Operational Impact of Shadow Evacuation on Regional Road Networks During Short-Notice Emergency Evacuations

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OPERATIONAL IMPACT OF SHADOW EVACUATION ON REGIONAL ROAD NETWORKS DURING SHORT-NOTICE EMERGENCY EVACUATIONS

A Thesis

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Science

in

The Department of Civil & Environmental Engineering

by
Efe Emre Tuncer
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Abstract

As part of evacuation planning, development of effective tactical and operational strategies are essential to safely and efficiently mobilize the public away from the threat. Evacuations are classified by the time between notification and the anticipated arrival of the threat which can be categorized as short, or no-notice emergencies. Emergencies involve the computation of the time required to evacuate the area of risk, which is the time to clear a radius of up to about 10-miles around the nuclear power plant, known as the emergency planning zone (EPZ). These evacuation time estimates (ETE) also account for the evacuation of the public outside the defined area of risk. Typically, this area extends five miles outside the EPZ boundary and it is commonly referred to as the shadow evacuation region. Although shadow evacuation could create significant traffic congestion that affects the EPZ clearance process, there is limited research quantifying this effect. The objective of this research was to study the impacts of shadow evacuation to the overall EPZ clearance process. To accomplish this, the research used microscopic traffic simulation to assess the effect of different shadow participation rates for three hypothetical nuclear power plants with distinct population sizes surrounding the plant (small, medium, and large) and roadway characteristics. The guidance in NUREG/CR-7002 for ETE studies recommends a 20 percent participation rate that was based on previous studies, research related to ETE demographics, public response, and other contributing factors. However, the 20 percent recommendation may be conservative. The results suggested that small population sites are not impacted significantly by varying the shadow participation rates. However, medium and large population sites showed a noticeable effect, particularly in those corridors with less capacity. If the shadow evacuation participation rate is increased to 40 percent, the ETE to evacuate 90 percent of the population is increased by up to 10 percent in medium-sized areas, and up to 19 percent in large areas. Under the same conditions, the ETE to evacuate 100 percent of the population increases by less than 5 percent for medium-sized areas and less than 3 percent for large areas.
1 Introduction

Historically, evacuations have been classified based on spatial and temporal relationships. The term "large scale" and "small scale" refer to the number of individuals being evacuated or the geometric size of the area under threat. Temporally, evacuations are classified by the time between notification and the anticipated arrival of the threat. When planning for an evacuation, it is advantageous to have some method of estimating how many people must be evacuated [84]. Where the timing and the magnitude of certain types of disasters may require faster reactions, unlike hurricane evacuations where there is ample time available to conduct the evacuation. Large-scale short-notice emergency evacuations (e.g. nuclear power plant, terrorist attacks and etc.) have a low probability of occurrence. Because of this and the small number of previous events, means that it is difficult to confidently forecast travel demand conditions during a short-notice evacuation. Unlike advance notice evacuations where evacuation orders can be issued prior to a threat, the response to short-notice events must rely on pre-planning. The development of efficient evacuation plans is essential to minimize the negative consequences associated with any type of emergency evacuation. Evacuation planning is one of the most practical and crucial components during emergencies and emergency preparedness and response [82][83].

With past emergency management and evacuation operations, transportation professionals have looked towards evacuation planning and modeling [81]. To address the evacuation planning problem, studies done earlier have turned to conventional transportation planning methods, for example, the four-step process. The conventional methods were designed for day-to-day travel, under standard situations, under which origin and destinations are easy to establish and it stays unchanged overtime, which is very unlikely in emergency situations. Emergency evacuations require rapid mobilizing and transportation of a large population from harm while facing a lot of uncertainty, for example, unknown road conditions (e.g. congestion and road blockages) that is associated with emergencies. Because of this, evacuation destinations are difficult to determine and are subject to change over time due to road conditions. To develop an effective plan for emergency evacuations, the range of unpredictable road and traffic conditions are essential to take into consideration to address the dynamic nature of the evacuation process. It is important for emergency plans to include all evacuation elements or the plans can create problems within itself, and to avoid such problems, emergency evacuation plans are regulated by the State or independent agencies set by Congress.

The U.S Nuclear Regulatory Commission (NRC) was created as an independent agency by Congress in 1974 to ensure the safe use of radioactive materials. The NRC regulates commercial nuclear power plants and other use of nuclear material and enforces its requirements. Section IV of Appendix E to 10 CFR Part 50 requires nuclear power reactor licensees to develop evacuation time estimate (ETE) analyses using United States Census Bureau decennial data [1]. Licensees are required to submit the ETE analysis to the Nuclear Regulatory Commission (NRC) before using it to form protective action recommendations (PARs) and before providing it to State and local governmental authorities for use in developing offsite protective action strategies.
Current U.S. nuclear regulatory commission regulation NUREG/CR-7002 [4] provides the technical basis for “Criteria for Development of Evacuation Time Estimates” which is essential for all nuclear power plant evacuations. Current and previous guidance updates were based on research related to demographics, public response, and other contributing factors. This research includes the entire process of developing traffic simulation models, populating the models and the analysis of key assumptions that have potential to create congestion and delay.

Figure 1.1 is an illustration of a generic emergency planning zone (EPZ). The figure was created as a general representation to illustrate key EPZ elements, including emergency response planning areas (ERPAs), and is not representative of an actual NPP site. As indicated in the figure, ERPAs are bounded by geographical or political boundaries and do not necessarily end at a 10-mile radius from an NPP. The ETE is a calculation of the time to evacuate the plume exposure pathway of the EPZ [1]. Five miles beyond the EPZ is the area commonly referred to as
“shadow area” or the voluntary evacuation outside the declared evacuation area. A shadow evacuation occurs when residents evacuate from areas beyond the officially designated evacuation area [4] [6] [11]. Current NRC regulatory guidance requires all ETE studies to include a 20 percent shadow evacuation response rate, which will be used as a basis for this study. However, it has been theorized that actual responses could vary significantly from the current assumed set of conditions in future emergencies and, as such, there is a need to gauge potential impacts under varying rates of response. Thus, the focus of this research will be to examine the congestive conditions of incrementally increasing rates of shadow participation and their potential, if any, to increase the EPZ clearance time.

1.1 Objectives

The overall research objectives were to develop insight, observations, and conclusions sufficient to quantify potential impacts of shadow evacuation on the evacuation of NPP EPZs. This includes determining the sensitivity of the shadow evacuation to EPZ clearance times. The insights, observations, and conclusions were identified through the development of traffic simulation models, acquisition of data for the models and analysis of results varying the shadow participation rates.

1.2 Scope

The overall research scope is to conduct an in-depth study of the impact and shadow evacuation to understand and quantify potential impacts to the ETE for NPPs. This research used the current NRC guidance that recommends a 20 percent shadow evacuation participation rate, roughly 10-mile EPZ, and 5-mile shadow population region. In order to completely understand the impact of shadow evacuation, three different microscopic simulations models were developed that had different population and road characteristics. The impact of shadow evacuation to the population that is under mandatory evacuation was simulated by varying the shadow population participation rates.

1.3 Background

A shadow evacuation occurs when residents evacuate from areas beyond the officially designated evacuation area [4] [6] [11]. Shadow evacuees tend to mobilize and evacuate after they monitor the progression of the emergency, and when they observe evacuees traveling through the area. There are no sirens within the shadow area, thus awareness propagates by way of news broadcasts, social interaction, and social media. Based on the perceived threat, residents make individual decisions of whether or not to evacuate. Typically, when residents decide to evacuate, they need to have received and understood the warning before they take action [31] [52].

Shadow evacuation was originally defined by Zeigler et al., in 1981, as the tendency of an official evacuation advisory to cause departure from a much larger area than intended [11]. The authors of that article observed this phenomenon in response to the accident at Three Mile Island (TMI). Shadow evacuations have since been observed in many large-scale evacuations but have
generally not affected the efficiency of these evacuations [6]. However, under certain conditions, such as a large number of shadow evacuees in areas with limited roadway capacity, the shadow has the potential to impact evacuees from a declared evacuation area. Limited roadway capacity does not necessarily suggest fewer streets, it could be caused by EPZ evacuee vehicles traveling through the area using the available capacity. Such an impact could put evacuees from the declared evacuation area at a greater risk. Therefore, the objectives of this task included determining the size of the shadow that would be necessary to increase evacuation times significantly.

At the time of the TMI accident, minimal emergency planning existed around NPPs, and coordination among OROs and decision makers was not well defined. Since TMI, the NRC and FEMA have developed detailed and extensive emergency planning regulations and guidelines, which have now been in place and implemented by licensees for more than 35 years [1] [5]. The regulations and guidance have resulted in robust emergency planning and infrastructure for NPPs. The emergency preparedness regimen includes detailed onsite and offsite communication protocols, siren systems with secondary and backup alert systems, prepared EAS messages, and many more response elements regulated under 10 CFR 50 [1]. Guidance on implementation of these regulations is provided in NUREG-0654/FEMA-REP-1, Rev. 1, the FEMA Program Manual for Radiological Emergency Preparedness [5] [53], and other documents. The NPP offsite emergency response plans are demonstrated by licensees biennially in full-scale exercises, which are documented in FEMA After Action Reports.

Federal regulation requires that provisions exist for prompt communications to emergency personnel and the public [1]. Supplement 3 to NUREG-0654/FEMA-REP-1, Rev. 1 identifies that an informed population contributes to reducing evacuation times by potentially reducing the size of the shadow evacuation [54]. Hurricane research identified that a low percentage of shadow evacuees in response to Hurricane Ike was attributed to effective evacuation warnings from authorities [44]. Additionally, NRC has conducted research regarding the understanding and response expectations of the general public residing within the EPZ and found that the public largely understands what to do in an NPP emergency [8]. Through this research, and the study of evacuations [6] [7] a shadow evacuation estimate of 20 percent of residents in the 5-mile area beyond the EPZ was identified for use in the ETE analysis [4]. This same shadow evacuation estimate is also provided in NUREG/CR-7002 guidance. The guidance identifies that there would be a decreasing participation rate for the shadow with people nearer the hazard area more likely to shadow evacuate than people farther from the hazard area [4]. In March 2013, the Government Accountability Office (GAO) recommended the NRC consider the effect of different shadow evacuation rates [55].

Previous research has found that shadow evacuations do not typically impact the efficiency of evacuation from the hazard area [6]. Furthermore, if a shadow evacuation occurs, and the original evacuation area ultimately needs to be expanded, a percentage of people from the expanded area will have already left as shadow evacuees. During emergency response planning, the potential impact to evacuees from the declared evacuation area can be estimated by including the shadow evacuation contribution in the ETE analysis. The parametric analysis conducted
herein provided observations and insights on potential impacts on the ETE for the small, medium, and large population EPZs. Chapter two will focus on primarily the past literature that studied different variables that effect evacuation clearance time.
2 Literature Review

2.1 Effect of Shadow Evacuation

Defined by Zeigler et al., in 1981, a shadow evacuation is the tendency of an evacuation advisory to cause departure from a much larger area than intended [11]. The first shadow evacuations were observed in the response to the Three Mile Island (TMI) accident [11] and shadow evacuations have been observed, researched, and documented for many large-scale evacuations ever since [6][59][31][74]. Some research attempted to quantify the shadow [74], but accuracy in quantifying shadow has been proven to be difficult because people in these areas evacuate at their own risk and are not monitored by emergency responders. Thus, there is limited knowledge available and data must be developed at some time after the incident.

The over response to evacuation orders for Hurricane Rita in 2005 has often been described as a large shadow evacuation that caused massive congestion and gridlock that many residents chose to return home rather than continue their evacuation. The overresponse to an evacuation is described as a shadow evacuation from many studies, where location that does not have a mandatory order also decide to evacuate causing unwanted congestion on roads. However, the evacuation orders for Hurricane Rita were thought to be the cause, combined with the devastation from Hurricane Katrina just weeks before. This was not an issue of people evacuating because they were near a hazard and believed they were at risk, these residents evacuated because they believed they were within the hazard area, as described by the House Research Organization (HRO) [60]. Many residents believed they had been ordered to evacuate. The biggest failure of Hurricane Rita evacuation was the inadequate communication with the public [60], which makes quantifying the shadow for this hazard virtually impossible. Hurricane Ike was the next major hurricane following Hurricane Rita, and the improved offsite response messaging was attributed to decreasing the shadow evacuation [44].

Emergency response personnel often explain that shadow evacuees are observed, but attempts are not made to quantify the shadow response because the majority of the efforts are focused on residents in the declared evacuation zone. The effort for quantifying the shadow has been made by researchers, but the results are difficult to interpret because published reports do not always adhere to the specific criteria of the shadow definition [15][56][57]. Although the shadow evacuation was defined quite explicitly from the beginning [11], Zeigler and Johnson [58] interchanged spontaneous evacuation and shadow evacuation terms, and this may have contributed to misuse of the term.

Shadow evacuations can be considered to be spontaneous because residents leave without having been ordered to do so. The definition of spontaneous evacuation is more appropriately applied to residents who leave before the official evacuation advisory is issued, such as those who observe or receive direct information on the hazard and respond prior to any issuance of a protective protocol. Thus, it has a temporal component that the generally accepted definition of shadow evacuation does not.
In post-evacuation research of the 2005 Graniteville train accident, where a Norfolk Southern Railway freight train traveling from Macon, Georgia, toward Columbia, South Carolina carrying 90 tons of chlorine missed a switch and crashed into a parked locomotive. This incident had a declared evacuation area of one-mile radius and Mitchell, et al., [56] determined that 59 percent of the residents from outside the one-mile radius had also evacuated as shadow. However, the study also noted that more than half of these residents were specifically instructed to evacuate, mostly from Reverse 911 or fire/police officials knocking on their doors. Anyone that was directed to evacuate should not have been included in the shadow contribution because this was not due to the tendency of the advisory to cause evacuation.

Weinisch and Bruekner, [62] reviewed 48 ETE studies to determine the impact of shadow evacuation using macroscopic simulation model, DYNEV. Each of the ETE studies reviewed that included a sensitivity analysis that increased the level of shadow participation from 20 percent to 60 percent of the public residing in the 5-mile area beyond the EPZ. Of the 48 ETEs reviewed, only 7 showed an increase of 30 minutes or more for the 100 percent ETE and more than 70 percent of the sites showed little to no change in the ETE [62]. Where the 100 percent ETE is usually used to determine the time it takes for 100 percent of the population to leave and the 90 percent ETE is usually used for protective action planning for NPPs.

The research presented in this paper uses representative ETE sites compared to specific ETE sites and it uses a microscopic simulation that has a higher level-of-detail compared to macroscopic simulations. Also, never discussed the reasons why the shadow participation had an effect on certain sites and not the others. The research that was conducted in this study will go into more detail on the reasons why the participation of the shadow population changes within different site characteristics.

### 2.2 Other Impacts

A study done by Dotson and Jones reviewed 50 previous evacuation cases and only found four traffic incidents that occurred in these events [76]. Out of those four incidents, three of them were caused by vehicles running out of gasoline. The fourth incident was related to roadways being blocked by heavy fire smoke, downed power lines, and abandoned vehicles. The severity of this incident was not reported but the victims lost their lives in the wildfire.

Although the frequency of traffic incidents during evacuations events are roughly eight percent (4 out of 50), Dotson and Jones revealed a statistically significant link between the occurrence of crashes and the degradation of evacuation performance. Chi-squared testing indicated that traffic incidents have a strong relation to evacuation efficiency. When ranking what causes the most issues during an evacuation, traffic incidents came in third, behind information dissemination and roadway availability. Dotson and Jones found that informed citizens will evacuate more efficiently, availability of major roadways is vital and that traffic incidents can impede the evacuation process.

Since traffic incidents reduce the capacity of roads, which reduces the availability of roads, the following section focuses on traffic incidents that occur on transportation infrastructure. When
ranking the most issues during an evacuation, it should have been further studied on why these roads were not available. This might cause traffic incidents to show a much larger impact during the evacuation process.

A study by Bahaaldin et al. [79] examined the effect of traffic incidents during a no-notice emergency evacuation in the eastern St. Louis metropolitan area road network using VISSIM, a micro-simulation software. This analysis was done by using incident locations based on historical data. Because traffic speeds are expected to be low during high volume evacuation scenarios, the authors only examined minor traffic incidents. Data collection was done using few sources. To build the simulation road network, aerial images of the area were obtained from the Geography Department at Southern Illinois University Edwardsville and from the East-West Gateway Council of Government the traffic volumes and Origin/Destinations Matrices for trip generations was obtained.

Average delay time was used as a key measure of effectiveness for evaluations. Three different traffic incidents locations were used to compare the results to the base scenario which had no incidents. The first two scenarios had very similar delays compared to the base scenario, where one was located on a bridge and other at a section of an Interstate. These two locations were located upstream of bottleneck locations. The third location was also located at a section of an Interstate but it had a significant effect on delay. This location was located just over one mile downstream of a bottleneck. This study found that incident location upstream of key bottlenecks do not significantly change traffic delay during a no-notice evacuation. On the contrary, incidents downstream of bottlenecks can significantly increase the evacuation duration [79].

Using historical data to predict incident locations can be considered as a limitation of this study. A traffic incident rarely happens in the same location, let alone have the same severity and traffic flow conditions. To have a better understanding of the effect of traffic incidents during evacuations, the next study built a module to predict where a traffic incident might happen.

The task of this study was to design a decision support system for contraflow evacuation planning for the 140-mile segment in Alabama I-65 [78]. This study consisted of three main modules: the demand module, the network optimization module and the focus of this literature review, the incident and characterization module.

Fonseca et al. designed an incident generator and characterization module that could be used with a traffic simulation tool. When triggered, the module temporarily reduced the flow capacities of road segments in the vicinity. The module iterated every 60 minutes of simulated time executing the stochastic generation of incidents and characterizing them based on their duration and impact on the overall capacity of the evacuation network. The module was designed and implemented based on traffic data, algorithmic procedures, heuristics from Alabama Department of Transportation’s evacuation logs of past hurricane events, Alabama Critical Analysis Reporting Environment (CARE) accident database, the Highway Capacity Manual and related works from other researchers. This work investigated and assessed the impact of traffic incidents on the overall evacuation travel time of vehicles exiting the affected area. The module was implemented in two different evacuation scenarios. In the first scenario, a low demand for
evacuation was assumed and the other when a high flux of departing traffic was present. This study suggests that incidents are more a safety factor than flow-disturbing events. The study showed that total travel time increased by 0.13 percent for low demand and 0.09 percent for high demand situations compared to no incident scenario [4]. Other studies have found that traffic incidents were predicted to increase evacuation duration by 7.2 to 8 percent [77].

Robinson et al. studied the impact of traffic incidents in Hampton Roads, VA during emergency evacuations. The research involved simulation of evacuation traffic over a 70-hour period and averaged almost 200 vehicular accidents and 1,400 incidents. The simulated scenarios were extracted from traffic databases and the incident locations, severities and durations were randomly selected from available traffic data that match historical values. The authors found that if catastrophic events occur completely closing the main interstate exit in Hampton Roads, the total time for the evacuation is extended by around 10 percent [80].
3 Approach

This research methodology utilized microscopic traffic simulation to quantify the impacts of shadow evacuation on three representative NPP sites. Broadly, the research methodology was carried out in four general tasks. The first task was site selection, the second task was model development, the third task was scenario selection and the final task was data extraction and analysis.

The general approach for this study was to implement the guidance provided in NUREG/CR-7002 [4] in development of three representative ETE models. Modeling the effects of the shadow evacuation, necessitated developing the model networks to distances beyond the EPZ boundary. The three traffic simulation models were built to a distance of 20 miles from the NPP to accommodate all of the calculations needed to complete the research objectives.

To build the traffic simulation models of each of the representative sites a number of individual tasks were necessary. These included the coding of key assumptions associated with both the behavioral responses of the evacuees as well as relevant aspects of the transportation network. Together, these as well and other steps (described later in this report), formed the basis of each model and, more critically, the bases upon which to vary specific parameters of interest to study the effects of shadow participation. The general process of model development used for each model included completion of each of the following activities:

- Establish representative sites and EPZ characteristics;
- Select a scenario for modeling;
- Obtain data for use in the models;
- Identify MOEs appropriate for the analyses;
- Develop and run base models;
- Conduct parametric analysis; and,
- Analyze results.

As a part of this effort, many existing ETE studies were reviewed and used to support some of the developed parameters. Additionally, the current guidance was studied to understand the approach and criteria for current ETE studies. This was necessary not only to support the development of the base model but also to evaluate the inputs and outputs that are typically provided in an ETE study.

3.1 Representative Sites and EPZ Characteristics

With more than 60 NPP sites located throughout the United States, conducting analyses that would be applicable across the fleet necessitated a generalized approach. ETE studies were obtained from the NRC ADAMS website and reviewed to identify common characteristics that would facilitate grouping of small, medium, and large population sites. The review identified that demographics and infrastructure within EPZs are as diverse as the regions of the country in which they are located. Plume exposure pathway EPZ boundaries are typically demarcated by
geographic or political boundaries to support emergency response and seldom conform to a precise 10-mile radius from the NPP.

A primary EPZ characteristic used in creating the representative sites was population. This included the population of the shadow evacuation areas. However, population alone does not assure representativeness. For example, EPZs that are coastal, whether on a great lake or an ocean, often have only half of the land area of a non-coastal EPZ. A coastal EPZ may quantitatively have a small or medium population, but the infrastructure may be more reflective of a medium or large population site. Similar condensed demographic distributions were observed in non-coastal EPZs, where large portions of the EPZ areas were encumbered by national, state, or local parks or large lakes and rivers. In the application of this research, small, medium, and large population sites were defined as an EPZ population of 0 – 50,000; 50,000 – 200,000; and > 200,000, respectively. For most of the analyses conducted herein, the use of representative sites presented a reasonable approach. However, site-specific conditions often contribute to important elements in ETEs. Thus, although grouping EPZs into three site categories was appropriate for this study, there are elements that may not be directly applicable to all sites.

Review of ETE studies identified that the transportation infrastructure within EPZs was generally proportional to the population. High population EPZs generally have more freeway miles within the EPZ than small population EPZs. However, the relationship was not consistent enough to provide hard criteria. Some high population density sites have no access to a freeway within the EPZ, while some small population sites have access to multiple freeways within the EPZ. EPZ geographic representation also varies among NPPs, with some EPZ boundaries extending 5 miles or more beyond the 10-mile radius. EPZs with little or no population in some sectors sometimes end the EPZ boundary at distances less than 10 miles from the NPP.

One of the more important characteristics of an ETE is the response of the public. Research has shown that once alerted, the public generally mobilizes and evacuates following the characteristic S-shaped evacuation response curve illustrated in Figure 3.2 [14] [15] [16]. In the figure, the alert and notification (e.g., siren and emergency alert system (EAS) message) occur at time zero. The curve flattens at the top, illustrating the evacuation tail, which represents a small percentage of people who take longer to evacuate. An estimate of 10 percent of the evacuating population contributes to the evacuation tail [4] [16].

For this study, the initial response of the public is assumed to begin when the sirens sound; however, that does not mean evacuees enter the roadway network immediately. As discussed later with the trip generation times, it takes time for the public to receive the warning, understand what is necessary, and prepare to respond. Some state and local governments include early protective actions, such as the evacuation of schools at a site area emergency (SAE), in the site-specific radiological and emergency preparedness plans. Early protective actions are not considered in this study.
The generic EPZ models were built considering the above characteristics and demographics and are not reflective of any actual NPP EPZ. Specifically, EPZ characteristics that make these models generic included the following:

- The modeled EPZs are precisely at 10 miles from the NPP;
- A single population group was modeled representing populations of the general public, transients, schools, special facilities, and employees;
- All roadways are assumed to be flat (e.g., level terrain) for the analysis;
- Default model parameter values in VISSIM were applied where appropriate; and,
- For the medium and large population sites, evacuee response curves were developed by averaging ETE response curves for similar population EPZs.

### 3.2 Scenario Selection

The ETE response scenario defines the specific conditions assumed for the analysis being conducted. Guidance is provided in NUREG/CR-7002 [4] to assist analysts in identifying
combinations of variables and events to be considered. Typically, 10 or more scenarios are developed in a site-specific ETE study. Only one scenario was used in this analysis.

The baseline scenario is a weekday, daytime, normal weather event, with normal background traffic on the roadway. This scenario was selected because of its general applicability. The consensus within ETE studies has been to develop a weekday, daytime, normal weather scenario as a de facto “base case” and then make a modification to this scenario to represent various other situations. Specific consideration of trip generation times for schools, special facilities, and transit-dependent residents was not included. However, the populations used in the analysis are sufficient to account for the vehicles from each of these population groups. Consistent with guidance in NUREG/CR-7002 [4], the scenario was developed with an assumption that evacuation is ordered promptly, coincident with sounding of the sirens and broadcast of an EAS message. Use of this planning basis allows the ETE to be consistently calculated beginning with the initial notification to the public [4].

To build this scenario, PTV VISSIM software package was used to create the traffic simulation models. Base models were populated with VISSIM default model values and with generic parameter values representing evacuation response characteristics. Chapter 4 explains the steps that were taken to build the base models.

### 3.3 Model Data

The evacuees within the EPZ were modeled as a single population group representative of a total evacuation contribution in the analysis. The population was spatially distributed within 16 sectors (e.g., 22.5-degree sectors) at one-mile distances creating model grid elements. Background traffic, pass through traffic, and shadow evacuees were also contributing populations in the model development. The roadway infrastructure implemented in the models is generally representative of small, medium, and large population EPZs. This assured that roadway types, intersection designs, roadway segments, and other infrastructure features were realistic. Default model parameter values were typically implemented.

### 3.4 Parametric Analysis

Upon completion of the base model runs, the ETE models were used to conduct parametric analyses related to shadow evacuation. The results produced with the analysis were compared to the base model results. In order to conduct a parametric analysis, data was collected (see section 4.8) at a certain location to analyze and compare ETE, average speeds and exit volumes at the EPZ.

### 3.5 Analysis of Results

Results produced from the base models established values from which to compare the shadow analysis conducted. To conduct all of the required analyses, the three models were built to a distance of 20 miles from the NPP. VISSIM requires the user to identify where data is to be
collected and to specify the metrics to be captured at each specified location. Data was collected at roadway crossings at the 2, 5, 10, 15, and 20-mile rings.

Data from all collection points were tabulated and reviewed to understand the network performance as well as the dispersion of MOEs. Furthermore, it provided insights regarding when to dig into the data to greater detail to understand why a specific collector point had larger or smaller values than an adjacent or similar collector points.
4 Model Development

The application of traffic simulation models to produce evacuation times reflects the current state of practice for ETE development. All current licensee ETEs have been developed using such models. Furthermore, all of the ETE studies employed models that included dynamic modeling features (e.g., dynamic traffic assignment (DTA)) which allow the modeled vehicles to change direction during the course of the evacuation, following what is perceived as the best path. Current guidance in NUREG/CR-7002 [4] addresses this state of practice, describing model inputs and outputs, outputs, and MOEs to be provided in ETE studies to support NRC review.

Section IV of Appendix E to 10 CFR Part 50 requires nuclear power reactor licensees develop ETE analyses [1]. Neither regulation nor guidance prescribes the method in which an ETE is to be calculated. The licensee may choose whatever is most appropriate for the EPZ, although all current ETEs studies make use of traffic simulation software. A wide variety of traffic simulation models capable of calculating ETEs are available. Characteristics of many of these models are described in the U.S. Department of Transportation (DOT) sponsored “Evacuation Management Operations (EMO) Modeling Assessment: Transportation Modeling Inventory,” [17]. Additionally, the Federal Highway Administration (FHWA) prepared a toolbox that includes comprehensive guidance on the development of traffic simulation models [18] [19] [20]. These documents are useful in assisting analysts in determining the most appropriate model for the specific site.

Traffic simulation models are categorized as microscopic, mesoscopic, and macroscopic [18], all of which are appropriate for use in calculating evacuation times [4]. As the descriptions of the model types indicate, they reflect different fidelities in both the inputs and outputs. Although the models differ in complexity, much of the fundamental data (e.g., roadway network, number of vehicles, etc.) used to develop inputs is applicable to each model type. Microscopic models simulate the movement of individual vehicles based on car following and lane changing theories and provide the ability to model signalized intersections and associated queuing in great detail [18]. However, to produce realistic results using a microscopic model, a significant amount of field data and accurate representation of driver behavior characteristics are needed. Macroscopic models employ deterministic relationships of speed, capacity, and density of the traffic stream, in accordance with the Highway Capacity Manual (HCM) [18] [22]. The simulations in macroscopic models are grouped, as it is governed by the average speed on a link, rather than based on individual vehicles [18]. Mesoscopic models implement properties of both microscopic and macroscopic using individual vehicles, in the grouped applications of a macroscopic model [18]. Mesoscopic models facilitate analyses that are more detailed than macroscopic and less detailed than microscopic. All three model types can be run with dynamic traffic assignment (DTA) applications. The DTA model implements time-dependent origin and destination (O-D) trips which are assigned based on traffic conditions.

The VISSIM microscopic simulator [21] was used to create the traffic simulation base models as it provides a greater level of detail needed for the analysis. VISSIM is a time-step and behavior-based model [21]. It can be applied to analyze traffic operations, which are influenced by roadway geometry, lane configuration, traffic composition, traffic signals, pedestrians, and other
network characteristics. In VISSIM, driver behavior is coded with the Wiedemann functions, which address car following distances, sight distances, wait times to change lanes, changes in speed, and other driver characteristics. These characteristics were developed based on Western European driving [21]. As with any microscopic model, to achieve realistic results, the inputs need to be adjusted for the scenario to be analyzed. The importance of these adjustments cannot be overemphasized, as stated in Volume III of the FHWA toolbox [20]. However, for the base models, default values were used.

The experience of developing the small, medium, and large population models for this research identified, as expected, that the level of effort for each of the models was increasingly complex. The increase in effort was not linear, with the small model requiring much less effort than the medium or large. This finding was consistent with conclusions of the FHWA study, “Guidance on the Level of Effort Required to Conduct Traffic Analysis Using Microsimulation,” [26] which compared the level of effort of small, medium and large microscopic traffic simulation model development. The FHWA study identified a factor of 5 increase in development of a large model compared to a small model.

The additional effort to code the microscopic model, select and adjust site-specific input parameters, and validate the performance against field conditions to ensure reasonable baseline results, makes microscopic models challenging for developing ETE studies, particularly when macroscopic simulation models have been shown to produce ETE values within a few percent of the microscopic simulation models [23] [28]. However, for testing and analysis of specific inputs, which was a focus of this study, microscopic modeling provided the extra level of detail intended to support the analyses. The base models were generally populated with VISSIM default values and with generic inputs to represent evacuation response characteristics.

Replicating driver behavior in simulation models presents one of the challenges in creating a realistic model. For example, as many drivers have experienced, geographical positioning system (GPS) travel assistants that perform real-time calculations to recommend the fastest route to a destination sometimes suggest unrealistic routing. Such a route may take an individual off a freeway and onto a frontage road only to recommend getting back on the freeway at the next onramp. The GPS calculation estimates small-time savings, but the action is not something rational drivers would implement. Less sophisticated systems always suggest a freeway route, regardless of congestion. Traffic simulation models operate with similar algorithms, sometimes routing vehicles along obscure paths that may not be reasonable. Models must be reviewed in detail to identify these situations and implement rules to avoid the actions.

4.1 Model Development Assumptions

The following assumptions were implemented in the base models developed for the three generic EPZs. These assumptions are specific to this study and are not necessarily intended to represent assumptions that would be used in a site-specific ETE study.

- EPZs for the entire NPP fleet can be reasonably represented with the small, medium, and large population sites used in this study.
- The model scenario is a midday, midweek evacuation that is ordered promptly, coincident with the sound of the sirens and broadcast of an EAS message.
- Modeling of individual trip generation times for schools, special facilities, and transit-dependent residents was not considered.
- A single loading curve for each of the small, medium and large population sites was reasonable to represent each EPZ.
- Consistent with the NRC guidance [4], pass-through traffic ceases to enter the EPZ two hour after the initial notification
- All modeled roadways are paved and flat, representing a level train.
- Traffic signals utilize pre-timed signal timing
- Default VISSIM values for model parameters are appropriate for the base models

4.2 Base Model Summary

The base models would be later used for other parameter analysis which required developing base models beyond the range typically included in an ETE study. The models were built to a 20-mile radius from the NPP. The 10-mile EPZ is represented as a radial distance from the NPP. The current guidance provides the shadow evacuation be evaluated to five miles beyond the EPZ [4]; as such, most ETE studies end the analysis at or near this distance. Congregate care centers and relocation centers are established at least five miles and preferably 10 miles beyond the plume exposure pathway EPZ [5]. To assess travel times to hypothetical locations of congregate care centers, the roadway networks were built to a distance of 20 miles from the NPP.

4.2.1 Summary of Model Characteristics

As described earlier, microsimulation requires substantial input to simulate the movement of individual vehicles. Table 4.1 lists model characteristics for the 0-20-mile network and the 10-mile EPZ.
Table 4.1. Base model characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Small</th>
<th>Medium</th>
<th>Large</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>0-20 Mile Network</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total number of origin points</td>
<td>65</td>
<td>413</td>
<td>457</td>
</tr>
<tr>
<td>Total number of destination points</td>
<td>42</td>
<td>15</td>
<td>18</td>
</tr>
<tr>
<td>Total number of links</td>
<td>376</td>
<td>2,645</td>
<td>10,605</td>
</tr>
<tr>
<td>Total number of connectors</td>
<td>863</td>
<td>3,846</td>
<td>14,719</td>
</tr>
<tr>
<td>Total miles of roadway modeled</td>
<td>1196</td>
<td>3313</td>
<td>3,712</td>
</tr>
<tr>
<td>Total number of signalized intersections</td>
<td>9</td>
<td>320</td>
<td>535</td>
</tr>
<tr>
<td>Total number of stop signs</td>
<td>165</td>
<td>129</td>
<td>439</td>
</tr>
<tr>
<td>Traffic signals</td>
<td>Pre-timed</td>
<td>Pre-timed</td>
<td>Pre-timed</td>
</tr>
<tr>
<td><strong>0-10 Mile EPZ</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total number of origin points within the EPZ</td>
<td>28</td>
<td>159</td>
<td>183</td>
</tr>
<tr>
<td>Average number of vehicles loaded at EPZ origin point</td>
<td>134</td>
<td>629</td>
<td>888</td>
</tr>
<tr>
<td>Maximum number of vehicles loaded at an EPZ origin point</td>
<td>1,150</td>
<td>1463</td>
<td>3860</td>
</tr>
<tr>
<td>Minimum number of vehicles loaded at an EPZ origin point</td>
<td>25</td>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>Total number of vehicles loaded for the EPZ</td>
<td>3750</td>
<td>100,000</td>
<td>162,500</td>
</tr>
<tr>
<td>Total miles of freeway within EPZ</td>
<td>0</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>Total miles of non-freeway within EPZ</td>
<td>280</td>
<td>498</td>
<td>1223</td>
</tr>
<tr>
<td>Total number of signalized intersections within EPZ</td>
<td>0</td>
<td>144</td>
<td>191</td>
</tr>
<tr>
<td>Total number of stop signs within EPZ</td>
<td>22</td>
<td>31</td>
<td>211</td>
</tr>
</tbody>
</table>

4.2.2 Boundary Conditions

Boundary conditions define the extent of the network that is to be modeled. Important changes in infrastructure, beyond the limits of the ETE study analysis area, can potentially impact the ETE. Review of ETE studies as a part of this research found that in many instances the modeled network was extended beyond the limits of the shadow region to capture these important infrastructure conditions in order to include the effects of such conditions in the calculation.
When building a traffic simulation model, boundary conditions should be established early. For ETEs, boundary conditions describe the arrangement by which the modeled network will terminate. The arrangement of the infrastructure beyond an EPZ study area has often been found to change within a short distance. For example, roadways may have a reduction in the number of lanes or a constraining intersection may be located a short distance from the boundary. The indiscriminate discharge of the modeled vehicles at predetermined radii provides an opportunity to miss these important changes in infrastructure. Such conditions can cause an impact to the ETE, particularly for medium and large population sites.

Impediments and constraints near the limit of the traffic simulation network should be included in the analysis to capture the impacts and support realistic results. The distance to which the network should be extended is case by case. If it is determined a roadway should be extended in one direction in the model to capture a lane reduction, this would not suggest a need to extend the entire network to the same distance. Only the affected roadway would need to be extended. Furthermore, an impediment that exists on a route with little evacuation traffic, may not need to be included in the analysis. The distances to which the calculations were performed for this study were predefined to support specific analyses making boundary conditions unnecessary for this effort. It may be beneficial to include boundary conditions in enhanced ETE guidance.

4.3 Demand Estimation

The process for developing an estimate of the number of people to be evacuated is called demand estimation. All persons located within the EPZ are included in the demand estimation. NRC guidance in NUREG/CR-7002 [4] further defines population groups, as follows:

- Permanent residents and transients (e.g., tourists, shoppers, employees, etc., who visit but do not reside in the area);
- Transit-dependent permanent residents;
- Special facility residents; and,
- Schools.

For the purpose of this research, the total populations modeled for each site included the contribution from the above categories; however, specific attributes such as individual trip generation times, specialized vehicles, and residents that are transit dependent from these population groups were not considered. After the population values were established, they were converted into vehicles for the analysis.

4.3.1 Site Populations

Evacuee and shadow populations were selected for the representative sites based on U.S. census information and a review of EPZs. Total evacuees for the generic EPZs were 7,500, 200,000, and 325,000 for the small, medium, and large population sites, respectively. These values represent the general public, transients, schools, special facilities, and employees within the EPZ at the time of the emergency. In addition, pass-through traffic and background traffic are also on the roadway when the evacuation order is issued.
Total shadow evacuee populations for the 5-mile area beyond the generic EPZs were 3,000, 30,000, and 60,000 for the small, medium, and large population sites, respectively. These values are intended to reflect a 20 percent contribution of the public from the 5-mile area beyond each generic EPZ. Table 4.2 provides a summary of the site populations considered in the analysis.

Resident populations within the area from 10 to 20 miles from the NPP were also included in the models. This data was used to populate the roadway networks beyond the EPZ with background traffic, such that when the EPZ evacuees and shadow evacuees travel in these areas, the interaction with background traffic is considered. Background and pass-through traffic volumes are explained in more detail in the next sub-section (4.3.2 Pass-Through and Background Traffic).

<table>
<thead>
<tr>
<th>Model</th>
<th>EPZ Population</th>
<th>Shadow Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>7,500</td>
<td>3,000</td>
</tr>
<tr>
<td>Medium</td>
<td>200,000</td>
<td>30,000</td>
</tr>
<tr>
<td>Large</td>
<td>325,000</td>
<td>60,000</td>
</tr>
</tbody>
</table>

4.3.2 Pass-Through and Background Traffic

Each model simulation begins with an empty roadway network. Therefore, the first step in loading a traffic simulation model (microscopic or macroscopic) is to seed the network for a predetermined time period. This may be referred to as seed time, fill time, model equilibration, or other terminology, depending on the model used. Model seeding is the process of populating a reasonable number of vehicles on the modeled roadway network to represent the scenario being evaluated. For evacuation models, the initial conditions are those of the roadway immediately prior to the start of the evacuation.

Pass-through traffic and background traffic contribute to the demand estimation because these are vehicles that are on the roadway network when the evacuation commences [4]. Pass-through traffic is defined as vehicles that enter the EPZ roadway network and ‘pass through’ prior to the establishment of access control points (ACPs) at the EPZ boundary. Pass-through vehicles would typically be expected to travel freeways and major arterials within an EPZ because these are the roadways that would facilitate the ‘pass through’ activity. Site-specific traffic control plans generally stipulate that ACPs will be established within 2 hours, to prohibit this traffic flow. ETE guidance utilizes this assumption [4]. A fixed number of pass-through vehicles, representative of the quantities of pass-through traffic that would be expected for the medium and large population sites, were added to the demand estimation. Because most small population sites are predominantly rural, with few major arterials and typically no freeways, pass through vehicles were not included in the small site model.

Background traffic refers to vehicles in the network that are not initially part of the active evacuation [31]. These vehicles consist of residents and transients within the EPZ. Estimates of the amount of background traffic on the roadway may vary for the specific scenario, as nighttime scenarios would have a lower volume of background traffic than a daytime scenario. Some
background traffic can be attributed to intermediate trips [31], which are trips that are undertaken by evacuees but are not the final departure out of the hazard area. Murray-Tuite and Mahmassani [32] [33] suggest this behavior be incorporated into evacuation modeling for no notice events. Incorporating such behavior in terms of an ETE analysis could increase the trip generation time slightly.

Background traffic was loaded onto collectors, arterials, and highways. These roadways represent the evacuation routes that were also used in loading the general public vehicles. Background traffic within the EPZ was loaded at a specified percentage of total vehicles over 15 minute periods. All of the analyses included two 15-minute background traffic seeding periods prior to the siren. During this 30-minute period, background traffic was loaded onto empty roadway networks with O-D matrices that direct the background traffic out of the EPZ. Since destinations only existed at the 20-mile radius, the background traffic was also assigned to same destinations that inevitably routed them away from the EPZ. Because the small population site used a static model, it did not require an O-D matrix. Instead, background traffic was loaded onto the network with the evacuation vehicles and followed the same routes. To prevent all of the background traffic from exiting the area before evacuees begin to travel, the background traffic continued to be loaded for the first 15-minute interval when evacuating vehicles are also loaded onto the network. Based on the loading curves established for this analysis, the small population site begins evacuation when the siren sounds, the medium population site begins 15 minutes after the siren, and the large population site begins 30 minutes after the siren. The background traffic was loaded as follows:

- **Small population site:** Within the EPZ, background volume was loaded at a rate of 10 percent of the total resident vehicles per hour (or 2.5 percent every 15 minutes) over each of two 15-minute seeding periods prior to the siren. An additional 2.5 percent of the total resident vehicles was loaded over the first 15-minute evacuation period coincident with evacuees beginning to enter the network. Thus, within the EPZ, background loading was implemented over three 15 minute periods. In the 10 to 20-mile network area, background traffic was loaded at 2.5 percent of the total 10 to 20-mile resident vehicles for each of 10 loading periods of 15 minutes.

With the static model, fixed turning percentages were assigned for the background traffic during the seeding period. During this period, turning movements of 20 percent left turns and 30 percent right turns were assigned with the remaining 50 percent continuing straight through the intersection. This was done to seed the model with traffic before the start of the evacuation event to ensure evacuee did not enter an empty network. The fixed turning movements cease after the three 15-minute seed periods at which time turning percentages were manually assigned at all intersections. Assignment of turning percentages was not necessary for the larger sites where DTA was implemented.

- **Medium population site:** A rate of one percent of the total vehicles was loaded over each of two 15-minute seeding periods, prior to the siren. An additional one percent was loaded over the first 15-minute period after the siren, prior to evacuees beginning to load
the network. An additional one percent was loaded over the first 15-minute evacuation period coincident with evacuees beginning to enter the network. Thus, within the EPZ, background loading was implemented over four 15 minute periods. In the area, 10 to 20 miles from the NPP, background traffic continued to be loaded at the one percent of the 10 to 20-mile total vehicles per 15-minute rate for another 28 15-minute intervals (7 hours). This rate was selected to provide an adequate amount of “friction” for the evacuating vehicles within the network. It was not intended to replicate any particular scenario beyond the general presence of ambient traffic through the entire region.

- Large population site: A rate of one percent of the total EPZ vehicles was loaded over each of two 15-minute seeding periods, prior to the siren. An additional one percent was loaded over the two 15 minute periods after the siren, prior to evacuees beginning to load the network. An additional one percent was loaded over the first 15-minute evacuation period coincident with evacuees beginning to enter the network. Thus, within the EPZ, background loading was implemented over five 15 minute periods. In the area, 10 to 20 miles from the NPP, background traffic continued to be loaded at one percent of the 10 to 20-mile total vehicles per 15-minute rate for another 28 15-minute intervals (7 hours).

The detail regarding implementation of the background traffic suggests it may be beneficial for enhanced guidance to provide that a description of the process for including background traffic and the basis for implementing the approach used be described in the ETE study.

4.3.3 Vehicle Volumes

NRC guidance provides that the populations for each demographic group be converted to vehicles for traffic simulation modeling. This is typically done by applying a person per vehicle ratio for each population group and is applicable to microscopic and macroscopic models. Because this effort modeled a single population group combining populations of the general public, transients, schools, special facilities, and employees, an average vehicle loading was developed. Many current ETE studies were reviewed and data was gathered on the general public, transient, and employees, each of which are itemized in the ETE studies. The ratio for employees was typically 1.0 to 1.1 persons per vehicle. The ratio for general public typically ranged from 1.7 to 2.4. The ratio for transients was broader still ranging from about 2 to over 4 persons per vehicle. Using the ratios and the contributions of each population group, an average person per vehicle ratio of 2.0 was developed.

Vehicles were loaded into the model to represent the EPZ population and EPZ background. Beyond the EPZ, the shadow population was loaded in the area from 10 to 15 miles from the plant and background traffic was loaded onto the entire 10 to 20-mile area and the pass-through traffic travels both from the 10-15 shadow area and the EPZ. Vehicle contributions for each model are identified in Table 4.3.
Table 4.3. Summary of modeled vehicle contribution inputs

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>3,750</td>
<td>752</td>
<td>1,500</td>
<td>*</td>
<td>6,350</td>
<td>12,352</td>
</tr>
<tr>
<td>Medium</td>
<td>100,000</td>
<td>4,000</td>
<td>15,000</td>
<td>5,000</td>
<td>48,220</td>
<td>172,220</td>
</tr>
<tr>
<td>Large</td>
<td>162,500</td>
<td>8,125</td>
<td>30,000</td>
<td>19,250</td>
<td>152,000</td>
<td>371,875</td>
</tr>
</tbody>
</table>

*Small population site did not include Pass-Through Traffic

Vehicle loading was spatially distributed within 16 sectors (i.e., 22.5-degree sectors) at one-mile distances, based on the population density. In some instances, where large populations reside, multiple origin nodes were assigned to a single grid element. In other instances, where there was little or no population, no loading occurs within the sector. When multiple loading points were applied in a sector, the population was evenly divided among the number of loading points equally.

4.3.3.1 Vehicle Types

Two vehicles types, passenger cars, and trucks (also referred to as heavy goods vehicles (HGVs)) were used in the models. The application of cars and trucks is applicable to microscopic and macroscopic models. The VISSIM model provides a variety of common types of cars and trucks from which to load the network and selects from a distribution of vehicle types to provide a broad vehicle mix for the scenario [21]. The performance characteristics of vehicles are specific to VISSIM; however, some characteristics, such as vehicle lengths, are applicable to microscopic as well as macroscopic models.

4.3.3.2 Percent Trucks

Current guidance does not address percent trucks in the vehicle fleet; however, it is well understood that the percent of trucks on the roadway impacts travel [21] [22] [37] [38]. Trucks, including all heavy vehicles with three or more axles, (e.g., buses, motor homes, and camper trailers) should be estimated for the evacuation scenario. The percent of trucks in a vehicle fleet is a contributing factor in developing ETEs for all types of models (e.g., microscopic and macroscopic). The parameter is important because trucks accelerate at a slower rate than passenger cars, and this slower acceleration can impact the throughput at intersections. Furthermore, speeds can decrease as grades increase. The number of trucks in the vehicle fleet also affects the sight distances in the microscopic model behavior parameters. The VISSIM User Manual illustrates (in Section 5.6.2.1 of the manual [21]) that an increase in percent of trucks produces a noticeable decrease in the saturation flow rate. A similar illustration of the impact of trucks is provided in the Oregon Protocol [24] showing an increase of five percent of trucks reduces the saturation flow rate up to 5 percent.

Determining an appropriate percentage of trucks is a site-specific consideration for EPZs. Regional characteristics that include the extent of commercial activity within or near an EPZ
could contribute to variations in truck percentage. The scenario being estimated (e.g., winter evening or summer daytime weekday) will also influence the percent of trucks to be modeled. Truck time-of-day patterns on urban and rural roads are consistent with other vehicular travel patterns with truck traffic dropping substantially late at night [36]; thus, adjustments for evening scenarios may be appropriate.

Research has identified that heavy vehicle traffic has increased, and 8 to 10 percent of heavy trucks may be normal for urban roadways [36] [37] [38] [41]. A Baltimore Metropolitan Council study [41], identifies truck traffic as now accounting for over 10 percent of all traffic on major roadways. Evacuees may also be expected to take boats, trailers, and campers [39] [40] which are more appropriately modeled as heavy vehicles than passenger cars.

Urban roadways make up the prevalent transportation network within EPZs, with very few EPZs having significant freeway mileage within the area. Pass-through traffic, which would include all freeway heavy vehicles and some major arterial heavy vehicles, is expected to be controlled within 2 hours of the start of an evacuation [4]. As evacuees mobilize consistent with loading curves, they are largely in personal vehicles, and the percent of trucks becomes dilute. Using the initial 8 to 10 percent heavy vehicles within the EPZ, by the time EPZ residents are fully mobilized, the percent of trucks that potentially impact traffic conditions would likely be less. A range of 5 to 10 percent of trucks and heavy vehicles may be more appropriate for a typical day, with recognition that many sites are located around large water bodies where there is typically a prevalence of recreational vehicles, campers, and boats. However, given the large number of vehicles on the roadway during an evacuation, the total number of heavy vehicles would likely represent a small overall proportion of vehicles within the network. With this in mind, the test models used a value of 2 percent trucks. It may be beneficial for enhanced guidance to provide that a description of the process for including percent of trucks in the ETE modeling be described in the ETE study.

**4.4 Roadway Capacity**

The capacity of a roadway is defined as the maximum rate at which vehicles can be expected to travel a section of roadway during a given period of time under specified roadway, traffic, and control conditions [22]. Microscopic and macroscopic simulation models calculate roadway capacity differently, with microscopic models estimating saturated flow and macroscopic models implementing the equations of the HCM. The HCM describes operating conditions as level of service (LOS) A through F, with LOS A as free flow and LOS F as forced flow. Evacuation congestion can be significant, particularly with medium and large population sites, making capacity the most important characteristic to measure accurately.

As roadways become congested (i.e., saturated), HCM methods are not adequate to represent aspects of traffic queue build up and discharge as well as intersection turn lane spillback. As such, detailed analyses of these specific interactions can only be performed using micro-level traffic simulation systems which use numerical representations of the behavior of individual drivers and computational processes the reflect how these behaviors influence (and are themselves influenced by) vehicle-to-vehicle interactions within a specific environment of traffic
demand, roadway geometry, intersection control, and other influences, such as pedestrian activity [4]. Thus, unlike macro-scale models which specify the capacity of individual road segments based on a set of assumed or entered conditions, microsimulation models use individual, “microscopic,” interactions to conceptually characterize a maximum rate of low, i.e., capacity, through sections of roadway providing a more detailed analysis of the traffic phenomenon.

In fact, the concept of capacity, though quite specifically defined in the HCM is an elusive number to quantify with specificity. Current emerging research strongly suggests that capacity is a variable parameter, influenced by a number of constantly changing, yet specifically occurring, conditions [48] [49] [50] [51] [52] [53]. In a microscopic model, capacity, or the maximum rate of flow that can be achieved along a specific section of roadway, can be thought to occur under a specific condition in which all vehicles are moving with a minimum spacing (known more technically as “distance headway”) and at a maximum speed. The obvious difficulty in this definition in a micro-level representation of traffic flow is, however, that every leading-following vehicle pair is spaced with a different headway and traveling at any range of specific speed. Because of this, traffic analysts tend to describe a general segment capacity based on the average headway and average speed of all vehicles traveling within a section, even though in reality the maximum flow rate is likely to be constantly changing in both time and space.

Tian and Urbanik, et al., [30], compared VISSIM to CORSIM and Sim Traffic which are all microscopic traffic simulation models. The authors investigated the variations in the performance measures generated, focusing on capacity and delay estimates at a signalized intersection. The highest variation in each simulation model normally occurred when the traffic demand approached capacity. The study identified that a large number of runs may be necessary to accurately estimate delay at, near, or over capacity. When the average values were considered from multiple runs, the throughput flow rates from all three models matched the input demand closely for under-capacity conditions. The three simulation models tested produced different results when the default traffic flow parameters from each simulation model were used. In general, VISSIM produced the highest capacity and lowest delay estimates, and SimTraffic produced the lowest capacity and highest delay estimates [30].

4.4.1 Roadway Types

The proper depiction of the roadway network in traffic simulation modeling is needed to capture the specific roadway characteristics. A similar effort is needed in the design of the network for microscopic or macroscopic simulations. As described earlier, roadway networks from three EPZs were used in this analysis. The types of roadways included in the networks are:

- Interstates/freeways,
- Interstate/freeway ramps,
- Highways,
- Major Arterials,
- Minor Arterials, and
- Collectors
For small population EPZs, it may be important to include residential streets in the analysis. But for the generic EPZs established for this research, the networks were well represented without the need for residential streets.

### 4.4.2 Roadway Geometry

Roadway geometry data was obtained by viewing aerial mapping of each network. The entire modeled network was reviewed using the aerial mapping to identify the following:

- Number of lanes in each direction;
- Lengths of links/segments;
- Right turn lane characteristics;
- Left turn lane characteristics; and
- Types of signalized and non-signalized intersection control.

Traffic simulation models (microscopic and macroscopic) define roadways via links and connectors (also called segments and nodes or other model specific terminology). Links are typically used to represent roadway segments that convey vehicles between geometric changes, such as intersections. Links typically proceed through a corridor with similar geometry. A connector is used to join links. Modeled roadway characteristics are presented in Table 4.4.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lane Width</td>
<td>12-ft</td>
<td>Standard roadway width. In a macroscopic model, this is used to support roadway capacity calculations.</td>
</tr>
<tr>
<td>Desired Speed</td>
<td>25 to 70mph</td>
<td>Estimated based on roadway classification</td>
</tr>
<tr>
<td>Roadway Grade</td>
<td>0 %</td>
<td>All roadways were modeled as level terrain</td>
</tr>
</tbody>
</table>

### 4.4.3 Roadway Grade

All roadways were modeled as level terrain for the base models. Guidance in NUREG/CR-7002 [4] provides that grades greater than about four percent should be included in the analysis and this is applicable to microscopic and macroscopic models. Highway analysis studies have indicated that grades between negative three percent and positive three percent have a negligible impact traffic performance. However, steep grades have the potential to significantly impact heavy vehicles [23]. When developing ETE studies, care should be taken when modeling roads with a higher percentage of heavy vehicles if the NPP is located in an area with grades steeper than three percent. It may be beneficial to request in enhanced ETE guidance that a description of how grades are addressed be included in ETE studies.

### 4.4.4 Intersections

Evacuation traffic can be significantly impacted by signalized intersections, particularly for evacuations in urban areas [31]. Capacity reduction and delay are both observed at sub-optimally performing intersections, which make up the majority of intersections in the U.S. [48].
Oak Ridge National Laboratory (ORNL) studied capacity reduction and found that the majority of capacity loss was due to less than optimal intersection performance on major arterials [48].

Microscopic and macroscopic models provide extensive capabilities in the modeling of signalized intersections. One of the major benefits of using microscopic simulation models is the ability to code signalized intersections with a high degree of representativeness to field conditions. Such detail can facilitate more accurate modeling of the traffic conditions, provided sufficient data can be obtained on the intersection control (e.g., protected turn lanes) and cycle times. Several driver behavior parameters in VISSIM are related to signalized and non-signalized intersection throughput, including turning speeds, headway times, standstill distance, and the safety distance reduction factor. VISSIM can also model right and left turn lanes, either protected (i.e. left turn movement have the right-of-way) or unprotected (i.e. left-turn movements yield to oncoming through traffic or pedestrians). Given the importance of intersection control, current guidance provides that all signalized intersections within the evacuation network should be included in the traffic simulation modeling when developing an ETE study [4]. Guidance further identifies that it is not necessary to obtain actual traffic signalization timing for every intersection, because current signalization systems can change throughout the day, depending on traffic flow [4].

4.4.4.1 Signalized Intersection Coding

Typical types of traffic signals include actuated, fixed time, and combinations of these systems [42]. Actuated signals represent the state of practice for intersection control. These signals vary the allocation of green time in response to vehicle detectors, typically providing longer through times for the major streets [42]. For the base models, actuated intersection control was initially built into the medium and large population models with a high degree of detail. However, such specific representations for individual intersections in a large-area modeling, as in the case of an NPP ETE study, is both labor intensive and impractical for such applications. Due to the large number of intersections, programing actuated signals within the model exceeded the computational processing capability of the simulation software. The initial testing of actuated signals caused a fatal error in the program. It was determined that the most appropriate resolution to this issue was to implement fixed time signals. With fixed time signal control, the green, yellow, and red times were constant values that repeated. Because there was no detector looking to update the signal timing, this was a less computationally burdensome approach. Use of the fixed time signals also provides a benefit to this study in that it reduces variability in the system. Since the intent of this research is to assess the impact on clearance times by varying shadow population participation, reducing compounding effects, such as may be introduced with actuated signal controls, helped confine the change in clearance time to the variable of interest.

Table 4.5 includes a summary description of the intersection signalization coded into the three base models. The table includes the approximate allocation of green time (i.e., phase splits) for the major and minor approach directions. In general, the phase splits favored the major street approach at a ratio of two to one. The highest green time allocation to any direction was 280 seconds and the lowest was 5 seconds. These two allocations represent an intersection serving
the maximum green time on the major approach and the minimum green time on the minor approach.

Once the decision was made to use fixed time control, all of the intersections were then coded with permissive actions, which means that left turns and right turns were allowed to complete turns after yielding to oncoming traffic. Conflict area functions were used to allow turning vehicles to stop in the intersection, wait for a gap in the oncoming traffic flow, and then proceed with the turn movement when the gap was acceptable. Upon completion of the fixed time intersection coding, interim test runs were conducted and intersection performance was reviewed. When excessive congestion was observed at intersections, the intersection control was adjusted to support more efficient performance. The review and adjustments were generally focused on intersections that appeared to be operating inconsistent with the rest of the system, such as a congested intersection in between two other intersections that were operating reasonably well. To improve the performance and reduce congestion, cycle times were adjusted or protected left turn control (exclusive left turn arrow) features were added. However, in some instances adjusting the green time allocation still did not allow for a reasonable approximation of traffic flow. This was because these intersections were very congested on single direction and required actuated control. Given the limitations discussed earlier, this was not possible. Therefore, to increase the efficiency of these intersections and compensate them for not having actuation, the minor street signal head was removed in the model. Using the VISSIM conflict area function, the minor street was set to yield to the major street. When a gap was identified in the major street traffic, the minor street traffic was allowed to cross the major street. The signal on the major street stop traffic on this street at the specified red cycle time. The cycle length was set at 240 seconds. This approach to modeling these intersections reduced the queue length of the minor road while still permitting efficient traffic flow on the major road. Although 240 seconds of cycle length might not be desirable for real-life scenario, this cycle length was used to simulate an actuated signal control when it was not permissible in these models, as explained earlier.

The difficulties associated with attempts to implement actuated signals on a large-scale in the microsimulation model, together with the assumptions required with respect to signal timing, suggest that care should be taken when developing the intersection control approach. Review of ETE studies conducted as part of this research found that modeling of actuated signals has not been identified as an issue with macroscopic models. It may be beneficial for guidance to request greater detail regarding non-standard intersection designs, including the basis for implementing designs that do not represent field conditions.
Table 4.5. Summary of signalized intersections

<table>
<thead>
<tr>
<th>Model</th>
<th>Major Road Phase Time (seconds)</th>
<th>Minor Road Phase Time (seconds)</th>
<th>Major Road Protected Left-Turn Phase Time (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>50</td>
<td>45</td>
<td>10</td>
</tr>
<tr>
<td>Medium</td>
<td>70</td>
<td>70</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>220</td>
<td>90</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>280</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Large</td>
<td>50</td>
<td>33</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>68</td>
<td>40</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>68</td>
<td>65</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>53</td>
<td>0</td>
</tr>
</tbody>
</table>

4.4.4.2 Non-signalized Intersection Coding

For intersections operating with a stop control, the stop sign was placed at the same location as the stop bar in the field. Conflict areas were used to assign the right-of-way. When an intersection consisted of yield entry, only conflict areas were utilized at the intersection.

4.4.4.3 Alternate Intersection Coding

In the large population site model, initially, all un-signalized intersections were coded as either 2-way or 4-way stop control as determined through aerial mapping review of intersection characteristics. However, issues arose with regard to system performance and with excessive travel times. First, system errors were appearing in the output file identifying that some origin nodes were not loading all of the vehicles onto the network during the model run.

To correct the system errors related to loading, alternative intersection control was employed at the origin nodes. All origin nodes, where vehicles were loaded onto the network, had been designed such that vehicles immediately entered a three-way stop-controlled intersection. The loaded vehicles were then forced to make a right-hand turn at the stop sign. These three-way intersections do not physically exist. It is common practice to build these into the model specifically to load the network. This stop control at these loading intersections was causing a delay in vehicles accessing evacuation routes. The delay was significant enough that the total vehicles assigned to the origin node were unable to enter the network during the time allocated for the simulation. The stop-controlled origin loading intersections were changed to a yield on the minor street and no control on the major street. These changes were implemented using the conflict area function in VISSIM. This allowed vehicles on the major street to pass through the
intersections freely. Vehicles approaching from the yield side of the intersection proceed to turn right when sufficient gaps in traffic are available. In developing an actual ETE study establishing additional loading origins, each with a smaller population may be the more realistic approach to resolve such an issue. But for the test model, the simplified correction sufficed.

4.5 Vehicle Routing

Vehicle routing within traffic simulation models includes the process of directing vehicles to specific destinations that are determined by the O-D matrices. The VISSIM User Manual [21] explains that static model assignment, implemented for the small population site, requires the analyst to specifically define the route vehicles will follow. Unless there is queuing and congestion, the inflow into any link in a static model is always assumed to be equal to the outflow. In the dynamic models, DTA tools address the needs of evacuation network performance under various scenarios using iterative algorithmic procedures to identify the best path [18] [46] [49]. Along with routing, the road network can have time-dependent characteristics [21] (such as congestion that builds and discharges over time) that may be exacerbated during an evacuation, making dynamic assignment the most appropriate ETEs. Dynamic network models are designed to represent the time-dependent characteristics (e.g., the interaction of travel choices, traffic flows, and time) [18]. DTA routing consists of providing an O-D for a vehicle, but the route used to achieve the O-D trip varies based on travel time, distance, or other factors.

These recognized benefits should not, however, suggest that DTA is without limitation, or that DTA is always the most appropriate method of routing for modeling all evacuation scenarios. In concept, DTA is founded on principles that are created to reflect routine normal daily traffic processes. As such, while many aspects of DTA are relevant to and appropriate for the modeling of evacuations, there are also many that are not. For example, DTA suggests that drivers are familiar with recurrent congestion patterns within the network and alternative routes to move around them. Ultimately, this results in an equilibrium assignment wherein traffic volume is relatively “equally” distributed among possible routes between origins and destinations in a network. An issue that can arise when applying these principles to an evacuation process is that, while they may appear logical, the driver population characteristics and network conditions that exist in such events may or may not be similar to a routine daily condition. After considerable discussion, it was concluded that given the comparatively small evacuation network for most NPP emergency scenarios and the assumption that a large majority of drivers would have an in-depth local knowledge of alternative routes, it was concluded that a DTA assignment process would be appropriate for the medium and large representative site models in this research.

It should also be noted that, as a mathematical representation of human behavior, DTA algorithms have limitations in the logical routing of vehicles during an emergency. As DTA processes seek to assign vehicles to shortest time travel paths, behaviors can occur that result in illogical routing. An example of this that was observed in this research – and one that has been known to occur with regularity in actual practice – is the behavior of evacuees returning back into the direction of the hazard source and taking circuitous routes during the simulation. To
limit these occurrences in this research, modeling measures were taken that involved modifications to various control, connectivity, and geometric features of the network to minimize the development of such situations. Similar instances, related to this research are described later in this document.

A static model was built for the small population site and dynamic models (with DTA) were used for the medium and large population sites. Static models were found to be inappropriate for the medium and large population sites, due to the numerous potential routes available to evacuees and the inability to reasonably predict each route for the evacuees. The Mississippi DOT has identified that analytic congestion functions used in static assignment models are unable to realistically describe the propagation and dissipation of system congestion under time-varying traveler demand patterns [49]. Furthermore, as the size of a network increases, it becomes difficult to assign specific routes for vehicles and balancing traffic flow on the roadways becomes judgment. A typical EPZ includes more than 300 square miles of roadway network with dispersed populations, plus the shadow evacuation area. Building a static model requires analysts to determine the specific routes evacuees would take to exit the area. DTA provides a more reasonable representation of the routing evacuees may take to exit an EPZ.

During the seeding period for the static model, fixed turning movements of 20 percent left turns and 30 percent right turns were assigned with the remaining 50 percent continuing straight through the intersection. This allowed the background vehicles to spread out and intermix randomly with the evacuee vehicles to ensure evacuees did not enter an empty road network. Since this research did not include any actual data collection at intersection, these turning percentages were based on engineering judgment and observation of the traffic behavior. The fixed turning movements ceased within the EPZ after the three 15-minute seed periods at which time turning percentages were assigned individually to reflect the likely path of evacuating traffic at each intersection.

During the static model evacuation portion of the analysis, evacuation routes were established through the use of turn percentages applied to all vehicles. Once the evacuation began, vehicles were generally routed radially away from the plant. This was done by establishing turning percentages of 100 percent through an intersection in the direction away from the plant. As roadways began to reach capacity, or when alternate routes were available that were also directionally away from the plant, turn percentages were in some cases allocated to these additional routes to help balance the network. The vehicle loading was balanced through iterative runs, until the routing was determined to be reasonable.

A multi-destination assignment for the DTA in the medium and large population sites was implemented specifically for this research to ensure vehicles were routed away from the nuclear power plant to final destinations zones located in different sectors. Prior to implementation of this approach, it was observed through review of preliminary model output that vehicles did not always follow a radial path and would return toward the NPP often following circuitous paths. This was identified through a review of the longest vehicle travel path in the output file of test runs.
Figure 4.1 and Figure 4.2 identifies the destination locations used in the DTA for the medium and large population sites, respectively. In the medium population site, there were 15 unique destination zones (414 to 426) in different sectors as seen in Figure 4-1. Unlike the large population site, the medium site had natural barriers that limited route choice. As such, the sectors with these natural barriers did not have destination zones assigned to them. Vehicles originating in the ENE and E sectors between the 5 and 10-mile rings were routed to either destination zone 416 located in the NNW, NNE, ENE and the E sectors. In addition to the 13 main destination zones, two additional destination zones (427 and 428) were added in sectors with freeways (ESE and NNW). Origin parking lots within half a mile to the freeway would be routed to either destination zones 427 (East quadrant) or 428 (North quadrant) depending on their proximity. These additional destination zones were added to the model after initial test runs showed vehicles originated near the freeways were oversaturating nearby frontage roads and not utilizing the freeways. Therefore, the additional destination zones allowed for routing vehicles more reasonably.

Figure 4.1. Destination zones for the medium population site
In the large population site illustrated in Figure 4.2, each sector was assigned one main destination zone (destinations zone numbers 458 to 473 colored in red) and two additional ones from adjacent sectors. Hence, three destinations zones were available to each origin: the main destination zone on that same sector and that same destination zone located on two adjacent sectors. For example, Figure 4.3 shows that vehicles originating in the N sector would exit at either destination zone number 458 located in the NNW, N, and NNE sectors. In addition to the 16 main destination zone numbers in the large population site, two additional destination zones (474 and 475) were added in sectors with freeways (ESE, S, SSW, and WNW). These additional destination zones allowed for routing vehicles more reasonably as in the medium population site model.

Figure 4.2. Destination zones for the large population site
The inset in Figure 4.3 illustrates the three-pronged outlet for destination zones 460, 461, and 462 that was used in the model to quickly dissipate vehicles at the exit points in the large population site model. As explained earlier, this “pitch-fork” approach was also implemented in the medium site model. The ESE sector in the medium model did not follow the assumed radial evacuation. The vehicles generated inside the ESE sector was assigned to the SE, ESE, E and as well as the NNE sector. This was done to take advantage of a high capacity road that was underutilized that faced Northbound exiting at the NNE sector.
Figure 4.4. Illustration of “pitch-fork” modeling approach for destination zones

More realistic route choice was also achieved assigning costs to routes. Travel time is a key component in the DTA computation process [54]. The common behavioral assumption of travelers is that they will choose a route that has the least cost (e.g., travel time) between their origin and destination and try to avoid routes that have the highest cost [54]. To set a hierarchy of road types, a cost per mile parameter was implemented in cost functions for the medium and the large population site road networks as shown in Table 4.6. This function allowed for vehicles to distinguish between the classification of local roads, evacuation routes and freeways.

Table 4.6. Medium and Large Site Cost functions

<table>
<thead>
<tr>
<th>Road Classification</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeways</td>
<td>0</td>
</tr>
<tr>
<td>Evacuation Routes</td>
<td>1</td>
</tr>
<tr>
<td>Local Roads</td>
<td>2</td>
</tr>
</tbody>
</table>

Additional controls, including closing in-bound lanes, were built into the model to prevent evacuee vehicles from returning to the EPZ. This directional approach constrains the evacuating vehicles to a narrower range of routes exiting the area and was specific to each of the base models.
4.6 Driver Behavior

The representation of driver behavior characteristics are a key component of microscopic models. Parameters that influence car-following, lane changing, and gap acceptance behaviors govern traffic flow and effectively dictate factors such as capacity, throughput, queuing, congestion, and delay. These are not considered in macroscopic models, which employ computational processes similar to those of the HCM to determine capacities and delays.

Driver behavior is an important element in microscopic traffic simulation modeling. Various driving behavior parameters are used as inputs to car-following, lane changing and gap acceptance models. VISSIM provides default values for each of these driving behavior models. Although site-specific values of some these parameters are typically generated in traffic engineering practice through calibration and validation processes [50, 45], calibration was not undertaken as part of this study. This was acceptable due to the conceptual and non-site-specific research nature of this research, as well as the absence of empirical, site-specific evacuation data needed to calibrate models to specifically reflect evacuation conditions. However, some parameters were varied to reflect more realistic behavior as discussed in the following.

4.6.1 Car Following Models

The traffic flow model in VISSIM is a discrete stochastic model that contains a psycho-physical car following model for all interactions along the same lane [21]. VISSIM implements two car-following models:

- Wiedemann 74 (W74): Model suitable for urban traffic and merging areas; and,
- Wiedemann 99 (W99): Model for freeway traffic with no merging areas.

The passenger car default values are provided in Table 4.7 and Table 4.8, respectively. A comprehensive list of the driver behavior parameters is provided in Appendix B. Some of the default driver behavior values are identified in the VISSIM User Manual [21], while others are provided as prepopulated values from the VISSIM model. Although VISSIM is a widely-used traffic simulation platform, the Wiedemann car-following models are not well documented in the general research literature.

Table 4.7. Driver behavior parameters for non-freeways (W74)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Modeled Value</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed vehicles</td>
<td>The number of observed vehicles affects how well vehicles in the link can predict other vehicle movements and react accordingly.</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Maximum look ahead distance</td>
<td>Maximum distance that a vehicle can see forward in order to react to other vehicles either in front or to the side.</td>
<td>820.21 ft</td>
<td>820.21 ft</td>
</tr>
<tr>
<td>Maximum look back distance</td>
<td></td>
<td>492.13 ft</td>
<td>492.13 ft</td>
</tr>
</tbody>
</table>
The W99 model uses ten Calibration Components (CC) listed in Table 4.8 as CC0 through CC9. The W99 parameters were only used on freeways, which require an onramp or offramp to enter or exit the roadway.

Table 4.8. Driver behavior parameters for freeways (W99)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Modeled Value</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC0 Standstill Distance</td>
<td>The average desired standstill distance between 2 vehicles (i.e., stopped cars)</td>
<td>4.92 ft</td>
<td>4.92 ft</td>
</tr>
<tr>
<td>CC1 Headway Time</td>
<td>The distance in seconds which a driver wants to maintain while following another car</td>
<td>0.9 s</td>
<td>0.9 s</td>
</tr>
<tr>
<td>CC2 ‘Following’ Variation</td>
<td>How much more distance than the desired distance a driver allows before intentionally moving closer to the car in front. (longitudinal oscillation)</td>
<td>13.12 ft</td>
<td>13.12 ft</td>
</tr>
<tr>
<td>CC3 Threshold for Entering ‘Following’</td>
<td>Controls the start of the deceleration process. The number of seconds before reaching the safety distance.</td>
<td>-8</td>
<td>-8</td>
</tr>
<tr>
<td>CC4 Negative ‘Following’ Threshold</td>
<td>Defines negative speed difference during the following process. Low values result in more sensitive driver reaction to the acceleration or deceleration of the preceding vehicle.</td>
<td>-0.35</td>
<td>-0.35</td>
</tr>
<tr>
<td>CC5 Positive ‘Following’ Threshold</td>
<td>Defines positive speed difference during the following process.</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>CC6 Speed Dependency of Oscillation</td>
<td>Influence of distance on speed oscillation while in the following process.</td>
<td>11.44</td>
<td>11.44</td>
</tr>
<tr>
<td>CC7 Oscillation Acceleration</td>
<td>Oscillation during acceleration.</td>
<td>0.82 ft/s²</td>
<td>0.82 ft/s²</td>
</tr>
<tr>
<td>CC8 Standstill Acceleration</td>
<td>Desired acceleration when starting from standstill.</td>
<td>11.48 ft/s²</td>
<td>11.48 ft/s²</td>
</tr>
<tr>
<td>CC9 Acceleration at 50 mph</td>
<td>Desired acceleration at 50 mph.</td>
<td>4.92 ft/s²</td>
<td>4.92 ft/s²</td>
</tr>
<tr>
<td>Maximum look ahead distance</td>
<td>Maximum distance that a vehicle can see forward in order to react to other vehicles either in front or to the side.</td>
<td>820.21 ft</td>
<td>820.21 ft</td>
</tr>
<tr>
<td>Maximum look back distance</td>
<td></td>
<td>492.13 ft</td>
<td>492.13 ft</td>
</tr>
</tbody>
</table>

4.6.2 Lane Channing Parameters

The VISSIM lane change parameters used in all three models are identified in Table 4.9. Default values were used, with the exception of the wait time before diffusion value. This parameter is
defined by the maximum time a vehicle waits at a certain location before they are taken out of the network. This parameter required significant adjustment for medium and large population models to perform under the saturated conditions of an evacuation. At the default value, vehicles became stuck in freeway congestion and were unable to exit at the designated point, as determined by the model. In such cases, VISSIM removes the vehicle from the system, causing a discrepancy between loaded vehicles and exiting vehicles. To eliminate the removal of vehicles, the wait time before diffusion was increased to the 900 seconds in the model. This value was reached by iterating different values to see how many vehicles would disappear from the base value of 60 seconds. In the small population model, value of 9,999 seconds was used.

Wait time before diffusion defines the maximum time vehicles wait on the freeway in a stopped position for a gap of sufficient distance to change lanes. A high value can result in excessive delay on the route, and a low value can result in vehicles being removed from the analysis. Both conditions may be unrealistic and a balance is needed. In microscopic and mesoscopic traffic simulation models, the removal of a small number of vehicles is common and would be expected in any large scale ETE study. Guidance may be appropriate to report the number of vehicles removed from the network or “lost” in the model. In general, it is common for this number to be in the range of two to three percent of the total number of vehicles modeled and in most cases, would not impact the overall findings of an ETE study.
Table 4.9. VISSIM lane changing parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Modeled Value</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum deceleration ( \frac{ft}{s^2} )</td>
<td>Maximum deceleration technically possible.</td>
<td>-13.12</td>
<td>-13.12</td>
</tr>
<tr>
<td>Accepted deceleration ( \frac{ft}{s^2} )</td>
<td>Used as the upper bound of deceleration in prescribed cases.</td>
<td>-3.28</td>
<td>-3.28</td>
</tr>
<tr>
<td>Maximum deceleration of trailing vehicle ( \frac{ft}{s^2} )</td>
<td>Maximum deceleration technically possible.</td>
<td>-9.84</td>
<td>-9.84</td>
</tr>
<tr>
<td>Accepted deceleration of trailing vehicle ( \frac{ft}{s^2} )</td>
<td>Used as the upper bound of deceleration in prescribed cases.</td>
<td>-3.28</td>
<td>-3.28</td>
</tr>
<tr>
<td>Wait time before diffusion (s)</td>
<td>Maximum time vehicles wait on the freeway in a stopped position for a gap of sufficient distance that they change lanes.</td>
<td>900* (medium and large model) 9999 (small model)</td>
<td>60</td>
</tr>
<tr>
<td>Minimum Headway front/rear (ft)</td>
<td>The minimum distance between 2 vehicles that must be available after a lane change, so that the change can take place.</td>
<td>1.64</td>
<td>1.64</td>
</tr>
</tbody>
</table>

4.6.3 Vehicle Speed

Speeds were implemented in the model using the VISSIM desired speed decision function. Desired speed, often referred to as FFS, is defined in the VISSIM User Manual [21] as the speed at which a driver would travel, if not hindered by other vehicles or network objects. Such hindrances may include intersections, driveways, or other on-road interactions. Desired speed is typically higher than the posted speed value because it is a design/modeling feature and is not intended to be reflective of the posted speed. For posted speeds of 40 mph and lower, desired speeds were set with a range of 5 mph above and below the posted speed. For posted speeds of 45 mph and higher, desired speeds were set with a range of 10 mph above and below the posted speed. In all cases, the 85th percentile was set at the posted speed. The range of modeled speed values is provided in Table 4.10.
When building the VISSIM model, the roadway speed is separate from the roadway type. At selected intersections, a speed decision point was established in each direction. When the modeled vehicle passed the decision point, the desired speed was assigned to the vehicle and the speed distribution profile was applied. In congested flow, the speed of the vehicle would be virtually the same as the vehicle in front. In uncongested flow, the speed profile may increase or decrease vehicle speed. The vehicle maintains the desired speed assignment until it crosses another speed decision point later in the network. For example, in the small population model, only one-speed decision point was established in the 2-mile area and one in the 5-mile area. Further away from the plant, multiple speed decision points were assigned. In a site-specific ETE study, guidance would suggest that speeds be reflective of the roadway network, and additional speed decision points would likely be employed.

### 4.6.4 Base Model Loading

Loading a traffic simulation model network for use in an evacuation analysis requires knowledge of the demographics, volume of vehicles evacuating, the rate at which vehicles enter the network, and the location at which the vehicles enter the network. The number of vehicles was developed from the populations. For ETE studies, the rate of loading is typically obtained from a site-specific survey of EPZ residents [4]. The locations at which the vehicles are loaded was based on a demographic distribution.

In this research, vehicle rates were input at the grid element level using 16 sectors and one-mile rings to create the grid. In VISSIM, vehicles are input into the model at origin parking lots which are simply loading points for the model. The dispersion of origin parking lots was generally based on the population density, such that higher density areas within an EPZ would have more origin parking lots from which to load vehicles into the system.

For the medium and large population models, loading was implemented via a short link built specifically to connect to a collector or arterial roadway. Typically, these connections were all designed initially as yield entry points.
The trip generation time is the time elapsed for each population group from when the evacuation order was disseminated, until the time when the evacuation trip begins [4]. It includes all activities necessary for evacuees to receive the notification and prepare to evacuate. The loading curves for the medium and large population sites were developed from an average of multiple ETEs that were representative of the population density sites. The trip generation time data from the ETEs was developed from telephone surveys of each EPZ during the development of the site ETE studies [5]. The loading curves used for the medium and large population sites incorporate average trip generation times. The loading curve used in the small population site was taken from a representative site. Following current guidance [4], the shadow evacuees were loaded consistent with the loading of the EPZ population.

Table 4.11. Traffic simulation loading curves for each site

<table>
<thead>
<tr>
<th>Traffic Simulation Model Time</th>
<th>Evacuation Interval Number</th>
<th>Evacuation Time</th>
<th>Evacuation Period</th>
<th>Small Site EPZ Area Loading</th>
<th>Medium Site EPZ Area Loading</th>
<th>Large Site EPZ Area Loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:30</td>
<td>1</td>
<td>0:00</td>
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1. A 30-minute initialization period is used to load routine background traffic into the network prior to the emergency notification
2. Evacuation order is given at simulation clock time 0:30.
Loading curves encompass both the spatial and temporal processes of vehicle departures from their points of origin. The assumption in the development of loading curves using information from telephone surveys is that resident’s point of origin is their driveway. In traffic simulation models, however, vehicles are loaded using “dummy connectors” that do not capture residential streets or driveways. This modeling approach may omit a portion of the vehicle time needed to drive from their driveway. In most cases this was negligible; however, in some situations, this assumption could have a larger impact. In these situations, measures can be and were taken within the base models to increase the efficiency of some stop-controlled intersections to compensate. The O-D approach provides a simplified and reasonable method for loading large numbers of vehicles at selected origin parking lots and is consistent with the current state of practice in traffic simulation modeling. But direct application, without consideration of the physical infrastructure characteristics, may lead to inaccurate ETEs. It may be beneficial to enhance guidance to include a description of the process for sizing and spacing origin nodes in ETE studies.

4.7 Simulation Coding

4.7.1 Time Step

Time interval of processing is an input variable used in traffic simulation to control the rate of processing and response of vehicles to changes in traffic conditions. In the VISSIM microscopic simulation platform, the time interval of processing (referred as simulation resolution) influences the behavior of vehicles and their interactions [21]. The simulation resolution in VISSIM varies from 1 to 20-time steps per second. To reduce the computational load within the simulation a time step of 1 simulation per second was used.

4.7.2 Number of Runs

Microscopic model results are typically presented as an average of a set of runs where each run is performed with a random seed. VISSIM implements this approach because distributions are built into the code for some probabilistic parameters [47]. For each random seed, the model selects a value from the embedded distributions and executes the calculation. Different seed numbers produce different results, and results are presented as an average of the number of runs. Typically, a minimum of 10 runs is suggested [20] [24]; however, such recommendations do not consider the large size of the EPZ networks modeled or the number of runs ultimately executed for this research. The base models for each site were run 10 times and average results were presented. Using the 90 percent ETE as the most important metric, a statistical calculation was performed to determine the number of runs needed for each parametric analysis to achieve a 95 percent confidence level and an error of 10 minutes was used. The 90 percent ETE was used as the most important metric because the NUREG/CR-7002 [4] states that it is the value that protective action is based on.
\[ n = \left( \frac{Z_{\alpha/2} \cdot \sigma}{E} \right)^2 \]  

(Eq.1)

Where:

- \( n \) is the number of simulation runs required
- \( Z_{\alpha/2} \) Z-score for a two-sided error of 2.5 percent (5 percent total) with \( n - 1 \) degrees of freedom
- \( \sigma \) is the standard deviation from the initial sample of 10 runs from the base model
- \( E \) is the confidence interval of the true mean i.e. how much error is acceptable when estimating the mean

The goal of this statistical analysis is to determine the number of runs required to sufficiently produce an average result that falls within the confidence interval of the unknown true mean [16]. The analysis results were output in 5-minute increments. For the small population site, the 90 percent ETE from the 10 runs produced 7 ETEs between 145 and 150 minutes and 3 ETEs between 150 and 155 minutes. To determine the number of runs, it was assumed that the 7 ETEs were 145 minutes and the 3 higher value ETEs were 155 minutes, producing the largest possible standard deviation for the set. It was also assumed that plus or minus 5 minutes represents an acceptable error for the small population site. The calculation results show that four runs are required to provide a 95 percent confidence interval.

Subsequent analyses to support the tasks were performed for the medium and large population sites with an acceptable error of 10 minutes. The analysis suggested a total of 4 runs were required to produce average results suitable for the task analysis for both the medium and large models.

The approach to developing the number of runs required for the stochastic microscopic models requires judgment with regard to the most important metric to be used in the equation. In the base models, the 90 percent ETE was used. ETE guidance [4] suggests that the 90 percent ETE be used when licensees make a PAR and thus this was a reasonable metric to base the number of runs analysis on. It may be beneficial to provide guidance on determining the number of runs used in any stochastic analysis, the confidence level, and acceptable error.

### 4.7.3 Verification and Model Adjustments

Each model was loaded with a reasonable volume of background traffic distributed in a manner representing the population distribution. Speed and volume outputs were spot checked on key roadways during the background loading period (i.e., seeding) similar to the method described in the Oregon Protocol [24]. This spot checking of the speed and volume outputs provided a verifiable method of quality assurance Murray-Tuite, et al., [31], emphasize the importance of validation stating, “Validation for evacuation models is a difficult but important task. With more complexity, the models will become more difficult to validate but this step cannot be ignored.” Model validation is a key aspect of simulation modeling. However, the base models used were not validated because they do not represent an actual EPZ and therefore no data or information was available for this process. VISSIM default parameters are calibrated and validated to represent a generic traffic scenario. The base models were developed to be representative and not
site specific. Therefore, for the purpose of this research, it was appropriate to use default parameters instead of site-specific calibrated and validated ones.

Spot checking a set of roadways for vehicle volumes and speeds, prior to the start of evacuees entering the roadway network provides an efficient means of verifying that important roadways in the network are performing as expected. It may be beneficial for updated guidance to include a description of any calibration, validation, or verification that was conducted to ensure the model was performing as expected at the start of the evacuation simulation. Such a verification/validation would only be conducted on the background traffic flow in the model. This would not be compared to field conditions because field conditions vary considerably depending upon the scenario. The model review validation would be intended to confirm a reasonable number and distribution of background vehicles has been loaded into the model and that these vehicles are on the roadway at the start of the evacuation model run.

Review of interim model results was performed often throughout the model builds as a means to validate the reasonableness of the ETE. The evacuation time was the metric of interest for most of the internal reviews. When an ETE was determined to be excessive, the coding was reviewed to determine where issues may be occurring. Because controlled intersections usually present the initial point of congestion in a network, the review began with intersections. With the large number of intersections in the medium and large population models, an initial approach was to look for intersections where congestion was occurring upstream or downstream of intersections that were performing well. Coding was reviewed for accuracy, and signal timing was reviewed for realism. As needed, cycle length or phase times were adjusted to allow the intersection to perform more efficiently. Intersections that could not be improved with signal timing were considered for traffic control points (TCP).

Testing and review of interim model results periodically revealed sections of the roadway network that were substantially underutilized during the evacuation period. This was considered an unrealistic travel phenomena for these roadway segments. As described earlier, traffic simulation models attempt to replicate driver behavior through a coded network that represents an actual infrastructure, and the model algorithms sometimes route vehicles along obscure paths that are not realistic. To resolve this issue, the cost function in VISSIM was adjusted.

Cost, with respect to traffic simulation modeling, is a term used to apply a travel penalty on a particular route to discourage use of one route and encourage use of another. For these sections of the network, the freeway and evacuation route cost, which are the more likely roadways of choice, were reduced such that these routes would weight heavier in the route selection, and the arterial road costs were increased to make them a less desirable route choice. Additionally, for the large population site, two extra destination points were established to facilitate travel on the freeway over the arterial roads. After several iterations, a reasonable final distribution of vehicles was established for these roadway segments. The cost function is not applicable to the small population model, which was developed with the static approach.
4.8 Base Model Data Collection and Analysis

The base model used in this research was designed and coded to reflect a reasonably representative set of roadway infrastructure, population demographics, and vehicle loading characteristics that could be found within the EPZs of NPPs located within regions of comparatively small, medium, and large population areas. Given the size and complexity of the models, the number of locations, and the number of MOEs that were collected, the simulation runs generated a significant amount of output data. This was particularly the case for the medium and large population site models. Thus, the first step in analyzing the data was to determine where and how the output data would be collected. Then the appropriate comparisons to address the research questions could be made.

Three measures of model performance were selected to serve as the primary bases of comparison. These included the:

- Evacuation time estimate (ETE), commonly referred to as clearance time,
- Average travel speed at selected locations, and
- Hourly volume at selected locations.

These measures are point location indicators and it was collected at specific locations of interest within each model.

4.8.1 Data Collector Locations

VISSIM microscopic simulation requires data collection points to be established in the network prior to running the simulation. Because this study was founded on NRC guidance, the initial set of collection points were established at EPZ outflow routes at the 10-mile EPZ boundary. However, to gain a more comprehensive understanding of the effects of the shadow evacuation and have a better understanding of travel to different distances within the evacuation study area, data collection points were also established at a radius of 15 miles from the NPP (as referred to as the “15-mile ring”). Ultimately, additional sets of collector points were established at the 2, 5, and 20-mile rings.

Given the number of roads within the analysis networks, and the need to collect data at radii of 2, 5, 10, 15 and 20 miles, the number of collection point was substantial. The small population model, even with a considerably less dense road network than the medium and large population models, incorporated 109 data collection points. The locations of these are illustrated in Figure 4.5. The medium population model incorporated 147 collection points and the large population model incorporated 308 collection points. Clearance time, speeds and vehicle volumes, collected by vehicle designation (evacuee, background traffic, or shadow evacuee) were collected in five-minute intervals within each model.
4.8.2 Data Quantity

The number and frequency of data collection point created an enormous amount of data. To illustrate, the speed measure from one location, in one scenario, of the large population site model, with a ten-hour clearance time in the Base Case scenario would have created $(10 \text{ hours}) \times 12$ (5 minute periods per hour), or 120 data records for each vehicle designation. Then, given that the large population model has 308 data collector locations; a single scenario run of the large site model would yield $308 \times 120$ (data collection locations) $\times 120$ (data records), or 36,960 data records for each vehicle designation. Then, given that there were three MOEs (volume, speed, and ETE/clearance time) that were collected in each scenario, this resulted in the creation of $36,960 \times 3$ (MOEs), for a total 110,880 individual MOE data records for a single scenario for each vehicles type.
Carrying this forward and assuming that the Base Case Scenario had a higher clearance time than the zero percent shadow participation scenario, but lower clearance time than the 30 or 40 percent shadow participation scenarios, it would reflect an “average” number of records for the four shadow scenarios. Thus, the total number of data records for all four of the large population site scenario would be on the order of 4 scenarios × 110,880 data records per scenario, or 443,520 data records. And, ultimately, if it was assumed that the medium and small site models yielded data records within the same order of magnitude, combined, the three models run for this task yielded about one million data records.

However, because there were so much data and so many recording locations in the models, displaying the speeds in a coherent and meaningful way was somewhat problematic. As such, a key necessity of this research was to find methods to condense and summarize data such that it was meaningful but did not overwhelm and obscure potentially small and subtle, yet meaningful differences.

4.8.3 Other Performance Indicators

Relatively early in the development process of the models, observations of system performance suggested that additional useful and valuable information could be obtained by collecting some additional performance indicators. As expected, medium and large population site models showed evidence of extensive vehicle queuing along evacuation routes. Visual observation and reviews of quantitative results suggested that extensive queuing was occurring at intersections throughout all periods of the evacuation in both of these models. In fact, queue formation began early and extended over entire roadway corridors within the EPZ in the medium and high population sites. The queue growth on some routes of the medium population model was so extensive that it became indistinguishable from congestion resulting from high traffic volume along the segments. As it would be expected, inside the medium population model, the size of the road network does not increase as vehicles move away from the NPP. Medium population site inhabits many natural barriers (e.g. rivers) that limit the road network, which could lead to the reason why high queue lengths were observed. Similar conditions were observed throughout the large population evacuation model runs as well.

Current NRC guidance requires that the longest queue length for the 10 intersections with the highest traffic volume be provided in an ETE study. However, based on observations of the queuing in the experimental base models, it was impossible to distinguish the actual lengths of the queues, particularly when an entire corridor was congested and in a queued state. Thus, a requirement to present queuing data in an ETE study would likely provide little value or benefit to the review. And, as such, it may be beneficial to remove this data request from future NRC regulatory guidance.

Additional network-wide performance measures were collected from the base models. These were statistics collected from the entire model (zero to 20 miles) from the start of the simulation until the end. Statistics were stratified by vehicle type (background vehicles and pass through vehicles, EPZ evacuee vehicles, and shadow evacuee vehicles). The statistic collected were average vehicle delay, number of stops, total delay, average speed, vehicles hours traveled,
vehicle miles traveled, and the vehicles arriving at their destination as well as the number of vehicles still active in the model when the simulation completed. In general, these statics were used to provide quality assurance during the model development stages. From a task analysis perspective, these statistics were not very informative between scenarios because simulation time and evacuation rings were grouped together as performance metrics. For example, it was not possible to evaluate vehicle miles traveled within the EPZ and outside the EPZ, nor was it possible to segregate out the statistics collected after the seeding period.

4.8.4 Base Model MOE Results

All base model results were based on the average of 10 runs for each site model. As the research objective was to develop a technical basis for the update of ETE guidance, the primary MOE was evacuation clearance time from the EPZ. However, speed, volume, and clearance times from other areas of the network were also collected.

4.8.4.1 Based Model Evacuation and Clearance Times

Consistent with NRC guidance [4], the 90 and 100 percent ETEs were tabulated at the 2, 5, and 10-mile rings of the EPZ for each population model. As an additional level of analysis, clearance times were also recorded for at points on the 15 and 20-mile rings. ETEs and clearance times for each site at 90 and 100 percent evacuation levels of completion are shown in Table 4.12.

Table 4.12. Base model average ETEs and clearance times for the specified distances

<table>
<thead>
<tr>
<th>Site</th>
<th>2 mile ETE (h:mm)</th>
<th>5 mile ETE (h:mm)</th>
<th>10 mile ETE (h:mm)</th>
<th>15 mile Clearance (h:mm)</th>
<th>20 mile Clearance (h:mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90%</td>
<td>100%</td>
<td>90%</td>
<td>100%</td>
<td>90%</td>
</tr>
<tr>
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<td>1:35</td>
<td>2:21</td>
<td>1:44</td>
</tr>
<tr>
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<td>4:03</td>
<td>2:47</td>
<td>5:08</td>
<td>5:02</td>
</tr>
</tbody>
</table>

In the Table 4.12, it can be seen that the 100 percent ETE for the small population site was 2 hours 31 minutes and the 90 percent ETE was 1 hours 44 minutes. This difference of 37 minutes suggests that the last ten percent of evacuees increased the clearance time by about 35 percent. This finding was relatively consistent with prior assumptions that suggest that the evacuation tail can significantly increase evacuation clearance time [78]. In many cases, the small population site ETEs were consistent in the loading times identified in Table 4.11. This phenomenon is not uncommon in small area evacuations and has been observed in other small population site ETEs where road networks provide capacity sufficient to keep traffic flowing at near-free flow speeds and minimal delay. Because of this, loading time tends to be the dominant contributor to the
ETE. Figure 4.6 illustrates the relationship between the loading curve and the ETE profiles for the small population site.

The ETE times at the various inner and outer ring distances provide insights into traffic flow conditions throughout the small population site model. As expected, the clearance times increased at further distances, however, the relative small time increases suggest the ability of small population sites to maintain high vehicular travel speeds, even at more distant locations. The data also show relative consistency between the 90 and 100 percent evacuations. The time required to evacuate the last 10 percent of vehicles at the 2, 5, 10, 15, and 20-mile rings took between 40 and 45 minutes on average.

![Small Site Evacuation Time Estimates](image)

Figure 4.6. ETE curves for the small population site

The 100 percent average ETE for the medium population site was 7 hours 41 minutes, approximately 2 hours 42 minutes longer than the 90 ETE time and 3 hours and 41 minutes longer from the loading time. The last ten percent of evacuees increase the model EPZ ETE by nearly 52 percent. The time elapsed between the loading curve and the 100 percent ETE suggest congestion caused approximately 3 hours of delay as demand exceeded the available capacity.

ETE values for 2, 5, and 10-miles as well as clearance times 15 and 20-mile locations and the loading curve can also be seen from Figure 4.7 for the medium population site. The ETE values
for the two and five-mile rings mirror the loading curve. This was an expected finding because the areas nearest the NPP were have low population and should perform similar to the small population site. After the five-mile ring, the population increase resulting in a divergence between the loading curve and the ten-mile ETE. This trend continues as population increase further from the NPP. As the evacuation progress, the network traffic begins to clear and the ETE values begin to converge back to the loading curve rate. This too was expected due to the long tail of the loading curve. After the majority of traffic has abated, travel times would be expected to resume free-flow conditions.

![Medium Site Evacuation Time Estimates Base Model](image)

**Figure 4.7. ETE curves for the medium population site**

The 100 percent ETE for the large population site was 9 hours and 2 minutes. This was 4 hours 19 minutes longer than the 90 ETE and 4 hours and 47 minutes longer than the loading curve. The spatial and temporal distribution of demand generated by the loading of evacuees, generated as much as 5 hours of added travel time during portions of the evacuation. This was the result of severe congestion, as demand exceeded the available capacity. A similar relationship can also be seen in Figure 4.8 for the large population site model.

Similar to the results of the other models, Figure 4.8 illustrates the traffic conditions within the large population site model. As expected, there was considerably more congestion early on in the evacuation as demonstrated by the approximate two additional hours taken to clear evacuees.
between the two to five-mile rings. Then similarly, further downstream between the 5 and 10-mile rings. Beyond the 10-mile EPZ boundary, the additional clearance time became smaller with only 12 additional minutes to clear the area between the 10 and 15-mile rings, then only an additional 11 minutes after that to clear between the 15 to 20-mile rings. These decreasing differences likely reflect the increasing robustness of the network with additional routes and capacity available to traffic as it moves into more distant and more populated areas of the region.

The differences between the 90 and 100 percent evacuation ETEs data also show longer durations, but relative consistency. A 1 hour 25 minute or 39 percent added time was required to clear the last ten percent of traffic at the 2-mile ring, then 2 hours and 37 minutes or an additional 66 percent of the time beyond the 90 percent was needed for the last ten percent at the 5-mile ring. Then, however, at the more distant 15-mile ring, the added time difference was a near doubling over that required for the 90 percent at 3 hours 54 minutes or 73 percent increase to clear the last ten percent of the vehicles. And, finally, 3 hours 40 minutes 64 percent more was required at the 20-mile ring. These results are notable from the perspective that they showed the tendency for the 100 percent clearance times to increase further away from NPP. This may be suggestive of considerable residual congestion at distances further away from the NPP and at times later in the evacuation.

Figure 4.8. ETE curves for the large population site
Table 4.13 identifies the 100 percent clearance times for the specified distances of the four 90 degree quadrants of each site. This information was useful in understanding the variation of clearance times by quadrant and comparing the values to the population distributions. It should be noted these are not ETE values. These numbers report the clearance times of that quadrant and at the mile ring only. It is independent of the traffic conditions of roads that pass through a quadrant but not necessarily exit at rings inside that quadrant. Multiple collectors are typically located on each specified ring, although, as indicated in the table, some quadrants had no collector points. The maximum value for the quadrant is presented in the table below. The other collectors within each quadrant had values equal to or less than those in the table. Note that “NC” indicates that there are no collectors located in the quadrant.

<table>
<thead>
<tr>
<th>Site Quadrant</th>
<th>2 mile 100%</th>
<th>5 mile 100%</th>
<th>10 mile 100%</th>
<th>15 mile 100%</th>
<th>20 mile 100%</th>
</tr>
</thead>
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<td>NC</td>
<td>NC</td>
<td>2:15</td>
<td>2:35</td>
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<tr>
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<tr>
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<td>2:35</td>
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<tr>
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<td>9:09</td>
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<tr>
<td>Large S</td>
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<tr>
<td>Large W</td>
<td>5:06</td>
<td>6:35</td>
<td>6:09</td>
<td>8:27</td>
<td>9:07</td>
</tr>
</tbody>
</table>

Based on these results, it is suggested that care should be taken in the assessment of clearance time information for areas beyond the EPZ, as these calculations were specific to this research. All models were structured to direct evacuees radially away from the NPP, until they exited the EPZ and continued through the 20-mile ring. As provided in NUREG-0654/FEMA-REP-1, Revision 1 [5], relocation centers are at least five miles and preferably 10 miles beyond the plume exposure pathway EPZ. EAS messaging and emergency response brochures would identify the locations of these centers, and results of national telephone survey of EPZ residents found that 34 percent of respondents were extremely likely to go to the reception centers [8].
The base models do not consider that portions of the population may cease their travel at some point within the 10 to 20-mile region beyond the EPZ.

Table 4.14 provides the high, low, and mean ETE results for the 10 and 15-mile areas for the three population site models. Once again, these values represent the mean value of ten separate model runs.

Table 4.14. Mean, high, and low ETE and clearance time results of the 10 simulation runs

<table>
<thead>
<tr>
<th>Site</th>
<th>10 Mile ETEs (h:mm)</th>
<th>15 Mile Clearance Times (h:mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>Mean</td>
</tr>
<tr>
<td>Small</td>
<td>2:30</td>
<td>2:31</td>
</tr>
<tr>
<td>Medium</td>
<td>7:30</td>
<td>7:41</td>
</tr>
<tr>
<td>Large</td>
<td>9:00</td>
<td>9:02</td>
</tr>
</tbody>
</table>

As shown in Table 4.14, the stochastic nature of the VISSIM system creates variation in the ETEs among the ten individual runs. This variation is intended to reflect the normal variation in traffic conditions from day to day; and even minute to minute. The variation among the ten runs for each of the sites was relatively low for the 10-mile EPZ. It was about five minutes or about three percent of the mean for the small site, 30 minutes or about six percent of the mean for the medium site, and about 15 minutes or just under three percent of the mean for the large population site model. These results suggest that it is important to use the mean value for a set of runs that establishes a level of variation. As such, it may be beneficial to provide guidance on using an average value of a number of runs in the unlikely event a microscopic model is used in an ETE analysis.

4.8.4.2 Base Model Travel Speeds

Average travel speeds observed at collector points throughout the various models were used to assess other specific aspects of travel conditions for vehicles traversing the network at key locations during the evacuation scenarios. Speeds were recorded for individual vehicles then grouped into averages in five-minute increments.

To accomplish this, detector locations were grouped into 16, 22.5 degree, compass sectors (N, NNE, NE, ENE, E, etc.). Within these sectors, speeds were averaged and grouped by time period, and summarized within each of the concentric compass rings. In this way, variations in speed could be displayed over time and in the various exit directions away from the NPP. Figure 4.9, 4.10, and 4.11 display the progression of travel speeds for the small, medium, and large population sites, respectively.

The speed data showed results consistent with the clearance time data for the small site. In general, operating speeds tended to be high throughout the small population model. In many cases, speeds averaged above-posted speeds in the network. This was consistent with observations made during peak hour traffic where volumes are below capacity. Traffic speeds tend to be higher than posted speed as drivers travel at their desired speed. VISSIM allows for
this by modeling individual vehicles and their desired speed as opposed to setting the maximum speed of a link, as is common with macroscopic models.

Figure 4.9 is useful because it illustrates several key features of the early periods of the small site evacuation at the 20 percent Base Case shadow participation level. The most obvious of these is the consistency of speeds during the early portion of the evacuation. The three curves align virtually exactly. This suggests that there was not much speed change over the first hour and a half of the evacuation. It further suggests that there was little-to-no build-up and discharge of congestion and delay during this time period. The figure also shows zero speeds in the NNE, SSW, and WSW sectors of the figure. These do not mean that vehicles were not moving, rather they reflect that no traffic moved out of the EPZ on routes within these sectors. Conversely, the high speeds in the southeasterly and northwesterly quadrants of the figure suggest that there was little-to-no congestion and that traffic was effectively moving at free-flow speeds through these regions of the EPZ.

Figure 4.9. 10-mile EPZ average speeds for the small population site

Figure 4.10 shows much greater speed variation of the evacuation for the medium model. The curves of this figure illustrate drops in speed within several of the sectors. However, not every sector saw a drop-in speed and some sectors experience a drop-in speed early in the model but then recovered. This suggests the population density within the medium population site was not
uniformly distributed. The speed data suggest that some sector, predominately in the south and southeast, were impacted greatly by the evacuation. This was expected because these sectors have the highest population density. Other sectors, in the north and west have low population density and travel speeds respond similarly to the small population site. The drop-in travel speeds and eventual recover in the north-northeast and east sectors suggest the formation of congestion in those areas during the middle parts of the evacuation, then a gradual recovery back to free flow speeds in the later stages of the clearance process. In fact, these data further suggest the network was able to eventually recover and it would be expected that conditions would converge back to free flow toward the end of the evacuation.

Figure 4.10. 10-mile EPZ average speeds for the medium population site

Figure 4.11 shows the average speed data for the large population site. Similar to the medium population site, this figure shows a diversity of travel speeds at various times through the evacuation. However, speed drops in this model were not as severe as they were in the medium population model and speeds were typically able to recover by the end of the simulation. This suggests the large population site was better able to cope with evacuation traffic when compared to the medium population site. This was likely because the large population site, while having a higher population density also had a higher concentration of roads to spread the evacuating vehicles upon. The road network in the large population site was not restricted with as many
bodies of water as was the medium model and therefore ultimately had more available exit routes to spread traffic out on. While the high population did cause significant congestion within the model, the abundance of exit routes made this site more resilient and better able to cope with the added stress of the evacuating vehicles.

Figure 4.11. 10-mile EPZ average speeds for the large population site

### 4.8.4.3 Base Model Vehicle Volumes

In addition to determining the clearance time based on the “last vehicle” leaving the EPZ, the volumes are captured from vehicles passing over the data collectors. Among these was that it gave the ability to track model input volumes and output volumes and provided a basis for assessing for the dispersion and destination of vehicles within the analysis areas.

In this research, vehicles were generated using (and statistics collected for) three different sets of vehicle classifications. These included:

- Background vehicles (including pass-through traffic for the medium and large population sites)
- Evacuee vehicles, and
- Shadow vehicles
A fourth category, total vehicles, or a combined summation of all vehicles in the network was also used for some analyses.

Table 4.15 summarizes the number of vehicles generated within and exiting the ten-mile EPZ, and other shadow and background vehicles generated and moving through the shadow areas. Once again, the values in the table represent averaged values from the ten runs conducted for each site.

Table 4.15. Summary of EPZ and Shadow evacuation vehicle inputs and exits

<table>
<thead>
<tr>
<th>Model</th>
<th>EPZ Evacuee Vehicles Input / Exit</th>
<th>Show Vehicles Input / Exit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>3,750 / 3,747</td>
<td>1,500 / 1,450</td>
</tr>
<tr>
<td>Medium</td>
<td>100,000 / 98,894</td>
<td>15,000 / 14,955</td>
</tr>
<tr>
<td>Large</td>
<td>162,500 / 160,836</td>
<td>30,000 / 29,866</td>
</tr>
</tbody>
</table>

The table shows that a number of vehicles were not generated or did not exit the EPZ. These vehicles were “lost” in the analysis. This is a feature of many microscale models and can occur for reasons ranging from vehicles unable to move for an extended amount of time to unrealistic routing. In VISSIM, the system allows vehicles to disappear or be removed from the analysis when certain conditions occur that prevent a vehicle from executing a desired function. Because this was generally a small number of vehicles within the overall traffic process, there was no effort to identify the cause of the lost vehicles.
5 Shadow Evacuation Analysis

5.1 Assumptions

In this research, a large number of assumptions were made in the development of the three base models as described in Section 4.1 of this report. A number of additional assumptions, related specifically to the shadow evacuation were also made. While it is understood that specific conditions could, in fact, vary significantly during any particular emergency, the primary key assumptions made in this research included the following:

- 20 percent shadow participation was used for the Base Models,
- The shadow contribution was assumed to be fixed rate throughout the 5-mile area beyond the EPZ
- The start of shadow evacuation was coincident with the EPZ evacuees, with same trip generation times.
- A maximum shadow participation of 40 percent of the public within the shadow region is available to evacuate as shadow for the medium and large population site.

5.1.1 Analysis of Shadow Participation

The shadow evacuation population implemented in the Base Models included

- Small population site: 3,000 shadow evacuees; 1,500 vehicles
- Medium population site: 30,000 shadow evacuees; 15,000 vehicles
- Large population site: 60,000 shadow evacuees; 30,000 vehicles

The criteria in Appendix E to 10 CFR 50 [1] and NUREG/CR-7002 [4], which identified a 25 percent increase in the ETE or 30 minutes, were used to determine whether the ETE was impacted significantly, with regard to increases in the shadow population. To determine the size of the evacuation that would be necessary to increase clearance times significantly, comparisons were made to the base values for the 10-mile ETEs for each site. All parameters and input values to the Base Models were held constant and only the shadow population was adjusted. The 90 and 100 percent ETEs were tabulated for each quadrant of the small, medium, and large population sites. The largest ETE value was selected from each quadrant for comparison to the ETE from the same collector point in the Base Model results. Shadow analysis data was collected at 2, 5, and 10-mile distances from the NPP site.

5.1.2 Output Data Groups and Bases of Comparison

As the primary variant in this task, the three different area population sizes served as primary sets of output. Then, within each of these three population groupings there were four separate rates of participation within the shadow region just outside the EPZ. These included a zero percent, 20 percent, and 40 percent levels participation. Because of the assumed likelihood of little effect a 100 percent participation in the shadow region of the small population model was also performed, in lieu of a 30 percent participation for this model. These test scenarios resulted in a total of 12 primary data sets which are summarized in Table 5.1.
### Table 5.1. Test Scenarios

<table>
<thead>
<tr>
<th>Site Population Size</th>
<th>Shadow Participation Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>20*</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Medium</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>20*</td>
</tr>
<tr>
<td></td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>40</td>
</tr>
<tr>
<td>Large</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>20*</td>
</tr>
<tr>
<td></td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>40</td>
</tr>
</tbody>
</table>

*note: 20 percent shadow participation scenarios are required as part of current NRC guidance and, thus serve as the Base Case scenario and primary basis of comparison for the three site population size models.

### 5.2 Limitations

The assumptions made in this research brought along some limitations. These limitations could, in fact, affect the results, discussed in the next section, significantly. One of the main limitations of this study was the assumptions made for the shadow evacuation process. It was assumed that the shadow participation rates were distributed evenly inside the shadow region. In a real-life scenario, it is likely that shadow population that is closer to the EPZ (e.g. between 10-11 mile rings) might have a higher participation rate than shadow population that is further away (e.g. between 14-15 mile rings). Having a higher population participation near the EPZ boundary can cause longer delays for the EPZ population compared to an evenly distributed shadow participation rate that was done in this study.

Another limitation of this study is the loading of the shadow population inside the models. The mobilization curves for the EPZ population and the shadow population were modeled the same with no time offset. However, this could vary significantly depending on many variables (e.g. evacuation type, threat severity, time of day and etc.) and can affect the results presented in this study. Also, the results presented in this research are limited to only the effects of shadow population to the EPZ population 10-miles away from the threat area. There could be other significant effects outside the EPZ from the increased shadow participation rates that this research does not include.
5.3 Results

Similar to the process used to develop the Base Model measures of performance, the shadow analyses were based on the execution of four individual simulations for the large and medium models and 10 for the small model, from which, averaged value of the performance metrics for each experimental trail was developed. These average values help to account for the model stochasticity of the VISSIM system. It also helped to lessen the likelihood of data interpretation being made on a single run that could have potentially produced an “outlier” result.

Similar to the base model, the bases of comparison for the shadow analysis were evacuation and clearance time, average travel speeds, and outflow volume on all links exiting the EPZ. Consistent with the manner in which all data were collected, the clearance times, average travel speeds, and outflow volumes were collected and tabulated in increments of five minutes. Also consistent with NRC regulatory guidance. The two output measures of performance were noted for both 90 percent and 100 percent evacuations of the EPZ.

As an additional avenue of exploration of clearance time results were also assessed by compass sector (i.e., North, N-North-East, North East, and etc.) for the large and medium models and compass sector quadrant (i.e., North, East, South, and West) for the small model. Similar to the clearance times, average travel speeds were also assessed by compass sector for all three models. It was hypothesized that sector level analyses would reveal more detailed aspects of the evacuation process that may not be apparent from a single clearance time value for the medium and large models but might not be necessary for the small model. Specifically, they were anticipated to give insight into site characteristics that exacerbate the effects of shadow evacuation. A presentation of the quantitative results and an associated discussion of notable aspects of the results for the all three models, beginning the 20 percent participation rate Base Models, are included in the sections that follow.

5.3.1 Evacuation and Clearance Times

This section discusses results of varying shadow population rates on evacuation and clearance time. The ETE for each model was calculated for the 2, 5, and 10-mile rings. Additionally, the sector clearance time was also calculated for the medium and large sites and quadrant clearance time was calculated for the small site. The quadrant analysis for the small site included the average ETE values that pooled the NNW, N, NNE and NE for the North quadrant, ENE, E, ESE and SE for the East Quadrant, SSE, S, SSW, and SW for the South Quadrant and WSW, W, WNW, and NW for the West Quadrant.

5.3.1.1 Small Model Evacuation and Clearance Times

For smaller population areas, it would not be expected that the shadow would have much, if any, impact. This was confirmed through review of prior sensitivity studies included in licensee submitted ETE studies, none of which identified a significant impact for small population sites. Thus, for research purposes, the shadow contribution was increased to 100 percent of the population in the shadow region for the small population site shadow analysis.
As discussed earlier, a reasonable maximum contribution for the shadow evacuation is 40 percent of the residents in the shadow area. However, the analysis of 100 percent of the shadow area consistently demonstrated that, even at these levels, there was no significant change in the ETE for the small population site as shown in Table 5.2. Increasing the shadow participation rate from 20 percent to 100 percent did not increase the 10-mile ETE by 30 minutes or 25 percent. It was therefore concluded that shadow evacuation participation rate for the representative small population site had no impact on the 10-mile ETE.

Table 5.2. ETE and clearance times for small population site shadow analysis

<table>
<thead>
<tr>
<th>Shadow Participation Rates</th>
<th>2 MILE RING</th>
<th>5 MILE RING</th>
<th>10 MILE RING</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90% ETE</td>
<td>100% ETE</td>
<td>90% ETE</td>
</tr>
<tr>
<td>0%</td>
<td>1:35</td>
<td>2:18</td>
<td>1:35</td>
</tr>
<tr>
<td>20% (base)</td>
<td>1:35</td>
<td>2:18</td>
<td>1:35</td>
</tr>
<tr>
<td>100%</td>
<td>1:35</td>
<td>2:18</td>
<td>1:35</td>
</tr>
</tbody>
</table>

Figure 5.1 shows the cumulative percent evacuated for the small population site at the 10-mile ring. This figure is a visual representation of the ETE times shown in Table 5.2. The figure also displays the evacuee loading curve for reference. From the figure the 10-mile ETE for the zero percent, 20 percent, and 100 percent shadow population participation are indistinguishable, further suggesting the participation rate of the shadow had a nominal impact on the small population site ETE.
Figure 5.1. 10 Mile ETE curve for the small population site

Table 5.3 identifies the clearance times by quadrant for the specified distances and progressively increasing shadow populations up to the 100 percent maximum for the small population sites. In addition, no discernable differences were seen by the increase in shadow participation from zero to 100 percent in the small model. This finding again, supports the hypothesis that shadow participation may not have a significant contribution to ETEs in small population sites.

<table>
<thead>
<tr>
<th>Quadrant</th>
<th>0%</th>
<th>20% (Base)</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90% ETE</td>
<td>100% ETE</td>
<td>90% ETE</td>
</tr>
<tr>
<td>South</td>
<td>1:44</td>
<td>2:30</td>
<td>1:44</td>
</tr>
<tr>
<td>West</td>
<td>1:44</td>
<td>2:29</td>
<td>1:44</td>
</tr>
</tbody>
</table>

5.3.1.2 Medium Model Evacuation and Clearance Times

Due to high demand and low availability of roads, the medium population site was expected to show a significant impact from an increased shadow evacuation participation rate. However, this
was not the case for the 100 percent ETE. Table 5.4 shows the 90 percent ETE and 100 percent ETE times from 2-mile, 5-mile, and 10-mile rings. It was expected that the zero percent shadow participation rate would consistently result in a lowest 90 percent and 100 percent ETE, followed by the base 20 percent, 30 percent, and 40 percent participation rates. The 5-mile 90 percent and 100 percent ETE times show slight variations, which contradict this convention. The zero percent shadow participation rate 90 percent and 100 percent ETEs have the highest clearance times compared to the other scenarios. This is most likely caused by the stochastic nature of the VISSIM model and the method used to calculate averages. Furthermore, the 100 percent ETE at the 10-mile followed the previous assumption where zero percent participation has the lowest ETE and the 40 percent participation has the highest ETE and there was no significant impact compared to the base scenario. However, this was not the case for the 90 percent ETE. There was a noticeable impact on the 90 percent ETE for the 40 percent shadow participation rates compared to the base scenario. The 90 percent ETE resulting from zero percent shadow participation and 40 percent participation rates differed by 36 minutes or approximately 12 percent and 34 minutes or nearly 11 percent between 20 and 40 shadow participation rates.

Table 5.4. ETE and clearance times for medium population site shadow analysis

<table>
<thead>
<tr>
<th>Shadow Participation Rates</th>
<th>2 MILE RING</th>
<th>5 MILE RING</th>
<th>10 MILE RING</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90% ETE</td>
<td>100% ETE</td>
<td>90% ETE</td>
</tr>
<tr>
<td>0%</td>
<td>2:40</td>
<td>4:03</td>
<td>2:50</td>
</tr>
<tr>
<td>20% (base)</td>
<td>2:40</td>
<td>4:03</td>
<td>2:47</td>
</tr>
<tr>
<td>30%</td>
<td>2:40</td>
<td>4:03</td>
<td>2:47</td>
</tr>
<tr>
<td>40%</td>
<td>2:40</td>
<td>4:03</td>
<td>2:45</td>
</tr>
</tbody>
</table>

Figure 5.2 shows the cumulative percent of vehicles evacuated from the medium population site at the 10-mile EPZ boundary. The figure illustrates the clustered nature of the ETEs that resulted from the varying shadow participation rates. In a non-congested network, as seen in the small model Figure 4-1, the shadow of the cumulative percent evacuated curve matches closely to the shape of the loading curve. Without congestion, these two curves are only separated by the free flow travel time between the origins and destinations. When congestion is present, the shape of the cumulative percent evacuated curve tends to be linear, as vehicles queue near the EPZ exit and leave the network at a uniform rate. This impact can be seen in the medium population site where severe congestion delays vehicles for all levels of shadow participation rates. Likewise, the noticeable impact to the 40 percent shadow participation rate on the 90 percent ETE can also be seen in this figure. Where the 40 percent curve starts to deviate from the rest at around three hours into the evacuation and this gap closes at the 100 percent ETE.
Figure 5.2. 10 Mile ETE curve for the medium population site

Figure 5.3 and 5.4 show the medium population site ETEs by sector. In both of the figures, most of the impact can be seen in the NE, ENE, E and the ESE sectors. Although Table 5.4 showed no impact on the 100 percent ETE, Figure 5.4 clearly shows that there is a noticeable impact in some sectors. These effects are not represented in Table 5.4 because NNW sector has the highest ETE value and it overshadows the other sectors. It is very important to study ETE by sector to see these kinds of impacts where it might not be visible from the single ETE value. ESE sector has experienced the highest impacts with 40 percent shadow region evacuation participation where the 90 percent ETE increased by one hour and 40 minutes and the 100 percent ETE increased by one hour and 45 minutes. This further suggests shadow region evacuation participation is not going to have the same effect throughout the entire roadwork.
Medium Site Evacuation Time Estimates by Sector
90% ETE Mile 10

Figure 5.3. 10 Mile medium population site 90 percent ETE by sector
5.3.1.3 Large Model Evacuation and Clearance Times

For the large population sites, it was expected that high shadow participation rates would have a significant impact on the ETEs. However, the results of the ETE analysis suggested this may only be partially true. The results of the analysis indicate that the 90 percent ETE was noticeably impacted by an increase in shadow participation, but the 100 percent ETE was not. Table 5.5 shows the large site 90 percent and 100 percent ETEs for zero, 20, 30 and 40 percent shadow participation rates. The 100 percent 10-mile ETE varied by less than 30 minutes between the zero and 40 percent participation rate. This suggests the 100 percent ETE was insensitive to the increased shadow participation rate. However, the 90 percent ETE varied by 50 minutes or approximately 19 percent between the zero percent and 40 percent shadow participation rates. Comparing the 20 percent and 40 percent participation, the 90 percent ETE varied by 35 minutes, approximately 12 percent increase in ETE. Initially, this discrepancy would appear to be significant but the range of 90 percent ETE values for zero, 20, and 30 percent were fairly small (12 minutes separate the 20 percent and 30 percent ETEs). This would suggest that an assumed participation rate anywhere from within the range of 20 to 30 percent would likely not have an impact on the decisions to evacuate. Only if the shadow participation rate increases beyond 30 percent, would evacuees begin to see delays that could impact the decisions to
evacuate or shelter in place. This may suggest the ETE corresponding to 40 percent shadow participation may disproportionally impact the analysis. Furthermore, there was minimal impact to the 2-mile ETEs where the only effect can be seen at the 40 percent shadow participation. The 90 percent ETE varied by one minute and the 100 percent ETE varied by six minutes compared to the other participation rates. Similarly, the 5-mile also showed no impact with different shadow participation rates. The difference between ETEs from zero and 40 percent participation rates were 14 minutes and 16 minutes for 90 and 100 percent ETE respectively.

Table 5.5. ETE and clearance times for large population site shadow analysis

<table>
<thead>
<tr>
<th>Shadow Participation Rates</th>
<th>2 MILE RING</th>
<th>5 MILE RING</th>
<th>10 MILE RING</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90% ETE</td>
<td>100% ETE</td>
<td>90% ETE</td>
</tr>
<tr>
<td>0%</td>
<td>3:40</td>
<td>5:05</td>
<td>3:53</td>
</tr>
<tr>
<td>20% (base)</td>
<td>3:40</td>
<td>5:05</td>
<td>3:57</td>
</tr>
<tr>
<td>30%</td>
<td>3:40</td>
<td>5:05</td>
<td>4:03</td>
</tr>
<tr>
<td>40%</td>
<td>3:41</td>
<td>5:11</td>
<td>4:07</td>
</tr>
</tbody>
</table>

Figure 5.5 shows the cumulative percent evacuated at the 10-mile ring for the large population site. A comparison with the loading curve suggests the evacuees experienced moderate to severe congestion. The figure also illustrates the 100 percent ETE for all participation rates converged at around nine hours and also shows the impact on the 90 percent ETEs. Furthermore, the figure suggests that up to 50 percent of the evacuees were able to exit the EPZ before any impact of the shadow region could be seen inside the EPZ and 70 percent of evacuees leave the 10-mile before the delays reach more than 30 minutes. The greatest impact can be seen between 70 to nearly 95 percent where the last 25 percent of evacuees experience the highest delays. After roughly 95 percent of evacuees had left the EPZ the all the curves converge toward the 100 percent evacuation completion.
Section IV of Appendix E to CRF part 50 requires ETE studies to provide analysis of time required to evacuate for various sectors that are within the plume exposure pathway for residents [1]. Figures 5.6 and 5.7 show the large population site ETEs by sector. It was expected that the 40 percent shadow participation would have the highest ETEs and similarly, 0 percent shadow participation would have the lowest ETEs. Figure 5.6 represents the 10-mile 90 percent ETE for each sector. N, NNE, SW, and WSW showed no effect to different shadow participation rates for the 90 percent ETE, where ENE, E, ESE, and SSW showed an effect with only 40 percent shadow participation. Rest of the sectors, NE, SE, SSE, S, W, WNW, NW, and NNW showed an increasing effect where zero percent had the least effect and 40 percent had the most effect on evacuation times. Unlike the medium model sector ETEs, the large model showed a negligible effect at 100 percent ETEs shown in Figure 5.7. The highest differences can be seen in the WNW sector between zero and 40 percent participation rates, where the change in ETE is roughly one hour.
Figure 5.6. 10 Mile large population site 90 percent ETE by sector
5.3.2 Average Travel Speeds

Travel speeds at detector locations were grouped into 16 compass sectors (N, NNE, NE, ENE, E, etc.) and speeds were averaged for various time periods at each of the concentric compass rings. In this way, speed increases and decreases could be displayed over various time spans in the various exit directions away from the NPP. This method for displaying speed data provided a reasonable means of comparing speeds between different models over the same time period.

5.3.2.1 Small Model Average Travel Speeds

Figures 5.8 and 5.9 show the average travel speed in the small model at 0:15 and 1:45 hours into the simulation for the 0, 20, and 100 percent shadow participation, respectively. The average speeds at 0:15 hours are indicative of free flow conditions and exemplify the “best case” scenario within each sector. No impact of shadow participation is seen in this figure. This was because the figure captured a time when evacuees are just beginning to enter the EPZ and shadow region. Figure 5.9 was taken at 1:45 into the simulation when most evacuees were loaded onto the road network. This figure shows the average travel speeds for the various shadow participation rates overlapped in the figure. This suggested that the shadow population participation rated had little to no impact on average travel speed in the small population site. Furthermore, by comparing...
Figures 5.8 and 5.9, it can be concluded that evacuees are able to travel at or near free flow speed 1:45 hours into the evacuation. This suggested that model was uncongested even at 100 percent participation of the shadow population.

![Small Site Average Speeds](image)

**Figure 5.8.** Small population site 10-mile average speeds at 0:15
5.3.2.2 Medium Model Average Travel Speeds

Figures 5.10, 5.11 and 5.12 show the average travel speed in the medium population site models at 2:30, 3:30, and 4:30 into the simulation for the 0, 20, 30, and 40 percent shadow participation, respectfully. By 2 hours and 30 minutes into the simulation, the figures show the onset of congestion in the NNW and ESE sectors and travel speeds are beginning to be impacted by the shadow participation rate. One hour later, the impact of congestion is beginning to dominate the NNW, N, E and ESE sectors and the influence of the shadow region on these severely congested areas are reducing speeds further. However, the other sectors of the model appear to be uncongested and unaffected by the shadow region. By four hours and 30 minutes, congestion in the E and ESE sectors has continued to reduce speeds. At this point, the shadow evacuation region has little impact in reducing speeds further. Also, at this point, the South portion of the model have mostly completed their evacuations, hence why the speeds are shown as zero. Taken as a whole, these three figures would suggest that shadow participation did impact the EPZ, and mostly the E and ESE sectors increasing the ETE by nearly two hours. Although the shadow participation affected the average speeds for NNW and N sectors it was not enough to impact the ETE by 30 minutes or 25 percent. However, these two sectors only got effected towards the
beginning of the evacuation and recovered towards the end, unlike E and ESE sectors. This could be the reason why there was no significant impact on the evacuation times.

Figure 5.10. Medium population site 10-mile average speeds at 2:30
Figure 5.11. Medium population site 10-mile average speeds at 3:30
Figure 5.12. Medium population site 10-mile average speeds at 4:30

5.3.2.3 Large Model Average Travel Speeds

Figures 5.13, 5.14, 5.15 show the progression of average travel speed in the large population model at all shadow participation levels during hours 2:30, 3:30, and 4:30, respectively. The average travel speeds are shown in Figure 5.13 at 2:30 hours into the simulation show only a few sectors experienced speed changes between the various shadow participation levels. This figure suggests zero percent participation over this time interval had a unique speed profile and had the highest impact in the ENE and ESE sectors when compared to the other participation rates. The finding may indicate the lack of a signification shadow population could have impacted the level of congestion early on in the simulation. However, by 3:30 hours into the simulation, the speed profiles for the various participation rates converged in Figure 5.14 with only slight speed discrepancy in the S, SSE, SE, and ESE sectors. Figure 5.15 also showed a similar consistency of average speed for the various shadow participation rates but with larger variations in speed for the South sector. These findings support the hypothesis that large population densities within the shadow region may serve to exacerbate the impact of the shadow evacuation. The speed analysis also suggested that once significant congestion built within the model, average speed tended to converge, regardless of the shadow participation rate. The shadow participation rate may have
played a role in when the speed drop occurred but, ultimately with congestion building in EPZ, an overall drop in average speed was likely unavoidable.

Figure 5.13. Large population site 10 mile average speeds at 2:30
Figure 5.14. Large population site 10-mile average speeds at 3:30
5.3.3 Flow Rates

The EPZ exit flow rate was the number of vehicles, which exited the 10-mile EPZ over each five-minute data collection interval. This flow rate was then converted into vehicles per hour to be constant with the standard practices of traffic engineering. Fundamentally, the 10-mile EPZ exit flow rate measured the diffusion of evacuation vehicles out of the EPZ and into the shadow evacuation region. It was expected that high shadow participation would impact the rate at which vehicles were able to exit the EPZ.

5.3.3.1 Small Model Exit Flow Rates

Figure 5.16 shows the small population site exit volume at the 10-mile ring for zero, 20, and 100 percent shadow participation rates. The figure suggested the small population site 10-mile ring exit volumes were not sensitive to the shadow participation rate. This was likely because the shadow area did not experience congestion, even during the 100 percent participation rate scenario, and thus EPZ evacuees were not significantly impacted by shadow evacuees.
5.3.3.2 Medium Model Flow Rates

Figure 5.17 shows the medium population site EPZ exit volumes for zero, 20, 30, and 40 percent shadow participation. The figure suggests the shadow participation rate did not significantly impact the exit volume of the EZP at rates less than 40 percent. However, the 40 percent participation rate did appear to affect the exit flow rates beginning at approximately two hours and 45 minutes and continuing for two hours. However, after this the exit flow rate increase beyond that of the base model and was able to effectively dissipate the additional queue, resulting in a 100 percent ETE similar to the base model. This suggests the 40 percent evacuation rate did impact the EPZ exit volumes but, not enough to increase the overall ETE by 30 minutes or 25 percent because the flow rates were able to recover.
Figure 5.17. Medium population site 10-mile exit volumes

### 5.3.3.3 Large Model Flow Rates

Figure 5.18 shows the large site exit volumes at the 10-mile ring for zero, 20, 30, and 40 percent shadow evacuation participation rates. The figure shows that exit volume increase steadily, for all participation rates until the exit links reached capacity at approximately 50,000 vehicles per hour. This was consistent with results seen in the small model, which indicated that ETEs are not sensitive to shadow participation rates while uncongested. Once the model reached its exit capacity, the exit volumes corresponding to the shadow participation rate diverged. This suggested once capacity was reached, the various participation rates did play a role in the ability of the evacuees to exit the EPZ into the shadow area. This finding was expected and consistent with the previous literature and ETE studies conducted by licensee across the county. The figure also indicates the exit volumes for the various participation rates again converged at approximate 4:20 hour into the simulation. The 40 percent shadow participation rate had a noticeable impact on the exit volume, causing a large drop, indicative of significant downstream congestion within the shadow region. Ultimately, as the congestion in the shadow area abated, the flow rates were able to recover, resulting in only a marginal increase in the 100 percent 10-mile ETE. This finding may explain why the 90 percent ETE was noticeably impacted by shadow participation and the 100 percent was not. The analysis of flows suggested the extended tail of the 100 percent
ETE allowed for the evacuees delayed by congestion in the shadow area to “catch up” and exit the network with approximately the same ETE. However, when the tail was truncated by a 90 percent ETE analysis, the delayed vehicles could not “catch up” and ultimately played a significant role in impacting the 90 percent ETE. This analysis may suggest the length of the evacuation tail can also play a role in masking the impact of the shadow evacuation.

Figure 5.18. Large population site 10-mile exit volumes
6 Analysis

6.1 Small Population Site

For small population areas, it would not be expected that the shadow evacuation participation would have much, if any, impact to the ETE. This was also confirmed through review of prior sensitivity studies included in licensee submitted ETE studies, none of which identified a significant impact on small population areas. Most of the prior studies incremented the shadow participation up to 40 percent. Thus, for research purposes, the small model in this research was incremented up to 100 percent participation.

The shadow participation rates were changed from zero, 30 and 100 percent from the base which was 20 percent participation. To analyze the results three measure of performances (MOP) was used, which were clearance time, average speeds and EPZ exit volumes. For the small population site changing the shadow, participation rates did not have any effect on these three MOPs. At the most fundamental level, evacuation processes can be described within a construct of supply and demand relationships. Evacuation travel demand is the number of people that must or can be evacuated during an emergency. Evacuation travel supply is the ability of the network to serve the demand placed upon it. In this context, when the demand, number of people evacuating, is greater than the supply, available capacity, congestion occurs that causes delay. For the small population, site increasing the demand by 6,000 additional vehicles (100 percent shadow participation) did not surpass the available capacity.

6.2 Medium Population Site

Unlike the small population site, it was expected that the medium population site would get affected by the increase in shadow participation. As discussed before, Figure 6.1 represents the 10-mile 100 percent ETE for each sector for the medium model. Section one represents the WNW, NW, NNW and N sectors, section two represents the NNE, NE, ENE, E, and ESE sectors, and section three represents the SE, SSE, S, SSW, SW, WSW and W sectors. Table 6.1 shows the shadow population distribution for each of the sections.

<table>
<thead>
<tr>
<th></th>
<th>0 Percent</th>
<th>20 Percent</th>
<th>30 Percent</th>
<th>40 Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section 1</td>
<td>0</td>
<td>1,669</td>
<td>2,504</td>
<td>3,338</td>
</tr>
<tr>
<td>Section 2</td>
<td>0</td>
<td>11,425</td>
<td>17,138</td>
<td>22,850</td>
</tr>
<tr>
<td>Section 3</td>
<td>0</td>
<td>1,906</td>
<td>2,859</td>
<td>3,812</td>
</tr>
<tr>
<td>Total</td>
<td>0</td>
<td>15,000</td>
<td>22,500</td>
<td>30,000</td>
</tr>
</tbody>
</table>

Section one inside the medium model experienced the longest evacuation times and the only minor difference can be seen with zero percent shadow participation where it experienced slightly lower times than the other three shadow participations rates. Similar supply and demand relationship explained in the previous section also applies to the medium model. In section one,
the available capacity was never reached or did not exceed with the change in demand, therefore the ETE never experienced any significant change.

Section two, on the other hand, experienced noticeable differences when the shadow participation rate was increased to 40 percent. The available capacity was never reached or did not exceed with the change in demand until 30 percent, where there are 17,138 shadow vehicles for this section. Increasing the shadow vehicles from 17,138 to 22,850 vehicles was the “tipping point” for this section where the available demand exceeded the available capacity increasing the evacuation times noticeably.

Finally, section three of the medium population site have very similar road and population characteristics to the small population site. Therefore, similar to the findings for the small population site, section three did not experience any changes in ETE with the change in demand inside the shadow region and the results can be compared to the small population site.

![Medium Site Evacuation Time Estimates by Sector](image)

**Figure 6.1 10 Mile medium population site 100 percent ETE by sector**

### 6.3 Large Population Site

For large population sites, it was expected that high shadow participation rates would have a significant impact on the ETEs. This was only true for only the WNW sector for in both 90 and 100 percent ETEs. Most of the sectors showed an impact at the 90 percent ETE but was able to
recover when the ETE reached 100 percent. However, this was not true for the WNW sector. The difference in ETE between zero and 40 percent shadow participation was greater than one hour for both the 90 and 100 percent ETE. This shows that only one sector of the large population site is sensitive to the change in shadow participation. Table 6.2 shows the effect of the shadow participation inside the NNW sector in more detail. It could be seen that each shadow increment had an effect on the NNW sector, showing how sensitive this sector is to increasing demand.

Table 6.2. Effect of shadow participation inside the NNW sector

<table>
<thead>
<tr>
<th>NNW Sector</th>
<th>90% ETE</th>
<th>Difference in 90%</th>
<th>100% ETE</th>
<th>Difference in 100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 Percent</td>
<td>4:16</td>
<td>-</td>
<td>5:27</td>
<td>-</td>
</tr>
<tr>
<td>20 Percent</td>
<td>4:47</td>
<td>0:31</td>
<td>5:57</td>
<td>0:30</td>
</tr>
<tr>
<td>30 Percent</td>
<td>5:11</td>
<td>0:24</td>
<td>6:13</td>
<td>0:16</td>
</tr>
<tr>
<td>40 Percent</td>
<td>5:28</td>
<td>0:17</td>
<td>6:32</td>
<td>0:19</td>
</tr>
<tr>
<td>Total Difference</td>
<td>-</td>
<td>1:12</td>
<td>-</td>
<td>1:05</td>
</tr>
</tbody>
</table>
7 Conclusion

The work described in this research reveal a variety of important considerations related to the application of modeling traffic under evacuations and emergency surge conditions, especially for nuclear power plant (NPP) emergencies. While many of the results reflect well-understood phenomena within the fields of traffic engineering and modeling, several others were unexpected. In general, it was most interesting to note that, ultimately, the processes that were observed as well as the results gained from them, followed well-established theories of traffic flow. Among the most interesting and potentially the most useful are the basic relationship between network capacity and travel demand.

It is a well-recognized fact that all roads have a capacity. And while there are many factors that can influence a road’s ability to carry traffic, the capability of a road to move vehicles has a limit and when this is exceeded, congestion and delays will result. Therefore, when demand increases with the increase of shadow participation, losses in mobility can be experienced. These are typically most apparent in terms of increased travel time, decreased speeds and, in the case of an emergency evacuation, likely increased clearance times.

The rationale and basis for the functions used here can also be applied more generally, including other locations and threat conditions ranging from hurricanes and typhoons to tsunamis, floods, wildfires, and other types of man-made disasters. This work also summarized many valuable lessons learned in the model development process, including techniques that were found to be particularly useful, limitations, and ways of combining simulation results to gain knowledge about different size networks, in both population and road network, under evacuation scenarios.

In general, it was found that rates of shadow evacuation participation did not impact the clearance times for the small population site. Ultimately, the increased demand conditions never exceeded the available capacity inside the small population site to have an impact on the population that is under mandatory evacuation. However, the clearance times were noticeably impacted by higher shadow evacuation participation for the medium and large population sites. This suggests that, with locations that have higher population densities, shadow evacuation can potentially have an impact. One of the ways that this general finding is illustrated can be seen in Figure 7.1. Also, when clearance times by sector were calculated, a significant impact was observed in some locations. This suggests that not every location experienced the same effects given the same variation in shadow participation because of different road characteristics that hold different available capacity. Although the overall clearance time might not be affected, different regions can experience noticeable effects in change in travel time, speeds and clearance times with the variation of shadow evacuation participation.
Determining the amount and availability of capacity within an emergency evacuation context can be equally as diverse and complex to quantify. The ability to move evacuees is not just a function of the number of outbound lanes. It may also be affected by the arrangement of roadways within a system, the location, orientation of these roads with respect to the populations they serve; the geometric configuration of the roadway; geographic characteristics of the evacuation area; traffic controls; occurrence of incidents; driving behaviors; and the mix of vehicles within the traffic stream. Because of the complex nature, it is important to analyze the “tipping point” on where the demand exceeds available capacity and significant impacts can be seen by location.

It is also worth noting that neither the demand nor supply variables remain static during most evacuations. Both often change frequently and are influenced by other spatial and temporal conditions during emergencies. For example, bottlenecks, flooded roads, and incidents can decrease the outflow capacity of a network, while the use of contraflow can increase it. Likewise, dynamic threat conditions, phased evacuation orders, shadow evacuation participation, previous evacuation treats and other factors and characteristics can change demand by influencing evacuee departure time, location, and loading into a system. Therefore, understanding and trying to predict the current demand and capacity conditions can be very advantageous during any emergency evacuations.

Human behavior can also have an impact and change demand conditions, especially outside the mandatory evacuation areas. If people have experienced or watched people that experienced a devastating emergency situation, this could lead them to overreact to threats that are still emerging. An example of this was seen with the Hurricane Katrina and Rita emergency evacuations, where Hurricane Rita approached the Houston area just a month after Hurricane Katrina. People that have experienced the aftermath of Hurricane Katrina overreacted to Hurricane Rita that resulted in unexpected demand conditions during the evacuation.

Therefore, because of the dynamic nature of estimating demand conditions during an emergency evacuation, especially inside shadow evacuation participation areas, it could be helpful for evacuation planners to simulate different participation rates in these areas to analyze the effects and to evaluate the “tipping point” where demand exceeds available capacity which results in significate effects on clearance times. As shown in this research, changes in demand conditions in shadow evacuation participation can significantly affect evacuation times inside the mandatory evacuation zones. This study illustrated these effects using test scenarios from NPP.
evacuations. However, evacuation officials for other evacuation types should have the
information on the effects of different shadow evacuation participation rates, where they can use
their own judgment based on local conditions during the emergency on when to call for an
emergency.
References


Vita

Efe Emre Tuncer was born in Ankara, Turkey, in 1992 and moved to the United States in 2001. After graduating from a high school in Connecticut, he has moved to Baton Rouge, Louisiana in 2010. Then, he enrolled in Louisiana State University and graduated in 2014 with a Bachelor of Science Degree in Civil Engineering. He decided to pursue a master’s degree in Civil Engineering and joined Louisiana State University in 2016. He expects to receive his Master in Science Degree in Civil Engineering in May 2018.