the explosive on board, ruptured. As a result, chlorine was released into the atmosphere, threatening the surrounding population. A group of researchers simulated the release of the chemical into a 2 x 2 km area in Baltimore, along with the traffic flow resulting from such an event.

Another example of microscopic simulation used in relation to evacuation came from Jha, Moore, and Pashaie [2004]. The evacuation simulation was carried out for the area around Los Alamos National Laboratory in New Mexico as a means of security planning. The group of researchers used origin-destination matrices to model links and nodes representing road segments in the surrounding area. To determine the number of vehicles per hour that were to be evacuated, the researchers assumed a maximum number of vehicles that could exit the parking lots. Another assumption made was that traffic is under normal conditions at the time of the evacuation.

Five different scenarios were simulated, including a baseline model in which all accessible roads were available; one road is closed to entering vehicles; two roads are closed and one road open only to vehicles coming from the west; and an evacuation with a road added to the southeast. After simulating the scenarios described above, their findings suggested that the evacuation time was similar for the scenarios in which all roads were accessible, one road was closed, and with two roads closed and one open, but restricted to vehicles coming from the west. This was due to the fact that congestion occurred on roads alongside those that were closed.

Adding a proposed road decreased evacuation time up to minute 90, when evacuation time began to increase (Jha et al., 2006).

Another specific model explored the possibility of using public transit to evacuate a large city in the event of an emergency (Elmitiny et al., 2007). Elmitiny's research team used VISSIM modeling software to evaluate the deployment of public transit in the event that the transit facility is in need of an evacuation. They found that rerouting traffic could reduce delays and evacuation clearance times.

Different simulation software packages have been used to gain insight on evacuation planning, including MITSIMLab, VISSIM, and AIMSUN, which were used to illustrate the scenarios listed above.

2.1.3 Software Packages

MITSIMLab, VISSIM, and AIMSUN are all microscopic traffic simulation programs. While they are similar in this respect, they do have differences.

MITSIMLab uses a network of links, nodes, road segments, and lanes to represent traffic flow at a microscopic level. Traffic density is determined based on origin-destination matrices input into the model. Driver behavior, specifically route choice, is captured through historical or real-time probabilistic models.

Vehicles move through the system as agents with specific characteristics assigned to them, such as level of aggressiveness (free-flow or car-following). The software uses lane-changing logic that is based on utility functions derived for the current lane and right or left lane. The logic is a combination of discretionary and mandatory lane changing. The driver evaluates an adjacent lane to determine if there is acceptable space for a lane change. If there is not, the driver continues on, while also continuing to analyze the adjacent lane. If a lane's utility results in a driver selecting it, the system uses a series of equations that ensure that the gap length falls within the minimum acceptable gap and lag lengths based on assumptions (Sterzin, 2004).

As mentioned above, AIMSUN (Advanced Interactive Microscopic Simulator for Urban and Non-urban Networks) is another example of a microscopic simulation software. It has similar capabilities as MITSIMLab, modeling each vehicle throughout its time in the system. AIMSUN is advanced enough to model and distinguish between vehicle types, determine the impact of traffic incidents occurring during simulation time, incorporate different road networks and signaling systems, and, with the use of O-D matrices, can calculate turning radii and traffic demands (Xiao et al., 2005).

VISSIM uses inputs such as lane layouts, traffic flow demands, speed distributions, acceleration and traffic signaling to create behavior-based simulations. It was specifically designed for use in analyzing urban traffic and public transportation systems (Xiao et al., 2005).

Xiao et al. compared AIMSUN and VISSIM's capabilities and found that the software is similar. The results showed that both packages are suitable for modeling basic transportation attributes, and that they had similar accuracy.

2.2 Evacuee Traffic Behavior

While the behavior of evacuees in many cases is unpredictable, studies have noted some trends in evacuee behavior based on historical disasters. Below are some generalized behaviors. It should be noted that while these behaviors were observed during past incidents, this is not good evidence to predict the behavior of evacuees in the future.

2.2.1 Evacuees will confirm their children's safety in an emergency situation

During the Cerro Grande Fire in New Mexico in 2000, the majority of employed persons picked up their children from school or daycare upon the start of the evacuation (Jha, 2004). Behavior such as this increases the level of difficulty when modeling evacuations.

2.2.2 Driving behavior will be influenced because of emergency situation

One challenge in simulating such a thing as an evacuation comes when determining real-time decision making for human beings. Often times in times of stress, people make decisions that they may not make when not under pressure. Therefore, it becomes difficult to predict a traveler's response during an evacuation. Because of the nature of an emergency situation, a driver's behavior is likely to be impacted in some way. Drivers are often influenced psychologically during evacuations, causing them to make different decisions than they might make under normal conditions. Their behavior and judgment may be impaired, affecting both them and other drivers on the road.

During times of emergency inducing panicked behaviors, driver reaction times increase. In general, women have slower reaction times as compared to reaction times of men. This remains true during emergencies. Unpredictable behavior, as mentioned above, is difficult to simulate. However, simulation still remains the most effective tool in modeling evacuations despite this limitation (Sisiopiku et al, 2004).

2.2.3 Residents outside of the immediate area will also evacuate

Due to the nature of emergency situations and uncertainty surrounding them, it is likely that not only will those in campus buildings evacuate, but people in the surrounding area will also leave their residences and drive to a safe location.

According to polls conducted following Hurricane Rita, which affected the Gulf coast in 2005, 42% of people outside of the area of concern also evacuated (Sallee, 2005).

2.2.4 Road incidents will affect evacuation time

Delays caused by traffic incidents, such as stalled vehicles or vehicle accidents will slow down evacuation time. These incidents contribute to 60% of total delay hours experienced when vehicles are in the flow of traffic, and particularly affect travel time when the volume of traffic reaches a road segment’s capacity. In fact, a traffic incident occurring on a congested road can result in 100-200 vehicle hours of delay in adjacent lanes traveling alongside the incident (Victoria Policy Transport Institute, 2010). As seen below in Figure 2-2, as traffic intensity increases, the effect of both bottlenecked traffic and incidents within either a 5 or 10 mile road segment appears to increase exponentially.

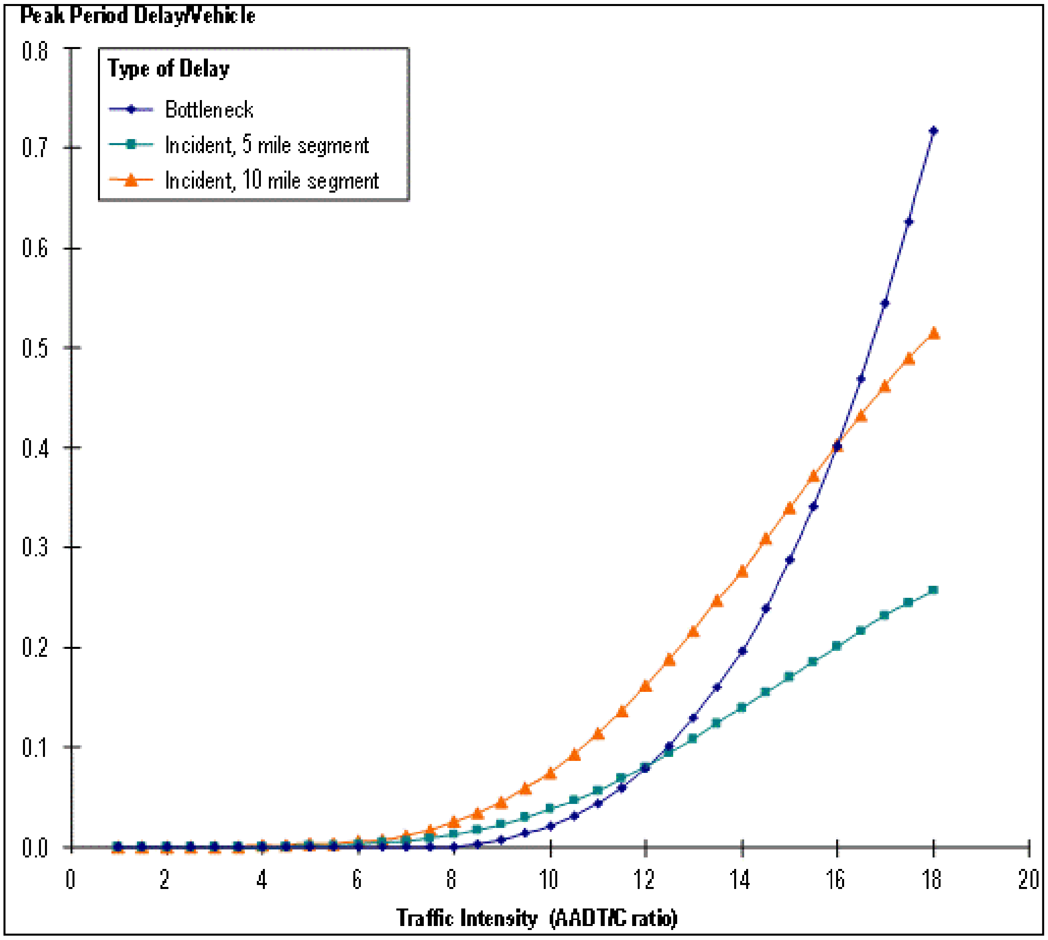


Figure 2-2 Effect of Traffic Intensity on Delays due to Incidents (U.S. Department of Transportation Federal Highway Administration, 2005).

Because of the variability present in traffic conditions from day-to-day there is little data regarding a percentage of incidents that occur during peak traffic.

2.2.5 Vehicle velocity will follow an exponential distribution

When vehicles are faced with traffic delays caused by congestion, their speed generally follows an exponential distribution. This suggests that the vehicles begin at a relatively high speed before slowing down due to congestion and being constrained to the speed of those in front of them. Once traffic begins to move forward, the speed may pick up again.

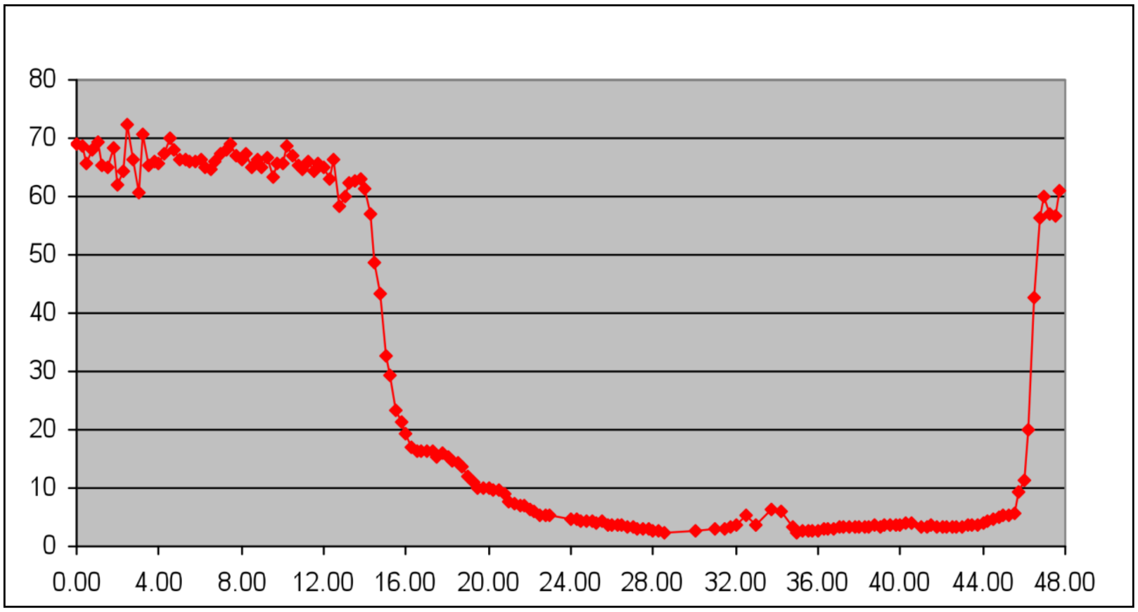


Figure 2-3 Distribution of Traffic Speed in Congestion as Seen in Hurricane Rita Evacuation (Lam, n.d.).

In Figure 2-3, above, the distribution of traffic speed during the Hurricane Rita evacuation is shown. In the figure, the y-axis represents speed in miles per hour, while the x-axis represents cumulative time in hours marked from the beginning of the evacuation. As can be seen in the figure, the vehicles began with a speed of approximately 70 miles per hour, before drastically reducing to as low as 3 miles per hour during the time when traffic congestion increased. The speed increased again up to 60 miles per hour after approximately 30 hours from the start of the evacuation (Lam, n.d.).

CHAPTER 3 - Methods

In order to determine the density of traffic the current road structure of Manhattan can accommodate, a discrete computer simulation was created for a scenario in which the Kansas State University campus and surrounding areas would be evacuated. Simulating a disaster response allows for emergency management personnel to gain insight into what routing, lane configurations, and traffic rules result in the shortest evacuation time or that can maximize the amount of traffic evacuated in a known period of time. It is also the most practical way to study an evacuation, as carrying out an actual evacuation process would require a large amount of planning, resources, time, and capital.

The methodology behind the simulation may be applied to other scenarios, road structures, and cities. However, it will be necessary to change certain inputs into the model to accurately model a different scenario. Discrete simulation is a practical tool that could be used for nearly any traffic operation, but is not as robust as other simulation tools designed specifically to simulate traffic movement, like the software described in section 2.1.3. The assumptions used to model an emergency evacuation are discussed below, along with an explanation of the creation of the model.

3.1 Assumptions

Certain assumptions were made to facilitate the creation of this simulation. While these assumptions may be true for the Kansas State University campus and surrounding areas, they may not apply to all emergency evacuation scenarios. Overall model assumptions are explained below. It should be noted that some assumptions will be discussed with specific modeling details related to them.

3.1.1 Assumption 1 – Shortest route

Manhattan residents are assumed to know the roads and which route leaving town is the shortest from their current location. This implies that those in the same location will likely be using the same route for exiting town. Furthermore, the route at which a vehicle begins will not change. In reality, the route may change if an event occurs that hinders the vehicle’s ability to continue in a certain direction. However, for the sake of simplicity, all routes will remain constant throughout a vehicle’s time spent evacuating through Manhattan.

Moreover, it is assumed that a vehicle will drive toward the closest major road from its starting location. A major road is defined as a segment in which there are two or more lanes of traffic going in the same direction.

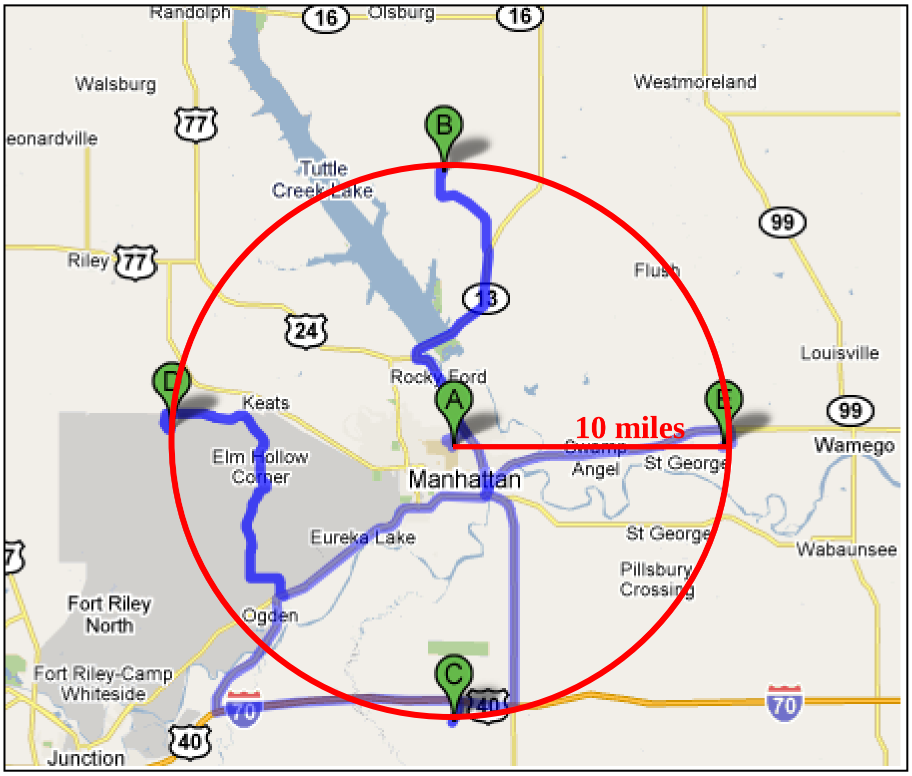


Figure 3-1 Experimental Study Radius with Safe Zone Definition (www.maps.google.com)

3.1.2 Assumption 2 – Safe zone definition

It is important to define a “safe zone” when considering an emergency evacuation situation. After having a conversation with a representative from NBAF, a safe zone area outside of Manhattan was chosen. The simulation area will include the region within a 10-mile radius of the proposed NBAF site. Therefore, the safe zone area is anything beyond the 10-mile radius. This is shown above in Figure 3-1. Much of this area is rural. However, there are a small number of towns that could contribute to the overall volume of traffic flow, such as St. George. In order to determine the 10-mile radius, the approximate latitude and longitude of the

NBAF site were recorded as 39.200434 and -96.582270, respectively. Then, using a global positioning system converter, the latitude and longitude of the locations 10 miles north, south, east, and west of the site were determined (Boulter), and a circle with a radius of 10 miles was drawn to connect the four points described above.

Based on the area inside the 10-mile radius, the major roads that will be used in the evacuation to route vehicles out of Manhattan are Highway 24, Highway 18, and K-177. Because K-177 runs south of the NBAF site, it is not a likely road for campus evacuees to travel, since its proximity is not as close as Highways 24 and 18. Most of the vehicles evacuating will be routed to the north, east, or west of the proposed NBAF site. Each quadrant of the loop representing the evacuating area and safe zone is represented in the next four figures. It should be noted that the approximate location of the proposed NBAF site is labeled with a letter ‘A’ on the maps.

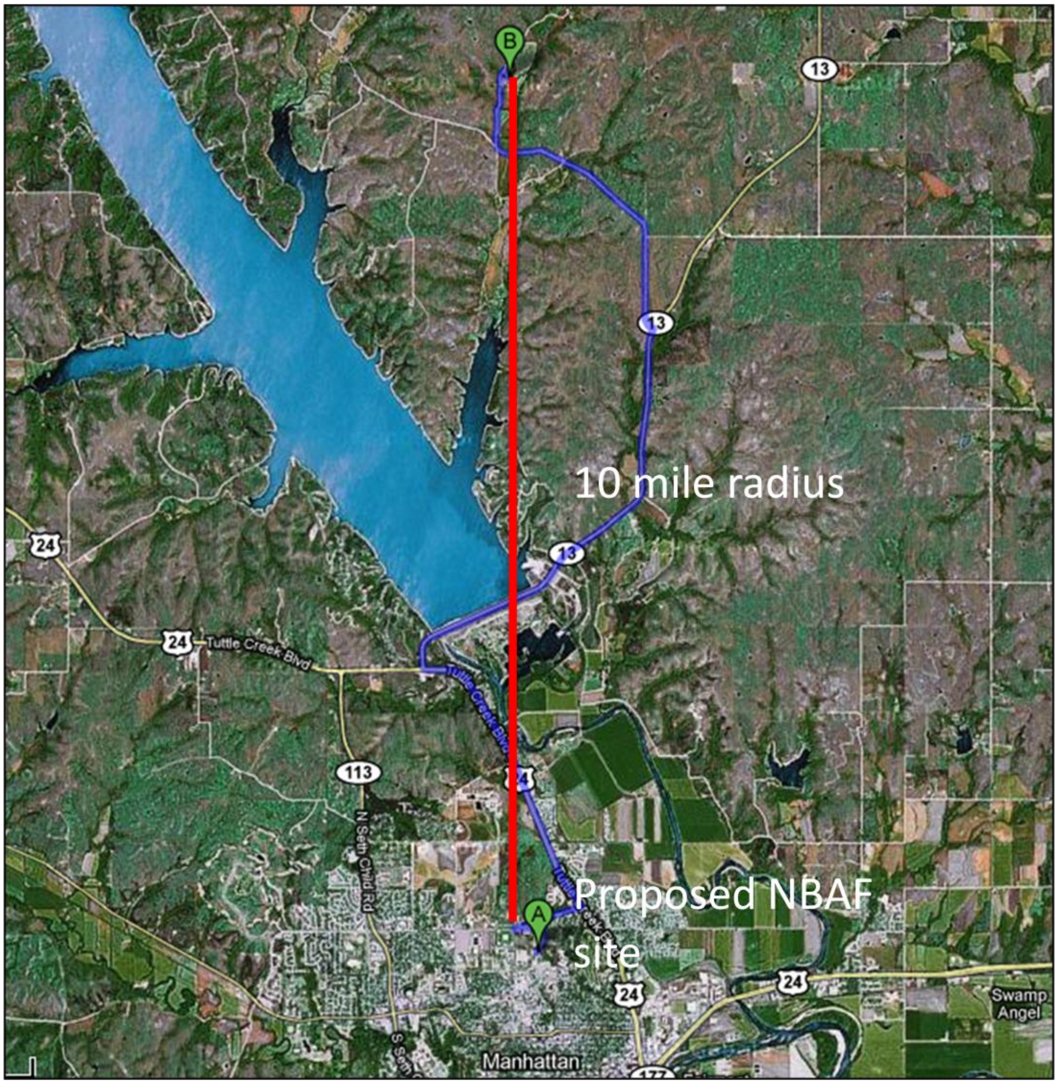


Figure 3-2 10 miles radius – North (www.maps.google.com)

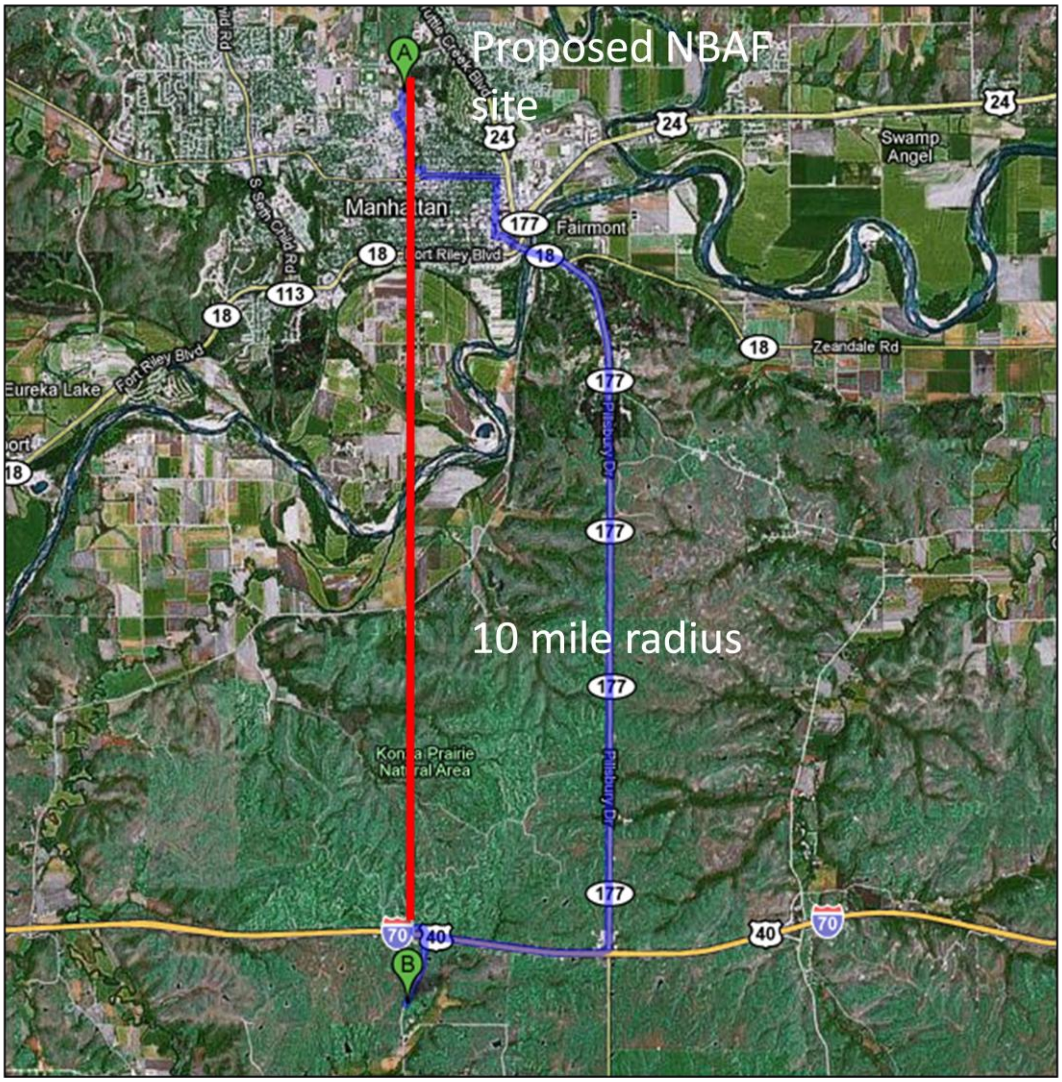


Figure 3-3 10 miles radius – South (www.maps.google.com)

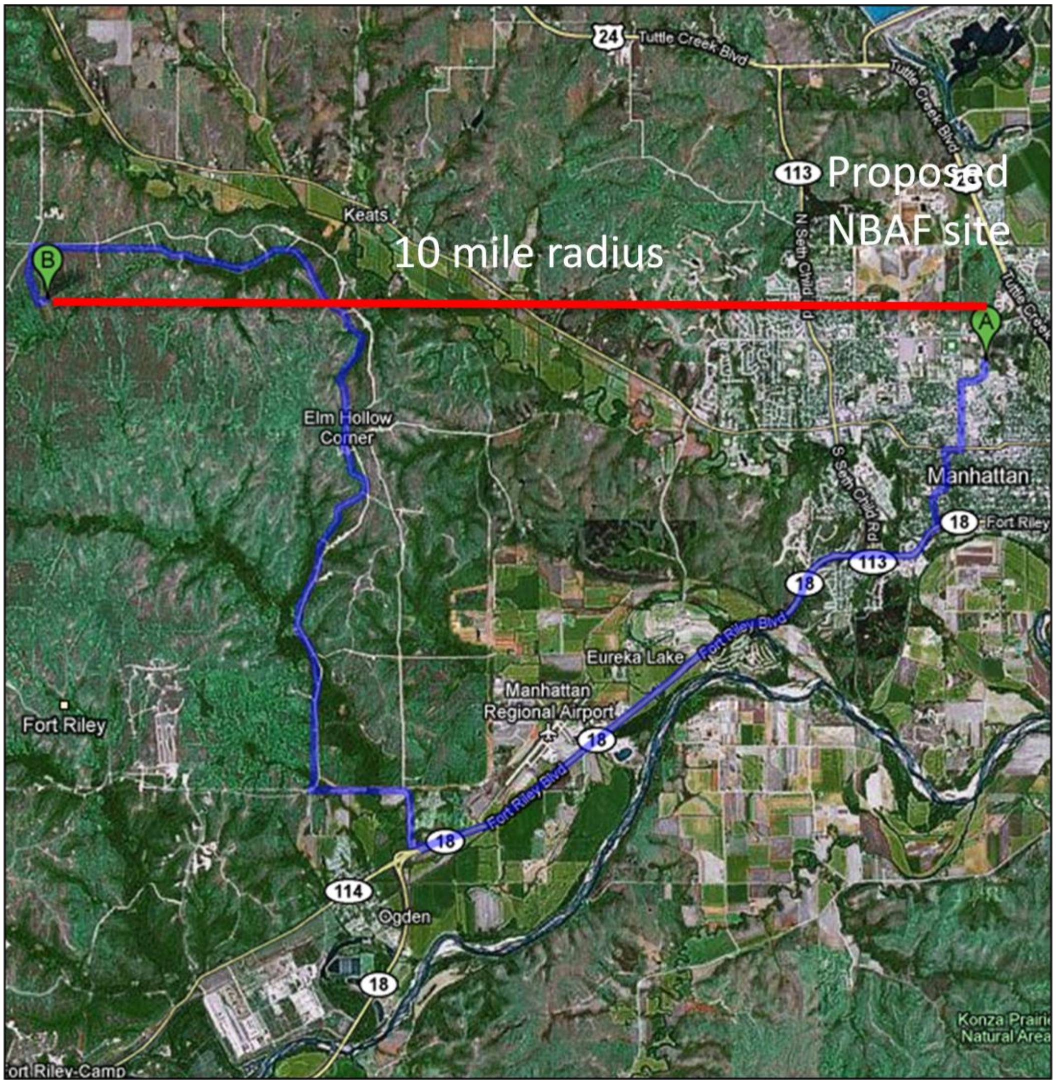


Figure 3-4 10 miles radius – West (www.maps.google.com)

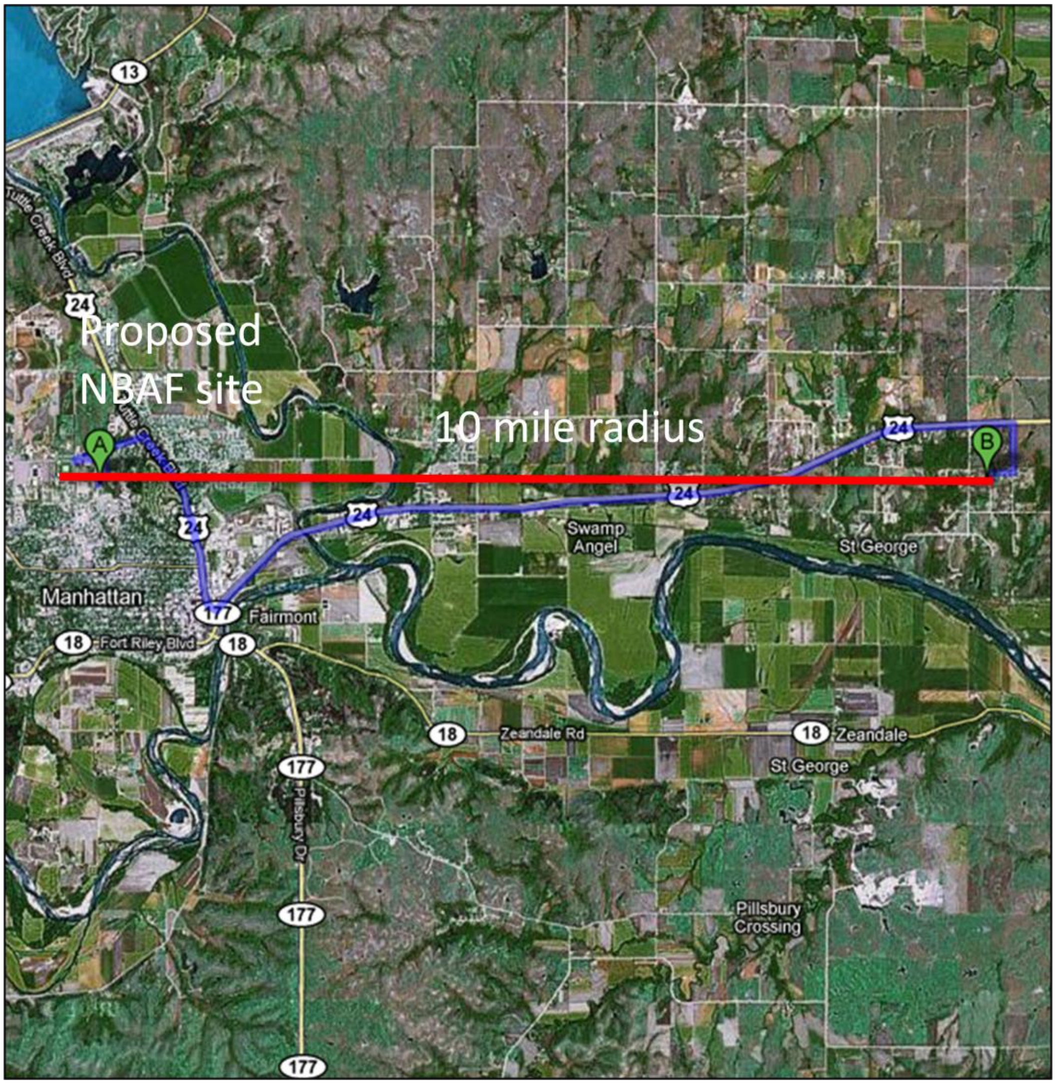


Figure 3-5 10 miles radius – East (www.maps.google.com)

Each of the main roads used in the evacuation of campus and the surrounding area can be seen in the figures above. The logic of determining which roads will be used will be explained in the Modeling Details section of this report.

3.1.3 Assumption 3 – Parents will verify their children's safety

While there has been no significant research done, it can be assumed that in an emergency evacuation situation, parents will ensure that their children are safe. This will be accounted for in the simulation using data from on-campus childcare centers. The number of children enrolled in these facilities will be equivalent to the number of vehicles that may be re-routed to include this particular location in their evacuation sequence. The percentage of vehicles that will be doing this will be relatively small. According to the enrollment office at Jardine's Child Development Center, there are 152 children currently enrolled. At Stone House's child care facility, there are 48 children attending. Total, there are approximately 200 children that would need to be picked up from one of these two facilities. These numbers indicate that out of the approximately 10,500 vehicles leaving from campus, 200 would need to be redirected to pick up their children. Therefore, approximately 2% of vehicles in the system will take a route to one of these facilities and then proceed to a safe zone.

3.1.4 Assumption 4 – The effect of traffic signals will not be considered

The length of time that traffic signals delay traffic can vary. For this model, it is assumed that traffic signals will not affect the evacuation time. This may be seen as a practical assumption since many times during traffic congestion, the direction of traffic is pre-determined by a member of the police force either physically directing traffic or by placing traffic cones in the direction of intended travel. Therefore, it can be assumed that traffic will continuously move on road segments, and that travel through intersections will operate as a 4-way stop with the priority being first come, first served. Additionally, a vehicle will join a road segment following an intersection only when the capacity allows it to.

3.1.5 Assumption 5 – Parking lots are at maximum capacity at start of evacuation

The majority of residents that will be evacuating will be in the approximately two mile by one-half mile rectangle created by the Kansas State University campus. There are a number of parking lots located on campus. For this simulation, it is assumed that the evacuation takes place when the parking lots are at maximum capacity due to the fact that university students, faculty, staff, and visitors are required to purchase a permit to park on campus. However, because classes are spread throughout the day, people come and go, vacating parking spots, allowing Parking Services to sell more parking permits than there are parking spaces on campus. With a high demand for parking spaces, it can be assumed that these parking lots will constantly be at maximum capacity, creating a worst-case scenario. It can also be assumed that if the evacuation were to take place at any time in which the parking lots were not at full capacity, such as during the summer months, the evacuation most likely would not take as much time as it would when the parking lots are full. Parking lot capacities were obtained from Kansas State's Parking Services.

3.1.6 Assumption 6 – Areas outside of campus will also evacuate

As mentioned in section 2.2.3, as the evacuation progresses, approximately 42% of residents outside of the campus area will also evacuate. This could be attributed to curiosity of drivers wondering why there has suddenly been an increase in traffic density, fear of coming into contact with an escaped pathogen, misinformation from a news source, or because of the fact that instructions were given to evacuate.

In order to determine the number of vehicles that 42% would equate to, data was collected from both Riley and Pottawatomie County offices on the total number of vehicles registered in each of these two counties. These values were then scaled based on the population within the 10-mile radius defined above. The final number of registered vehicles that could contribute to the area in the 10-mile radius was totaled to be 38,243. Forty-two percent of this value is equal to approximately 16,000 vehicles that might also evacuate at the time that all vehicles in campus parking lots are evacuating.

3.1.7 Assumption 7 – Average length of vehicle

In order to define the capacity of each road segment, the number of zones had to also be defined. A zone is equal to one vehicle length plus following distance. It was assumed that the average length of vehicle is equal to 16 feet (Fairfield, n.d.), and that, due to congestion a vehicle will follow at a close 10 feet, for a total zone length of 26 feet.

3.1.8 Assumption 8 – Drivers using cell phones will slow down congested traffic even further

Following a study performed by the University of Utah, researchers found that not only is talking on a cell phone while driving a safety risk, but it also slows down traffic. According to the study, driving while using a cell phone may increase commuting time by 5 to 10 percent, resulting in an overall addition of approximately 20 hours of commuting time per year. Subjects participating in the study made fewer lane changes and drove 2 to 3 percent slower in medium to high traffic congestion when driving while using a cell phone. Due to the fact that as many as 1 in 10 drivers is using a cell phone at any given time in traffic, this could severely increase the amount of time a line of traffic takes to evacuate from an area, depending on the population density and road capacity (Parker-Pope, 2008). The percentage of drivers talking on cell phones while driving can be expected to increase in the coming years with the accessibility of cell phones increasing, creating even further delays in total commute time.

3.2 Modeling Details

ARENA 10.0 software was used to create the discrete-event simulation described in this section. Details regarding inputs and modeling processes are explained below. Any assumptions made will also be explained where necessary.

3.2.1 ARENA Software

ARENA is a sophisticated microscopic simulation software that can be used to model operational processes. It has advanced material handling modeling capabilities, and can illustrate the movement of guided vehicles. The software can also be used to model congestion, making it a good option for an evacuation scenario. The appeal of using ARENA versus other software comes from the fact that it is versatile, and processes can be modeled using a number of different methods.

3.2.2 Vehicle Network

3.2.2.1 Vehicle Population

KSU's Parking Services provided the maximum number of parking spaces available in each parking lot on campus. The sum of these numbers represents a portion of the maximum number of vehicles, or entities, that could be in the system at any given time. The other portion comes from the number of registered vehicles within the 10-mile radius of the NBAF site. In order to define the maximum number of entities in the system, each parking area generates up to the number of parking spaces available in its lot. Again, this is due to the combination of Parking Services selling more parking permits than parking lots can hold and the fact that vehicles come and go throughout the day, which generates a worst-case scenario concerning evacuating vehicles from campus.

3.2.2.2 Intersections

In order for vehicles to move through the system, intersections must be defined. An intersection is located at the beginning and ending points of a link, which will be defined in a later section. Links can also be associated with a station, which will be also be explained further below.

Information needed to create an intersection includes travel length and velocity change factor. Travel length was determined using a global positioning system software to map out the road segments in Manhattan. This will be measured in feet.

Velocity change factor refers to the percentage of velocity that a vehicle maintains when turning a corner. This is assumed to be 100% in the case of an emergency evacuation, since during congestion vehicles are moving slowly enough that they may safely make a turn while maintaining full vehicular velocity. These inputs are entered into the *Intersections* element in ARENA's interface.

3.2.2.3 Links

The network of roads in Manhattan and the surrounding area makes up the road system used in the simulation. The majority of the network used for this simulation is shown below in Figures 3-6 and 3-7. As seen in the figures, the road network resembles a grid structure, with the major roads surrounding and through campus being Denison Avenue, Anderson Avenue, Claflin Road, North Manhattan Avenue, and Kimball Avenue. It should be noted that the approximate location of the proposed NBAF site is located at the marker labeled 'A'.

Each intersection, defined above in section 3.2.1.2, is connected by a link. In order to determine the capacity of each link, or road segment, the distance between two intersections was found using a satellite mapping system, Google Maps. The process of inputting a link into the *Links* element of ARENA 10.0 includes defining the intersection on either side of the link, along with a beginning and ending direction, link length, number of zones, and length of each zone.

The intersections placed on either side of the link can be found from the intersections input into the *Intersections* element. The beginning and ending travel direction of a vehicle is found by defining the 0° direction, and determining the direction of travel relative to this point on a particular link. It is based on a 360° circular area. The link length, as stated above, was found using a satellite resource. The zone length is based on the average vehicle length, which was found to be 16 feet, as stated above. In order to determine the number of zones available on a particular link, the link length is divided by the zone length.

Each vehicle uses the information input into the *Links* element to determine if there is sufficient capacity for it to be added on to the link.

Figure 3-6 Kansas State University Road Network (http://www.maps.google.com)

Figure 3-7 Kansas State University Road Network (www.maps.google.com)

3.2.2.4 Stations

Stations are similar to intersections. A station represents a beginning point for a road segment and intersection. Stations are associated with an intersection by an intersection ID. Because intersections are connected by links, stations are then tied to links as well. Any guided vehicle directed to a station causes the vehicle to move to the associated intersection in its defined system sequence, or map. It should be noted that a station must be connected to an intersection, but not all intersections must be connected to a station.

3.2.2.5 Sequences

A sequence is a route that a particular vehicle will take. Each sequence is defined in the *Sequences* element. When a transporter is routed using a TRANSPORT block, the user can define a vehicle's route based on a particular sequence from the *Sequences* element.

The *Sequences* element is made up of a sequential list of stations that the user specifies for the vehicle to visit. A sequence is assigned to a vehicle by setting the variable *NS* (sequence number) equal to the sequence number from the *Sequences* element. In this simulation, each parking area will have its own sequence since vehicles from each lot will likely be taking different routes depending on their starting and ending locations.

3.2.2.6 Networks

Similar to a sequence, a network holds each link that a guided vehicle will be traveling on when completing its route. The links connecting all intersections included in a guided transporter's system map should be added to each network. Each link can be thought of as an expanse of road segment that a guided transport follows from one intersection to the next intersection on its route. Since a network pulls from only the links that a guided vehicle needs to complete its route rather than all links defined in the system, it allows the computer to use less memory. A network is defined in the *Networks* element be starting and ending links. The starting and ending links will be the same, since a vehicle begins on at the beginning intersection on a link, and ends at the ending intersection on the same link before progressing to the next link.

A list of each parking lot, along with the network of roads each will follow to arrive at its destination is listed in the Appendix in Table A-2.

3.2.2.7 Transporters

The *Transporters* element establishes features of a transporter, whether it is free-path or guided. In this case, guided transporters, which necessitate intersections, links, and networks, as stated above, are utilized. This element has several inputs, which are described below.

- Number of units: defines the number of individual transporter units that are available for utilization. For this simulation, each parking lot uses its own transporter unit, so the number of units is equal to the maximum number of spaces in the lot.

- System map type: defines whether a transporter will be following a network or distance map. If the transporter is free-path, it will follow a distance map. It will follow a network if the transporter is a guided vehicle.
- Map ID: declares the name of the network that a guided vehicle will follow.
- Velocity: defines the initial velocity of the transporter. The vehicle's velocity may be altered during run time by changing the value assigned to the variable *VT*. Assigning a value to *VT* changes the velocity of all transporters in the set. However, changing the velocity of a particular transporter can be done using the variable *VTU*. Velocity may also be altered in the *Transport* block. It is entered in distance per time unit, depending on the base units, which in this case are feet per hour.
- Acceleration/Deceleration: defines the vehicle set's acceleration and deceleration rates in distance per time unit squared.
- Turning velocity: defines the percentage of velocity maintained when a vehicle initiates a change in direction. As stated above, this will remain at 100 percent for this situation, given the fact that traffic is congested during an evacuation, and vehicles will likely be moving at slow enough speeds that all velocity will be maintained during a direction change.
- Initial position: defines the station from which the transporters will move. The station will be associated with the first link specified in the *Networks* element for guided vehicles.
- Initial status: specifies whether each transporter unit is active or inactive. The default status is active. A transporter may also be inactivated using a HALT block during run time.

Transporters move through the system using REQUEST and TRANSPORT blocks. An entity, or driver, requests a vehicle, and an available transporter arrives at the transporter's initial location. It is then transported using the TRANSPORT block. Its destination must be defined in the TRANSPORT block. When using networks, a guided vehicle is transported according to a defined sequence. Entering *SEQ* into the destination ensures that the vehicle gets routed according to the sequence assigned when the entity enters the system.

3.2.3 Model Design

Within the simulation are two major processes taking place. The first is the actual routing of the vehicles to their destinations. The second is a process of each vehicle making decisions in the inner workings of the model. Figure 3-8 shows the process from a vehicle's perspective. While it is simplified in the figure, there are a number of things working behind the scenes that contribute to the overall model's operational capabilities.

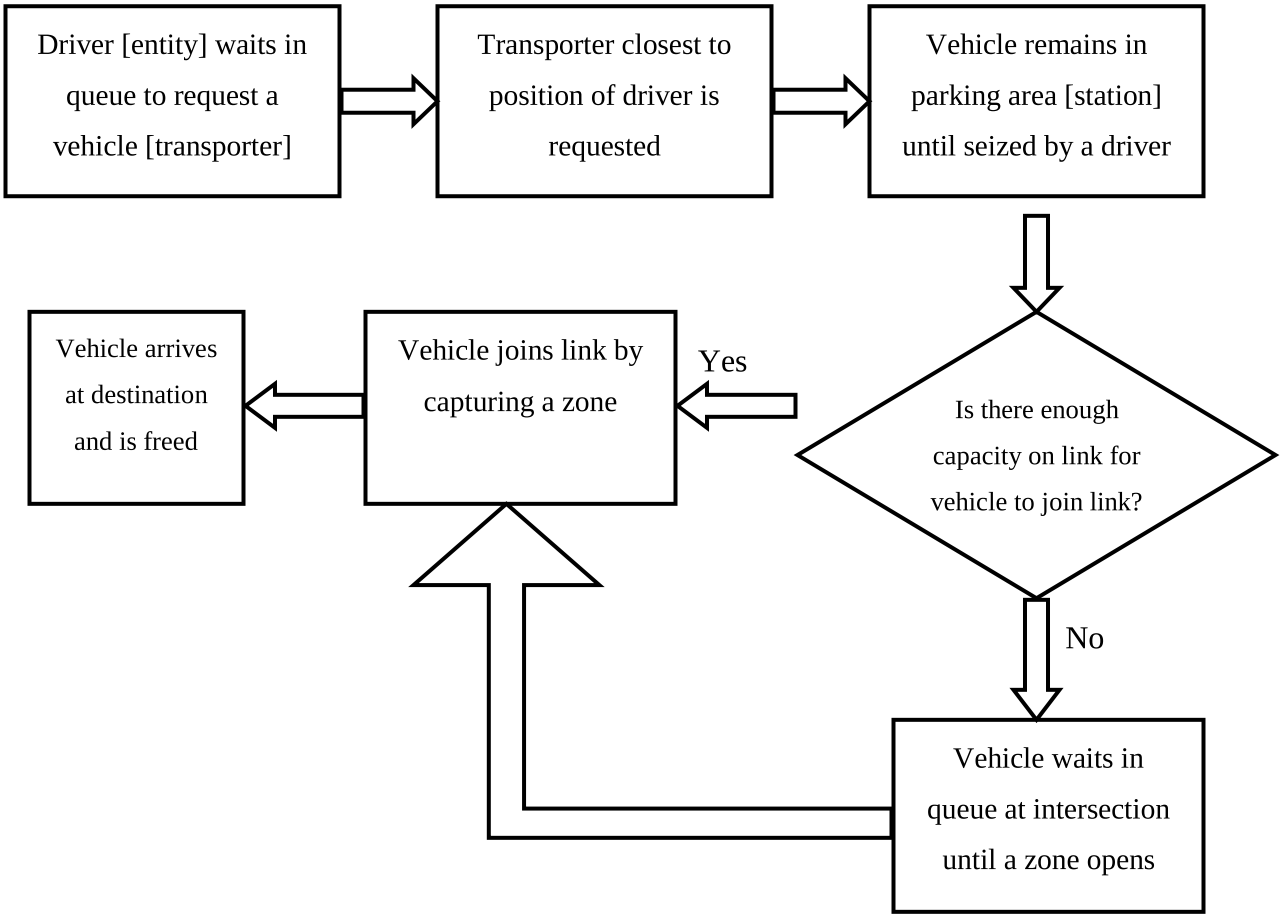


Figure 3-8 Process Map of Routing Vehicles through System

3.2.3.1 Entities

The sole entity used in the system represents vehicle drivers. Entities enter the system using a CREATE basic process block. Because it is assumed that all drivers arrive at the initial location of their vehicles, an entity enters the system at an exponential rate up to the maximum number of spaces in a parking lot. Each parking lot has its own entity creation process to account for the differing number of vehicles in each lot.

Once created, the path of the entity continues to an ASSIGN block. After passing through the ASSIGN block, each entity has been allocated an *NS* value equal to the sequence number that the entity will follow throughout its course in the system and an attribute called *Type*, which assigns a value that increment from 1 to each batch of entities. This attribute assignment will be used for differentiating between sequences within the same network, and will be explained further. Another attribute assigned is a value of TNOW that represents *Time In System*. The *Time in System* attribute will be used to calculate how much time each entity has been in the system, which will be equivalent to the total evacuation time for that entity.

The next block the entity travels through is a STATION block. The STATION designated is the initial position of the transporter for the parking lot at which each entity was created. Once the entity travels through the STATION block, it recognizes its location, and can begin the process of seizing a vehicle.

3.2.3.2 Seizing a vehicle

The basic process an entity uses to request and move a vehicle is through the use of QUEUE and REQUEST blocks. Because the number of transporters created is equal to the number of entities generated, the queue time for each entity is small. The REQUEST block matches an entity with a transporter. By indicating *SDS* next to the name of the requested transporter, the transporter closest in proximity to the entity waiting for it is paired with the entity.

3.2.3.3 Transporting a vehicle

After a transporter is requested, it needs to move to the next station listed in its assigned sequence. In order to accomplish this, a TRANSPORT block is used. The transporter name is specified, and by entering *SEQ* into the destination field, the transporter is sent to the next stop in the defined sequence. Also in the TRANSPORT block is an input for transporter velocity. Any value or distribution entered in the block overrides the initial velocity entered in the *Transporters* element. The distribution of velocity used is based on data gathered during the Hurricane Rita evacuation, and will be described further in a later section.

The routing portion of the simulation continues using STATION and TRANSPORT blocks. STATION blocks, once again, alert a transporter that their location has changed, and TRANSPORT blocks move the transporter from its current location to the next station defined in its sequence.

3.2.3.4 Transporting a vehicle with a different sequence in the same network

Some vehicles that have different sequence definitions will go through some of the same stations along their route. This is especially common since many vehicles from different parking lots are following one another and taking the same routes out of Manhattan. These vehicles will be put on the same network, but will have an independent creation of entities and transporters, since their initial positions will not be the same. In order to allow different transporters to go through the same STATION block, a BRANCH block was used. Using the *Type* attribute assigned when each entity initially enters the system, the branch separates each type so that each parking lot's transporter may be used to route according to its sequence.

A snapshot of the ARENA blocks used for the seizing and routing of vehicles is shown below in Figure 3-9.

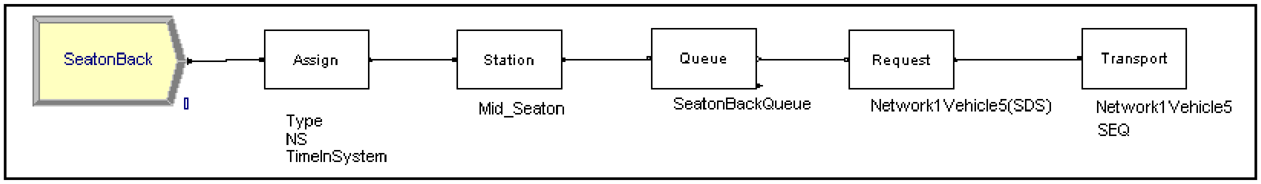


Figure 3-9 ARENA Transportation Logic

3.2.3.5 Speed distribution

When the evacuation begins, traffic will be free flowing since vehicles are entering the system using an exponential distribution, meaning the increase in traffic will be exponential when compared versus time. However, once the congestion begins to build, traffic will inevitably be slowed, at times perhaps to nearly a standstill. When drivers approach their destinations, traffic speeds increase nearly back to the free flow speed. Many drivers have experienced the traffic conditions described above.

Data collected during the Hurricane Rita evacuation in 2005 validated this assumption. At time 0, vehicles were moving at the maximum speed limit of 70 miles per hour. After approximately one hour, the speed has decreased to approximately 65 miles per hour.

The data collected following Hurricane Rita are displayed below in Figure 3-10. One can clearly see that as time on the x-axis increases, speed in miles per hour on the y-axis decreases. After 46 hours of travel time for the nearly 2 million evacuees, vehicle speed began to increase rather than decrease.

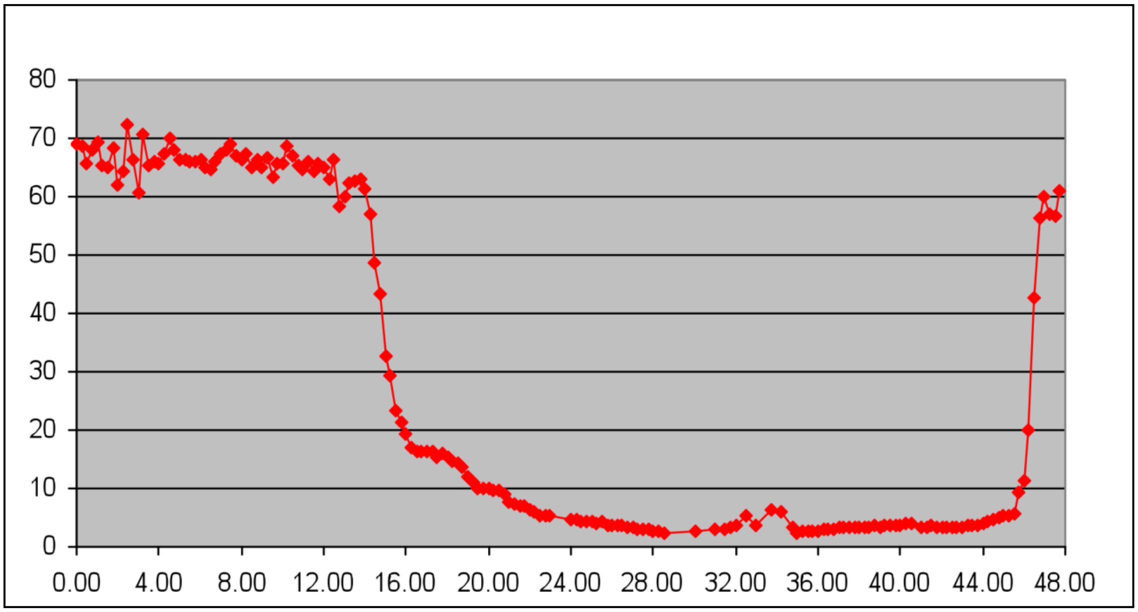


Figure 3-10 Vehicle speed distribution – Hurricane Rita (Lam, n.d.).

Because the maximum speed limit throughout the city of Manhattan differs depending upon the road segment being traveled, the data were scaled to accurately portray the change in speed. In order to accomplish this, the top value of 70 miles per hour used during the Hurricane Rita evacuation was scaled to both 30 and 50 miles per hour by dividing each of these values by 70. The result obtained is the percentage of a 70 mile per hour speed limit that 30 and 50 miles per hour are. By multiplying the collected data by this fraction, speeds scaled to 30 and 50 miles per hour result, which can then be used to determine the parameters of the distribution.

Then, to account for the drop in speed due to increased congestion, a curve fit was done for the first 12 hours of data. Because of the relatively small population of evacuating cars and based on preliminary simulation runs, 12 hours was determined to be the maximum evacuation time for any scenario. For each of the scaled speeds, the minimum, maximum, and mean speed was determined. A triangular distribution with minimum, maximum, and mean speeds as the input parameters was used to define vehicle velocity depending on the maximum speed limit of the road segment being traveled on. The parameters for each of the maximum speed limits are shown below in Table 3-1. It should be noted that the parameters are in feet per hour due to the fact that the base measurements in the simulation are feet.

Table 3-1 Triangular Distribution Parameters

Maximum Speed Limit	**Triangular Distribution Parameters**
30 mph (158,400 fph)	TRIA(146181, 149122, 154214)
50 mph (264,000 fph)	TRIA(243634, 248537, 257023)
70 mph (369,600 fph)	TRIA(341088, 347952, 359832)

3.2.3.6 Built-in transporter logic

As the transporters make their way through each of their defined sequences, ARENA has built-in logic that allows them to behave as vehicles traveling a stretch of road would.

First, a vehicle occupies only its defined zone, which eliminates the opportunity for vehicles to collide into one another. Because a road segment is defined by the number of zones available along its course, there is an automatic check that each vehicle waiting to enter a road segment completes to determine if adding its zone length to the road segment would be allowed, or if the road segment is currently at capacity, in which case the vehicle will wait until sufficient capacity is available.

While vehicles following one another will not collide if they are following the same speed distribution, vehicles moving opposite directions on the same link do have the possibility of crashing. However, this situation can be avoided by creating two different unidirectional links that span the same road segment, but allow two different directions of travel.

3.2.3.7 Release entities

Each of the drivers requesting a vehicle must be disposed from the system after freeing its vehicle. The entities pass through a FREE block, which allows them to become unassociated with the vehicle, and the entity continues to a DISPOSE block, where it is counted and remains in system memory.

3.3 Simulation Scenarios

For comparison purposes, six different scenarios will be simulated. Data will then be collected for each scenario so that both the number of vehicles exiting the system per hour and a vehicle's average time in the system can be analyzed. Each of the six scenarios is described below.

3.3.1 Scenario 1 – Campus traffic only

The first scenario will represent the evacuation of campus traffic only. While evacuating only campus would take a significant amount of planning regarding sealing off roads adjacent to campus, it would be possible to stage an evacuation only for campus vehicles. However, evacuating only campus is an unlikely event. The main purpose of including this scenario is for treating it as a base case from which to compare the other scenarios.

3.3.2 Scenario 2 – Campus and outside traffic

The second scenario is more likely, as it includes the evacuation of both campus and 42% of the normal flow of traffic. Based on data collected by the Kansas Department of Transportation (KDOT), approximately 42% of total traffic flow in Manhattan is on the following roads: Kimball Avenue, College Avenue, Denison Avenue, Tuttle Creek Boulevard, McCall Road, Bluemont Avenue, North Manhattan Avenue, Anderson Avenue, Sunset Avenue, Claflin Road, Seth Child Road, and Poyntz Avenue.

In order to incorporate new routes from outside of campus into the campus only model, new sequences were created for the areas that each of the above roads span. Initial starting position was determined by referencing a traffic flow map created by KDOT. The traffic map showed traffic counts for a 24-hour period around the city. After accounting for 42% of outside traffic, 13,626 vehicles have been added to the base case scenario. This number is lower than the original approximated value of 16,000 vehicles due to the fact that the normal traffic flow numbers are not as high as expected. This model will be evaluated in the analysis section of this report.

3.3.3 Scenario 3 – Outside traffic and effect of cell phone use

The third model is similar to the model detailed in section 3.3.2, but with the addition of the effect of cell phone usage. The city of Manhattan will be implementing a cell phone ban beginning in July of this year. However, this ban does not limit the use of talking on mobile hands-free devices. Also, in times of emergency, it can be expected that some drivers will disregard the rule to keep others updated on their whereabouts or to report any progress taking place during the evacuation.

3.3.4 Scenario 4 – Outside traffic and effect of picking up children

There are two childcare facilities at Kansas State University. One is located off of Denison Avenue at the Jardine complex, and one is located off of North Manhattan Avenue near the dorms on the east side of campus. They are known as the Child Development Center and Stone House, respectively.

Each facility is responsible for caring for children of faculty, staff, and students at K-State. Enrollment at the Child Development Center is equal to 152 children, while the enrollment at Stone House is 48 children. While these values are only a small percentage of the overall number of vehicles that will be evacuating, a scenario in which children are picked up at each of these facilities needs to be considered. In the event of an emergency, the childcare centers do not have the capability of transporting multiple young children, therefore, parents must be relied on to transport them out of harm’s way.

Based on the enrollment numbers obtained from each of the facilities, 1.43% of vehicles will be re-routed to the Child Development Center and 0.45% of vehicles will be re-routed to Stone House. In order to determine what the effect of following a different route would be, the same logic was used, but different sequences were created for the number of vehicles represented by the percentages above. The sequences began from the 4 furthest points from each of the facilities – in this case, Natatorium parking, the Recreation Center and Sports Complex parking, and Beach Museum of Art parking. Entities and transporters begin in the same lots that vehicles going directly out of Manhattan begin in, but their routes then lead to either the Child Development Center or Stone House, where they join the progression of the evacuation at that point.

3.3.5 Scenario 5 – Increase in traffic flow

The fifth scenario that will be modeled will increase traffic flow to see the effect on number of vehicles leaving the system, along with average time in the system. Increasing the traffic flow can be done by simply increasing the number of vehicles and entities created in the CREATE block. One would hypothesize that increasing traffic flow would increase the amount of time each vehicle spends prior to reaching a safe zone. This scenario will be compared with the others.

3.3.6 Scenario 6 – Vehicle breakdown

The sixth scenario that will be used for comparisons will represent a vehicle breaking down, and the traffic back up that will take place. In order to break down a vehicle, a random vehicle will be chosen from normal traffic flow, and will then go through a HALT block. This will inactivate the transporter unit. A DELAY block with a defined delay time of one hour will follow the HALT block. The one-hour delay signifies the amount of time it takes to either move the vehicle from blocking the flow of traffic or to be towed out of the road. When the delay has passed, the transporter will need to be activated. An ACTIVATE block was used to re-activate the transporter, and TRANSPORT blocks are reintroduced as a means of moving the previously inactive vehicle.

3.3.7 Scenario 7 – Effect of wind on evacuation direction

Because the effects of some substances and pathogens being researched at the NBAF facility could be negative for anyone coming into contact with them, the response to situations in which they are released into the atmosphere should be addressed. Pathogens could escape into the air due to human error or such threats as chemical warfare, forming a plume of air containing contaminants. Due to the fact that the wind will likely carry the plume in its path, roads leading in the direction of the wind will be closed off, necessitating a re-routing.

According to a report generated from March of 2006 to March 2010, the average wind direction in Manhattan is from south to north (www.wunderground.com). Therefore, in the event that a plume exits the NBAF facility, it will likely hover and blow toward the north before eventually disappearing. Traffic routing north will be re-routed to go south. To accomplish this, their sequences will be changed to move the traffic south rather than north. This eliminates the route for vehicles originally going north on Marlatt Avenue to Tuttle Creek Boulevard, across the dam to McIntyre Road, and the route for vehicles originally going west on Claflin Road to Seth Child Road to Highway 406. Approximately 10,000 vehicles will be redirected.

CHAPTER 4 - Results and Model Validation

4.1 System Setup

Local data from the KDOT and Kansas State University were used as inputs for this system. Additionally, statistical evidence given or assumed in the literature and global positioning system software were used to define such things as distances used between two intersections or vehicle speed.

4.2 Analysis

Each of the scenarios presented above in section 3.3 was simulated every hour for 5 hours, with 5 replications per scenario. A collection of statistics was generated following each simulation period. The statistics of interest include the number of vehicles leaving the system per hour from each initial starting point, and the average time each vehicle that leaves the system spends traveling before reaching its destination. By comparing these values and performing statistical analyses, one can determine if each change from the base model is statistically significant.

4.2.1 Total Flow Out

The first means of comparison that will be used to analyze each of the scenarios is based on total percentage of vehicles flowing out of the system per hour in a five hour time-frame. A line graph of percentage of vehicles leaving per hour for each scenario is shown below in Figure 4-1.

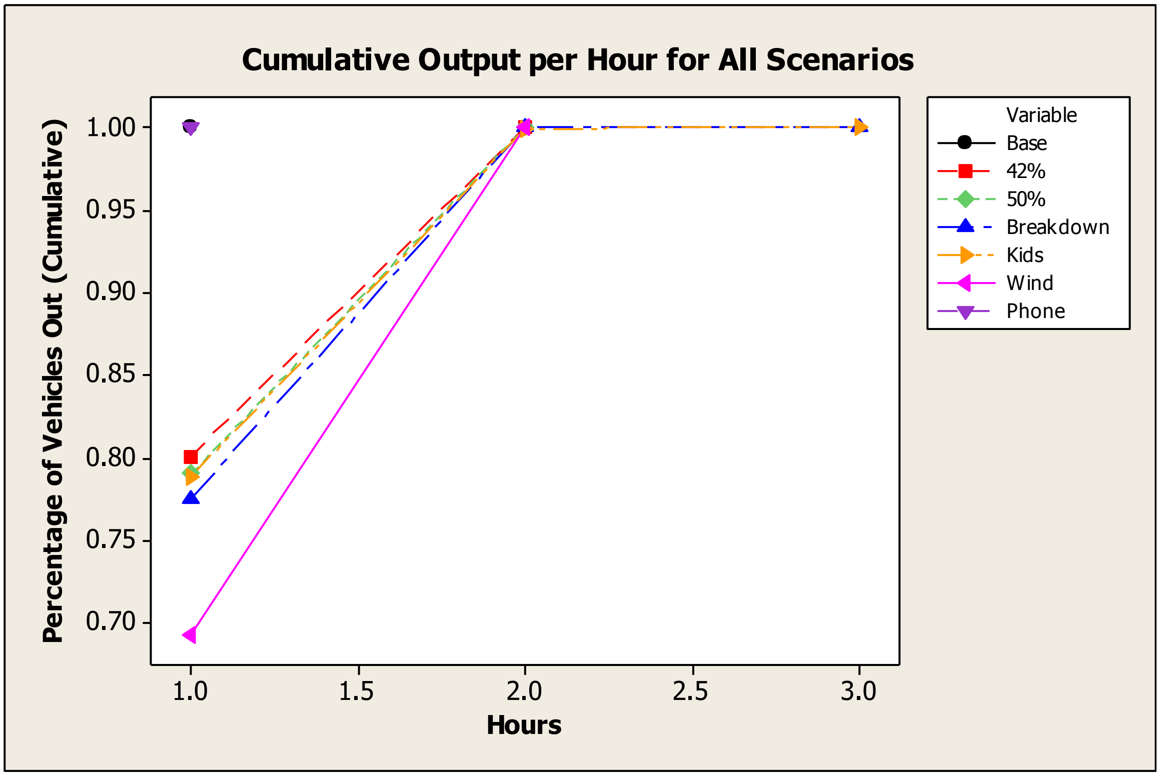


Figure 4-1 Percentage of Vehicles Leaving per Hour for All Scenarios (Output from MiniTab)

By visually inspecting the graph, one can see that within the first hour, the base case scenario of only campus vehicles and the scenario in which campus traffic is slowed by 3% due to cell phone usage, all vehicles have arrived at their respective safe zones. Also during the first hour is the time in which the vehicle breakdown occurs. The delay causes traffic to back up, resulting in a lower output during the first hour. Closing roads to the north also causes a lower output compared to the other scenarios.

By the second hour, nearly 100% of all vehicles for all scenarios have arrived at their safe zones. Finally, to evacuate 100% of vehicles for all scenarios, three hours is needed. One should keep in mind the fact that these scenarios do not represent the entire population of vehicles in Manhattan, and the evacuation is directed.

Also by inspecting the graph above, one can draw conclusions on the effect of certain changes to each model. It appears that decreasing the vehicles' speed by 3% had no effect on the percentage of output, as both the base model and the model illustrating the effect of cell phone usage had 100% output after the first hour. By increasing traffic, adding a vehicle breakdown, re-routing parents to pick up children, and blocking off roadways, the percentage of output was significantly lower within the first hour of evacuating. However, after the first hour, output increased nearly to 100%. This is no surprise since during the first hour will be the time at which the congestion is building the most.

A table summarizing each scenario and the resulting percentage output is shown below in Table 4-1. A table summarizing the number of vehicles entering each system, along with the hourly output is shown in the Appendix in Table A-1.

Table 4-1 Hourly Percent Output for All Scenarios

Scenario	Hour 1	Hour 2	Hour 3
Base Case	100%	-	-
42% Outside Traffic	80.1%	100%	-
50% Increase in Outside Traffic	79%	100%	-
Vehicle Breakdown	77.5%	99%	100%
Picking up Kids	78.8%	99%	100%
Lower Speeds due to Cell Phone Usage	100%	-	-
Effect of Plume and Wind	69%	100%	-

4.2.2 Significance

In order to determine whether or not changes to the base model are significant, paired T-tests comparing each model were completed. By examining the p-value for the test, one can conclude the significance of the change. If the p-value is below an alpha value of 0.05, the null hypothesis for equal means is rejected, and the conclusion states that there is a significant difference between the models. In this case, the means being tested are the number of vehicles arriving to the safe zone in the first hour of the evacuation.

The first tests completed compared the base model against each of the other scenarios.

4.2.2.1 Base Case vs 42% Outside Traffic

The base case scenario, once again, is evacuating only campus traffic from each of the parking areas. By taking into account the normal flow of traffic already on the roads, paired with the fact that approximately 42% of this traffic will also evacuate, a more realistic scenario is created. This is the 42% outside traffic model. In order to determine if the addition of outside traffic to the model significantly affects the percentage of output per hour, the paired T-test was carried out. The output resulting from the test is shown in Figure 4-2, below.

```
Paired T-Test and CI: Base, 42%

Paired T for Base - 42%

             N      Mean  StDev  SE Mean
Base         5   10591.8    1.3      0.6
42%          5   19396.6    1.5      0.7
Difference   5  -8804.80   1.30     0.58


95% CI for mean difference: (-8806.42, -8803.18)
T-Test of mean difference = 0 (vs not = 0): T-Value = -15100.11  P-Value =
     0.000
```

Figure 4-2 Paired T-Test Results for Base Case vs 42% Outside Traffic Scenario (Output from MiniTab)

Looking at the low p-value of 0.000, one can conclude that the difference in the number of vehicles arriving at a safe zone between these two models is very significant. The base model had all vehicles leaving, but the model with outside traffic had even more that left the system within one hour. This contributes to the significant t-test results.

4.2.2.2 Base Case vs 50% Increase in Outside Traffic

The next test compared the base case scenario and a scenario similar to the one described above. However, the outside traffic was increased by 50%. The output from this test is shown below in Figure 4-3.

```
Paired T-Test and CI: Base, 50%

Paired T for Base - 50%

             N      Mean  StDev  SE Mean
Base         5   10591.8    1.3      0.6
50%          5   24223.0    3.5      1.6
Difference   5  -13631.2    4.1      1.9


95% CI for mean difference: (-13636.3, -13626.1)
T-Test of mean difference = 0 (vs not = 0): T-Value = -7349.45  P-Value = 0.000
```

Figure 4-3 Paired T-Test Results for Base Case vs 50% Increase in Outside Traffic Scenario (Output from MiniTab)

The results for this test are similar. With a low p-value of 0.000, one can reject a hypothesis for equal means and conclude that there is a significant difference between the models based on the number of vehicles leaving during the first hour.

4.2.2.3 Base Case vs Vehicle Breakdown

The next comparison was for the base case scenario versus the model with a vehicle breaking down during the first hour of the evacuation. The vehicle remains inactive for one hour before being reactivated and continuing with the evacuation route. During the time that the vehicle is inactive, traffic becomes backed up behind the broken down vehicle.

With a p-value of 0.000, having a vehicle breakdown on a certain route is seen as affecting the overall number of vehicles output. More investigation could be done to determine how long an average breakdown lasts during road congestion, and if the road chosen for the breakdown affects the percentage of output. Output from this test is shown below in Figure 4-4.

Paired T-Test and CI: Base, Breakdown

```
Paired T for Base - Breakdown

             N      Mean  StDev  SE Mean
Base         5   10591.8    1.3      0.6
Breakdown    5   18765.4    3.4      1.5
Difference   5  -8173.60   3.58     1.60


95% CI for mean difference: (-8178.04, -8169.16)
T-Test of mean difference = 0 (vs not = 0): T-Value = -5108.50  P-Value = 0.000
```

Figure 4-4 Paired T-Test Results for Base Case vs Vehicle Breakdown Scenario (Output from MiniTab)

4.2.2.4 42% Outside Traffic vs 50% Increase in Outside Traffic

The next comparison is for two models that include outside traffic. The first model accounts for the normal flow of traffic that will evacuate even though they are outside of the affected area. The second scenario increases the normal flow by 50%. The output for this test is shown below in Figure 4-5.

Paired T-Test and CI: 42%, 50%

```
Paired T for 42% - 50%

            N      Mean  StDev  SE Mean
42%         5   19396.6    1.5      0.7
50%         5   24223.0    3.5      1.6
Difference  5  -4826.40   3.91     1.75


95% CI for mean difference: (-4831.26, -4821.54)
T-Test of mean difference = 0 (vs not = 0): T-Value = -2759.07  P-Value = 0.000
```

Figure 4-5 Paired T-Test Results for 42% Outside Traffic vs 50% Increase in Outside Traffic Scenario (Output from MiniTab)

From the low resulting p-value of 0.000, one can conclude that increasing traffic will affect the number evacuated per hour. Since the model is essentially the same, but with increased traffic, this makes sense.

4.2.2.5 Vehicle Breakdown vs Outside Traffic

The next two comparisons evaluated the vehicle breakdown scenario versus the scenarios including outside traffic. Both the normal traffic flow, as well as the 50% increase in outside traffic flow scenarios were considered. The results are shown below in Figures 4-6 and 4-7.

Paired T-Test and CI: 42%, Breakdown

```
Paired T for 42% - Breakdown

            N     Mean  StDev  SE Mean
42%         5  19396.6    1.5      0.7
Breakdown   5  18765.4    3.4      1.5
Difference  5   631.20   3.70     1.66


95% CI for mean difference: (626.60, 635.80)
T-Test of mean difference = 0 (vs not = 0): T-Value = 381.32  P-Value = 0.000
```

Figure 4-6 Paired T-Test Results for Vehicle Breakdown vs 42% Outside Traffic Scenario (Output from MiniTab)

```
Paired T-Test and CI: 50%, Breakdown

Paired T for 50% - Breakdown

             N     Mean  StDev  SE Mean
50%          5  24223.0    3.5      1.6
Breakdown    5  18765.4    3.4      1.5
Difference   5  5457.60   4.56     2.04


95% CI for mean difference: (5451.94, 5463.26)
T-Test of mean difference = 0 (vs not = 0): T-Value = 2675.81  P-Value = 0.000
```

Figure 4-7 Paired T-Test Results for Vehicle Breakdown vs 50% Increase in Outside Traffic Scenario (Output from MiniTab)

Once again, based on the low p-values of 0.000, one can conclude that a breakdown in the system with outside traffic will affect the number of vehicles output per hour. Also, the model with a 50% increase in traffic flow has an increased output compared to the breakdown scenario, so the differences in these two models are significant. This is further shown in a low p-value of 0.000.

4.2.2.6 Effect of Picking up Children

The next comparisons that were done were to determine the effect of having 2% of the evacuating traffic go first to pick their children from one of two childcare centers on campus, and then join the evacuating traffic from these points.

After performing t-tests of output from picking up children versus each of the other scenarios, one can conclude that this is only significant when compared to models with increased traffic, vehicle breakdowns, and a blocked route due to the combination of a plume and wind. The most extreme (whether low or high) percentages result from each of these scenarios. The t-test output for comparing the mean percentage of output of the model including picking up children versus these three scenarios is shown below in Figures 4-8, 4-9, and 4-10.

Paired T-Test and CI: 50%, Kids

```
Paired T for 50% - Kids

             N      Mean  StDev  SE Mean
50%          5   24223.0    3.5      1.6
Kids         5   19107.8    2.7      1.2
Difference   5   5115.20   5.36     2.40


95% CI for mean difference: (5108.55, 5121.85)
T-Test of mean difference = 0 (vs not = 0): T-Value = 2135.04  P-Value = 0.000
```

Figure 4-8 Paired T-Test Results for 50% Increase in Outside Traffic Scenario vs Parents Picking up Children (Output from MiniTab)

From the output above, it can be concluded that the change in the model from increasing traffic by 50% to having parents picking up their children from the childcare facilities is a significant change. The p-value of 0.000 confirms this.

Paired T-Test and CI: Breakdown, Kids

```
Paired T for Breakdown - Kids

             N      Mean  StDev  SE Mean
Breakdown    5   18765.4    3.4      1.5
Kids         5   19107.8    2.7      1.2
Difference   5   -342.40   5.46     2.44


95% CI for mean difference: (-349.18, -335.62)
T-Test of mean difference = 0 (vs not = 0): T-Value = -140.25  P-Value = 0.000
```

Figure 4-9 Paired T-Test Results for Vehicle Breakdown vs Parents Picking up Children (Output from MiniTab)

The test comparing the percentage of output for the model with a vehicle breaking down and parents picking up their children is also significant with a p-value of 0.000. The model with only 2% of traffic being redirected had a slightly higher output in one hour compared to the model with the vehicle breakdown.

```
Paired T-Test and CI: Kids, Wind

Paired T for Kids - Wind

              N     Mean  StDev  SE Mean
Kids          5  19107.8    2.7      1.2
Wind          5  10596.2    2.4      1.1
Difference    5  8511.60   3.78     1.69


95% CI for mean difference: (8506.90, 8516.30)
T-Test of mean difference = 0 (vs not = 0): T-Value = 5033.01  P-Value = 0.000
```

Figure 4-10 Paired T-Test Results for Road Block due to Plume vs Parents Picking up Children (Output from MiniTab)

Finally, the model comparing a road blockage and parents being redirected to pick up their children is also significant with a p-value of 0.000. However, the model with blocked roads did have a lower average output than the model with vehicles being redirected.

4.2.2.7 Effect of Road Blockage due to Plume

If a situation was to arise causing a plume of pathogens to escape from the NBAF facility, the wind would be a factor in determining the direction of travel for evacuees. The direction of the wind would likely carry the plume with it. Therefore, emergency planners should be aware of the implications of wind speed and direction in an emergency situation.

Due to the fact that the average wind direction in Manhattan is from south to north, all sequences in which vehicles are to arrive at a safe zone to the north will be redirected. Essentially, the roads leading to the north will need to be blocked off. Simulating a road blockage generated the lowest amount of output since the traffic is added on to the remaining active traffic sequences, flooding the system with over 10,000 additional vehicles. Therefore, the difference between the percentage of output resulting from this scenario and all others is considered significant. The output from the t-tests which illustrate this is shown below in Figures 4-11, 4-12, 4-13, and 4-14.

Paired T-Test and CI: Base, Wind

```
Paired T for Base - Wind

            N     Mean  StDev  SE Mean
Base        5  10591.8    1.3      0.6
Wind        5  16806.4    3.0      1.4
Difference  5 -6214.60   1.82     0.81


95% CI for mean difference: (-6216.86, -6212.34)
T-Test of mean difference = 0 (vs not = 0): T-Value = -7649.64  P-Value = 0.000
```

Figure 4-11 Paired T-Test Results for Road Block due to Plume vs Base Case (Output from MiniTab)

Paired T-Test and CI: 42%, Wind

```
Paired T for 42% - Wind

            N    Mean  StDev  SE Mean
42%         5  19396.6    1.5      0.7
Wind        5  10596.2    2.4      1.1
Difference  5  8800.40   2.41     1.08


95% CI for mean difference: (8797.41, 8803.39)
T-Test of mean difference = 0 (vs not = 0): T-Value = 8170.97  P-Value = 0.000
```

Figure 4-12 Paired T-Test Results for Road Block due to Plume vs 42% Outside Traffic Flow Scenario (Output from MiniTab)

Paired T-Test and CI: 50%, Wind

```
Paired T for 50% - Wind

            N    Mean  StDev  SE Mean
50%         5  24223.0    3.5      1.6
Wind        5  10596.2    2.4      1.1
Difference  5  13626.8    2.9      1.3


95% CI for mean difference: (13623.1, 13630.5)
T-Test of mean difference = 0 (vs not = 0): T-Value = 10330.45  P-Value = 0.000
```

Figure 4-13 Paired T-Test Results for Road Block due to Plume vs 50% Increase in Traffic Flow (Output from MiniTab)

```
Paired T-Test and CI: Breakdown, Wind

Paired T for Breakdown - Wind

             N     Mean  StDev  SE Mean
Breakdown    5  18765.4    3.4      1.5
Wind         5  10596.2    2.4      1.1
Difference   5  8169.20   5.12     2.29


95% CI for mean difference: (8162.84, 8175.56)
T-Test of mean difference = 0 (vs not = 0): T-Value = 3568.73  P-Value = 0.000
```

Figure 4-14 Paired T-Test Results for Road Block due to Plume vs Vehicle Breakdown Scenario (Output from MiniTab)

Once again, each scenario when compared to the road blockage situation is significant. Each scenario evacuated 100% of vehicles within 1 to 3 hours, but since the number of vehicles leaving in one hour for each scenario varied, the change is significant.

4.2.2.7 Effect of Cell Phone Usage

The case in which 1 in 10 drivers are actively using cell phones while driving, causing a 3% decrease in speed resulted in the lowest percentage of output per hour. Due to the fact that in traffic congestion, drivers are constrained by the speed of the driver in front of them, all vehicles experienced a loss of speed.

When testing the significance of a decreased speed model against the base model, the result is significant when comparing to an alpha level of 0.05. The cell phone model resulted in the same output as the base model. Therefore, the t-test could not be completed since all data were equal.

The next two tests were for cell phone usage versus outside traffic and increased outside traffic. Both tests were significant with p-values of 0.001. Once again, the model representing decreased traveling speeds due to cell phone usage resulted in lower output compared to the increased traffic models. Output for these t-tests is shown in Figures 4-15 and 4-16, below.

```
Paired T-Test and CI: 42%, Phone

Paired T for 42% - Phone

             N     Mean  StDev  SE Mean
42%          5  19396.6    1.5      0.7
Phone        5  16806.4    3.0      1.4
Difference   5  2590.20   2.17     0.97


95% CI for mean difference: (2587.51, 2592.89)
T-Test of mean difference = 0 (vs not = 0): T-Value = 2671.59  P-Value = 0.000
```

Figure 4-15 Paired T-Test Results for Cell Phone Usage vs 42% Outside Traffic Flow Scenario (Output from MiniTab)

```
Paired T-Test and CI: 50%, Phone

Paired T for 50% - Phone

             N     Mean  StDev  SE Mean
50%          5  24223.0    3.5      1.6
Phone        5  16806.4    3.0      1.4
Difference   5  7416.60   5.27     2.36


95% CI for mean difference: (7410.05, 7423.15)
T-Test of mean difference = 0 (vs not = 0): T-Value = 3145.34  P-Value = 0.000
```

Figure 4-16 Paired T-Test Results for 50% Increase in Outside Traffic Scenario vs Cell Phone Usage (Output from MiniTab)

Once again, all changes were seen to be significant due to the p-values less than 0.05. Sensitivity analysis could be performed to determine what lowered speed would most affect the output.

The scenario in which a traffic breakdown occurs for one hour generated a greater number of vehicles leaving than the scenario with vehicles traveling at overall lowered speeds. The change was seen as significant as seen by a p-value of 0.000. The output is shown below in Figure 4-17.

Paired T-Test and CI: Breakdown, Phone

```
Paired T for Breakdown - Phone

             N     Mean  StDev  SE Mean
Breakdown    5  18765.4    3.4      1.5
Phone        5  16806.4    3.0      1.4
Difference   5  1959.00   4.74     2.12


95% CI for mean difference: (1953.11, 1964.89)
T-Test of mean difference = 0 (vs not = 0): T-Value = 923.48  P-Value = 0.000
```

Figure 4-17 Paired T-Test Results for Cell Phone Usage vs Vehicle Breakdown Scenario (Output from MiniTab)

Cell phone usage versus parents using alternative routing to pick up their children from campus childcare centers is also significant with a low p-value of 0.000. The output is shown below in Figure 4-18.

Paired T-Test and CI: Kids, Phone

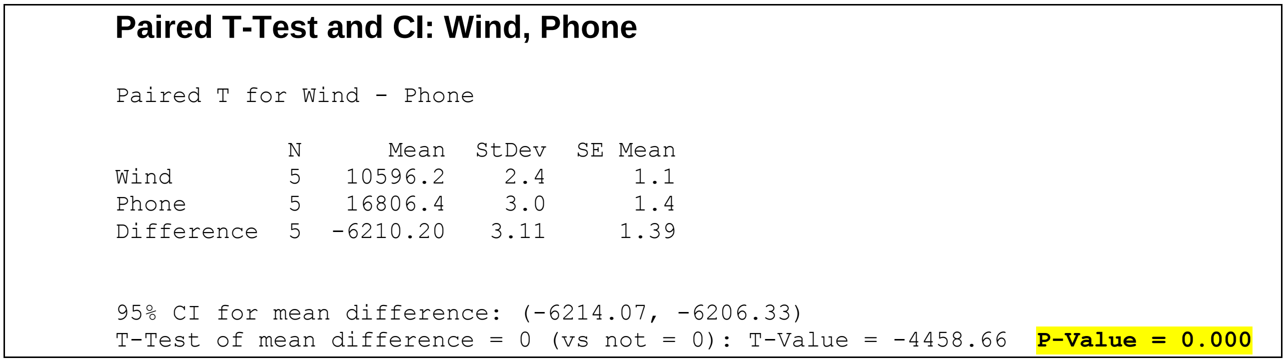
```
Paired T for Kids - Phone

             N     Mean  StDev  SE Mean
Kids         5  19107.8    2.7      1.2
Phone        5  16806.4    3.0      1.4
Difference   5  2301.40   4.34     1.94


95% CI for mean difference: (2296.02, 2306.78)
T-Test of mean difference = 0 (vs not = 0): T-Value = 1186.86  P-Value = 0.000
```

Figure 4-18 Paired T-Test Results for Cell Phone Usage vs Parents Picking up Children (Output from MiniTab)

Finally, testing the effect of a model with reduced speed due to cell phone usage versus having to block off a road and re-route traffic due to a potentially hazardous plume traveling north is significant according to its low p-value of 0.000. The output is shown below in Figure 4-19.



Paired T-Test and CI: Wind, Phone

```
Paired T for Wind - Phone

             N      Mean  StDev  SE Mean
Wind         5   10596.2    2.4      1.1
Phone        5   16806.4    3.0      1.4
Difference   5  -6210.20   3.11     1.39


95% CI for mean difference: (-6214.07, -6206.33)
T-Test of mean difference = 0 (vs not = 0): T-Value = -4458.66  P-Value = 0.000
```

Figure 4-19 Paired T-Test Results for Road Block due to Plume vs Cell Phone Usage (Output from MiniTab)

A summary of tests and p-values is shown below in Table 4-2. It should be noted that all of the p-values are significant, and all are 0. This is both because of the fact that a different number of vehicles entered some of the models, and that with each change, a different number of vehicles arrived at the safe zones within one hour. The significant p-values are highlighted.

Table 4-2 T-test summary for all scenarios

Scenario	Base Case	42% Outside Traffic	50% Increase in Outside Traffic	Vehicle Breakdown	Picking up Kids	Lower Speeds due to Cell Phone Usage	Effect of Plume and Wind
Base Case	X	0	0	0	0	--	0
42% Outside Traffic	0	X	0	0	0	0	0
50% Increase in Outside Traffic	0	0	X	0	0	0	0
Vehicle Breakdown	0	0	0	X	0	0	0
Picking up Kids	0	0	0	0	X	0	0
Lower Speeds due to Cell Phone Usage	--	0	0	0	0	X	0
Effect of Plume and Wind	0	0	0	0	0	0	X

4.2.3 Network Effectiveness

After running each simulation, the networks that facilitate the most traffic flow and highest percentages of vehicles arriving at safe zones can be determined. A summary of the results is shown below in Table 4-3.

Table 4-3 Highest percentage output by scenario not evacuating within 1 hour

Scenario	Network with Highest % Out (1 hour)	Network Destination
42% Outside Traffic	3 (91.71%), 5 (99.29%)	Highway 406, Highway 24
50% Increase in Outside Traffic	3 (98.63%), 5 (99.23%)	Highway 406, Highway 24
Vehicle Breakdown	3 (91.81%), 5 (99.28%)	Highway 406, Highway 24
Picking up Kids	3 (92.09%), 5 (99.10%)	Highway 406, Highway 24
Effect of Plume and Wind	5 (96.58%)	Highway 24

As seen above in the table, similar results were obtained for each of the scenarios. All scenarios saw very high percentages of output in networks 3 and 5, with the exception of the road blockage situation, which had a lower, but still best, percentage of output on network 5. Vehicles assigned to network 3 drive to Seth Child Road and go north to Tuttle Creek Boulevard, which eventually turns in to Highway 406. Vehicles assigned to network 5 travel east on Bluemont Avenue to Tuttle Creek Boulevard, and then travel south before turning back east on Highway 24. The best performance of these two networks is not attributed to a low number of vehicles, as network 5 has the second highest number of vehicles following it at 5,673 vehicles, and network 3 is close behind at 4,223 vehicles. Rather, it is attributed to the fact that the vehicles traveling on these networks originate in locations closer to the roads with increased speeds. Therefore, a larger percentage of their total traveling distance is on roads with higher speed limits.

Emergency planners should consider this information when determining which roads to direct a higher number of vehicles to. A sensitivity analysis could be performed to determine if there is a threshold value of vehicles on a particular network that depletes performance after a certain number of vehicles use the roads in the network.

4.2.4 Evacuation Time

Evacuation began immediately with a queue to leave a parking area for all vehicles. In each scenario, vehicles began arriving at each safe zone at different times. Table 4-4, below, summarizes each situation, along with how long it took for the first vehicle to reach a safe zone, and where the vehicle originated.

Table 4-4 Approximate time of first vehicles leaving system

Scenario	Approximate Time First Vehicle Leaves System	Vehicle Origination
Base Case	20 minutes	Claflin Road (mid campus), Natatorium Parking
42% Outside Traffic	20 minutes	Claflin Road (mid campus)
50% Increase in Outside Traffic	13 minutes	McCall Road
Vehicle Breakdown	15 minutes	McCall Road, Bluemont & Tuttle Creek Boulevard
Picking up Kids	20 minutes	Claflin Road (mid campus)
Lower Speeds due to Cell Phone Usage	24 minutes	Claflin Road (mid campus), Natatorium Parking
Effect of Plume and Wind	14 minutes	McCall Road

The varied times of evacuation can be explained due to the fact that each vehicle's originating location is a different proximity from the safe zone destination. Those vehicles that begin closer to the destination are likely to arrive more quickly than those that are farther away.

The majority of scenarios resulted in approximately 90% of the total volume of traffic reaching safe zones by the first hour of the simulation. However, some situations allowed the system to empty of vehicles more quickly than others. A snapshot of approximate times for evacuating 25%, 50%, 75%, and 100% of the vehicles for each scenario is shown below in Table 4-5.

Table 4-5 Approximate time of evacuation

Scenario	Approximate Time at 25% Output	Approximate Time at 50% Output	Approximate Time at 75% Output	Approximate Time at 100% Output
Base Case	.3 hours	.5 hours	.7 hours	1 hour
42% Outside Traffic	.5 hours	1 hour	1.25 hours	2 hours
50% Increase in Outside Traffic	.75 hours	1 hour	1.33 hours	2 hours
Vehicle Breakdown	.75 hours	1 hour	1.33 hours	3 hours
Picking up Kids	.75 hours	1 hour	1.33 hours	3 hours
Lower Speeds due to Cell Phone Usage	.35 hours	.6 hours	.75 hours	1 hour
Effect of Plume and Wind	.75 hours	1 hours	1.5 hours	2 hours

In the table, above, one will notice that overall, the evacuation times are quite similar. Depending on the road capacity and volume of traffic, the result could change. Emergency planners will need to consider this when determining which roads to close. In some cases, the detrimental effect of having traffic move through a hazardous area will trump a lengthy evacuation, but if main roads can be used, they will likely greatly reduce travel time.

It should be noted that while the overall time for every vehicle to reach a safe zone varies by scenario, in certain circumstances, the time for a certain network to evacuate was higher compared to other networks, specifically in the case of redirecting to pick up children. Those who went to pick up their children were in the system for an average of 1 hour longer than those who immediately began evacuating. This comes as no surprise since parents had to first arrive at the facility and then join in the evacuation traffic.

CHAPTER 5 - Conclusions and Validation

Although discrete simulation is a powerful tool, Rockwell ARENA software is not a very robust system for simulating traffic scenarios. Simulation is useful in situations that would otherwise require a significant amount of resources to physically achieve similar results. It is also a tool that can be used to track the sensitivity of changes to a model and how they affect output. However, there are other software packages made specifically for simulating traffic flow that would lead to more reliable conclusions. While the likelihood of physically carrying out an emergency evacuation, it is important to understand the limitations of a system in the event that an evacuation would need to take place.

According to the simulation created based on the assumptions outlined in section 3.1, the network of roads in Manhattan and the surrounding area are sufficient based on the traffic flow generated by vehicles parked at Kansas State University, along with 42% of normal traffic flow based on 24 hour averages, which were scaled to one hour averages, and increasing the normal flow by 50%. However, in the instance of a main road being closed to through traffic, the capacity of the remaining active roads becomes almost meaningless, as flooding a road with a large number of excess vehicles will greatly increase the time it takes for all vehicles to reach a safe zone. In this case, the traffic and disaster planners will need to analyze how to handle a situation in which a plume or other hazard prevents through traffic from traveling in the direction of the hazard.

The roads generating the highest percentage output included Seth Child Road to Highway 406 and Tuttle Creek Boulevard to Highway 24. Once again, it is important to realize which roads to exploit the use of in order to maximize the number of vehicles reaching a safe zone during an emergency evacuation. It is up to traffic planners to be aware of such roads.

5.1 Improvements

The models described in this report simulate situations that might be considered for the first steps in an emergency planning program. Improvements to the simulations modeled could be made due to the fact that assumptions had to be made. Many inputs regarding traffic behaviors were assumed, and may be true in some cases, but in others, may not accurately portray the behavior of a large amount of vehicles. Also, it should be noted that the simulation in this report is based on a directed simulation in which roads are cordoned off, and traffic is directed. Therefore, most roads in Manhattan are not used as outlets for traffic. In the event of an actual evacuation, it is likely that traffic will not be directed, especially if humans are in danger of coming into contact with a harmful substance.

Model Inputs and Variable Values

Checking and improving upon the integrity of values in the model will increase the model's validity and will make it a more useful tool for making decisions regarding emergency evacuation planning. While statistics were available in some situations, it is difficult to use simulation as a tool for modeling human decisions. Also, many of the statistics available had to be scaled to a specific time period, which may create causes of variation in the output.

Until better and more extensive data, specifically regarding vehicle behavior during emergency evacuations, the contribution of this model will be low.

General Model

The precision and accuracy of the model can be improved by including all vehicles in the area and all roads. The higher the road capacity available, the faster the vehicles can exit the system. However, they are constrained based on the capacity of the roads leading to the safe zones. Adding more vehicles, roads, and routes will add to the complexity of the model, but will result in more accurate results.

Another method of checking the validity of the model could be to use a software package specifically designed to model the flow of traffic, such as those described in section 2.1.3.

Decision Rules

For the purpose of this project, 5 replications of the simulation were carried out. Due to the large amount of memory used to carry out a replication, the run time was very high. This was one of the deciding factors of running the simulation for only 5 replications. Because the purpose of the simulation was to demonstrate the ability to use simulation as a tool for both modeling and comparing different traffic flow models, an increased number of replications were unnecessary. However, for models with an increased amount of input data, more replications would be helpful for making decisions based on output.

5.2 Model Validation

While the results given through simulating each scenario give an acceptable baseline for evacuation times and percentages, they should be compared with another simulation to determine whether the results are valid.

The simulation done by Jha, Moore, and Pashaie [2004], for evacuating Los Alamos National Laboratory is a very similar case. The laboratory houses approximately 15,000 employees and 9,400 vehicles.

After simulating the different scenarios described in section 2.1.2, they found that each vehicle for all scenarios could be evacuated within 3 hours' time or less. These results are comparable to the conclusions made following the simulations carried out for this study. Therefore, this model may be considered valid.

5.3 Areas for Future Research

In order to continue this study, the models developed for this report should be validated. This could be done using one of the software programs discussed in section 2.1.3. These software packages were created specifically for simulating the flow of traffic, so would be ideal for validating the models.

In the event that the total time to evacuate all vehicles is undesirable, further scenarios can be studied. Reversing the remaining lanes of traffic on road segments so that all traffic is headed in one direction would likely reduce the amount of time an evacuation will take. In order to accomplish this in ARENA, the size of the zone would be altered to create extra capacity for more vehicles.

Further research should also be conducted to collect data on traffic signaling within the study area. The simulation can then take into account further delays due to waiting time for traffic signaling. Because time is a critical aspect of an emergency evacuation, in the event that the evacuation would not be facilitated by law enforcement, the time lost due to waiting at stop signs or lights should be determined. The simulation could also be expanded to include all vehicles in the area rather than just 42% of those outside of the critical area. Another traffic rule that could be used to enhance the results is to allow vehicles to change lanes in the event of traffic jams or disruptions. This may more accurately portray different driving aggression levels of drivers, and would affect the resulting evacuation time for specific agents in the system.

In addition, more research could be done regarding the presence of wind being a factor affecting the direction of evacuation and the spread of a pathogen. Furthermore, because the research at NBAF focuses on zoonotic diseases, an evacuation and quarantine plan could be developed to ensure that if an animal were to be infected with a communicable disease, other livestock could be moved to a safe location to avoid contracting the same disease.

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Appendix

Table A-1 Total number of vehicles in each scenario and hourly output

Scenario	# Entered	Hour 1	Hour 2	Hour 3
Base Case	10,593	10,593	-	-
42% Outside Traffic	24,219	19,396	24,219	-
50% Increase in Outside Traffic	30,654	24,222	30,654	-
Vehicle Breakdown	24,219	18,767	24,216	24,219
Picking up Kids	24,247	19,104	24,236	24,247
Lower Speeds due to Cell Phone Usage	10,593	10,593	-	-
Effect of Plume and Wind	24,219	16,802	24,219	-

Table A-2 Parking lot and starting point capacities (includes starting positions of outside traffic)

Network	Parking Lot	Capacity
Network 1	**Natatorium**	958
	Alumni Center West	40
	Alumni Center East	19
	Parking Garage	1388
	Seaton Hall Center	52
	Anderson Sunset Normal Flow	651
	Anderson 17th Normal Flow	2133
Network 2	**Lafene Health Center**	105
	Recreation Complex North	557
	Kimball College Normal Flow	1954
Network 3	**Goodnow Hall South**	190
	Marlatt Hall North	119
	Marlatt Hall South	211
	Goodnow Hall North	22
	Engineering	454
	Durland Hall South	33
	Bushnell Hall	590
	Dykstra Hall	56
	Umberger Hall	249
	Shellenberger Hall	40
	Hale Library	104
Network 3	**Ahearn Fieldhouse**	52

	Claflin Seth Child Normal Flow	590
	Claflin College Normal Flow	755
	Anderson Seth Child Normal Flow	758
Network 4	**Jardine**	1005
	Recreation Complex East	141
	Veterinary Medicine West	266
	Davenport Building (Facilities)	46
	Ford/West Hall South	226
	Dorm North	664
	Dorm Upper North	1345
	Haymaker Hall	55
	Dole/Call Hall	144
	Call Hall North	115
	Veterinary Medicine East	388
	Putnam Complex	137
	Kimball Denison Normal Flow	750
	Kimball Tuttle Creek Normal Flow	739
Network 5	**BMA East**	95
	BMA	35
	All Faiths Chapel/McCain Loop	26
	Anderson/Fairchild Hall	49
	Justin Hall	227
	Holton Hall	11
	President's House/Vattier	379
	Bluemont Tuttle Creek Normal Flow	701
	N. Manhattan Bluemont Normal Flow	2430
	Tuttle Creek McCall Normal Flow	1060
	North Manhattan Normal Flow	660
Network 6	**Poyntz Normal Flow**	445

Table A-3 Main routing for each network

Network	Main Roads Traveled
1	Denison Avenue, Anderson Avenue (west), Keats Park
2	Claflin Road, Seth Child Road (south), Ft. Riley Boulevard, Highway 18
3	Claflin Road, Seth Child Road (north), Tuttle Creek Boulevard, Highway 406
4	Denison Avenue, Marlatt Road, Tuttle Creek Boulevard (north), Carnahan Road, McIntyre Road
5	Bluemont Avenue, Tuttle Creek Boulevard (south), Highway 24
6	South Juliette Road, Fort Riley Boulevard (east), Highway 177, I-70