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SIMULATION AND MATHEMATICAL MODELING TO SUPPORT COMMUNITY-WIDE EVACUATION DECISIONS FOR MULTIPLE POPULATION GROUPS

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Abstract

Evacuating a large population from an at-risk area has been the subject of extensive research over the past few decades. In order to measure trip completion and total evacuation times accurately, most researchers have implemented some combination of simulation and optimization methods to provide vehicular flow and congestion data. While the general at-risk population comprises the majority of travelers on the road network, there are often specific groups to consider when assessing the ability to evacuate an entire population. In particular, healthcare facilities (e.g., hospitals) may require evacuation, and the trip times may become an important health issue for patients being evacuated. Emergency vehicles from these facilities will share the same roadways and exit paths that are used by the local community, and it becomes increasingly important to minimize long travel times when patient care must be provided during transport.

As the size of the area to model grows larger, predicting individual vehicle performance becomes more difficult. Standard transportation-specific micro-simulation, which models vehicle interactions and driver behaviors in detail, may perform very well on road networks that are smaller in size. In this research, a novel modeling approach, based on cell transmission and a speed-flow relationship, is proposed that combines the "micro" and "meso" approaches of simulation modeling. The model is developed using a general purpose simulation software package. This allows for an analysis at each vehicle level in the travel network.

In addition, using these method and approaches, we can carry out dynamic trip planning where evacuees decide their route according to current road and traffic conditions. By translating this concept to an actual implementation, a traffic management center could identify current best travel routes between several origins and destinations, while continuing to update this list periodically. The model could suggest routings that favor either a user-optimal or system-optimal objective. This research also extended the concept of dynamic traffic assignment while modeling evacuation traffic. This extension includes the utilization of Wardrop's System Optimum theory, where flow throughout the network is controlled in order to lower the risk of traffic congestion. Within this framework traffic flow is optimized to provide a route assignment under dynamic traffic conditions.

This dissertation provides a practical and effective solution for a comprehensive evacuation analysis of a large, metropolitan area and the evacuation routes extending over 100 miles. Using the methodologies in this dissertation, we were able to create evacuation input data for general as well as special needs populations. These data were fed into the tailored simulation model to determine critical evacuation start times and evacuation windows for both the community-wide evacuation. Moreover, our analysis suggested that a hospital evacuation would need to precede a community-wide evacuation if the community-wide evacuation does not begin more than 24 hours before a hurricane landfall. To provide a more proactive approach, we further suggested a routing strategy, through a dynamic traffic assignment framework, for supporting an optimal flow of traffic during an evacuation. The dynamic traffic assignment approach also provides a mechanism for recommending specific time intervals when traffic should be diverted in order to reduce traffic congestion.

Dedication

I dedicate my work to my loving mother, father and sister who have given their forever support and encouragement all the time in my life.

Acknowledgements

First of all, I want to show my sincere thanks to my advisor, Dr. Kevin Taaffe, for his highly academic, smart, and insightful guidance to my research. Not only has he helped me to be a good academic researcher, he has also taught me important lessons that I will take with me into my professional career; without his compassion and assistance, I couldn't have completed my PhD study. He is the most important teacher in my life who has changed me from a student to a scientific researcher. I also want to thank Professor Chowdhury, who has opened a door for me to the area of civil engineering. Being a co-chair of my doctoral committee, he has also given me important guidance to transportation system research. I would also like to thank Professor Melloy and Professor Kurz for being in my committee. They provided me invaluable comments and suggestions, which helped improve my research.

Special thanks go to all the faculty members in our department. This five-year study has been the happiest time in my life; I made great progress in my knowledge, not only in academics, but also in the methodologies of research and problem solving. The research methodologies I learned at Clemson will be the most important treasure in my future work. Clemson has provided the most valuable knowledge that will be instrumental to my future professional success.

My mother, father and sister are my whole world. No matter what, they have always been ready to support me, encourage me and take care of me. They are the source

and power which kept me working hard to overcome the difficulties and move forward. Without them, I could not have completed my Ph.D.! Thank you to all who have positively changed my life!

Table of contents

List of Figures

List of Tables

1 Introduction

Traffic evacuation planning is an important function of public agencies. A reliable evacuation plan is critical to saving lives during emergencies. One of the most important components of an evacuation is in taking the at-risk population out of the harm's way as quickly and as efficiently as possible. In this research, we consider both the community at large as well as special needs populations (such as hospital patients) when proposing traffic flow plans.

Traffic simulation is a useful and cost effective tool to support evacuation planning, and we will offer several techniques within this research for developing and testing robust models, as well as novel methods for dynamically rerouting traffic. The work presented in this dissertation primarily includes four parts. The first is to find an effective way to analyze the data we need and form our model input. The second part is about the methods and algorithms we use to build a robust evacuation simulation model. The third part presents a case study and analysis of a simulation-based dynamic trip assignment framework. Finally, the fourth part is an extension of the traditional dynamic traffic assignment framework to minimize the total travel time of evacuation traffic. These contributions are summarized below.

1.1 Contribution 1: A method for effectively compiling the required input data

A simulation model starts from data preparation. For an evacuation, it is important to understand the scale and scope of the evacuation mission. For example, what is the scope of the evacuation area and how many people need to be evacuated? In addition, some geographical factors also need to be considered. Traditional 4-step travel demand modeling is a common approach in traffic demand analysis. In an evacuation setting, two critical data preparation issues are as follows: the proper use of Traffic Analysis Zones (TAZs) and the distribution (or time of entry and location of) evacuees into the model. To solve these main input tasks, we need to carry out the work in several steps, such as collecting census data, investigating the possible evacuation routes, dividing the TAZs according to the planned evacuation routes, and scheduling the distribution of the evacuees in the evacuation time window.

By systematically combining these and additional steps together, a general and effective methodology for evacuation input modeling was developed. The methods described here can be utilized in the modeling of any large, regional evacuation. This contribution is detailed in Chapter 2.

1.2 Contribution 2: A novel traffic simulation model that measures evacuation performance at the vehicle level over a large region

Simulation is very effective for traffic research. There are many commercially available traffic simulation tools. Some of these tools focus on individual vehicle behavior or vehicle-to-vehicle interactions, while others focus on the relationship between traffic flow and densities. Most of them are used for road condition analysis or evaluation of traffic control policies and infrastructure design or operations. Due to the complex computational requirements, it is difficult to carry out a long distance traffic analysis through microscopic simulation. In addition, optimizing a traffic plan is an equally challenging task. Many traffic simulation programs do not have built-in optimization tools with the ability to vary input parameters and identify system-wide minimum travel times. To overcome these shortcomings, we adopted the general-purpose simulation language Arena [1] in the development of our models.

We have developed tailored algorithms that are embedded into the simulation model. The algorithms adhere to the relationship between density and operating speed. These algorithms are very effective in analyzing evacuation traffic. Under high density conditions, the opportunity for individual aggressive behavior is greatly reduced, and drivers will follow an upper limit of safety distance under a certain speed. Thus, road segments are actually utilizing the available capacity and keeping traffic in a stable flow condition with the highest possible density. Under this research task, a deterministic route choice model was used to represent drivers' route choice decisions. The model also includes a graphical user interface for animating vehicle movements in the network and displaying aggregate traffic information, such as speed and density. This contribution is detailed in Chapter 3.

1.3 Contribution 3: User-optimized dynamic route choice during evacuations

This research simulates evacuees' behavior with a User Equilibrium (UE) principle in a dynamic evacuation process. In addition, other factors such as information refresh rate, demand level and active control are also tested under different traffic scenarios.

There has been limited research on how real-time traffic information can affect evacuation traffic flow management. Our model can be utilized to carry out such investigation in a relatively simple fashion. A traffic management unit can broadcast the shortest path to the evacuation traffic in a real time status. This is a dynamic simulation of a UE model. Evacuees will all choose the best route and rush toward it. After a while, congestion might still form due to an overwhelming number of evacuees. Another important issue will be the frequency of information updates, so that the new preferred route does not become quickly oversaturated. We developed a detailed relationship between frequency of information updates and total travel time in this research. In addition, we also combined UE and System Optimum (SO) assignments in the model by forcing some evacuees to take a defined route instead of competing for the best route. The result should be very helpful to decision makers in evaluating their evacuation plan.

1.4 Contribution 4: A methodology of traffic control using DTA under congestion

Previous research on Dynamic Traffic Assignment (DTA) using the SO approach presented the idea of considering the real travel speed with a dynamic traffic situation. The travel flow is normally derived from a link performance function. However, this link performance function often cannot give a detailed and accurate description of when congestion has occurred.

In this dissertation, a new idea is brought forward. By exerting traffic control techniques, a special traffic exiting point is located and regarded as a bottleneck. Thus the outflow of this point is constant or at least can be estimated. With this known factor, traffic management units can exert a more accurate detour time threshold. Evacuees can experience less travel time as well as less risk of congestion under this operational strategy.

In fact, some of the segments (or links) can be used as a buffer and evacuees can still enter this congested link until some special control level is reached; this accurate detour trigger time may greatly reduce the entire system's travel time and congestion risks. The SO approach is an easy and effective solution to DTA in an evacuation environment. Compared to the general DTA model, it is easier to solve. This contribution is detailed in Chapter 5.

Note that each chapter contains material submitted as a journal paper, along with additional details that went beyond the scope or page limitations of the particular journal. There may be some repetition in terminology across chapters for this reason; however it is necessary for the completeness of each chapter.

2 A Simulation Modeling Framework for Evacuation Planning

2.1 Abstract

Simulation is a useful and cost effective tool for evacuation planning. However, extensive data collection and preparation is necessary to build a traffic evacuation simulation model that can closely replicate real life conditions. Input data related to simulation of traffic evacuations include:

1) Traffic and roadway geometry,
2) Geographic distribution of the affected area,
3) Travel demand modeling,
4) Behavioral analysis of potential evacuees.

This chapter presents a framework for preparing simulation inputs and ultimately developing a simulation model. Brief excerpts from a case study on evacuation simulation of Charleston, South Carolina are also included in this chapter. An accurate input analysis is very important to the success of a simulation project since without correct input data, the output of a simulation can’t contribute to an accurate evaluation or effective decision making. This chapter presents a simple and efficient methodology for data preparation regarding a large scale city evacuation simulation involving long distance trips.

2.2 Introduction

Traffic evacuation planning is an important function of public agencies and reliable planning is critical to saving lives during emergencies. One of the most important components of evacuation is planning for traffic in order to take the at-risk population out of harm's way as quickly and as efficiently as possible. Traffic simulation is a useful and cost effective tool to support evacuation planning. In order to build a model to simulate a regional evacuation, the following basic questions need to be answered:

1) How many vehicles will be in the evacuation traffic?
2) Where will be the evacuee's possible destinations?
3) How many alternate routes will the evacuees have?
4) When will the evacuees start their trips after the evacuation order?

The responses to these questions will be the basis for the simulation model replicating the evacuation traffic. Currently, there has been a lack of standard procedures for developing a traffic evacuation simulation model. Moreover, existing microscopic simulation models require extensive data input including geometric design details for each road and traffic control parameters, which sometime can be prohibitively costly and time consuming to obtain. For a large network representing a mass evacuation, a mesoscopic model can be more suitable, since it integrates some necessary details of individual vehicle operation while reducing the need for intensive data requirements of microscopic models. Arena [1], which is a widely-used general purpose simulation tool, provides an excellent opportunity for developing such a mesoscopic model. The objective of this chapter is to develop a framework for the data preparation for traffic simulation modeling of a large scale, regional evacuation. This study also introduces data and sample results from an actual evacuation scenario of Charleston, South Carolina as a case study.

2.3 Previous behavior studies as an input to the proposed framework

Behavior research focuses on understanding how people respond to an evacuation alert, including their choice of when to leave, and which route they will take. This information will provide support for the development of traffic arrival rates to the exit routes, as well as the development of the origin-destination (O-D) distribution matrix in the framework presented in this chapter.

A general travel demand forecasting process for hurricane evacuations was first described by Lewis [2], where the traditional urban travel demand forecasting methodology was utilized. Many post hurricane surveys and behavioral studies were given in FEMA [3], Irwin et al. [4], RDS [5], and PBS&J [6]. FEMA/Corps Hurricane Study Program [3] provided a detailed and comprehensive case study of a hurricane evacuation in Florida. It contained a systematic data analysis concerning people's evacuation behavior, i.e., their evacuation destination distribution and their evacuation response time. Figure 2.1 presents the behavioral response curves (or S-Curves) that depict slow, medium and rapid responses by the public to an evacuation order. Typically, a small percentage of households will start evacuating before an order is issued. Upon receiving the evacuation order, some percentage of households will leave within an hour, some within two hours, some within three, and thereafter. A curve can be drawn to show the cumulative percentage of households that has entered the evacuation network over several hours. Regardless of whether the response is considered rapid, medium, or slow, the evacuation rate reaches its peak roughly when half of the evacuees have already departed.

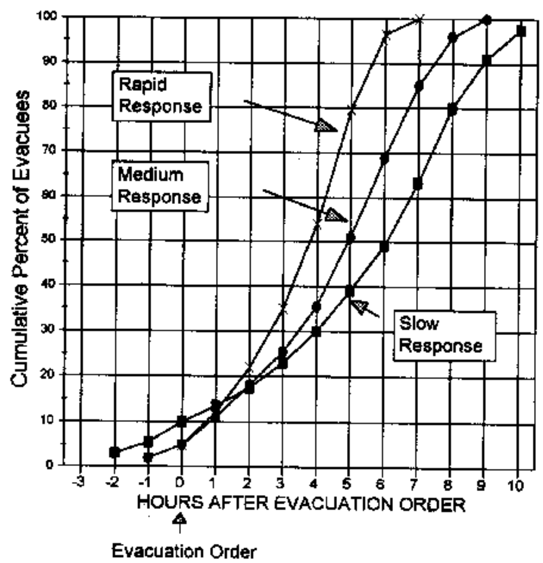

Figure 2.1: Evacuation order response curve

In a case according to FEMA [3], a steep increase exists in the curve, especially from hour 2 to hour 7, during which 80% of the evacuees responded to the evacuation order. While not specifically shown in Figure 2.1, the curve representative of such an exit response rate would be a little steeper than the medium response curve. In this chapter, the proposed simulation modeling framework defines the evacuation arrival rate to follow the general S-curve shape.

The FEMA [3] S-curves were chosen to be further analyzed as a loading model in the simulation modeling framework presented in this chapter. Equation (1) shows a cumulative percentage function (Radwan et al. [7]):

$$P(t) = \left(1 + e^{-\propto(t-H)}\right)^{-1} \tag{1}$$

where $P(t)$ is the cumulative percentage of the total trips generated by time t, α denotes the response of the public to the disaster and alters the slope of the cumulative response curve, and H is the half loading time. H defines the midpoint of the loading curve and can be varied by the user according to disaster characteristics. Using Equation (1) as a basis for their research, Ozbay et al. [8] introduced the percent evacuation with half loading times set at 12 hours while varying the response time rates. Those curves are symmetric, indicating an increasing hourly arrival rate for the first 12 hours and a decreasing hourly arrival rate for the following 12 hours; however, the shape and peak values vary based on the chosen response time rate.

The response time curve is also expressed as a deformation of Rayleigh's cumulative function (Tweedie et al. [9]). The cumulative function estimated the response percentage as below:

$$F_i(t) = 1 - e^{-(t^{a_i}/b_i)}, \tag{2}$$

where $F_i(t)$ represents the total value of vehicle departures, and a_i and b_i are parameters estimated for each evacuation case *i*.

Ma et al. [10] described a study on evacuation clearance time with the aid of a survey. The results from this study were very similar to Rayleigh's distribution. Based on behavior mode research, if we can obtain the total demand data, we can distribute the demand according to the behavior curve along with a predefined time window.

2.4 Data collection and preparation framework

The data collection and preparation, described in the following sections, are necessary for developing an evacuation traffic simulation model. The data collection and preparation framework includes three areas: 1) Traffic Analysis Zones (TAZs), which are the geographic input; 2) arrival rate calculation, which is used to allocate the evacuees throughout the evacuation time window; and 3) roadway and traffic data, which are used to define the roadway conditions in the model. The main steps in the data collection and preparation are:

1) Define the evacuation area;
2) Define the evacuation route;
3) Divide the area into Traffic Analysis Zones (TAZs) in TransCAD;

4) Overlay the census data with the TAZs and derive the total number of vehicles in TransCAD;
5) Identify entrance points for each route;
6) Convert total vehicle numbers into arrival rates.

2.4.1 Traffic analysis zones

Traffic Analysis Zone (TAZ) is the concept most commonly used in transportation planning models. The size of a zone varies, however, for any typical metropolitan planning process a zone of under 3,000 people is common. The spatial extent of zones typically varies in models, ranging from very large areas in the commuter town to as small as city blocks or buildings in central business districts. Zones are constructed by census block information, where several blocks form a zone. Typically these blocks are used in transportation models by providing socio-economic data. Most often the critical information that is attributable to a zone is the number of automobiles per household, household income, or employment within these zones. This information helps to further the understanding of trips that are produced and attracted within the zone. The following sections describe the traffic analysis zones in a regional evacuation scenario and route distributions.

2.4.1.1 Traffic analysis zones in regional evacuation

The concept of TAZ used in this chapter for evacuation modeling is somewhat different from the basic definition given in travel demand forecasting. The most obvious difference is that the key factor in defining TAZ is the geographic population distribution near an important or high capacity highway. Those areas are mainly defined by geographic territories, for example, the areas are divided by rivers, interstates, hills and resident clusters. Thus, the “3000-people” general rule doesn’t seem to work in evacuation modeling. In an evacuation scenario, the focus is how people can be evacuated in the shortest amount of time. To address this, the traditional travel demand forecast process can be modified slightly as follows:

1) Trip generation. Trip generation is very straight-forward compared to the traditional traffic forecasting modeling. Only a one-way trip is considered in evacuation modeling, that is, from endangered zones to safety area.

2) Trip distribution. The traditional gravity model seems redundant in a city evacuation model. FEMA [3] reported that people will go to their relatives’ or friends’ houses, or find a motel. This makes it difficult to estimate the accurate trip numbers from an evacuated city to another specific place. Under the South Carolina DOT evacuation plan [11] for Charleston, South Carolina, all evacuees must follow a specific direction according to the evacuating guidance. The advantage of this type of designated evacuation route is that it is easy to control the traffic and avoid the disturbance caused by inter zone travel and route competition.

3) In the framework presented in this chapter, mode split is not considered since only personal vehicles were assumed to be included in the evacuation.

4) Trip assignment. There are two ways to assign the evacuees, 1) Static assignment, as most states do. 2) Dynamic Traffic Assignment, using Wardrop's principles in a dynamic way. It is impossible to forecast an assignment dynamically, but an evacuation process can be simulated to observe the results in a DTA environment. In addition, we can also actively control and assign the traffic within the System Optimum (SO) model. We will describe these two methods in the later chapters. Currently, we use a static assignment.

2.4.1.2 Derive data from TAZs

As we discussed before, the TAZs in this framework are related with the geographic distribution and highway network that will be selected as the evacuation route. It is not difficult to outline those TAZs. In most states, the Department of Transportation has already provided a detailed division of the areas [11].

After dividing the TAZs, the real number of evacuees or vehicles in that area need to be identified. This can be accomplished via TransCAD, the first and only Geographic Information System (GIS) designed specifically for use by transportation professionals to store, display, manage, and analyze transportation data. Researchers can download the census data and import them into the TAZ model. By overlaying Year 2000 census data, the total number of households and vehicles are then derived from TransCAD. The increase of annual population and number of vehicles should also be considered. However, since not all vehicles will take part in the evacuation, this reduction can counteract the increase in vehicles from year to year. Thus the original population and associated traffic estimates are used as an approximation.

2.4.2 Case study of Charleston County

The following sections provide a case study with the evacuation plan for Charleston, South Carolina utilizing the proposed simulation modeling framework.

The TAZs are divided by SCDOT's hurricane evacuation route guidance [11]. In that manual, SCDOT groups the evacuees according to their living areas and assigns them with different routes. Only a vaguely defined geographic distribution is highlighted. With that guidance, the researchers divided Charleston County into approximately 13 zones. The outlines of each TAZ have been drawn out in TransCAD. The census data was then overlapped onto the TAZ map in TransCAD. From this information, the number of vehicles for each TAZ was derived using TransCAD's database.

Table 2.1 and Table 2.2 present the evacuation plan and possible evacuation demand in Charleston according to SCDOT's designated hurricane evacuation routes [11]. For each TAZ, there may be more than one entering point. Table 2.3 and Table 2.4 show the name of each entrance point, the highway number that evacuees will enter and the total amount of evacuees for each entrance. We can see that the entrance quantity for Zone 10 is only half of the total demand; the reason is that half of the evacuees will be assigned to the reverse lane, which is not modeled in our simulation. Since Zones 1 to 3 and Zone 5 are beyond our modeling range, their data are not included in Table 2.3 and Table 2.4.

Table 2.1: Evacuation plan and TAZs (Part 1)

Area	Edisto Island, Adams Run	Yonges Island, Meggett, Hollywood, Ravenel	Johns Island, Kiawah Island and Seabrook
Route plan	Evacuees will take SC 174 to US 17. They will then take US 17 south to SC 64. This will take them to Walterboro, and then on to North Augusta.	Use SC 165 to US 17, then US 17 south to SC 64	Evacuees will use SC 700 to Road S-20 (Bohicket Road) to US 17. Evacuees will take US 17 south to SC 64 where they will go to Walterboro, then on to North Augusta.
TAZ ID	1	2	3
Total Vehicles	3702	5425	12144
Area	West Ashley	James Island and Folly Beach	North Charleston(West)
Route plan	The west side of the city (West Ashley) will use SC 61 to US 78, then to Aiken and North Augusta.	Evacuees will use SC 700 to Road S-20 (Bohicket Road) to US 17. Evacuees will take US 17 south to SC 64 where they will go to Walterboro, then on to North Augusta.	Evacuees using SC 642 will travel west toward Summerville and take road S-22 (Old Orangeburg Road) to US 78 west.
TAZ ID	4	5	6
Total Vehicles	15269	32672	27414
Area	North Charleston	Charleston Downtown	East Cooper(Sullivan's island)
Route plan	Evacuees will take US 52 (Rivers Avenue) to US 78 to US 178 to Orangeburg or continue on US 52 to US 176 or continue north on US 52. The right lane of US 52 at Goose Creek will continue on to Moncks Corner. In Moncks Corner, it will be directed onto SC 6, where SC 6 will take evacuees toward Columbia. The left lane of US 52 at Goose Creek will go onto US 176 to Columbia. Evacuees using SC 642 will travel west toward Summerville and take road S-22 (Old Orangeburg Road) to US 78 west.	Downtown will use normal lanes of I-26.	Evacuees leaving Mount Pleasant will take I-526 or US 17 south to I-26. Those leaving Sullivan's Island will use SC 703 to I-526 Business to access I-526, then I-26. Evacuees on I-526 approaching I-26 from East Cooper will be directed to the normal lanes of I-26 if in the right lane of I-526. Those in the left lane of I-526 will be directed into the reversed lanes of I-26.
TAZ ID	7	8, 9	10
Total Vehicles	36541	9271+9381	16376

Table 2.2: Evacuation plan and TAZs (Part 2)

Area	East Cooper(Isle of Palms)	East Cooper(Mt Pleasant)	Awendaw and McClellanville
Route plan	Evacuees from the Isle of Palms will use the Isle of Palms connector (SC 517) to go to US 17, where the right lane will turn north on US 17, then proceed to SC 41, to SC 402, then to US 52 to SC 375, then to US 521, to SC 261 to US 378 to Columbia. Evacuees using the left lanes of the Isle of Palms connector will turn left to go to I-526 and then on to I-26.	Evacuees leaving Mount Pleasant will take I-526 or US 17 south to I-26.	Evacuees will take SC 45 to US 52 where they will be directed right onto US 52 to SC 375 to US 521 to SC 261 to US 378 to Columbia.
TAZ ID	11	12	13
Total Vehicles	7930	20743	2509

Table 2.3: Name and traffic flow of each entrance (Part 1)

TAZ	4	6		7			8
Entrance name	En84	En36	En46	En87	En97	En107	En38
Highway name	US78	I-26	I-26	US52	US52	US52	I-26
Toward	Orangeburg	Columbia	Columbia	Orangeburg/Columbia			Columbia
Total Amount	15269	12960	14400	7200	7200	21600	9271

Table 2.4: Name and traffic flow of each entrance (Part 2)

TAZ	9	10	11		12	13
Entrance name	En59	En310	En311L	En1111R	En312R	En1313
Highway name	I-26	I-526	I526	SC41	I526	US52
Toward	Columbia	Columbia	Columbia	Columbia	Columbia	Columbia
Total Amount	9360	8100	3960	3960	10080	2509

Figure 2.2 presents the vehicle distribution created in TransCAD. As shown in Figure 2.2, each TAZ has been outlined with solid lines. The clusters of black dots represent the density of vehicles, e.g., the more dots in a TAZ, the more vehicles in the TAZ.

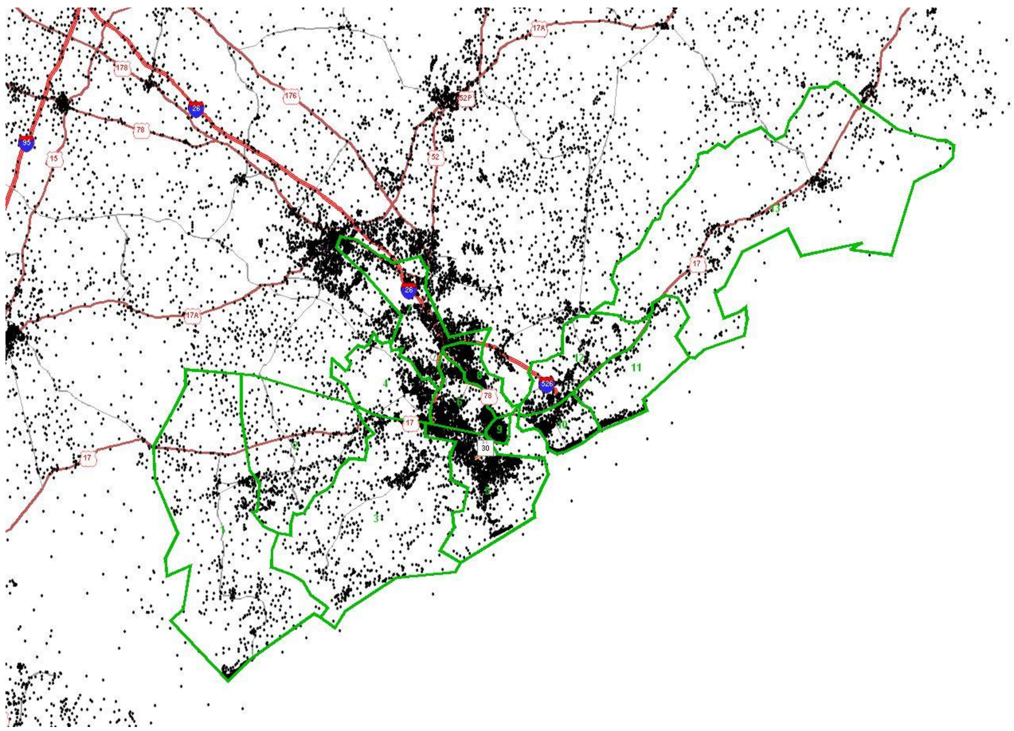

Figure 2.2: Vehicles distribution

Figure 2.3 presents the distribution of vehicles owned by households in the Charleston area derived from TransCAD. The bar in each TAZ shows the number of vehicles. Larger bars represent higher vehicle counts in those areas.

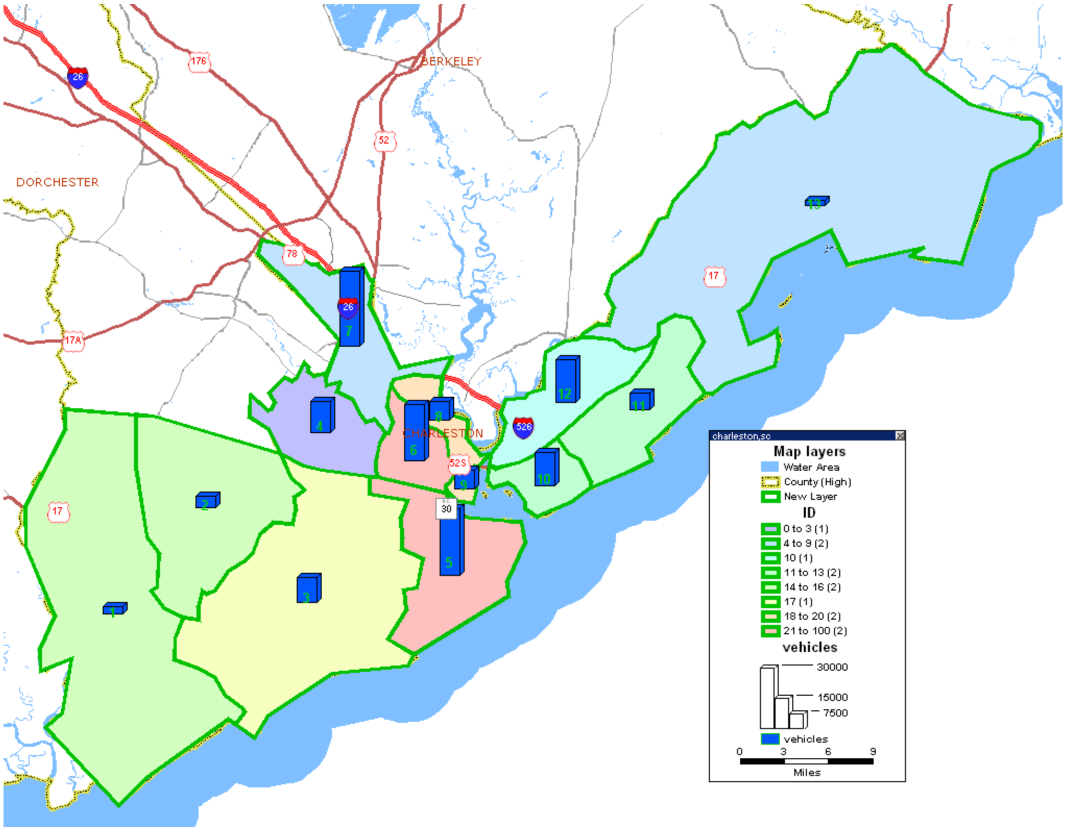

Figure 2.3: Vehicles in each TAZ

2.4.2.1 Roadway and traffic data

According to SCDOT's evacuation plan, there are 11 routes for evacuation. Table 2.5 shows the ID and basic road information for each evacuation route. Those routes originate from each TAZ and end at four cities: Florence, Columbia, Sumter and Orangeburg.

Table 2.5: Evacuation routes

Route	from	via	to	ID
1	Charleston downtown	I-26, I-95	Florence	FH
2	North Charleston	US-52	Florence	FL
3	Charleston downtown	I-26	Columbia	CH
4	North Charleston	US-52, S-176,	Columbia	CL176
5	Charleston downtown	I-26, I-95, US-301	Orangeburg	OH
6	North Charleston	US-52, US-78, US-178	Orangeburg	OL
7	Charleston downtown	I-26, I-95, US-301, US-15	Sumter	SH
8	North Charleston	US-52, US521	Sumter	SL
9	North Charleston	US-52, SC-6, S-176	Columbia	CLSC6
10	Eastern Coop	SC-41, US-52, SC-402, US-378	Columbia	CLSC41EC
11	Awendaw	SC-45, SC-402, US-378	Columbia	CLAWE

Table 2.6 indicates the names of entrance for each TAZs and their assigned route number according to SCDOT's manual. Unlike the original evacuation manual, we split the evacuees at the intersection towards these Florence and Columbia. In addition, since Sumter is near Florence and Orangeburg is very close to Columbia, 80% of the people will be assigned to Columbia or Florence, and 20% will be guided to Orangeburg or Sumter. For route 10 and route 11, evacuees will be guided to Columbia since those routes are less likely connected with any of the other three cities. Currently, the routes are fixed throughout the whole evacuation process. In later chapters, we will test the effect of dynamically assigning the routes.

Table 2.6: Entrance points for evacuees and their destination

	Entering place	Route ID	Florence	Columbia	Sumter	Orangeburg
En84	Zone 4	6				100%
En36	Zone 6	1, 3, 5, 7	40%	40%	10%	10%
En46	Zone 6	1, 3, 5, 7	40%	40%	10%	10%
En87	Zone 7	6				100%
En97	Zone 7	2, 4, 6, 8, 9	40%	40%	10%	10%
En107	Zone 7	2, 4, 6, 8, 9	40%	40%	10%	10%
En38	Zone 8	1, 3, 5, 7	40%	40%	10%	10%
En59	Zone 9	1, 3, 5, 7	40%	40%	10%	10%
En310	Zone 10	1, 3, 5, 7	40%	40%	10%	10%
En311L	Zone 11	10		100%		
En1111R	Zone 11	1, 3, 5, 7	40%	40%	10%	10%
En312R	Zone 12	1, 3, 5, 7	40%	40%	10%	10%
En1313	Zone 13	11		100%		

2.4.2.2 Arrival rate calculation

The analysis presented earlier provides an estimation of the total amount that should be evacuated from each of the entry points of the evacuation routes from different TAZs. The next step is to organize the evacuees and arrange them according to arrival rate functions.

We begin our work by using Rayleigh's cumulative function shown in Equation (1). By differentiating this equation, the relationship between flow and time is obtained and shown in Equation (3):

$$A = \frac{a_i}{b_i} t^{a_i - 1} e^{(-a_i/b_i)} \tag{3}$$

where A is the arrival rate based on a portion of the total evacuation demand. As stated earlier (FEMA [3]), in a 24-hour evacuation window, 80% of the evacuees will begin their trips within a 10-hour interval (e.g., from 7:00 am to 5:00 pm). We further compressed this peak travel window or interval into 8 hours instead of 10 hours to indicate how traffic would behave if evacuees tended to travel during convenient times and in a slightly shorter time window. So, at 8:00 am, at least 10% of the evacuees will arrive; in addition, by 12:00 pm + 4 hours = 4:00 pm, at least 90% of the evacuees will have arrived. Inserting these numbers into Equation (2) as below:

$$\begin{cases} F(8\text{ hours}) = 1 - \exp\left(-8^a / b\right) = 10\% \\ F(16\text{ hours}) = 1 - \exp\left(-16^a / b\right) = 90\% \end{cases}$$

we have the following solution: a = 4.45, b = 99309.

We use simulation to test and evaluate different evacuation schemes, with pre-alert times varied from 24 hours to 42 hours. Thus, we need to define different arrival rate expressions. The following evacuation requirements are listed:

1) There are 4 evacuation order trigger times (or pre-alert times) under consideration:

   - 24 hours before landfall
   - 30 hours before landfall
   - 36 hours before landfall
   - 42 hours before landfall

2) For each pre-alert time range, the evacuees should start the action at least 6 hours before landfall. For example, if the evacuation order is issued 24 hours before landfall, the evacuation window is 24-6 = 18 hours; for the 30/36/42-hour pre-alert times, the evacuation windows are 24/30/36 hours, respectively.

3) The peak arrival or evacuation rates are condensed in the same manner as was previously described for the 24-hour case. For the 18/30/36-hour windows, the "peak arrival" time slot becomes less than 7.5/12.5/15 hours, respectively. Table 2.7 provides the value of *a* and *b* for each scenario.

Table 2.7: Parameter values for different scenarios

evacuation time (hour)	24.000	30.000	36.000	42.000
arrival rate interval (hour)	18.000	24.000	30.000	36.000
10% start time (hour)	6.000	8.000	10.000	12.000
90% finish time (hour)	12.000	16.000	20.000	24.000
a=	4.455	4.455	4.455	4.455
b=	27894	99309	271558	611815

Figure 2.4 presents the arrival rate for different evacuation windows from 18 hours to 36 hours. The x-axis is the elapsed time (in hours) since the trigger time; the y-axis is the percentage of total evacuees who arrive at that entrance per hour. For each entrance, these hourly percentages can be combined with the total arrival quantity to determine the correct number of evacuees in that hour.

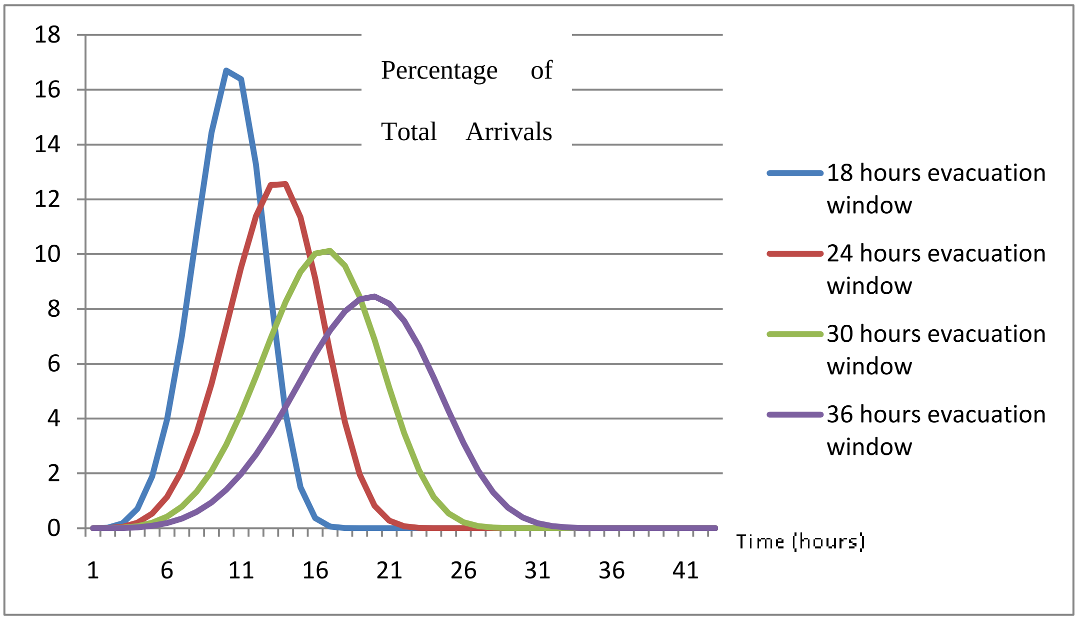

Figure 2.4: Arrival rates for different evacuation windows

From Figure 2.4, it can be seen that the curves are symmetric, so the half-loading time mentioned by Radwan et al. [7] forms naturally. Even though the shape is very similar to Ozbay et al.'s work, the physical meaning is quite different. Since the half load times are unique for each case, the evacuation windows vary from one curve to another. As we can see, the parameters are easier to solve, and it is suggested to use Equation (2) in the arrival rate calculation.

2.4.2.3 Peak value and evacuation time window

There are different evacuation time windows in the evacuation process. Thus peak hours for each time window are different. We need to calculate the highest value at the peak hours and then use them as the input to define the shape of the arrival rate in Arena. Using Equation (3) and Table 2.7, the peak values for each time window can be obtained.

Since we define the evacuation route into cells, the entering points might be assigned to more than one cell. This implies that, in some TAZs, there are multiple entering points and those entering points are assigned to several different cells. Table 2.8 shows the peak values of different evacuation time windows. The total amount in the last column shows the value of the flow in one lane. Some evacuation routes have 3 lanes, for example, at En59, from downtown, traveling by I-26. Since the total demand is 9360 vehicles, the table depicts a total evacuation quantity for one lane of 3120 vehicles.

Since the simulation model is a mesoscopic model, some of the details need to be integrated. It is assumed that the three highway lanes function at the same level. Thus, we focus on the performance of one lane and assume the other two will have identical performance. In addition, since the Cell Transmission Model is run based on the speed-flow relationship, where we need to apply the algorithm on only one lane, the simulation model is also built based on one lane's dynamic situation. This will be discussed in greater detail in later sections. Table 2.8 also gives a 24-hour leveled evacuation arrival rate value. We will use this leveled arrival curve to investigate the difference between a naturally formed arrival flow and an actively controlled arrival flow.

Table 2.8: Entering points and peak values

Resource Point	18	24	30	36	48	24-hour leveled	total amount
En59	494	408.2	342.42	288.6	130	195	3120
En36	684	565.2	474.12	399.6	180	270	4320
En84-1	604.2	499.26	418.806	352.98	159	238.5	3816
En84-2	604.2	499.26	418.806	352.98	159	238.5	3816
En84-3	604.2	499.26	418.806	352.98	159	238.5	3816
En84-4	604.2	499.26	418.806	352.98	159	238.5	3816
En46	760	628	526.8	444	200	300	4800
En38	494	408.2	342.42	288.6	130	195	3120
En87	570	471	395.1	333	150	225	3600
En97-1	190	157	131.7	111	50	75	1200
En97-2	190	157	131.7	111	50	75	1200
En107-1	285	235.5	197.55	166.5	75	112.5	1800
En107-2	285	235.5	197.55	166.5	75	112.5	1800
En107-3	285	235.5	197.55	166.5	75	112.5	1800
En107-4	285	235.5	197.55	166.5	75	112.5	1800
En310	855	706.5	592.65	499.5	225	337.5	5400
En1111R	627	518.1	434.61	366.3	165	247.5	3960
En311L	209	172.7	144.87	122.1	55	82.5	1320
En312R	532	439.6	368.76	310.8	140	210	3360
En1313	397.1	328.13	275.253	231.99	104.5	156.75	2508

2.4.2.4 Simulation model input building

The arrival rate will be programmed as a “Schedule” in the arrival module. Figure 2.5 shows the arrival rate on entrance “En36” of the evacuation route in a 24-hour evacuation window. Each blue bar is the arrival rate per hour in duration of 15 minutes. The peak value is about 565 vehicles per hour and the shape appears to be similar to Rayleigh’s curve. The shape is very similar to the curve with a 24-hour evacuation window in Figure 2.5.

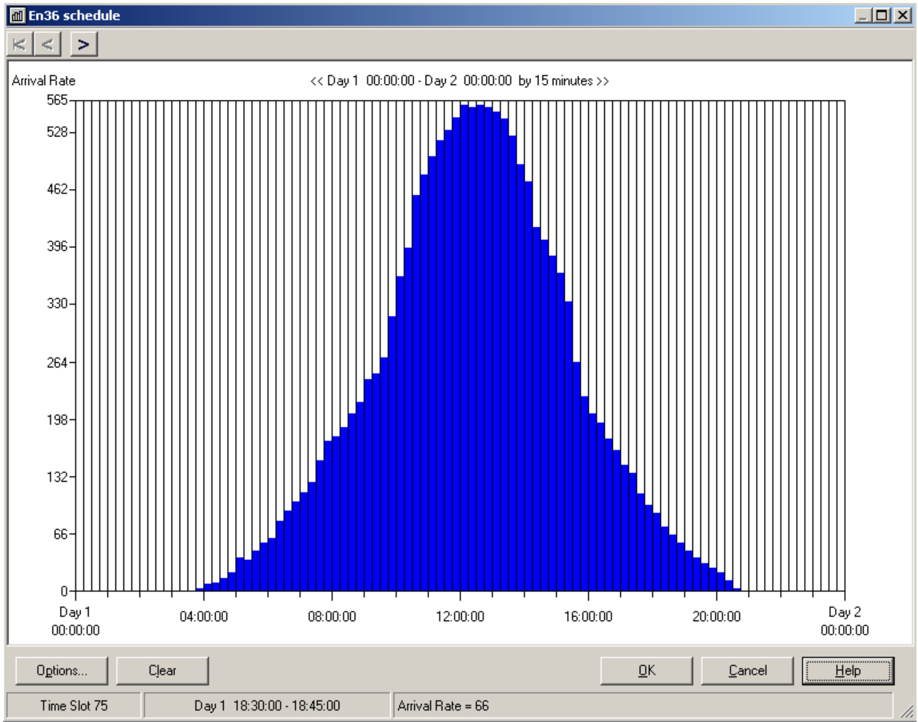

Figure 2.5: Arrival rate example in simulation model

2.5 Elementary simulation tests

In this section, we give a brief description about the results of the simulation and compare them with the estimation derived from analytical calculations.

2.5.1 The contribution of arrival rate expression, sample data analysis

Before beginning with simulation, an analysis is carried out to predict the possible outputs. Since the speed changes dynamically with the density, we cannot give a precise prediction about the real travel time. This is also the reason why we rely on simulation to test the result. We do know that if the arrival rate reaches the highway's capacity, which is about 2500 vehicles per hour [12], congestion might occur.

The arrival rate in Equation (3) is fundamental to the research carried out in this dissertation. All results and analysis are based on the assumption that the behavior of evacuees is described according to that equation. In the following section, we use the 24-hour evacuation window as an example to have an estimate of the possible locations of congestion on the evacuation routes. Figure 2.6 is a simplified map for the entering points (represented by Entering Number or En) on the evacuation route of some related zones, followed by the total vehicle numbers for each lane. There are 3 lanes on each branch of the evacuation network.

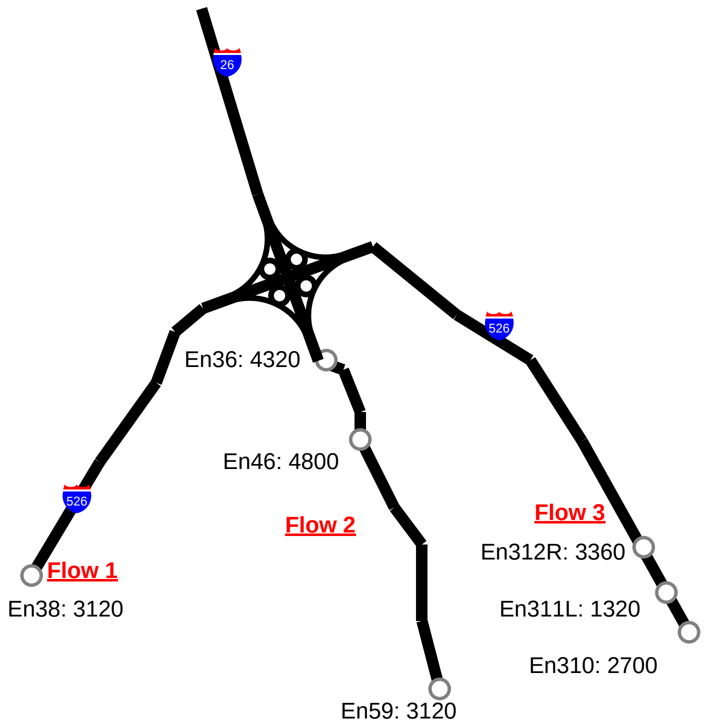

Figure 2.6: Highway network entering quantities

The evacuation routes were driven by the author several times to estimate an average travel time. The field data suggested the average travel time from En59 at highway I-26 to the final merging point with highway I-526 is about 8 minutes. The average speed on this section is 65 m/h. Traveling from En38 to merging point takes about 8 minutes with 55m/h. In addition, travel time from En310 to merging points takes about 13 minutes with the average speed is 60m/h. The following presents the calculations related to the estimation of the congestion location and time on the evacuation route.

The arrival rate from the west is contributed by flow 1:

$$Ar_1 = 3\times(3120)\left(\frac{4.45}{99309.8}\right)\left(t-\frac{8}{60}\right)^{4.45-1}\times e^{\left(-\frac{\left(t-\frac{8}{60}\right)^{4.45}}{99309.8}\right)}$$

$$Ar_1 = 0.419\times(t-0.133)^{3.45}\times e^{\left(-\frac{(t-0.133)^{4.45}}{99309}\right)}$$

The arrival rate from the east is contributed by flow 3:

$$Ar_3 = 3\times(3360+1320+2700)\left(\frac{4.45}{99309.8}\right)\left(t-\frac{13}{60}\right)^{4.45-1}\times e^{\left(-\frac{\left(t-\frac{13}{60}\right)^{4.45}}{99309.8}\right)}$$

$$Ar_3 = 0.922\times(t-0.217)^{3.45}\times e^{\left(-\frac{(t-0.217)^{4.45}}{99309}\right)}$$

The arrival rate from the south or center flow (I-26) is:

$$Ar_2 = 3\times(3120+4800+4320)\left(\frac{4.45}{99309.8}\right)\left(t-\frac{8}{60}\right)^{4.45-1}\times e^{\left(-\frac{\left(t-\frac{8}{60}\right)^{4.45}}{99309.8}\right)}$$

$$Ar_2 = 1.645\times(t-0.133)^{3.45}\times e^{\left(-\frac{(t-0.133)^{4.45}}{99309}\right)}$$

Figure 2.7 shows the total arrival rate at the merging location. As shown, around hour 11, the downstream route beyond the merging location almost reaches its capacity (which is about 7500 pc/h (Highway Capacity Manual 2000 [12]).

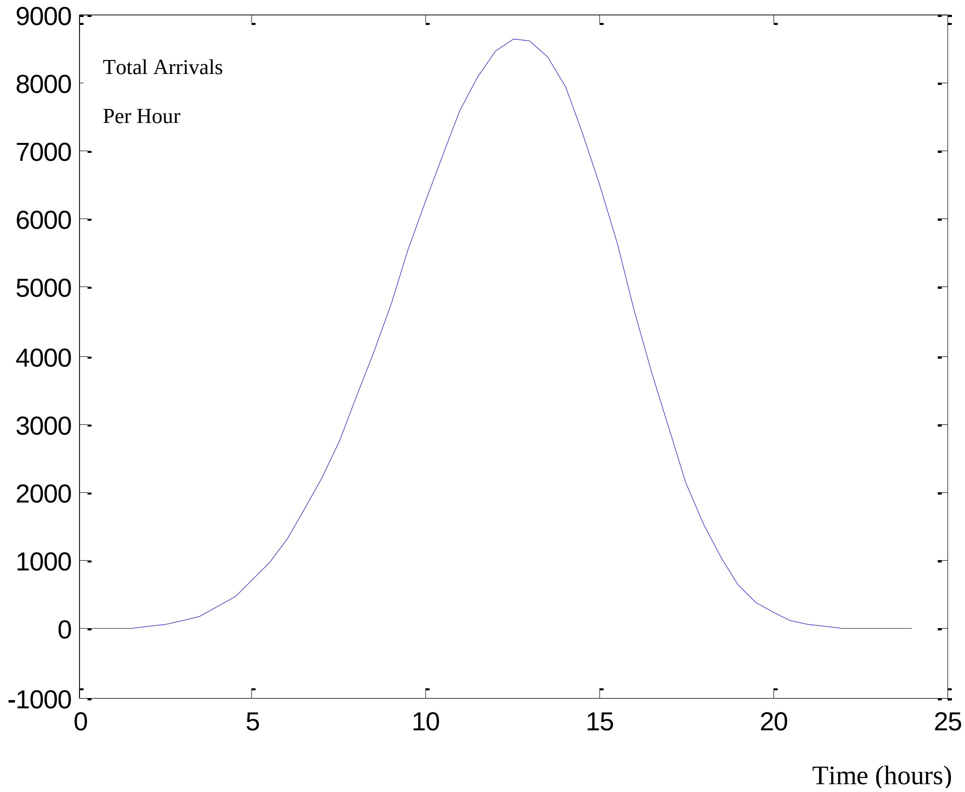

Figure 2.7: Arrival rate in center merging place

Even though the flow in the downstream merging area reaches its capacity, the estimation of the time the entering area reaches its capacity is needed. The west and east branches will merge at I-26, thus $Ar_1(t)+Ar_3(t)$ should be less than the merging area's capacity. According to Highway Capacity Manual 2000 [12], the upstream capacity of a merging area is 2500 pc/hour. This estimation results in $Ar_1(t)+Ar_3(t)<2500. \rightarrow t \approx 9.6$. So, after about 9.6 hours, the merging ramp has already reaches its capacity.

2.5.2 Simulation analysis

The simulation model will be explored in great detail in Chapter 3. As part of the work (and journal paper) submitted for Chapter 2, however, an introduction to the simulation model and results was necessary. This is the subject of this section.

Table 2.9 shows a record for eight random tests on the evacuation route Florence Highway (FH) in a 24-hour evacuation window. Eight vehicles are randomly selected and their start time, travel time and journey completion time are recorded. If there is no congestion, the travel time from the origination to destination is around 2.17 hours. According to the calculation in section 2.5.1, since the ramp has already reached its capacity at t = 9.6 hours, the traffic condition will become very unstable after this point. Comparing with

Table 2.9, the vehicle beginning at t = 9.35 hours (Test 3) required a little more time than it otherwise would have under normal traffic conditions. With more vehicles arriving and the accumulation of a queue, the delay becomes much longer for the fourth vehicle. Thus, the mathematical estimation supports the simulation results. The mathematical estimation also suggests that it is highly likely that the evacuation could not be completed in the 24 hours before landfall.

As shown in

Table 2.9, the third trip experienced congestion and the fourth trip had even a longer delay. By a rough estimation, the congestion started at about 10 to 12 hours after the trigger time. However, to obtain the dynamic result throughout the entire process, we need to run the simulation model described in Chapter 3.

Table 2.9: Random tests' record

FH	24-hour evacuation window		
Test	start time	journey time	finish time
1	0	2.18	2.18
2	4.68	2.17	6.85
3	9.35	2.44	11.79
4	14.29	14.73	29.02
5	31.52	2.18	33.7
6	36.2	2.18	38.38
7	40.88	2.18	43.06
8	45.56	2.17	47.73

2.6 Conclusions

Traffic evacuation modeling is an important tool for planning a regional evacuation of an at-risk population. Traffic evacuation modeling combines the knowledge of different academic and professional disciplines, such as operations research, traffic demand forecasting, Geographic Information System (GIS), traffic flow theory including traffic engineering and human behavioral analysis. Thus, modeling such an evacuation is a complex task and is especially challenging for a large region. This chapter presents a framework for preparing the input parameters and ultimately developing a simulation model that does not require extensive data collection and preparation as required in off-the-shelf microscopic simulation models. Thus, the proposed framework is suitable for modeling the evacuation of a large area that includes long evacuation routes in the scale of hundreds of miles.

This chapter brings forward a simple but effective function to calculate the arrival rate curve concerning different evacuation or traffic evacuation windows, which are very important for evacuation modeling. By calculating the parameters *a* and *b* with the algorithms shown in section 2.4.2.2 and inserting them in the arrival rate equation, the arrival rate curve becomes suitable to any specific evacuation window. A case study on evacuation simulation is presented for Charleston, South Carolina using the proposed framework. The simulation output related to the estimated time when congestion occurs on selected sections of the evacuation highway network closely approximated the results derived from a mathematical analysis for the same evacuation scenario. Thus, the input data and mathematic calculation can also help evaluate the traffic system and validate the result of the simulation model in Chapter 3.

3 Minimizing Patient Transport Times during Mass Population Evacuation

3.1 Abstract

Emergency evacuation in healthcare has focused on methods for evacuating the facility, resources for transferring patients, and sufficient capacity at the sheltering facilities. What has been overlooked is the interaction between the healthcare and any community-wide evacuation that would result in significant roadway congestion. In this chapter, we focus on how to route hospital vehicles during a hurricane evacuation. To provide an analytical comparison of evacuation time, delay, and routes across various evacuation scenarios, we developed a simulation model that combines the hospital and general population traffic together. The tailored model incorporates mesoscopic traffic flow concepts (such as cell transmission and speed-flow relationship) to enable the evaluation of a region covering several hundred miles, while still providing the ability to control speeds and accommodate decision making at the individual vehicle level. With this novel modeling approach, evacuation planners can easily program the routes, test the travel times, and consider different scenarios quickly. This analysis considers the evacuation of the Charleston metropolitan area during a hurricane threat. The study found that in order to evacuate all patients six hours prior to a hurricane landfall, the hospital evacuation must start at least 12 hours prior to the mandatory evacuation order (a typical

24-hour notice). Alternatively, the hospital evacuation can take place at the same time as the mandatory evacuation if both begin 48 hours prior to landfall.

3.2 Hospital evacuation background

The South Carolina Department of Health and Environmental Control issued an order requiring that all hospitals in the state have an evacuation plan with the following components: sheltering, transportation, and staffing [13]. Similar requirements exist in other states as well. Hospitals typically carry out tests to become familiar with the sequence of events that need to occur for an effective evacuation. Hospitals are often very prepared for planning the movement and transfer of their patients, but they do not have sufficient information for estimating the travel time to reach the emergency shelter or receiving facilities.

Tayfur and Taaffe [14] proposed a deterministic optimization model in order to find the scheduling and allocation of resources required during hospital evacuations with the objective of minimizing cost within a pre-specified evacuation completion time. However, many of the events surrounding hospital evacuation are inherently probabilistic, and task durations are often uncertain, leading to the use of stochastic modeling. As a result, Tayfur and Taaffe [15] proposed a simulation-optimization framework that examines nurse and vehicle transport requirements for the evacuation of all patients while minimizing cost within a pre-specified evacuation completion time. To incorporate roadway traffic congestion in this model, we included a traffic factor that would apply additional delay in the travel time between the evacuating hospital and the receiving facility based on the estimated amount of traffic at specific times during the community-wide evacuation. While the traffic factor was only an estimate based on anticipated traffic volumes, many details could be studied in the hospital evacuation plan while providing a rough estimate for vehicle travel times – without the overhead required in combining this with a traffic simulation.

The focus of this chapter is on the actual traffic network and the vehicles (both ambulances and the general traffic) competing for space on that network. We consider the number of round-trips each ambulance may be required to take in order to transfer patients out of the evacuation area under the city evacuation environment. The key research contributions include: (1) developing a novel simulation approach to modeling traffic flow over large distances, and (2) applying the model to estimate ambulance trip times based on various hospital evacuation start times and evacuation window ranges. The case study uses a large hospital in downtown Charleston, SC as the evacuating facility.

3.3 Evacuation literature and research methodology

To simulate the traffic behavior, we need to replicate the interaction between flow, speed and density in the road. For example, when more people arrive on a road in a short time and they cannot be processed in a timely fashion, the road density will increase and thus, the travel speed will decrease. This is the key algorithm we need to consider when creating a traffic model. In order to solve this problem, we create the customized speed-flow relation and apply it in an updated cell transmission model (CTM). In addition, the CTM is the basic unit in our simulation model. To support the research presented in this chapter, the following section includes a discussion of the literature and research methods about speed-flow algorithms, cell transmission modeling, and simulation.

3.3.1 Speed-flow relationship

There are different algorithms that explain the relationship between speed and flow in traffic; however, they are all similar in that they can only estimate car following behavior; in other words, there is no perfect solution to apply in all traffic situations. Thus, we present several classical speed-flow algorithms. The basic speed-flow relationship can be expressed as follows:

$$q = k_j\left(v - \frac{v^2}{v_f}\right), \tag{4}$$

Where, q denotes the flow rate (vehicles/hour), v is the travel speed, v_f is the free-flow speed (miles/hour), and k_j is the jam density (vehicles/mile). More recent models attempted to refine earlier models by considering two separate regimes for free-flow and congested-flow. Examples of single-regime models include the Greenberg model, the Underwood model, and the Northwestern model [16]. Multi-regime models, on the other hand, include Edie's model, the two-regime linear model, the modified Greenberg model, and the three-regime linear model [16].

The Highway Capacity Manual (HCM 2000) [17] provides a comprehensive set of speed-flow models for basic freeway segments, multilane highways and urban streets. More recently, Akcelik et.al [17] developed a time-dependent speed-flow model and used it in various applications successfully; the model has been commonly referred to as the Akcelik function. This function is based on queuing theory concepts, providing a smooth transition between a steady-state queuing delay function for under-saturated conditions and a deterministic delay function for over-saturated conditions. The difference between all of these models (and how they impact the speed-flow relationship) is not that large.

In the simulation model presented in this chapter, we approximate the speed-flow relationship with a customized algorithm that provides updates at the mesoscopic to microscopic simulation level. The speed-flow curve is very similar with the curve in Highway Capacity Manual [12]. A detailed introduction is provided in section 3.4.

3.3.2 Introduction to CTM and its application in evacuation

The Cell Transmission Model (CTM) was proposed by Daganzo [18] in 1992. The main concept is to simulate traffic flow behavior with hydrodynamic theory (described through the Flow Conservation Equation). It can be regarded as a "discrete hydrodynamic model," which can predict traffic behavior for one link by evaluating flow at a finite number of carefully selected intermediate points, including the entrance and exit. Thus, CTM is a mesoscopic to macroscopic traffic model which focuses on network flow behavior instead of the interaction of individual vehicle. It is very effective in analyzing the traffic assignment, density and shockwave behavior.

CTM discretizes the time horizon into small and equal intervals and divides the links of a traffic network into small homogeneous cells. The length of the cell is equal to the travel distance within a time interval at the defined free-flow speed. Based on the flow conservation theory, the CTM is actually become a recursion expression. Cells are typically numbered consecutively from upstream to downstream as 1, 2, …, *i, i*+1*, etc*. Denoting the number of vehicles in cell *i* at time *t* as $n_i(t)$, the value for the next time interval in the same cell becomes:

$$n_i(t+1) = n_i(t) + y_i(t) - y_{i+1}(t) \tag{5}$$

where $y_i(t)$ is the inflow to cell *i* in the time interval (t, t + 1). $y_i(t)$ is calculated as:

$$y_i(t) = \min\{n_{i-1}(t), Q_i(t), \delta[N_i(t) - n_i(t)]\}, \tag{6}$$

$Ni(t)$ denotes the maximum number of vehicles allowed in cell *i* during time interval *t*, and $Qi(t)$ defines the maximum acceptable number of vehicles that can flow into cell *i* when the clock advances from *t* to *t + 1*. $\delta = w/v$, *w* denoting the back wave speed when traffic is congested and *v* denoting the free flow speed. To be more accurate in formulating the discontinuities, δ is defined as:

$$\delta = \begin{cases} 1, & n_{i-1}(t) \leq Q_i(t) \\ w/v, & n_{i-1}(t) > Q_i(t) \end{cases} \quad (7)$$

Ziliaskopoulos [19] formulated a single destination system dynamic traffic assignment problem with CTM. The decision variables is $n_i(t)$ and the constrains are a set of inbound and outbound $y_i(t)$ that follow the constraints (4)-(6).

Dixit et al. [20] created a CTM model to find the optimal evacuation orders for related cities. The model is similar as Ziliaskopoulos' model [19], but cell lengths can be as long as 6 minutes in distance. While there may be some tradeoff in accuracy, the method is still very helpful to judge the overall evacuation process. Chiu et al. [21] also use the LP model to solve an optimal evacuation destination-route-flow-staging decision process. They introduce a small disturbance in the input to confirm the correctness of the optimal traffic assignment.

CTM also helps the decision making of contraflow routes in evacuation. Dixit et al. [22] used their model to assess different contraflow plans. The results are very close with the output of a microscopic model but reduce the computer resource requirement. Tuydes et al. [23] also created a CTM model to find the optimized contraflow allocation in a network using a "total coupled" capacity to simulate the possible contraflow capacity and optimize the capacity allocation.

While almost any traffic network can be formulated using cell transmission, the size of the model can grow very quickly depending on the chosen cell size for each roadway segment. A CTM cannot change the flow and speed across different segments.

In addition, Q_i and N_i will actually depend on the flow and speed of what is currently passing through a particular cell. However, the methodologies embedded in CTM are still very useful. This concept provides a basis for the development of the traffic simulation model proposed in section 3.4.

3.3.3 Traffic simulation and evacuation

Many researchers have focused on evacuation and traffic simulation. Southworth [24] gave a comprehensive introduction to a regional evacuation modeling framework and future development. Hobeika et al. [25] focus on the user equilibrium assignment in nuclear station evacuation simulation. Fu et al. [26] developed a hurricane evacuation response curve based on both mathematic analysis and field data. This model develops different response characteristics concerning the input conditions of hurricanes. Wilmot and Mei [27] tested different evacuation trip generation models and also compared their relative accuracy. Chien and Korikanthimath [28] developed a mathematical model to estimate evacuation time and delay and compared the impact of staged evacuation and simultaneous evacuation. Wolshon's [29, 30] research presents a comprehensive assessment and review about the important factors related with evacuation, such as the evacuation process, plan and policies.

Sheffi [31] et al., Hobeika and Jamei [32], Pidd et al. [33], and Hobeika and Kim [25] have used statistical analysis tools including macro/meso-simulation and network-based methods to evaluate traffic flow. As technology has improved and computer power increased, the application of micro-simulation and dynamic optimization has increased (see, e.g., Franzese and Joshi [34], Cova and Johnson [35], Radwan et al. [36]). Many of these researchers propose operational policies for mass evacuations. In another study focusing on the Charleston, S.C. area, Stephen [37] built a model to test the effect of reverse lane traffic and the resulting traffic congestion at a main merge point. Recently, Robinson et al. [38] developed a mesoscopic simulation model (by CUBE) that allows the analysis of much larger travel distances. CUBE is a simulation tool which is built according to the relationship between flow and speed in a traffic network.

While many simulation studies are based on the use of commercial traffic simulation products, we choose to use a general purpose simulation software package called Arena to create our own mesoscopic evacuation simulation program. This program captures the long travel distances necessary to provide benefits when evaluating a hospital evacuation.

3.4 Model description

The concepts introduced in section 3.3 provide the basis for how the simulation model was developed. It combines the logic of traffic simulators with the flexibility of a general purpose simulation language in Arena. The sections that followed describe how the speed-flow relationship and cell transmission are incorporated into the model, as well as how the structure of the model was developed in Arena.

3.4.1 Speed-flow algorithms for simulation

The "Speed-Flow (or "Concentration-Flow") relationship from section 3.3.1 is the base point in determining a vehicle travel speed. In this research, the travel speed is the average operating speed in the segment collected from Google maps and validated by field data collected by the authors. Here are some key notations:

S: Space requirement per vehicle (in feet)

l: Car length (in feet)

f: Space factor

d: Car following distance (in feet)

q: Flow rate (in vehicles / hour)

k: Density or concentration of vehicles on a segment (in vehicles / hour)

We build upon the presentation of this relationship in Papacostas et al. [39]. Based on the above variable definition, we can see that

$$S = l + d. \tag{8}$$

Car following distance is defined according to the relationship between safety distance and speed. It was assumed that drivers follow the rule of the road in keeping a gap of one car length for each 10 mi/h increment of speed [39]. Given a space factor of *f* and vehicle speed of *v*, then safe spacing between vehicles can be expressed as:

$$d = \frac{vfl}{10} \tag{9}$$

This leads to the following expression for the space requirement per vehicle:

$$S = l\left(1 + \frac{vf}{10}\right) \tag{10}$$

Based on the required space per vehicle and the speed of the vehicle, readers can determine a flow rate estimate. Figure 3.1 provides the speed-flow relationship where the choice of a spacing factor and average car length will result in a unique curve to be applied in car following theory. Lines 1–4 are all based on the equations introduced thus far, while line 5 defines the speed-flow relationship at speeds higher than 50 miles/hour (to be discussed in section 3.4.1.1). For curves 1, 3, and 4, the space factors are 2.0, 1.175 and 1.0, respectively.

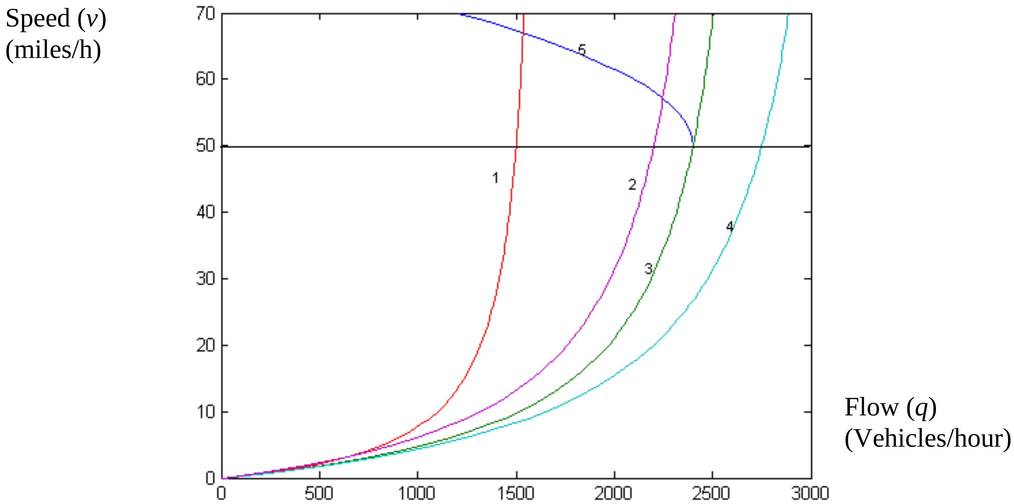

Figure 3.1: Speed-flow curve comparison

It is obvious that as the space factor is reduced (and, thus, the car following distance is reduced), the overall flow rate increases. However, it will become unrealistic when cars travel close together while at high speeds. Normally, the average car length is assumed to be 16 feet, with a space factor of 2. However, in evacuation research, it is anticipated that at speeds below 50 miles per hour, a space factor of 2 is too conservative, when considering the number of vehicles wanting to exit an area during an evacuation. Instead, we use a space factor of 1.175 to estimate the speed-flow relationship. Moreover, we assume that individuals will want to travel at the maximum allowable speed. Thus, curves 3 and 5 represent an estimation of the speeds applied within our model.

Often, cars are observed travel at distances closer than the safety requirements. As an example, defining the car length as 20, the space factor as 1, the relationship in Equation (10) becomes 20 + 2v feet / vehicle. Introducing a concentration factor k such that k = 1/S, and converting from miles per hour to feet per hour, the flow rate can be defined as

$$q = vk \tag{11}$$

$$= 5280v/S = 5280v/\left(l\left(1 + \frac{vf}{10}\right)\right) \tag{12}$$

$$q = 2640v/(10 + v) \text{ (vehicles/hour)} \tag{13}$$

Line 2 in Figure 3.1 is the curve based on Equation (13).

The modeling approach assigns vehicle speed based on two main factors: (1) average speed in a segment, and (2) the number of vehicles currently traveling on a segment. We also consider unique speed calculations for average operating speeds both higher than and lower than 50 miles/hour.

3.4.1.1 Speeds higher than 50 miles per hour

When the vehicle speed is 50 miles per hour, the flow rate typically reaches its peak value. Given a space factor of f = 1.175, the peak flow would be 2400 vehicles per hour (see curve 3 in Figure 3.1). However, to handle average operating speeds in excess of 50 miles per hour, a separate function is required. In particular, the space factors increase as vehicle speed increases. At 70 miles per hour, the actual flow can be no higher than 1200 vehicles per hour in an assumed safe range, which implies that the space factor is greater than 2. Using an approximation based on HCM 2000 [40], the authors develop the following flow/speed relationship for vehicles traveling between 50 to 70 miles per hour to approximate curve 5 in Figure 3.1:

$$q = 2400 - 3(v - 50)^2, \qquad 50 \leq v \leq 70 \tag{14}$$

When a vehicle is at the entrance of a cell, if the operating speed limit in that cell is higher than 50 miles per hour, then the first step is to determine if the car following distance will allow that operating speed. Based on Equations (12) and (14), under ideal flow conditions, the minimum required space for a vehicle will be:

$$S_{min} = \frac{5280v}{q} = \frac{5280v}{2400 - 3(v - 50)^2}$$

If L denotes the cell length and N represents the actual number of vehicles in that cell, the actual space requirement S becomes

$$S = \frac{L}{N}$$

There are two conditions that allow a vehicle to operate at 50 miles per hour or greater.

Condition 1: $S \geq S_{\min}$

There is enough space to hold more cars and keep the speed at the highest value. That is, the density is low and v = operating speed limit.

Note that the flow will have a converging point at 50 miles per hour as shown in Figure 3.1, where the car following distance is

$$d = \frac{vfl}{10} = \frac{50 \times 1.175 \times 16}{10} = 94 \text{ feet.}$$

Accounting for car length, the total space requirement is $d + l$ or 110 feet.

Condition 2: $S_{min} > S \geq 110$

There is no space to let the car run at the speed limit, but the car can still be assigned a speed higher than 50 miles per hour. Since Equations (12) and (14) are equivalent expressions for q under ideal conditions, we combine and solve for the maximum allowable speed *v* as follows:

$$\frac{5280v}{s} = 2400 - 3(v - 50)^2 \tag{15}$$

This is a simple one variable quadratic function (in terms of *v)* which is easy to solve. Then the maximum allowable speed V_m is obtained as:

$$V_m = \frac{(300S - 5280) + \sqrt{(5280 - 300S)^2 - 61200S^2}}{6S} \tag{16}$$

3.4.1.2 Speeds lower than 50 miles or distance closer than 94 feet

As already indicated, when the average operating speed is 50 miles per hour, the car following distance is 94 feet, and the default spacing factor is 1.175, the maximum flow is 2400 cars per hour. When the number of vehicles increases, people must lower the speed while maintaining the car following distance described in Equation (9). This is a conservative estimation. This speed was chosen to represent the speed at which traffic can flow on any segment and maintain a minimum safety distance, and flow speed and density can also be maintained. Let N denote the total number of vehicles currently on a particular roadway segment. Assuming a car length of l=16 feet, and knowing that car space can be equal to the segment length L divided by the total number of vehicles on that road (i.e., $S = L/N$), we can use the relationship from Equation (8) to find an expression for v:

$$d = S - l$$

$$\frac{vfl}{10} = \frac{L}{N} - 16$$

Substituting for each variable, our new expression for v can be shown as

$$\frac{v \times 1.175 \times 16}{10} = \frac{L}{N} - 16$$

$$v = \frac{\left(\frac{L}{N} - 16\right)}{1.88}$$

We then truncate 1.88 to 1.8 to allow more vehicles to remain in a segment and to allow a slightly faster speed. Thus, vehicle speed is calculated as:

$$v = \frac{\left(\frac{L}{N} - 16\right)}{1.8} \tag{17}$$

Equation (17) can only be used when the minimum car following distance is not violated (i.e., there are not more vehicles on the road segment than allowed with the formula), and a minimum travel speed can be maintained. We estimate this speed to be

20 miles per hour, and it represents the speed above which traffic can flow on any segment and maintain a minimum safety distance during evacuation.

3.4.1.3 Oversaturated roadway segments

For precise car following behavior to be followed for all vehicles, a complete microsimulation approach would break down over the long distances which the study area covers. To improve upon the ability of cell transmission, we offer the following approach for handling oversaturation.

It is assumed that the maximum vehicle speed without an unstable "surge and stop" movement is 20 miles per hour. Given that v = 20 miles per hour, f = 1.175, and l = 16 feet, we use Equation (9) to arrive at:

$$d = \frac{vfl}{10} = \frac{20 \times 1.175 \times 16}{10} = 37.6$$

We round this minimum car following distance down to 37.5 feet for convenience, which also allows cars to be slightly closer. If N is large enough such that a minimum speed of 20 miles per hour cannot be maintained, the first step is to calculate the maximum number of cars that can maintain a distance of 37.5 feet. Then, the remaining vehicles are assumed to move at a much slower speed of 5 miles per hour. Thus, the total roadway segment consists of vehicles moving at 20 miles per hour as well as additional vehicles moving at 5 miles per hour, the occupancy is 20 feet.

Given N total vehicles on the segment, then it will have x_1 vehicles moving at 20 miles per hour and x_2 vehicles moving at 5 miles per hour, where $x_1 + x_2 = N$. The total segment length (L) can be described by $(37.5 + 16)x_1 + 20x_2 = L$, which leads to the determination of x_1 and x_2:

$$x_2 = (53.5N - 5280L)/33.5 \tag{18}$$

$$x_1 = N - x_2 \tag{19}$$

It is also assumed that if the car following distance is less than 4 feet, a new vehicle cannot enter this segment.

3.4.1.4 Speed-Flow Summary

This section summarizes the speed-flow algorithms and cell transmission approach that have been developed within the evacuation model. We denote the highest operating speed limit as V_l and calculate $S = L/N$.

Average Operating Speed Limit is 50 or above

Define $S_{min} = 5280V_l/(2400 - 3(V_l - 50)^2)$ to be the minimum required space to operate at the speed limit.

1) If $V_l > 50$ and $S \geq S_{min}$, then assign a travel speed *v* equal to V_l.

2) If $110 \leq S < S_{min}$, then assign a travel speed equal to:

$$v = \frac{(300S - 5280) + \sqrt{(5280 - 300S)^2 - 61200S^2}}{6S}$$

3) If $53.5 \leq S < 110$, then assign a travel speed equal to:

$$v = \frac{\left(\frac{L}{N} - 16\right)}{1.8}$$

4) If $S < 53.5$, apply the procedure outlined in Section 3.4.1.3.

Average Highest Operating Speed Limit is Below 50

Define $d_{min} = V_l fl/10$ to be the minimum required car following distance and calculate $d = S - 16$.

1) If $V_l \leq 50$ and $d \geq d_{min}$, then assign a travel speed *v* equal to V_l.

2) If $37.5 \leq d < d_{min}$, then assign a travel speed equal to:

$$v = \frac{\left(\frac{L}{N} - 16\right)}{1.8} \tag{20}$$

3) If $d < 37.5$, apply the procedure outlined in section 3.4.1.3.

3.4.2 Developing the simulation model

In the Simulated Cell Transmission Model (SCTM), the conditions shown in Equations (5) – (7) can easily be accounted with more flexibility through the use of dynamic density and travel speed updates.

In Daganzo's CTM model, the free flow speed cannot be greater than the cell length divided by the specified time interval of the model; this speed can be expressed as below:

$$v \leq \frac{x}{t}$$

In this expression, x is the cell size and t is the time interval. The cells are sequentially connected. If v exceeded the above limit, the vehicles would "jump" to the second downstream cell and thus, CTM would not function properly. To imitate a continuously formed backwave, CTM introduces a factor δ.

In contrast, our model is run in a continuous fashion. Whenever a vehicle leaves the cell, the state of the cell is updated immediately, thus the new speed calculation will be based on the entrance condition for the entering vehicles in real time. Another property for CTM is that the travel speed must be a constant. The model presented in this chapter controls the entering behavior based on current road congestion and sets unique travel speeds for each entering vehicle in a real time and dynamic fashion. If congestion forms, the accumulation of vehicles will cause the assigned speed of upstream vehicles to be slower, thus forming an actual backwave. However, we still need to assign an appropriate cell length to keep the model accurate.

In our simulation, there is a unique sub-model that contains all information related to that cell, including the current allowable speed for an entering vehicle and dynamic representation for $n_i(t)$. There are counters at the entrance and exit points for each cell that increment and decrement the total vehicle count in cell i by 1 for each arriving and leaving vehicle. The following is a brief description about how the simulation model is constructed.

The model consists of around 120 sub models, 80 of which are segments and the remaining sub models are intersections. Within each segment or cell, the arrivals are generated from entering points and flow according to the defined or calculated routes. The arrival rates are derived from TransCAD data and shaped according to Equation (3) and the framework described in Chapter 2. Those arrivals are modeled by the Arena entity generator engine named “schedule” and released by the module “arrive”. The travel speed algorithm is based on car following theory and the Highway Capacity Manual [12], described in section 3.4.1. Figure 3.2 is a typical model description of a road segment.

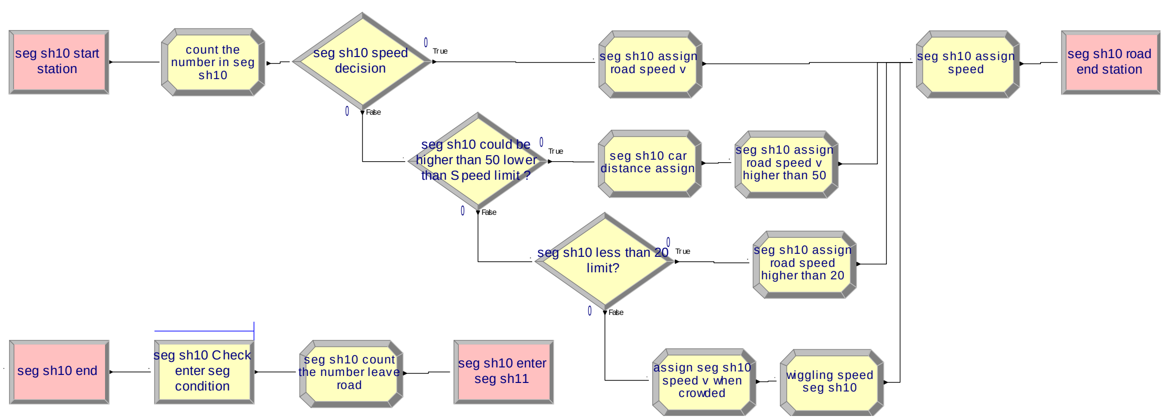

Figure 3.2: Typical cell structure

Traffic lights are simulated by a conveyor that periodically stops advancing based on a red light delay time. The delay time is a triangular distribution with mode 0.3 minutes and range from 0.2 to 0.5 minutes. The queue length has a maximum allowable length of 18. Figure 3.3 is an example of the traffic light.

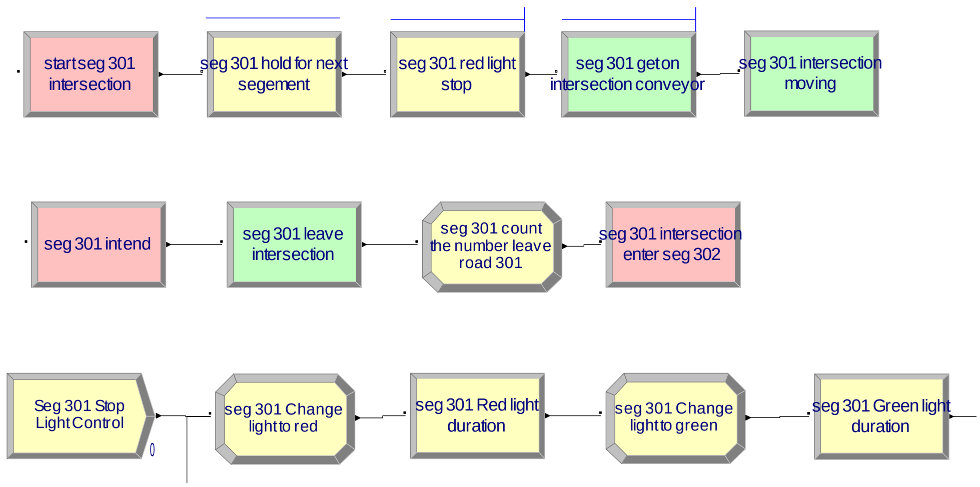

Figure 3.3: Traffic light model

In summary, we are using the concept of cell transmission, and applying it in a discrete event simulation model. The result, in this case, is a mesoscopic simulation model that has characteristics of both meso and micro simulation. While it is mesoscopic in nature (based on the traffic flow logic that has been implemented), the model has additional flexibility in tracking and manipulating individual vehicles that is not typically included in mesoscopic models. The model has complete control over each vehicle at any decision point within the model.

3.4.3 Case study inputs

To make a systematic evaluation for the hospital evacuation plan, we developed a hurricane evacuation traffic model and simulated the interaction of hospital ambulances with the general population traveling under such a traffic environment. Data collection process has been described in Chapter 2. It mainly includes:

1) Define TAZ.
2) Retrieve census data with TransCAD.
3) Calculate the arrival distribution curve.
4) Transform the arrival curve into "schedules" and input the simulation model.

After we complete the data preparation work, we can use those data to test different scenarios.

3.4.4 Scenario analysis – mandatory and hospital evacuation start times

In this analysis, we would like to determine appropriate start times for both the mandatory evacuation and the hospital evacuation in order to (1) complete the evacuation well in advance of the emergency event, and (2) avoid extremely long roadway delays where patients are in a less stable environment. To address these issues, we consider multiple mandatory evacuation start times (24/30/36/42/48 hours before landfall) as well as multiple hospital evacuation start times (0/6/12 hours prior to mandatory evacuation order). The following assumptions that hold across all of the scenarios tested are included:

<u>Vehicle Requirements and Time Estimation</u>

To gain an understanding of how well each evacuation route performs, we assume that we have one ambulance per route (for a total of 11 ambulances). Then, each ambulance is required to make 8 trips on that route, for a total of 88 trips.

<u>Evacuee Departure Times</u>

All vehicles participating in the evacuation will begin their trip at least 6 hours before hurricane landfall. Thus, if the evacuation order is issued 24 hours before the landfall, the evacuation window of evacuating traffic to the roadway system will be 18 hours.

In the information that follows, data are grouped by evacuation route ID (provided in Table 2.5), with each group representing a set of eight trip times from the origin to the destination for that particular route.

3.4.4.1 Extending the evacuation window

In particular, for the 18-hour evacuation window, ambulances on three separate routes require over ten hours to reach the sheltering hospital, as opposed to only one trip exceeding eight hours when the evacuation window is 36 hours (see Figure 3.4). In a 36-hour time window, although we assume there is one peak in the arrival rate, the slope is not very steep and the hours near the peak arrival rate are flatter than the general shape of 24-hour and 18-hour evacuation windows (see Figure 2.4).

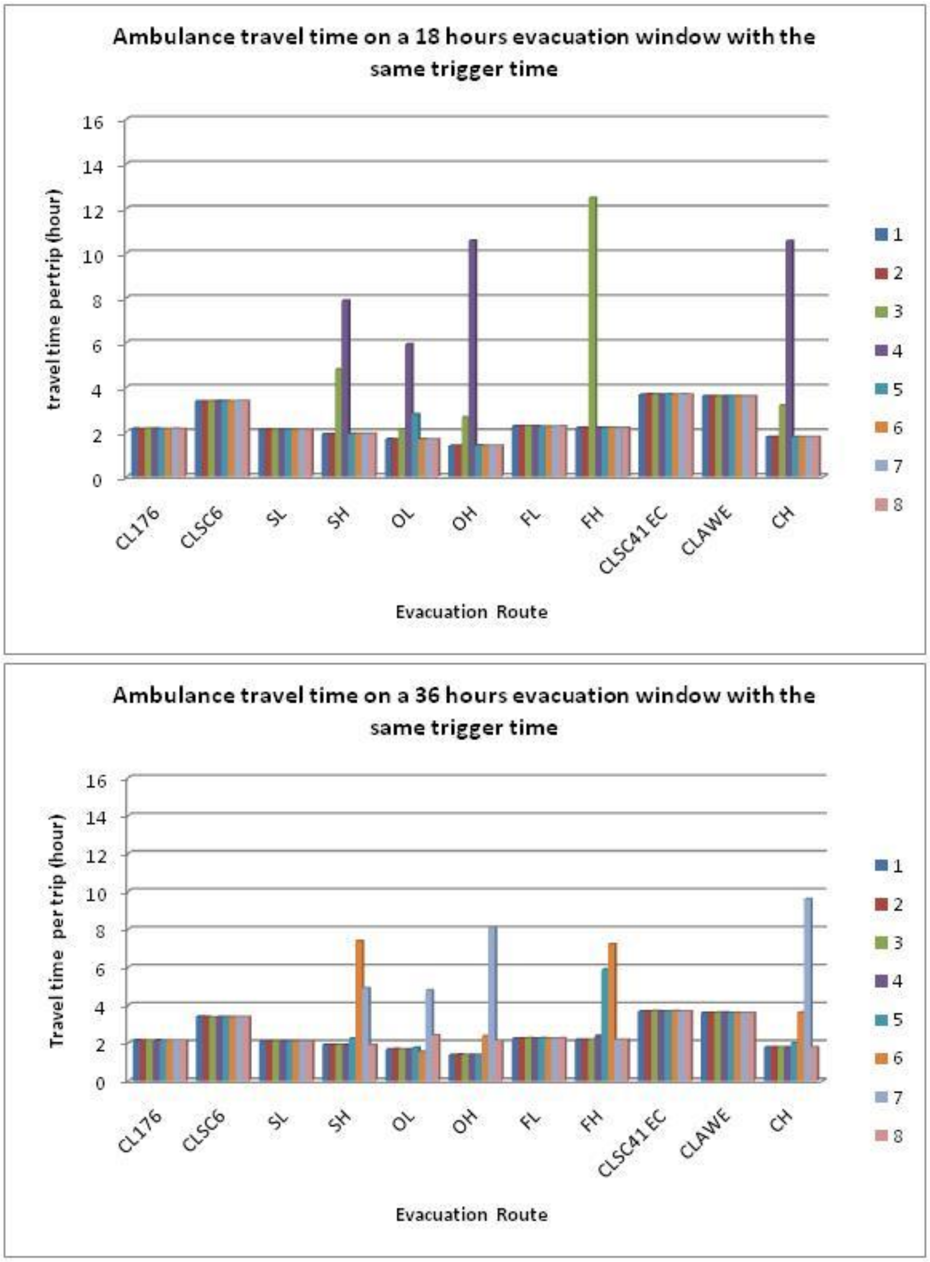

Figure 3.4: Ambulance trip time with different evacuation window

Consider the example of performance on a particular exit route below in Table 3.1. Both evacuation scenarios require well over 40 hours to complete, which implies that the last hospital patients will not be safely transported to the receiving facility in time. Initiating a hospital evacuation prior to the mandatory evacuation is necessary when the hospital requires ambulances to make round trips to transfer patients. We conducted several simulation tests to determine the required trip times based on hospital evacuation start times either 0, 6, or 12 hours in advance of the mandatory evacuation. (Note that the 24-hour window has a longer travel maximum trip time than the 18-hour window. This is dependent on when each ambulance returns and begins its next trip. It does not mean that the 24-hour window is not preferred to the 18-hour window.)

Table 3.1: Comparison of 18- and 24-hour evacuation window

FH	18 hour evacuation window		24 hour evacuation window	
Trip cycle	finish time	travel time	finish time	travel time
1	2.18	2.18	2.18	2.18
2	6.85	2.17	6.85	2.17
3	21.82	12.47	11.79	2.44
4	26.49	2.17	29.02	14.73
5	31.17	2.17	33.70	2.18
6	35.85	2.18	38.38	2.18
7	40.52	2.17	43.06	2.18
8	45.20	2.17	47.73	2.17

3.4.4.2 Increasing the evacuation window and pre-alert time

By extending the evacuation window to 42 hours (i.e., beginning the evacuation 48 hours prior to landfall), it is assumed that there is one arrival peak each day, where the peak on the first day is higher than the peak on the second day. This result shows that for the Charleston area, there is no congestion during the evacuation process, and all evacuees are safely moved from the evacuated area.

3.4.4.3 Leveling the arrival rate

In section 3.4.4.1 we find that if we try to avoid some very steep peaks, we will have a smooth evacuation process. If local authorities have a detailed evacuation arrangement and try to keep the arrival rate (or evacuation rate) within a manageable range, the evacuation could actually be completed in less time while also avoiding the congestion. We assume that local authorities can control traffic to influence the evacuee arrival rate as follows. The height of the original arrival rate distribution is 50% of the original 24-hour peak height, where it reaches a leveled peak at 12 hours. The rate of the first hours increases gradually from 0; meanwhile, the last four hours reduces gradually to 0. Refer back to Table 2.8 to find the peak values of a 24-hour leveled arrival rate. Figure 3.5 is a typical shape of the leveled arrival rate. Figure 3.6 shows the result based on this shape of arrival. Although there is still some congestion, we find the process is still running in a smooth process.

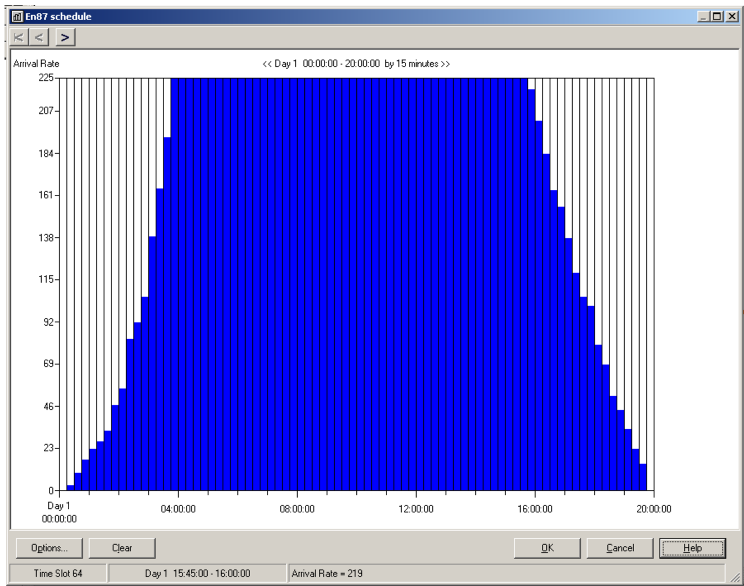

Figure 3.5: An example of a leveled arrival rate

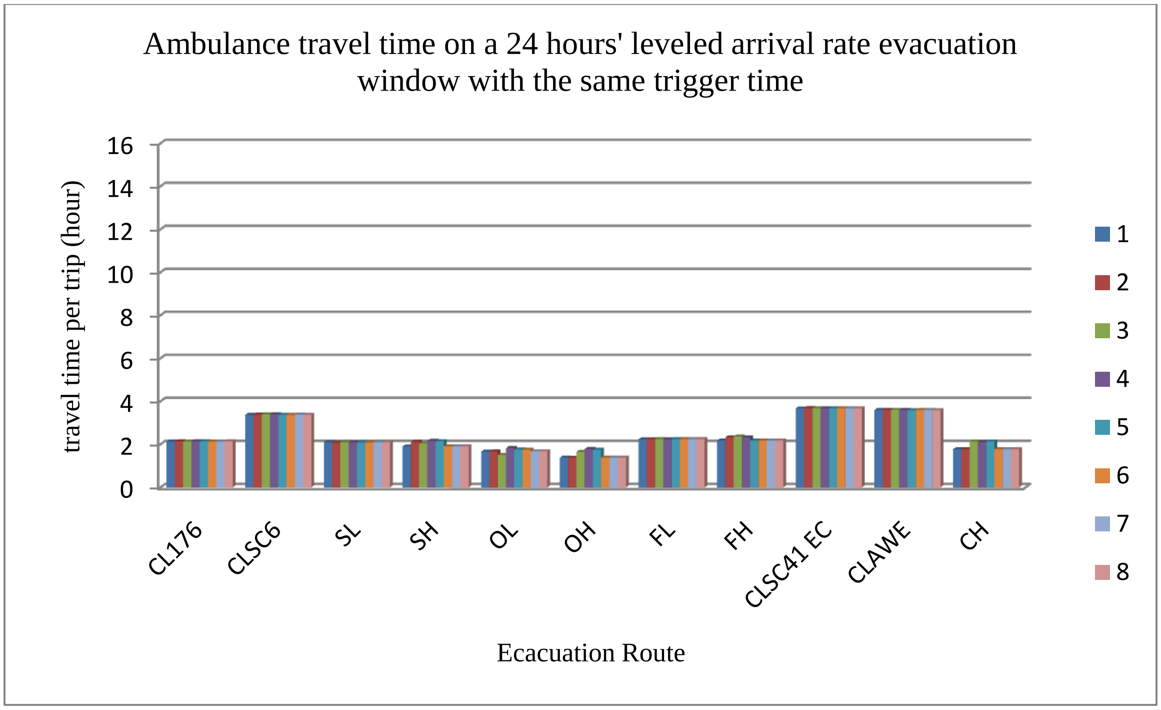

Figure 3.6: 8 cycles with 24-hour evacuation window and leveled arrival rate

3.4.4.4 Effects of local traffic

If we control the local traffic outside of the evacuation area and keep the traffic network only for evacuation, the evacuation can still experience high congestion. Figure 3.7 is the result of the evacuation with a 36-hour evacuation window. Compared with Figure 3.4, the longest cycle time does decrease. However, the delay still exists, which means the local traffic is not the main reason contributing to the congestion.

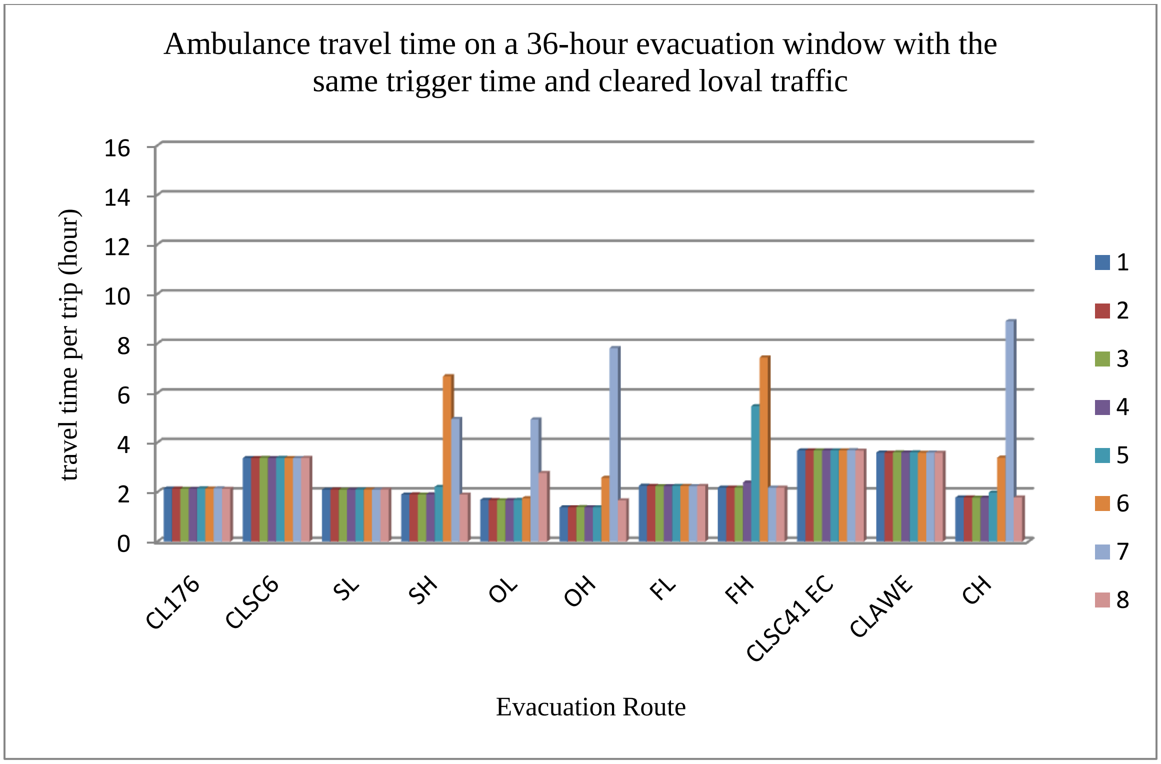

Figure 3.7: 8 cycles with 36-hour evacuation window and no local traffic

3.4.4.5 The effect of travel direction

Originally, we used a 50/50 split for directing traffic to Florence and Columbia. The total numbers of evacuees that move toward these two directions are based on SCDOT's TAZ data and SCDOT's plan. Now, we attempt two more extreme cases. First, 25% of evacuees proceed to Columbia and 75% to Florence; second, 25% of evacuees proceed to Florence and 75% to Columbia.

Table 3.2 and Table 3.3 show the results under a 24-hour evacuation window. For these 11 routes, the left column for each route ID is the travel time of 8 trips with 25% Columbia and the right part is the result of 75% flow of Columbia flow.

Table 3.2: Flow direction comparison (part 1)

	CL176		CLSC6		SL		SH (Hwy)		OL		OH (Hwy)	
	25% Co	75% Co	25% Co	75% Co	25% Co	75% Co	25% Co	75% Co	25% Co	75% Co	25% Co	75% Co
1	2.13	2.13	3.36	3.37	2.09	2.10	1.90	1.91	1.68	1.67	1.39	1.39
2	2.14	2.13	3.37	3.38	2.11	2.08	1.91	1.90	1.67	1.68	1.38	1.39
3	2.13	2.14	3.37	3.38	2.09	2.09	1.90	2.12	1.67	1.67	1.38	1.39
4	2.13	2.13	3.39	3.39	39.97	2.09	6.18	6.52	1.50	1.77	2.29	2.17
5	2.14	2.14	3.38	3.38	14.45	2.11	6.27	8.01	5.61	5.31	10.11	12.28
6	2.13	2.14	3.38	3.38	6.92	2.10	1.90	1.91	2.61	2.92	1.38	1.38
7	2.14	2.15	3.37	3.37	2.12	2.09	1.90	1.90	1.68	1.68	1.39	1.38
8	2.14	2.13	3.38	3.38	2.10	2.08	1.90	1.90	1.67	1.67	1.38	1.38

Table 3.3: Flow direction comparison (part 2)

	FL		FH (Hwy)		CLSC41 EC		CLAWE		CH (Hwy)	
	25% Co	75% Co	25% Co	75% Co	25% Co	75% Co	25% Co	75% Co	25% Co	75% Co
1	2.24	2.23	2.18	2.18	3.69	3.68	3.60	3.60	1.78	1.78
2	2.25	2.24	2.17	2.18	3.69	3.68	3.59	3.59	1.78	1.77
3	4.96	2.25	2.54	2.43	8.61	3.67	6.53	3.60	1.78	1.77
4	38.98	2.25	11.12	13.07	27.30	3.68	7.79	3.59	3.05	3.32
5	13.25	2.26	2.17	2.17	8.95	3.67	18.98	3.59	10.11	12.24
6	3.50	2.25	2.17	2.18	5.00	3.67	5.60	3.59	1.77	1.77
7	2.26	2.24	2.17	2.17	3.70	3.68	5.45	3.59	1.77	1.77
8	2.24	2.24	2.18	2.18	3.68	3.69	3.75	3.60	1.77	1.78

From Table 3.2 and Table 3.3 we can see that there are some special issues observed in this scenario. The traffic assignment has less effect on highway traffic. In fact the delay occurs before the intersection of I-26 and I-95. Thus, no matter what percentage we assign to Columbia or Florence, all the evacuees need to pass the bottleneck and then split. The congestions starts at the intersection of I-26 and I-526 where several trip generation zone traffic merges together.

The traffic assignment had maximum affect on Florence local route (FL). Florence local and Sumter local routes are more sensitive to a high arrival rate. As we can see, if we assign 75% local evacuees to Florence direction, the local congestion becomes extremely high, at approximately 38 hours. However, if most of the traffic is toward Columbia, the traffic doesn't change.

Traffic from East Cooper and Awendaw area are delayed if 75% of the evacuees are directed to Florence. Since these locations share some segments with Florence local routes, those segments create a bottleneck if there is too much traffic competition. Columbia local roads have capacity to hold the evacuee traffic since more than one route has been designed for evacuees to travel toward Columbia. There may actually be alternate paths (via additional secondary road options) that all lead to Columbia, but there is minimal risk of congestion with staying on the main routes. In fact, we can assign more traffic onto those routes.

3.5 Conclusions and future work

In this chapter, we developed a tailored simulation model, which has flexible, microsimulation capabilities, and it incorporates mesoscopic traffic flow concepts, such as cell transmission and the speed-flow relationship across longer travel links to allow the evaluation of a region covering several hundred miles. The simulation model are able to maintain complete control and flexibility in identifying individual vehicles (e.g., ambulances) and tracking their progression, while having the ability to consider a region covering several hundred miles. Prior to this investigation, there were no simulation tools that combined hospital-specific traffic with community-wide traffic participating in a mandatory evacuation.

The model provides a clear relationship between travel time and evacuation time windows. In particular, this research found that for a hurricane evacuation of the Greater Charleston metropolitan area, in order to evacuate all patients prior to hurricane landfall, the hospital evacuation must start at least 12 hours prior to the mandatory evacuation order (given a typical 24-hour notice). Alternatively, the hospital evacuation can take place at the same time as the mandatory evacuation if both begin 48 hours prior to landfall.

Future research could include the testing of staggered start times for the mandatory evacuation, as well as quantifying the differences in evacuation trip times for alternate destinations. In addition, by adding the function of route searching in the model, we will enable the model to search and detour the trip in a dynamic fashion within a practical range to observe how the travel time changes in different situations. In order for a city and its healthcare facilities to make robust and informed decisions, it is important to understand how total evacuation time and individual ambulance transfer times change when the destinations of the evacuees change.

4 Analysis of Dynamic Evacuation Planning with Arena

4.1 Abstract

In this chapter we carry out dynamic trip planning research utilizing a simulation model. This chapter starts with an introduction about the concepts of dynamic traffic assignment (DTA). Traditional DTA models neglect some real life factors in a system, which often limits their application to only static analysis under a specific traffic condition. In this chapter, we exploit the benefits of simulation by periodically reviewing the preferred path from multiple starting locations (or originations) to multiple destinations. These preferred paths are then used by all evacuees for those particular O-D pairs. We conduct scenario analysis based on the User Equilibrium (UE) principle since it represents the natural behavior in an evacuation process. From different scenarios, we observed that under a dynamic traffic assignment environment, UE can be utilized to reduce the total evacuation time, however, may cause higher congestion at certain times. We have also shown that an active control might be helpful in decreasing the average travel time. Using a system optimization approach, if the preventive action can be applied, the performance can be greatly improved.

4.2 Introduction of dynamic traffic assignment

Transportation systems are typically the central component in an evacuation process, and an effective and timely traffic management and control system is vital to a successful action plan. Unlike the traditional traffic assignment process, we cannot predict the flow in a static way. Demands are changing with time, and road congestion might occur at any point, as was illustrated in Chapter 3. To begin, some important concepts need to be introduced. In the following sections, a brief description about transportation system and traffic assignment is provided. These concepts will be used throughout Chapters 4 and 5.

4.2.1 Transportation system modeling

In transportation system analysis, a transportation system is often simplified into a form of network and zoning systems. The term *network* includes two elements: a set of nodes and a set of links that combine the nodes together. Links can represent the real structure of roads or can be an integrated symbol of a connection between different areas. Similarly, a node can be a real intersection or just a symbol of special areas, called a centroid. The most important characters related with links are length, free flow travel time and link capacity. The speed and delay of a traffic network system can be estimated from those characters interacting between each link. As described in Chapter 3, various speed-flow functions have been created to model the speed-flow relationship and this relationship also decides the performance of the network. Some examples of travel time functions can be found in Patriksson [41]. In addition to links, the term *route* or *path* is defined to represent a sequence of directed links leading from one node to another. For example, in our dissertation, the routes refer to a set of links that connect the start point of each TAZ till the destinations.

As described in section 2.4.1, the term *zone* in the zoning system refers to a partition of an urban area. Within each of these zones, various data can be collected for calibrating and validating the transport model. Each zone is represented in the network by a special node called a *centroid*. Each centroid can either be an *origin* node from which traffic enters the network, or a *destination* node to which traffic leaves the network.

A traffic assignment model is generated from the transportation model. It focuses on estimating how traffic flows through a road system and the associated effects of traffic on the system. These effects can be measured by a number of criteria including distance travelled, travel time, delay, fuel consumption and environmental pollution. In the evacuation model, we focus on the criteria of travel time since people need to be evacuated to safe places as soon as possible.

Modeling and solving a traffic assignment framework requires three different components. They mainly include: 1) travel demand, 2) geographic structure of the network and link performance in the network, and 3) methodologies that can be used to assign the demand distribution.

The first two components have been explained in Chapter 2 and Chapter 3. Given the demand for travel and the characteristics of a transport system, the third kind of information is a way of estimating the corresponding distribution of the travel demand over the transport system. The most widely accepted way is through the principles of traffic assignment proposed by Wardrop [42].

4.2.2 Traffic assignment in city evacuation

Traditional travel forecasting problems are solved with a classical four–step process. Generally speaking, traffic assignment is the final stage for travel forecasting. We generate the trip; distribute the trip by their origin-destination matrix; and define their travel modes. The final stage is to assign the trips along the routes in the network. Those routes are normally travel paths with lowest costs for each origin-destination pair.

However, in a dynamic traffic assignment process characteristic in city evacuations, the problems markedly differ. During evacuations, the shortest path is not necessarily the fastest. The "best routes" are those selected by considering a trade-off between speed, capacity and risks of accident and long time delay. Trip assignment modeling for evacuation does not require too much data as the choice of alternatives is limited. Though our model considers optional backup routes in case of possible congestion, the detour behavior is limited to some predefined routes.

4.3 Dynamic traffic assignment (DTA) simulation in city evacuation

In a real-world traffic system, traffic characteristics are dynamically changing based on time and road density. A traffic assignment model should be able to assign the traffic according to the relationship between the travel demand and the performance of the transport system. For example, travel times are increasing with travel demand, due to the decreased travel speeds since the roads are getting crowded.

4.3.1 Wardrop's principles

In estimating the corresponding distribution of the travel demand over an entire region, the most widely accepted method is through the two principles of traffic assignment proposed by Wardrop [42] in either static or dynamic traffic environments. These principles can also be used to control the distribution instead of only to predict or forecast the traffic flow. A brief introduction of Wardrop's principles in traffic assignment is presented below.

1) Wardrop's first principle – User Equilibrium (UE)

Wardrop's first principle is known as the equilibrium principle, where "the travel times on all the routes actually used are equal, and less than those unused routes." The underlying assumption of this principle is that all travelers will have the same travel times if they encounter the same traffic conditions provided that all travelers are also privy to the same perfect information on all possible routes through the network [43].

2) Wardrop's second principle – System Optimum (SO)

Under the first principle (User Equilibrium), each individual attempts to minimize his or her personal travel cost, without regard to the overall total system travel cost. The discrepancy between the behavior of individuals and the group behavior across the entire system is known as the "divergence between private cost and social cost" in economical theories. According to this observation, Wardrop proposed his second principle, also known as the System Optimum principle, in which the average travel time for all users is minimized. This principle is incorporated in the process of developing a DTA model for city evacuation in this research.

Under system optimal conditions, some travelers may be directed to routes that have higher costs than other less expensive routes even though they are also accessible to them. Such higher cost routes are selected because the additional costs incurred by those travelers will be outweighed by the savings gained by other travelers using the quicker routes. The SO assignment can also be formulated mathematically as a static minimization problem of the total system travel time spent in the network [43]. Chow [43] gave a detailed and comprehensive description of Wardrop's principles in his literature review work.

4.4 User equilibrium in evacuation

User equilibrium trip assignment can be solved by different methods, the most widely used methods are 1) iteration algorithms [39] and 2) mathematical programs [44]. With those methods, a known demand will be assigned to a set of routes with limited capacities, and all routes experience the same travel time concerning a defined O-D pair.

In a dynamic environment, normally, some UE solutions actually discretize the time into small continuous pieces and conduct an iterative assignment and travel time update for each piece [45]. This method actually utilizes the static forecast methodologies where an equilibrium assignment is achieved in a time range. However, the shorter the time range, the less likely the equilibrium assignment is achieved. Since user equilibrium is obtained over longer durations while the accumulated flow and travel speeds change according to the *link-capacity function* to reach an equilibrium state. This kind of process to reach the equilibrium state will experience more oscillation when the demand is exceeding capacity (as is the case in an evacuation process). In addition, the dynamic algorithms neglect the important process about how the UE can be formed. In fact, if the travelers rely on road condition information, short discrete time solutions will be inaccurate. Since reaching the equilibrium balance in such a short time is unrealistic, we create a simulation model to further explore path assignment and conduct scenario analysis.

In an evacuation process, most evacuees receive the information about road conditions from information boards shown on the highway or the radio. Once an evacuee selects an evacuation road, there is little chance to deviate from this path as detours are often not permitted. The further they drive, the less likely the possibility exists for changing their routes. In addition, most of the alternate local roads may have limited capacities and some of them might direct back to the highway.

We use the same concept in setting up the route planning in the simulation model. We allow evacuees to choose their route plan; once it is decided, they stick with that route throughout their journey. In reality, some of the evacuation routes might have intersections. If a highway can be directed to multiple downstream roads after the intersection point, we actually define them as several different routes. For example, if road A has 2 branches B and C after the intersection, we actually define the evacuation routes as 2 different route choices as Route “A-B” and Route “A-C”. Evacuees can choose either AB or AC as their route at the point A.

We simulate people’s behavior according to Waldrop’s first principle. That is, everyone chooses the fastest path at the beginning of the evacuation according to current information. It is quite natural that too many people in a short time choose the same route. Consequently, when a route gets congested and it is no longer the best to choose, subsequent evacuees will receive the updated information and start to choose the new optimum routes.

Some factors to consider when conducting dynamic route planning are the sensitivity of trip times (i.e., performance) to the information refresh rate, the level of demand, the level of DTA (regional vs. whole network), and the effect of active traffic control. In later sections, we will test and analyze those factors in detail.

4.5 DTA scenario studies

In this section, we carry out some tests to investigate the results of Dynamic Traffic Behavior under Wardrop’s first principle: User Equilibrium. We mainly focus on an 18-hour evacuation window. The data we used and the routes are different from Chapter 3; for example, to remove some unimportant data noise which is not related with the behavior of DTA, we deleted En84 and En87. Since evacuees from En84 and En87 are forced to take only the Orangeburg Local Route (Route 6), it actually has no effect on the DTA process.

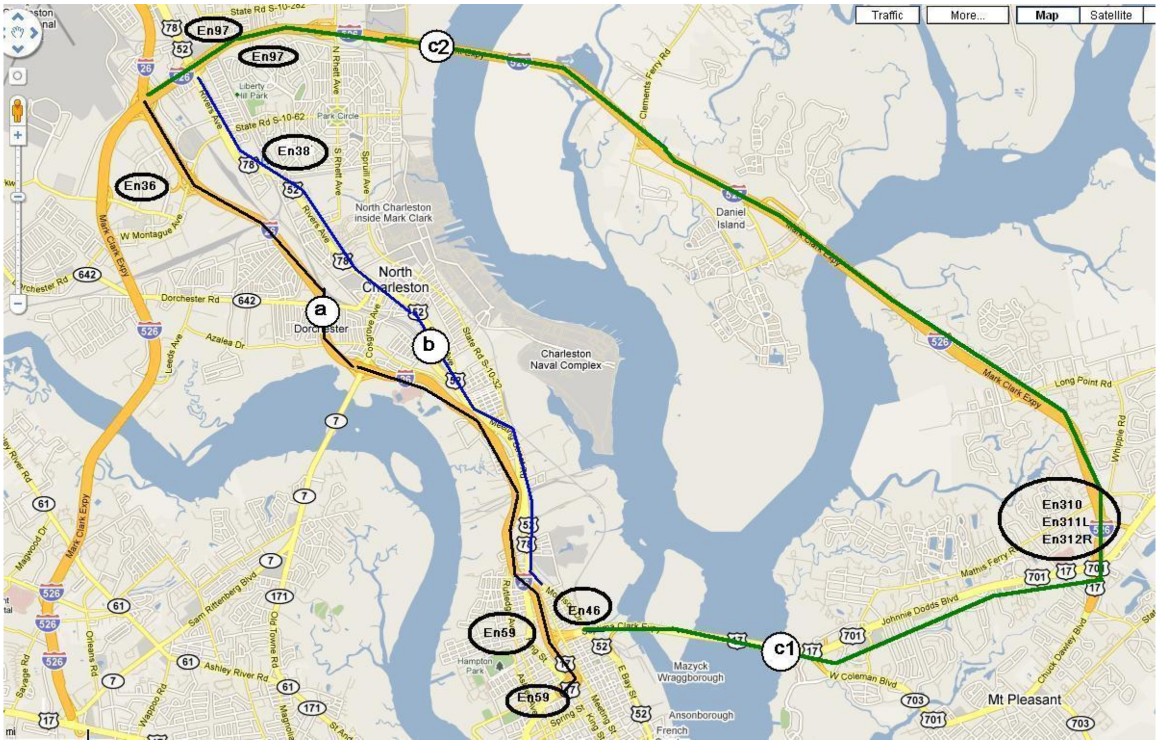

Figure 4.1: Dynamic route options

Figure 4.1 shows the dynamic route options for the originating points near the center of Charleston County. For each of the original loading points, the route choices are:

1) Route a: From En59 to west En38.
2) Route b: From En46 to west En38 and En97.
3) Route c (include c1 and c2): From En46 toward east via En310/311L/312R (Route c1), after that, either go toward North (Route c2) or toward east.

Once a route is selected, the route will be followed according to the SCDOT routings shown in Table 2.5. For En38 and En97, there is not an option to travel downtown and then over to Mt. Pleasant – these evacuees can either choose the highway or local option to start their evacuation toward north.

Table 4.1 is an example of possible route choices for En59. For example, given a destination of Florence, evacuees have five choices along Route a, b or c:

1) Take Route a via I-26, the same as Route 1;
2) Take Route b via I-52 toward I-526, then take Route 2;
3) Take Route c1c2 to Mt Pleasant and I-526, then take Route 1.
4) Take Route c1c2 to Mt Pleasant and I-526, then take Route 2.
5) Take Route b via I-52 and continue the rest as Route 1.

Table 4.1: Route choice for En59

En59	Florence	Columbia
1	Route a + Route 1	Route a +Route 3
2	Route b +Route 2	Route b + Route 4
3	Route c1c2 +Route 1	Route c1c2 + Route 3
4	Route c1c2 +Route 2	Route c1c2 + Route 4
5	Route b + Route 1	Route b + Route 3
6		Route c1 to Mt Pleasant and continue with SC701 to Route 10
7		Route c1 to Mt Pleasant and continue with SC701 to Route 11

For Columbia, the first five choices are similar to items 1) to 5) in the choices for Florence; in addition, evacuees can also go further to East Cooper and take Route 10 or

Route 11. For the other origination points, the schedules are very similar. For example, evacuees from Mt. Pleasant can go to downtown or directly take I-526 to leave; in addition, they can either choose to take SC-52 or I-26 to leave Charleston when after choosing SC-701 to downtown.

The following sections present the results of different scenarios from DTA and non-DTA models. We focus on two major statistical results:

1) Average transfer time;

2) Maximum travel time.

4.5.1 Traffic information updated every 15 minutes

In this scenario, we use the original model and compare the result with DTA settings based on the road information updated every 15 minutes. No other settings in the model were changed. Table 4.2 shows the result comparison. It can be seen that a better average travel time is obtained using the dynamic traffic information.

Table 4.2: Base case comparison

	Average Transfer time (hour)	Maximum Travel Time (hour)
No DTA Scenario	3.47	10.27
DTA scenario	2.54	6.74

4.5.2 Scenarios using different demand levels

The data in section 4.5.1 is obtained from an 18-hour evacuation window. The demand is very high and routes get congested in a very short amount of time. To test the effect of different congested situations, we add a scale factor that controls the arrival densities, where 0.1 to 1.0 represents 10% to 100% of the original demand level.

Table 4.3 presents the results of DTA using different demand levels. From Table 4.3 we can see that the average travel time becomes closer to the non-DTA case with the decrease of demand, with DTA providing better average performance than non-DTA cases. For the maximum transfer time, in low volume cases, DTA is slower than non-DTA scenarios. We will have a detailed analysis concerning this issue.

Table 4.3: Transfer time comparison with different demand scale factors

Scale Factor	Average Transfer time under DTA (hour)	Average Transfer time without DTA (hour)	Maximum Travel Time under DTA (hour)	Maximum Travel Time without DTA (hour)
1	2.54	3.47	6.74	10.27
0.8	2.28	3.53	6.51	8.86
0.6	2.12	2.51	6.06	4.86
0.4	1.95	2.02	5.18	3.67
0.2	1.78	1.88	4.29	3.67
0.1	1.71	1.82	2.90	3.67

Figure 4.2 shows the comparison of average transfer time concerning different demand levels. When the demand is not that high (scale factors from 0.1 to 0.5), we can see that the average transfer time is very close. It seems that DTA is a little better than

non-DTA cases. It is noticed that the advantage of DTA might be set back by a long delay in some segment since when people overwhelmingly select the “fastest path”, that path might become the slowest. Consequently, the evacuees who are stuck in the slowest congested route will contribute to a slow transfer time and thus will lower the overall performance. This is the reason why frequent updates or “actively controlling the traffic flow” during a high demand process to avoid oversaturation is desirable. This is further illustrated in the following part and in Chapter 5.

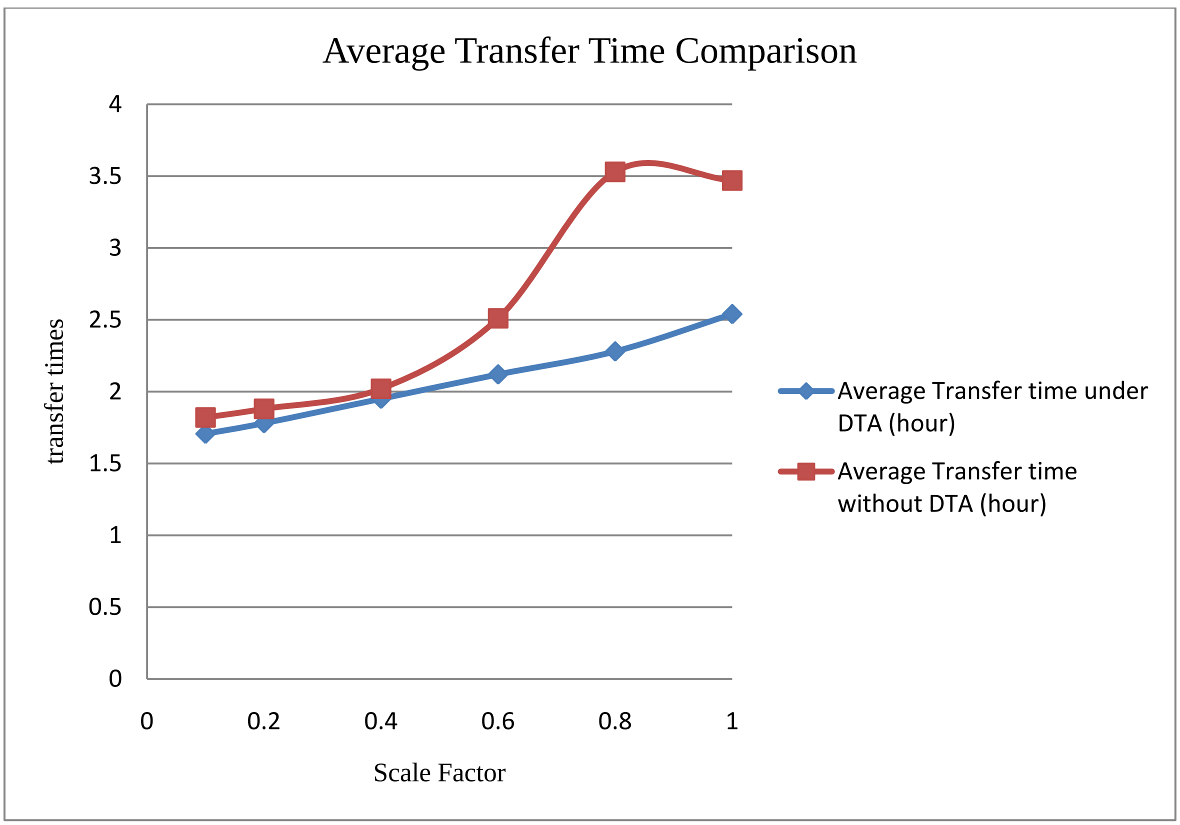

Figure 4.2: Average transfer time

Figure 4.3 shows the comparison of maximum transfer time. The maximum transfer time is a symbol about the extent of congestion. As we can see, both DTA and non-DTA cases show that with the increase in demand, the maximum travel time increases. The reason why non-DTA shows a worse result is because the vehicles cannot be dispersed evenly to other routes. Under DTA, evacuees might have a chance to detour and the high demand is then more evenly spread throughout the whole network. Even though the transfer time is still high, the extreme cases might be avoided, which implies that the road network can be utilized a little more efficiently.

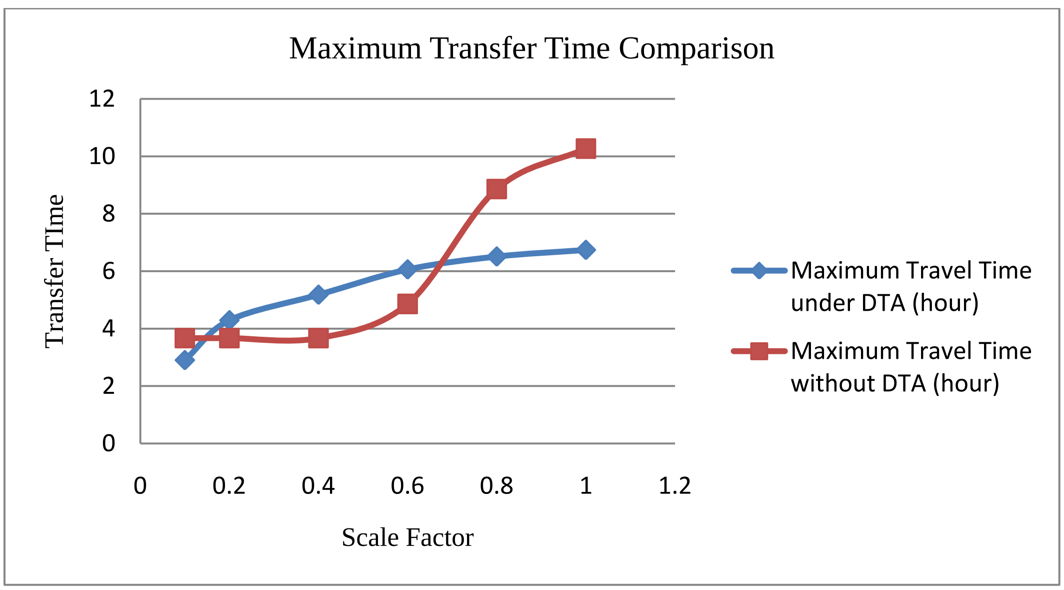

Figure 4.3: Maximum transfer time Comparison

However, with the decrease in demand, the maximum travel time of non-DTA cases decreases much more quickly than DTA cases. Actually, for non-DTA cases, when the demand scale factor is lower than 0.5, the maximum travel time is equal to the free-flow travel time on the longest route. However, when there is no congestion, some travel times are wasted on the long pre-defined routes. On the contrary, some competition and surging still occurs under DTA cases, where evacuees seek the fastest paths. If we keep decreasing the demand, all evacuees might use the same shortest path without severe congestion, and we would expect both the maximum transfer time and average transfer time to outperform the non-DTA cases.

4.5.3 Effect of the information refresh rate

Sometimes we can imagine that the reason why people overwhelm some shortest path is that they receive the same information at their starting point and the information has not been updated recently. We can expect that if evacuees received the newest real time situation report, the observed maximum travel times would decrease. In this section, we investigate the effect of the information refresh rate in the evacuation process.

We choose scale factors of 0.8 and 0.2 (based on section 4.5.2) in our model and increase the refresh time from 0.15 minutes to 240 minutes.

Table 4.4: Travel time and information refresh rate

Refresh Rate (minute)	Scale Factor=0.8, Average Transfer Time under DTA (hour)	Scale Factor=0.8, Maximum Transfer Time under DTA (hour)	Scale Factor=0.2, Average Transfer Time under DTA (hour)	Scale Factor=0.2, Maximum Transfer Time under DTA (hour)
0.15	2.27	6.33	1.77	4.3

2	2.28	6.18	1.77	4.3
10	2.29	6.29	1.77	4.29
30	2.27	6.49	1.78	4.3
60	2.28	6.37	1.79	4.3
120	2.37	6.26	1.78	3.72
240	2.75	7.49	1.78	4.3

From Table 4.4 we can see that the total travel time and maximum travel time are fairly consistent across a wide range of refresh rates. The reason might be related to the time to form the congestion and the time to relieve it. In addition, it is also related to link length and structure of the evacuation network, and this causes the status of a route to change slowly. It will take one hour or more before the “current best route” is crowded with evacuees who followed a former route suggestion but now have no chance to detour even though the information about the best route has finally changed. Their chosen route ultimately becomes overwhelmed, since too many evacuees are now using a route that is no longer the preferred route.

4.5.4 The concept of preventive time

Considering the 18-hour evacuation window from Figure 2.4, if the arrival rate is not very high, it is very hard to form the congestion. In addition, since all routes would be underutilized, the road segments or links in the model can accommodate a large number of vehicles in the next information interval.

So, if the refresh rate is 2 hours, as we defined in a previous scenario, more than 20% of the demand will be on the best route at the peak hours. This will definitely cause a traffic jam. During the next information update, this route will not be assigned any evacuees. Although we have 11 routes, there are many shared segments which will form the bottleneck, and the routes containing these segments will control the total travel time on the network. In reality, we have four main independent routes that can each potentially hold 25% of evacuation demand. This will cover the eight peak hours with the highest demand. On the other hand, if the refresh rate is less than 2 hours, there is the opportunity to change the preferred route more frequently. In fact, each of the main independent routes will take turns becoming the leading or preferred route under a crowded situation, and the demand is also evenly assigned to the network.

As a result, if the demand is very high (scale factor of 0.8), every route will be fully occupied and this congestion will continue for hours. On the contrary, if the demand is not that high and the congestion is growing at a very slow pace, a single route will remain the preferred choice (in the leading position) for an extended period of time. In this case, the dissipation of a traffic jam is very quick since the arrival rate is very low and the queues are easier to clear if people can choose another route. Thus, the average and maximum travel time actually have only slight changes under different refresh rates.

From above analysis we can see that the real decision time is the gap time (i.e., how long a route can take the leading position until it is fully occupied by the interested evacuees). However, we still need to avoid long delays between information updates since the risk of an accident will increase under a congested situation.

As we analyzed above, the key problem for a traffic jam is the information refresh system. To avoid this type of misleading information, we need to develop a new forecasting method called “preventive time for congestion.” This method creates a warning to inform the evacuees that some place might have congestion in the near future and people should select other routes earlier. This is more effective than a passive report of information. It can be regarded as a pre-calculated System Optimum assignment, and it is the subject of Chapter 5.

4.5.5 Regional DTA and whole network DTA

In SCDOT’s plan, the evacuation routes are divided according to different TAZs. However, in the current DTA model, evacuees can choose routes from other TAZs. They can first travel over to the TAZ that possesses the origin point of the fastest route and then take the route along with evacuees originating from that location. In this section, we consider whether or not this is a good policy. Specifically, we will compare various options of DTA, based on evacuee location and the current time within the evacuation.

We divide the evacuation zone into two groups – west evacuation group and east evacuation group. Except Zone 13 and part of Zone 11 in Figure 2.4, all the other TAZs belong to the west group. We test four scenarios:

1) Totally divided – in this case, west group and east group cannot share travel routes.
2) Permit trans-group DTA after 75 hours.
3) Permit trans-group DTA after 5 hours.
4) Whole network DTA without time limitation.

In cases 2 to 4, the east group and west group can share the best route via highway US-17. Highway US-17 is the corridor that connects these two groups together.

Table 4.5 shows the results of travel time concerning different cases. As we can see, if there is no trans-group DTA, the average travel time increases a little but the maximum travel time decreases. This is because more vehicles take the longer local route but competition via US-17 decreases; the average travel time increases but the maximum travel time under congestion decreases. In addition, we found that if we open the trans-group DTA after 5 hours, the average transfer time decreases but the maximum travel time begins to increase. If we continue to delay the DTA time, the average time increases while the maximum time decreases. We can imagine that the increase in maximum time is due to the highly congested route, but the average time can be saved by the DTA policy. Consider that if the route on the west part is not congested and east part evacuees are permitted to travel to the west side. In such a situation, the total travel time can still be saved. This leads to another potential policy, where we permit DTA at the beginning, force divided evacuation routes during peak travel to avoid overburdening main roads, and then reopen the DTA process. In the next section, we will show the result of such a flexible DTA control.

Table 4.5: Travel time and DTA start time

	Average Transfer time under DTA (hour)	Maximum Travel Time under DTA (hour)
Totally Divided	2.34	5.12
Permit DTA after 75 hours	2.34	5.12

Permit DTA after 5 hours	2.29	6.48
Fully DTA	2.28	6.48

4.5.6 Active control and optimization in evacuation

Section 4.5.5 demonstrates that a divided DTA can avoid long time congestion in city evacuation. However, if we control the traffic flow flexibly according to the situation in the network, we might have even better performance. Currently, we have the following measures to control the evacuation flow:

1) At the beginning, allow evacuees from East Cooper and Awendaw take the highway I -26 from downtown.

2) When I-26 is getting congested, evacuees from the east might be restricted from moving westward. This is actually the "preventive" measure mentioned in section 4.5.3; we call this time t_d.

3) When the west part is not as congested, east evacuees are permitted to use highway I-26 again. We call it reopen time t_r.

To address this, we incorporated an optimization component within the simulation model previously developed, with the objective of minimizing the average travel time. Arena has the optimization package named OptQuest. It uses heuristic methods to identify high-quality input parameters that provide the best value for the stated objective. Since there are two originating points from the east - East Cooper and Awendaw, we define two input parameters (these can be considered as variables in the simulation-optimization problem) for each time range.

Some key notation is defined below:

Z: Objective value

$t_{average}$: the average travel time for evacuees (an output from the simulation model)

t_{di}: the time to close the trans-group DTA ($i=1, 2$)

t_{ri}: the time to reopen the trans-group DTA ($i=1, 2$)

Minimize $$Z = t_{average}$$

Subject to:

$$0 < t_{d1} < 30;$$
$$0 < t_{d2} < 30;$$
$$30 < t_{r1} < 150;$$
$$30 < t_{r2} < 150;$$

Table 4.6 shows the optimized results. The best results can be obtained by different parameter combinations. As we can see that although the average transfer time only decreased 0.6 hours, since there are around 60000 evacuees entering the system, the whole system will save thousands of hours. This result is also much better than the scenarios we tested before in this chapter. This is a demonstration of what an active and preventive control can achieve in under a system optimal process. In particular, to prevent congestion, at t = 15, evacuees from East Cooper cannot go to downtown. Even at an earlier time of t = 6, evacuees from Awendaw are forced to stay on their local roads.

Actually, at t = 6, there is no congestion. If the traffic management team only reports the real time situation on the road, many more evacuees will continue to flow to the best route across the corridor, and the congestion cannot be avoided. So, the preventive traffic control based on system optimization can help us lower the total travel time and accident risk.

Table 4.6: Optimized results

	average transfer time (hours)	t_{d1}	t_{d2}	t_{r1}	t_{r2}	maximum travel time (hours)
1	2.2	15	6	132	80	5.78
2	2.2	15	6	150	118	5.78
3	2.2	15	6	121	142	5.78
4	2.2	15	6	123	126	5.78
5	2.2	15	6	132	83	5.78
6	2.2	15	6	132	74	5.78

4.6 Conclusions

In this chapter we simulated the dynamic route selection process in an evacuation environment based on Wardrop's first principle – User Equilibrium (UE). Traditional dynamic traffic assignment simulation models provide optimal route selection using frequent updates to the exact path used in traveling from origin to destination. This method does not fit well for evacuations, where people have less opportunity to change their routes once they start their trips. In addition, traditional DTA algorithms cannot simulate the decision making process and cannot model the situation for how people respond to road information. Traditional DTA algorithms do not provide an accurate evaluation in a congested and quickly changing traffic environment, as in mass evacuation.

Using the simulation model presented in this chapter, we observe that there is some level of naturally formed congestion that does not require re-routing. If the demand is not very high, we suggest using predefined routes for evacuation to avoid congestion when people compete for the best routes.

Not only can we simulate the decision making process for evacuees, we also suggest better solutions for evacuation information guidance methodologies such as preventive forecasting and system optimized forecast. Using a system optimization approach, if the preventive action can be applied, the performance can be greatly improved.

5 A Dynamic Traffic Assignment Model for Evacuation Management

5.1 Abstract

This chapter presents a framework of dynamic traffic assignment (DTA) under a congested evacuation process. The primary objective of the framework is to sustain an acceptable speed of the evacuation traffic since an unstable traffic flow or over saturated condition may cause even longer delays and higher risks of an incident. As a part of the proposed DTA framework, this chapter presents a method to estimate the minimum speed to maintain a stable traffic flow, and a method to control and manage the congested traffic. The proposed framework presented in this chapter allows a long segment of the road network to be used as a buffer to keep the traffic flow moving at an acceptable rate. Concurrently, a detour trigger time is estimated to minimize the total travel time of the network during a traffic assignment process. The buffer concept introduced in this chapter was found to be useful in the DTA process. A case study of the evacuation of the city of Charleston demonstrated that this idea is useful in different types of congested traffic environments. It also simplifies the computation of complex network programming, including optimization of traffic management and control processes.

5.2 Introduction

As we can see, transportation systems are typically the central component in an evacuation process, and an effective and timely traffic management and control system is vital to a successful action plan. In this chapter, we will use mathematical methods to carry out a theoretical analysis for system-level optimization. Though a great deal of research has been conducted in evacuation in the areas related to transportation, such as planning and policies[5, 30], route selection [46, 47], pickup location selection [48] and resource optimization [49], there are not much traffic management research as it pertains to the evacuation process, particularly in congested long distance urban environments.

This chapter advances a new concept that combines the dynamic traffic assignment process with the aid of Wardrop's second principle of traffic assignment under the evacuation process, especially during periods of peak congestion. Practical solutions are derived to solve the difficulties of traffic assignment and control in congested environments during an evacuation process. This chapter begins with a brief introduction of traffic assignment theory and city evacuation, followed by a brief description on the analysis of the bottleneck in an evacuation network and its use in a buffer system for System Optimum (SO) solutions. Finally, a framework for applying this SO evacuation plan is presented with a real-case study for a Charleston evacuation scenario.

5.3 Dynamic Traffic Assignment framework in city evacuation

A significant portion of DTA research in evacuation is based on simulation; in fact, simulation is often integrated into optimization analysis as well. Afshar and Haghani [50] used a mesoscopic traffic simulator in a optimization algorithm to find the system-optimum dynamic traffic assignment. Han et al. [51] obtain an optimal destination and route assignment based on the one-destination evacuation concept, where one “super” destination is constructed for problem solving. Other evacuation simulation models can be found in Gangi [52], Brown et al. [53], and Robinson et al. [38]. All in all, the basic DTA methodology for evacuation is to use an algorithm embedded within a simulation software as a tool to observe the evacuation process by applying their optimized input variables into this dynamic traffic environment.

DTA problem can also be solved by analytical approaches. There are a lot of models concerning this problem based on Wardrop’s User Equilibrium (first principle) or System Optimum (second principle) theories [54-57]. Especially, in an evacuation environment, if the researchers consider the active control in some important road segment, SO model is important and very helpful to forecast DTA in mass evacuation. In this chapter, the authors advance several concepts and factors that are important to the success of a large scale urban evacuation management plan. In the next sections, four aspects of DTA are discussed: 1) Wardrop’s principles; 2) link performance analysis; 3) exit flow estimation; and 4) optimization in evacuation.

5.3.1 Optimization and Wardrop's principles

A traffic assignment model should be formulated in mathematical terms before it can be analyzed and solved numerically. In the previous chapter, we have already introduced the concepts of Wardrop's principles and simulated the first principle – User Equilibrium. Here we introduce the mathematical model for Wardrop's second principle – System Optimum formulation.

The following System Optimum formulation is adopted from Peeta [58] and Care [59]. The following parameters and decision variables are used in the formulation:

x^{ta} : The number of vehicles on link *a* at the beginning of interval *t*.

$h_{ta}(x^{ta})$: The cost incurred (in terms of disutility such as delay, travel time and transportation cost) when link *a* contains x^{ta} vehicles at the beginning of time interval *t*.

m^{ta} : The number of vehicles exiting link *a* in interval *t*.

d^{ta} : The number of vehicles entering link *a* in interval *t*.

I^t_n : The number of vehicles generated or joining the network at node *n* in the time interval *t*.

O^t_n : The number of vehicles reaching their destination node *n* in interval *t*.

B(n) : Link traffic flow leaving node *n*.

$g_a(x^{ta})$: The exit function, is assumed to be a continuous, non-decreasing, concave function. It is the maximum number of vehicles that can exit from link *a* at time *t* and is a function of the traffic conditions on the link and its geometric characteristics.

C(n) : Link traffic flow entering node *n*.

Minimize $$z(x) = \sum_t \sum_a h_{ta}\left(x^{ta}\right) \tag{21}$$

Subject to: $$\sum_b d^{tb} = \sum_c m^{tc} + I_n^t \text{ -}O_n^t \quad \forall t,\ n, \quad c \in C(n),\ b \in \tag{22}$$

$$m^{ta} \le g_a\left(x^{ta}\right) \qquad \forall t, a \tag{23}$$

$$m^{ta} = x^{ta} - x^{t+1a} + d^{ta} \qquad \forall t, a \tag{24}$$

$$x^{ta} \ge 0,\ m^{ta} \ge 0,\ d^{ta} \ge 0 \qquad \forall t, a \tag{25}$$

Equation (22) represents the node balance conditions. That is, the total number of vehicles leaving (entering set *b*) is equal to the total entering vehicles (leaving set *c*), minus those vehicles entering and are absorbed, plus those vehicles generated from within. Equation (23) is the exit capacity limit and Equation (24) is for the update of link balance. Peeta [58] also mentioned that no first-in first-out (FIFO) constraint is defined in the formulas. Because the objective function represents the result in a series of time intervals, a dynamic traffic behavior can be considered by defining different time slots.

The “congestion buffer” idea presented in this chapter originated from these formulations, and will discussed later in detail.

5.3.2 Link capacity functions

When the link density is changed due to a different arrival rate, the entering and exiting flow rates, as well as the travel speed, will also change. Thus, the travelers should select their routes accordingly.

In his reviews of the measurement and formulation of link capacity functions, Branston [60] determined the relationship between entering and exiting flow in a link (or segment). Since both flows have set capacities, they might not be analogous. Assuming that the entry capacity is higher than the exit capacity in daily traffic fluctuations, the entry flow first keeps increasing and then decreasing until settling to the level of the exit capacity, at which point the entire link reaches a balance of flow [60]. Indeed, when the traffic is oversaturated, it is very possible that because the higher arrival rate causes shockwave and congestion, the inflow sometimes is much lower than the exit capacity, resulting in an unstable traffic condition. One possible effective method for keeping the inflow equal to the outflow in the balanced state involves rerouting some traffic flow at a specific time to avoid congestion. However, Branston’s theory of flow fluctuation can assist researchers in forming new traffic management concepts to further improve a city evacuation process. First, the transportation stakeholder allows a higher traffic arrival for a time and uses the link as a “buffer” to absorb as much traffic as possible. If the high traffic rate continues, a detour order is then issued when the density reaches a predefined level; thus, a congestion might be avoided and the original link is kept in an inflow rate which is equal to or less than the outflow rate since the additional arrivals will be forced to detour. Thus, Branston's theory is realized. Considering real traffic condition with high traffic densities under evacuation, the only method for avoiding congestion and additional delays involves maintaining traffic moving at a minimum but acceptable speed so that traffic flows can be maintained in a relatively safe and continuous way to avoid unnecessary surges and jams.

5.3.3 Maximum flow at exit

The following subsection presents an analysis of speed at exits of evacuation routes. The minimum speed is determined by considering the traffic variability in the evacuation process, merge area and exit flow analysis.

5.3.3.1 Traffic variability in an evacuation process

As we discussed in Chapter 2, during actual evacuation events, the arrival rate of traffic first increases with time, and upon reaching peak value it then decreases. Consequently, in a very small window of time, vehicles will overwhelm the whole route, resulting in extremely high traffic densities. After lengthy delays, these long queues will ultimately be dissipated. Simultaneously, the arrival rate will decrease as most of the people (and their vehicles) will have left the endangered zones. Figure 5.1 provides an example of an arrival rate / response time curve in a 24-hour evacuation time window. The *x*-axis shows the time, the *y*-axis represents the portion of total demanding arrived with time passing by.

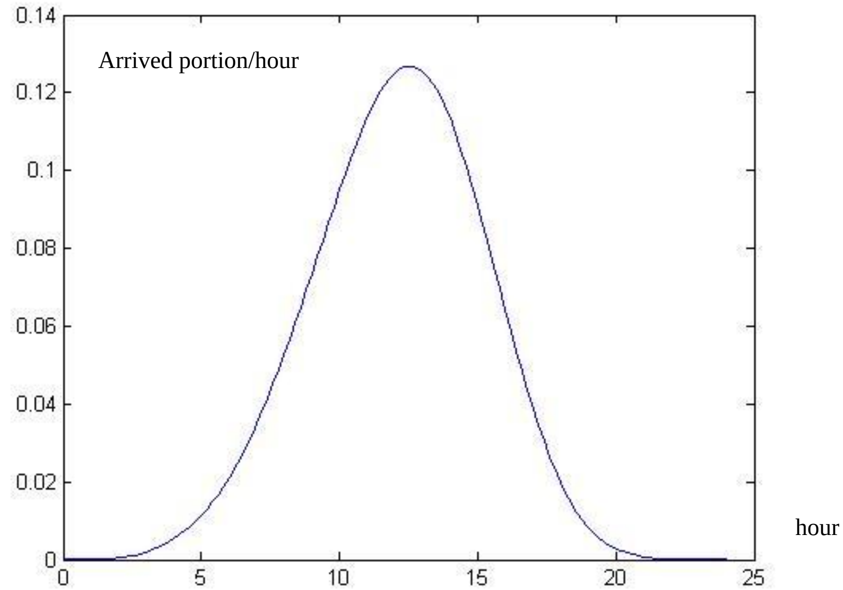

Figure 5.1: Arrival rate curve for a 24 hours evacuation window

Based on the analysis, should the traffic density reach an endangered level in which a minimum stable flow speed cannot be maintained, a detour order will be issued and the entering rate is now constrained.

5.3.3.2 Merging area capacity

Traffic can increase quickly at the merging points within an evacuation traffic network, overwhelming its merging capacity. Indeed, the exit point of various links may reach capacity more quickly if several highways merge together at a common point. Such centers of merging should be considered as bottlenecks in determining the real performance of an exit point. We assume that a capacity of 2500 vehicles per hour is applied for each of the lanes at the evacuation routes. When the inflow rate is higher than this capacity value, it is very likely that the traffic will become unstable [12]. Normally, the outflow rate shouldn't exceed the capacity; consequently, the road density will increase, resulting in an even lower level of service.

5.3.3.3 Merging flow analysis

Consider a merging location at the end of a segment. When a vehicle enters the merging area and the main roadway is saturated with traffic, if this entering vehicle observes a vehicle in front of it in the main roadway while it is entering, it will first accelerate to keep up with the front vehicle until it is forced to slow down to maintain minimum acceptable following distance. If the followed vehicle on the main roadway is affected by the behavior of the entering car, it must first reduce its speed and then maintain a similar but slightly slower speed than the entering vehicle. If a certain measurable distance holds x vehicles, each keeps a minimum safe distance from front, after the additional one enter the merging corridor, $x+1$ vehicles will occupy the distance. To keep safe, the last vehicle within that distance has to be "pushed out" and delayed slightly, resulting in a possible shock wave.

If the density of the involved lane is still within its capacity, additional entering vehicles are accommodated smoothly. The slowing at the merging ramp will not affect the performance of this involved lane, and the entire traffic situation will remain stable. However, if the merging ramp has already reached capacity, the merging will result in a delay to each succeeded vehicle. If considering the yield or slowdown for courteous behavior, the merged flow rate will be even lower. In congested situations, even if the main roadway is less congested than the ramp, it is unlikely that the maximum merged flow rate will equal or exceed the flow at the merging ramp – and this merge point becomes a bottleneck. Section 2.5.1 and Section 5.5.1 present an analysis of the exit point in which the merging area located and describes the values from subsequent road tests. The results are useful for the dynamic evacuation analysis.

5.3.4 An optimization expression

This section presents an optimization model specially for traffic assignment during evacuations, closely analogous to Peeta's [58] SO expression presented in Equations (21)-(25). While most SO expressions are clearly understandable, they are often quite difficult to solve in real case studies, and consequently give limited contribution to actual traffic forecast or management, because it is hard to model the general traffic fluctuation and thus the total travel time cannot be obtained in an algebraic way. However, in evacuation process, we can predict the arrival rate and the algorithm of total travel time is also solvable with the integration algorithm which will be described in Chapter 3.

Peeta showed the trip assignment for a specific time interval t. Similarly, in the evacuation model, two time controls are added: 1) t_0 (the time to start the calculation), and 2) t_{stop} the time to change the status of the traffic situation, for example, the time to trigger the detour when the link reaches its defined level. Thus, combining other time stages, an optimized traffic control model is obtained. Some node flow generation or absorption expressions are neglected since in the evacuation network, most of the traffic is determined by the beginning and ending points. There are no additional entities generated within the link, and all vehicles finish their trip at the end node. Thus, the model becomes much easier to solve and a SO traffic control procedure is achieved in a simple but effective way. Equations (26)-(31) provide a model tailored for an evacuation network SO assignment. The following notation is required for the model:

For all link *a*:

i:	Different time stages in the evacuation process.
$X^a{}_i$:	Total vehicles arrived at link *a* in time stage *i*.
$x^a = f_i(t)^a$:	The number of vehicles at time *t* on stage *i* in link *a*,
$h^a(X_i)$:	The cost incurred by vehicles arrived in link *a* during time stage *i*.
$A_{ri}(t)^a$:	The arrival rate onto link *a* in time stage *i*.
$A_{di}(t)^a$:	The departure rate of vehicles exiting link *a* in time stage *i*.
$B(n)$:	Link traffic flow leaving node *n*.
$C(n)$:	Link traffic flow into node *n*.
$C_{a:}$	The exit capacity.
t_i:	The time at which stage *i* begins, in a defined time stage, it is named as t_0.

Minimize $$z = \sum_a \sum_i h^a(X_i) \tag{26}$$

Subject to: $$\sum_b \int_i A_{ri}(t)\mathrm{dt} = \sum_c \int_i A_{di}(x) \ \forall i, \mathrm{n}, \mathrm{c} \in \mathrm{C}(n), \mathrm{b} \in \mathrm{B}(n), \tag{27}$$

$$A_{di}(t)^a \ \le C_a \ \ \forall i, a \ , \tag{28}$$

$$\int_i A_d(t)^a \, dt = \left(\left(f_i(t_i) \right)^a - \left(f_{i+1}(t_{i+1}) \right)^a \right) + \int_i A_r(t)^a dt \quad \forall i, a \tag{29}$$

$$x^a \ge 0, A_r(t)^a \ge 0, A_d(t)^a \ge 0 \tag{30}$$

$$t \in \left(t_0, t_{stop}\right) \tag{31}$$

In the above equations, the objective function (Equation (26)) is to minimize the total travel time cost incurred on roadway links in a time stages. Equation (27) represents the node balance constraints, i.e., inflow equals outflow for any particular node, it actually controls the bottleneck behavior in a buffer link model. Equation (28) confirms that each link’s outflow cannot exceed the link’s capacity. Equation (29) is the link balance condition. That is, for each time stage, the departed vehicle is the sum of the conserved and entered vehicles minus the new conserved vehicles at the beginning of the next time stage. When using t_i in Equation (29), this implies that $f_i(t_i)^a$ is the number of conserved vehicles in link a at the beginning of time stage i.

The value of z is normally obtained by integration as described in section 5.4. The integration method is very helpful in solving the traffic assignment problem since complex queuing calculations are not required, yet the solution automatically conforms to the FIFO principle in dynamic traffic assignment. The following buffer analysis and case study in section 5.4 and section 5.5 will show the process of calculating a congested travel time cost in a buffer link. In this group of optimization functions, there is only one increasing and decreasing arrival rate cycle (see Figure 5.1). If the arrival rate behaves in a more complex mode in which there is more than one cycle, the solution approach remains the same. However, the set of I will include more time stages or intervals.

5.4 Buffer analysis in a roadway segment

Before the dynamic traffic assignment process can be presented, it is necessary to introduce the concept of buffer analysis in traffic assignment. In an evacuation process, the key to avoid an incident and have a successful evacuation is to keep the traffic moving in a stable fashion. Thus, a minimum acceptable travel speed must be estimated at bottleneck points where several highway links merge together, since this may well be the earliest point reaching capacity. Such points can then be used to derive the exit flow rate for a link.

Hereafter the traffic situation is classified into three categories according to the arrival rate and flow conditions:

1) *Under capacity with low density*: The traffic is smooth and stable. According to Highway Capacity Manual [12], this corresponds to a level of service of A or B, where the exit rate from the link is the same as the arrival rate.
2) *Congested with no detour*: With an increase in the arrival rate, travel speed decreases and the links become increasingly congested; however, the travel time on the route is still less than the travel time if alternative links were used.
3) *Congested with detour*: When some part of the network reaches its capacity and bottlenecks form, traffic controllers estimate a time to enact a partial detour (i.e., a portion of the arrival rate is forced to another route). This decision can also be made according to the real density on the road in which sensors are installed to collect the real-time data.

As discussed in section 5.3.2, when the arrival rate (denoted as $A_r(t)$) is higher than the departure rate (denoted as $A_d(t)$), a high arrival rate flow that enters into the segment can be maintained for a certain period, and after some time the entry rate will equilibrate to the same level as the exit rate. This is an ideal situation in which no shockwave occurs. In actual traffic conditions, the shockwave is a natural effect when the arrival rate is higher than the exit rate in a link without any control system. To maximize the utilization of the road capacity, traffic management personnel can first let the entering flow with high arrival rate enter the link and then force part of the entering flow to detour, thus avoiding the main cause of traffic jams – the uncontrollable accumulation within queues. The link behaves as a buffer to absorb the first arrivals as much as possible, and if the real-time density reaches a certain threshold which is the boundary condition, to avoid congestion, traffic managers begin to deflect the remaining vehicles via detours. A well optimized detour trigger time can both avoid oversaturation and also minimize the average travel time across the system. The key aspect for optimizing the system is to determine this detour trigger time t_{stop}.

Here we define a time stage i for our discussion, we assign the start time t_0 at the time when departure rate reached its capacity. Assuming the initial number of conserved vehicles in the link is c_i, which represents the same meaning as $x=f(t_0)$, it takes t_{clear} to let c_i leave the link. From time $t_0 = 0$ to time when the density reached a defined level, a detour has to be triggered, named t_{stop}, this problem is divided into two cases to determine regarding if all c_i have left the link when the detour begins: $t_{clear} \leq t_{stop}$ or $t_{clear} > t_{stop}$. Denoting C as the summation of travel time cost for all related vehicles, the unit for C should be (vehicle*hour).

Case 1: $t_{clear} \leq t_{stop}$

From t_0 to t_{stop} the departure rate is denoted as a constant $A_d(t)=A_d$. During that time, the total number of vehicles without c_i that leave the buffer link is Q_{left}:

$$Q_{left} = A_d \times \left(t_{stop} - t_0\right) - c_i \tag{32}$$

According to Equation (29), the final number of conserved vehicles, $Q_{conserve}$, is the difference of the integrated result between arrived and departed vehicles plus those initially conserved. So,

$$Q_{conserve} = \int_{t_0}^{t_{stop}} A_r(t)dt - \int_{t_0}^{t_{stop}} A_d(t)dt + c_i \tag{33}$$

Considering the FIFO principle, it will need t_{form} to form the last conserved vehicles. This time represents the elapsed time from the first vehicle entering the link in the final conserved group until t_{stop}. The entering time can be expressed as:

$$t_{enter} = t_{stop} - t_{form} + \varepsilon \tag{34}$$

where ε is a very small amount of time.

In addition, based on Equation (29), the number of conserved vehicles on link *i* at any time *t* is:

$$\begin{aligned} x = f_i(t) &= \int_{t_0}^{t} A_r(t)dt - \int_{t_0}^{t} A_d(t)dt + c_i \\ &= \left(A_{rT} F(t) \Big|_{t_0}^{t} \right) - A_d(t - t_0) \\ &= A_{rT} \left[\left(1 - e^{-\left(t^a/b\right)}\right) \Big|_{t_0}^{t} \right] - A_d(t - t_0) + c_i \end{aligned} \tag{35}$$

A_{rT} is the total expected arrival vehicles in that link. When a vehicle enters the link, it will need t_{dc} to leave the link. This is the time needed to evacuate the leading vehicles (those in front of the entering one).

$$t_{dc} = \frac{x}{A_d} \tag{36}$$

Based on the above analysis, the total travel cost related with the arriving vehicles from t_0 to t_{stop} can be represented by the following five components:

1) The cost to form the final conserved quantity $Q_{conserve}$:

$$C_1 = \int_{t_{stop}-t_{form}}^{t_{stop}} A_r(t)\left(t_{stop} - t\right)dt \tag{37}$$

2) The total travel time cost for the conserved vehicles *($Q_{conserve}$)* to leave the buffer link can be shown as:

$$C_2 = \int_0^{t_{leave}} A_d\left(t_{leave} - t\right)dt \tag{38}$$

where $t_{leave} = Q_{conserve} / A_d$ represents the time required to leave the buffer link.

3) The time cost for the $Q_{conserve}$ vehicles to complete their travel. Given that the remaining travel time after these vehicles leave the buffer link is t_2, the cost will be:

$$C_3 = Q_{conserve} t_2 \tag{39}$$

4) The total travel time cost for the departed vehicles *(Q_{left})* to leave the buffered link is:

$$C_4 = \int_{t_0}^{t_{stop}-t_{form}} \left(A_r(t)t_{dc}\right) dt \tag{40}$$

where t_{dc} is obtained through Equation (35) and (36).

5) The time for the all the vehicles evacuated from the buffer link to finish their remaining trip:

$$C_5 = A_d t_{stop} t_2 \tag{41}$$

In this process, those initially conserved vehicles' travel cost C_{ci} should be removed from C_5 since they actually stayed in the link before t_0 and should not be considered as newly arrived vehicles' travel time.

$$C_{ci} = c_i t_2 \tag{42}$$

Then, the total travel time cost C_{Case1} can be formulated as:

$$C_{Case1} = \sum_{i=1}^{5} C_i - C_{ci} \tag{43}$$

<u>Case 2: $t_{clear} > t_{stop}$</u>

In this case, the following components comprise the total travel time cost for new arrived vehicles in time stage i. Denoting the newly entered vehicles' total entering travel cost as C_6, we have:

$$C_6 = \int_{t_0}^{t_{stop}} A_r(t)\left(t_{stop} - t\right)dt \tag{44}$$

Similar with Equation (40), the total travel time cost for the new arrived vehicles to leave the buffered link is:

$$C_7 = \int_{t_0}^{t_{stop}} \left(A_r(t)t_{dc}\right) dt \tag{45}$$

Finally, these vehicles require the following travel time cost to complete their remaining trips; given that the remaining travel time after these vehicles leave the buffer link is t_2:

$$C_8 = \left(\int_{t_0}^{t_{stop}} A_r(t)dt\right)d_2 \tag{46}$$

Then, the total travel time can be represented by:

$$C_{Case2} = \sum_{i=6}^{8} C_i \tag{47}$$

Since in most cases all of the initial vehicles will leave the buffer at time t_{stop}, Case 2 is not the common situation in an evacuation. However, under certain extreme conditions, such as during an accident or traffic jam, Case 2 might occur as well.

5.5 Case study: evacuation of Charleston, South Carolina

This section depicts an actual case study conducted for the I-26 Corridor, which is the primary evacuation route out of Charleston, South Carolina. According to the evacuation guidance issued by SCDOT, a major part of the evacuation will be carried out via Highway I-26 and its two branches called I-526 as shown in Figure 5.2. All of these routes will lead the evacuees toward a final destination of Columbia (or any point beyond I-95, the interstate that runs parallel to the coastline but 60+ miles inland). The case study includes the estimation of the maximum acceptable traffic speed and flow rate, together with the calculation of C_{Case1} in a link of an evacuation network.

5.5.1 Traffic on the main I-26 corridor

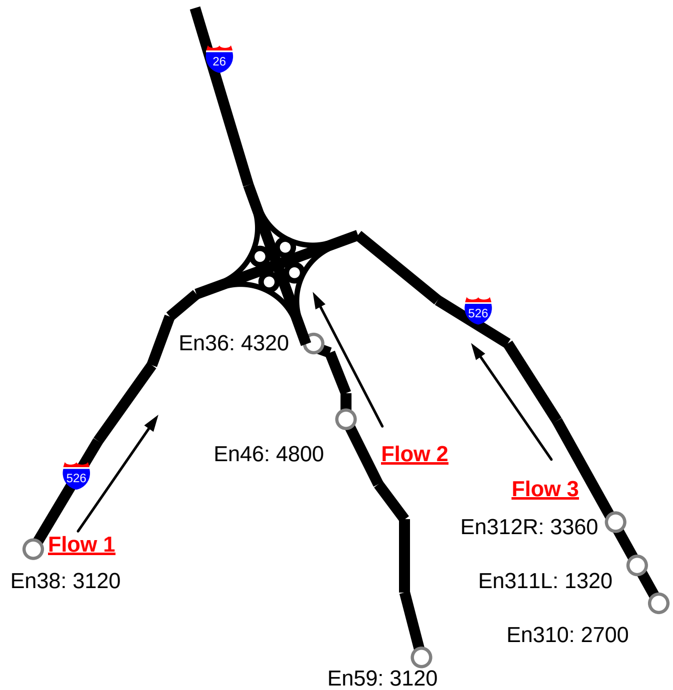

Figure 5.2: Merging flows of traffic evacuation from Charleston, S.C.

In Figure 5.2, the number of vehicles shown in each entering point named "En-" is the total vehicles arrived in a 24-hour window per lane. There are 3 lanes for each branch. The arrival rate curve in a 24-hour period is shown in Figure 5.1. By a rough estimation, 13% of the total evacuees will arrive at each link in the peak evacuation hour.

Assuming the capacity for each lane is about 2500 vehicles/hour, there are three lanes toward Columbia after the merging point. The total capacity is about 2500×3=7500 (vehicles/hour). According to Figure 5.2, the total demand from three upstream is about 22740 per lane. It can be estimated that the merging point will exceed the capacity at some time. If the upstream traffic keeps increasing, the traffic becomes unstable, necessitating the use of a control method like DTA to prevent the congestion. In addition, to simplify the calculation, since the link is not very long, all of the vehicles entering from different points are assumed to experience the same travel time as the vehicles entering from the furthest entrance. Based on actual road tests, the travel times are shown in Table 5.1.

Table 5.1: Travel times

Arrival Segment start point	Travel Time	Operation Speed
En59	8 minutes	65 miles/hour
En38	8 minutes	55 miles/hour
En310	13 minutes	60 miles/hour

This information can then be used to calculate the dynamic arrival rates at the merging point coming from the three Flows – West (1), South (2), and East (3).

According to Equation (3), and the results shown in section 2.4.2.2, we obtained the following expressions, before bottleneck level is reached:

The arrival rate from the west is

$$A_{r1}(t) = 3\times(3120)\left(\frac{4.45}{99309.8}\right)\left(t-\frac{8}{60}\right)^{4.45-1}\times e^{\left(-\frac{\left(t-\frac{8}{60}\right)^{4.45}}{99309.8}\right)}$$

$$= 0.419\times(t-0.133)^{3.45}\times e^{\left(-\frac{(t-0.133)^{4.45}}{99309.8}\right)}$$

The arrival rate from the south is

$$
\begin{aligned}
A_{r2}(t) &= 3\times(3120+4800+4320)\left(\frac{4.45}{99309.8}\right)\left(t-\frac{8}{60}\right)^{4.45-1}\times e^{\left(-\frac{\left(t-\frac{8}{60}\right)^{4.45}}{99309.8}\right)} \\
&= 1.645\times(t-0.133)^{3.45}\times e^{\left(-\frac{(t-0.133)^{4.45}}{99309.8}\right)}
\end{aligned}
$$

The arrival rate from the east is:

$$
\begin{aligned}
A_{r3}(t) &= 3\times(3360+1320+2700)\left(\frac{4.45}{99309.8}\right)\left(t-\frac{13}{60}\right)^{4.45-1}\times e^{\left(-\frac{\left(t-\frac{13}{60}\right)^{4.45}}{99309.8}\right)} \\
&= 0.922\times(t-0.217)^{3.45}\times e^{\left(-\frac{(t-0.217)^{4.45}}{99309.8}\right)}
\end{aligned}
$$

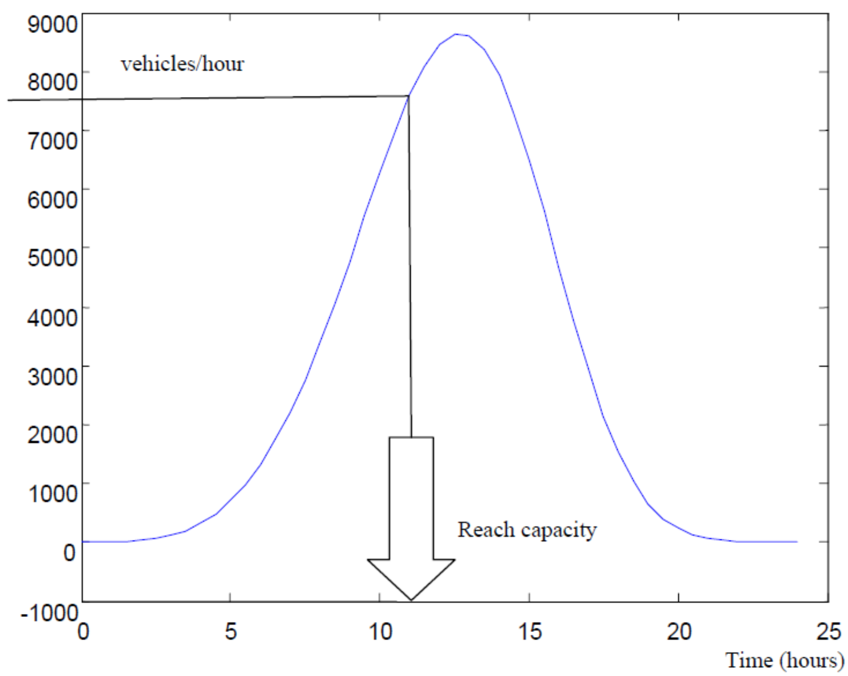

Figure 5.3: Arrival rate at merging point

Figure 5.3 shows the arrival rate at the merging point. It can be observed that at t = 11 hours, the road reaches a flow rate of 7500 vehicles per hour, or 2500 vehicles per hour per lane. More importantly, the time the entering ramp reaches its capacity must also be estimated. Because the left and right branch will merge into I-26 in very close proximity to each other, they can be considered together as a single merging lane.

The arrival rates from the east and west flows merging onto I-26 should be less than the merging ramp's capacity according to HCM 2000 [12]. Denote A_{d1} and A_{d3} as the departure rate of the east and west branches. The expression can be shown as

$$A_{d1}(t) + A_{d3}(t) \leq 2500. \quad (48)$$

It can be shown that the time when the combined arrival rate reaches 2,500 (vehicles/hour) occurs at $\bar{t} = 9.6$ hours. Considering the complex situation in an evacuation route, the bottom line is to maintain a constant flow. A conservative minimum stable speed without surging and stopping could be assumed to 20-25 miles per hour, based on estimation through observation for evacuation traffic. When six lanes merge together with a maximum flow rate of 2500 (vehicles/hour) per lane, the average road occupancy for each car becomes 20*5280/2500 = 43 feet, which is still acceptable according to the safe car following distance calculation.

Beginning at $t = 9.6$, the two branches' outflow rate is limited to the upper bound, A_{d1} becomes a constant value of 700 (vehicles/hour), while A_{d3} becomes 1800 (vehicles/hour). The flows are allocated according to the approximate ration for each branch. Meanwhile, the flow of A_{d2} is 3072 (vehicles/hour).

Though the arrival rate of each is still under the capacity of 2500 vehicles/hour per lane (given three lanes), the merging point has reached the upper limit. With traffic continuing to increase, the east and west branches will now act as buffers until the density finally reaches the upper bound level for traveling at about 20 miles per hour.

5.5.1.1 Latest time for inflow control

The maximum number of vehicles conserved in the left branch can be estimated using safe following distance value and the total length of the road L_1. Given a road length of L_1=7 miles, and assuming the average car length is 16 feet, the maximum occupancy D_{safe} becomes approximately 55 feet/car [39], which is acceptable since it is even less congested than the estimate of 43.2 feet provided in section 5.5.1. Here we have a conservative maximum number of $L_1 / D_{safe} = 7 \times 5280 / 55 = 669$ vehicles. This is a simple estimation since we just assume the ending part can merge together with a density of about 55 feet/car, and it is extended throughout an entire link by a single lane; actually the density can have a relatively higher value considering there are three lanes in the left branch.

Since it took 8 minutes to travel from entrance to exit, the entering cars before t = (9.6-8/60) = 9.467 hours have already left the link at t = 9.6 hours. Thus, the real conserved vehicle number at t_0 is: $c_1 = x(9.6) = \int_{9.467}^{9.6} A_{r1} dt = 106(\text{vehicle*hour})$.

The latest time a detour should be initiated is also the time when the conserved value reaches 669, which is the maximum buffer size or the saturation level. This time is denoted as t_{latest}, considering the definition of t_{stop}, we have: $t_{stop} \leq t_{latest}$.

t_{latest} is calculated as follows:

$$\begin{aligned} &\int_{9.6}^{t_{latest}} A_{r1} dt - 700(t_{latest} - 9.6) + 106 = 669 \\ &\Rightarrow t_{latest} \approx 11.55 \end{aligned},$$

At t = 11.55 hours, even though the ingress is still permitted to arrival vehicles, the whole system experiences a progressively higher risk of instability — a detour must take place. To simplify the expression, the new Δt = t_{latest} = 11.55 – 9.6 = 1.95 hours is set. Case 1 then can be used to calculate the total travel time of the vehicles from t_0 = 9.6 to t_{latest} = 11.55.

1) After calculating, t_{form} = 0.6 hours, the travel time cost to form the final conserved quantity $Q_{conserve}$ is

$$C_1 = \int_{t_{stop}-t_{form}}^{t_{stop}} A_r\left(t_{stop} - t\right)dt = 191 \text{ (vehicle*hour)}$$

2) According to Equation (38), since the conserved vehicles require $t_{drc} = \frac{669}{700} = 0.956$ hours to be emptied. The associated travel time cost is

$$C_2 = \int_{0}^{0.956} A_d\left(0.956 - t\right)dt = 320 \text{ (vehicle*hour)}$$

3) Here, the remaining travel time after the buffer link is t_2. Given that there is no congestion, let t_2=1.25(hours), and the travel time cost for C_3 is:

$$C_3 = 669 \times 1.25 = 836 \text{ (vehicle*hour)}$$

4) According to Equation (40) and Equation (36), the buffer link travel cost for Q_{left} is obtained as follows.

   a) By calculation, at t_0 = 9.6 hours, according to Equation (2), the total vehicles arrived and left buffer link is 1972. Based on Equation (36), after t = 9.6 hours,

$$t_{dc} = \frac{x}{A_d} = \frac{\int_0^t A_r(t)\,dt - 1972 - \int_{t_0}^t A_d\,dt + c_i}{700}$$

$$= \frac{A_{rT} \times F(t) - 1972 - d\left(t - t_{start}\right) + c_i}{700} = \frac{9360 \times \left(1 - e^{-\left(t^{4.45}/99309.8\right)}\right) - 1972 - A_d \times \left(t - t_{start}\right) + c_i}{700}$$

b) C_4 is then calculated as follows:

$$C_4 = \int_{9.6}^{t_{stop} - t_{form}} \left(A_r \times t_{dc}\right) dt_L$$

$$= \int_{9.6}^{10.95} 0.419 \times \left(t - 0.133\right)^{3.45} \times e^{\left(-\frac{(t-0.133)^{4.45}}{99309.8}\right)} \times \frac{\left(9360 \times \left(1 - e^{-\left(t^{4.45}/99308.8\right)}\right) - 1972 - 700 \times \left(t - 9.6\right) + 106\right)}{700} dt$$

$= 437$ (vehicle*hour)

5) The time for the vehicles in item 4 to finish the remaining trip is:

$$C_5 = A_d t_{stop} t_2 = 700 \times \left(11.55 - 9.6\right) \times 1.25$$

$$C_5 = 1706 \text{ (vehicle*hour)}$$

According to Equation (42), a total of about 133 (vehicle*hour) can be removed.

6) Therefore, the total arrived vehicle takes C_{case1} to finish this trip.

$$C_{Case1} = 191 + 320 + 836 + 437 + 1706 - 133 = 3357 \text{ (vehicle*hour)}$$

In conclusion, after calculation, from t = 9.6 hours to t = 11.55 hours, a total of 1928 vehicles enter the system. If these vehicles take the left branch as a buffer link and detour after t = 11.55, they will spend a total of around 3357 vehicle-hours to finish the trip.

If vehicles travel in uncongested traffic conditions, in total, all the vehicles will require only $C_{total} = \left(\frac{8}{60} + t_2\right) \times 1928 = 2667$ (vehicle*hour) to complete the evacuation. Considering a detour route that requires approximately 3.5 hours to complete at a free flow speed, if all vehicles take the detour at time 9.6, they will use $C_{detour1} = 3.5 \times 1928 = 6748$ vehicle-hours to complete their trips. In this case, the use of the merge lane as a buffer provides a travel time savings over the detour.

However, if the detour travel time requires only 1.7 hours long, then the detour travel cost is $C_{detour2} = 1928 \times 1.6 = 3084$ (vehicle*hour), which is lower than the total cost as we described above when we use up all the buffer capacity and the link reaches its saturation level; that is : $t_{stop} = t_{latest}$; but higher than the free flow travel time cost. At this time, we must set a time point t_x or t_{stop} to start the detour to minimize the total travel time. t_x should be less that t_{latest}. Figure 5.4 is an example of the total travel time changed with different detour trigger time from $t = 9.6$ to $t = 11.55$. As shown in Figure 5.4, from $t = 9.6$ to $t = 11.55$, if the detour travel time is not very long (about 1.6 hours), the best time to trigger a detour is $t \approx 10.8$. If we choose an incorrect detour trigger time, we might waste several hundred hours in total. Thus, we can use the system optimum model described in section 5.3.4 to find the optimized trigger time t_x to achieve the maximum amount of time saved. For example: we can divide the time stage as: 1) from $t = 9.6$ to $t = t_x$; 2) from $t = t_x$ *to* $t = t_{recovery}$, where $t_{recovery}$ is the time the arrival rate drops back to lower than 700 vehicles per hour. In addition, the model can combine all the links in the system together to have a system optimum result.

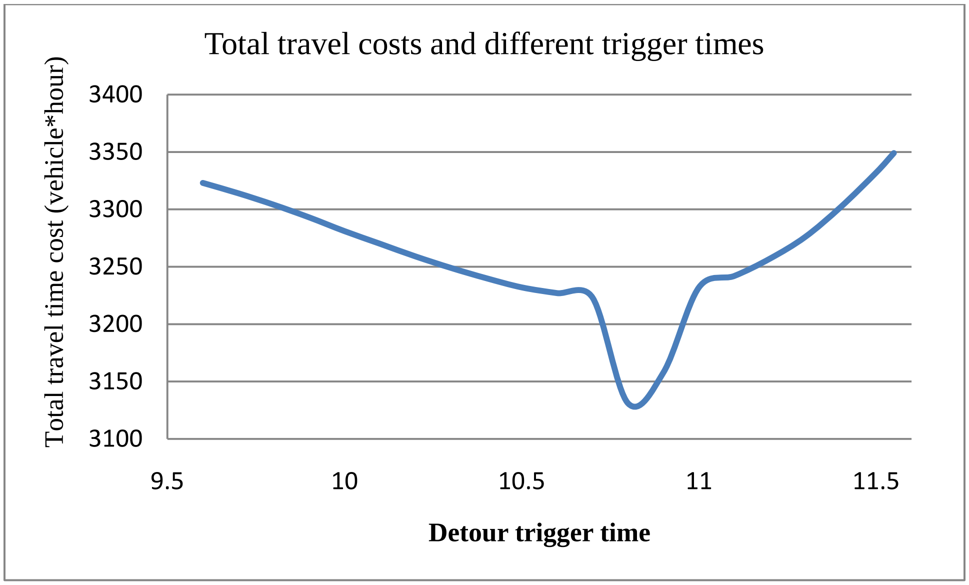

Figure 5.4: Total travel cost with different trigger time

5.5.2 Summary and findings

The buffer concept was found to be a useful tool for traffic assignment during an evacuation to minimize the total travel time as well as lower the risk of congestion. Previous Dynamic Traffic Assignment modeling efforts have yielded a variety of algorithms for use in determining the flow rate on each link. However, these models and algorithms are difficult to implement in the field, particularly in a large scale evacuation process with complex road networks and high traffic volumes.

5.6 Conclusions

This chapter presents a simple and effective way to analyze, assign and control evacuation traffic. The microscopic traffic behavior in congested roads, which results in a complication of DTA methodologies can be simplified by only considering the performance in the bottlenecks. In addition, the total travel time in the system is converted into a simple integration calculation based upon the flow rate at the entrance and exit points of the evacuation routes. What's more, a FIFO principle is met naturally. In an evacuation process, a skilled evacuation management team must determine the pivotal locus in each link as the bottleneck in which maximum density is determined by considering the risk of unstable traffic. By applying different levels of risk criteria, the outflow of the bottleneck may be delineated at various levels. The traffic diversion trigger time t_{stop} may also differ. For example, if the arrival rate increases in a relatively low speed within a short duration, we may apply a relatively high density to determine the buffer size since the risk of traffic congestion is not as high as a quickly increased arrival rate, thus, we may calculate the number of conserved vehicles from the corresponding traffic density. Once the conserved vehicle number is obtained, the optimization function can be solved easily.

The proposed framework has shown to be effective in managing the traffic in a link under a traffic incident scenario. For example, from the point of an incident, the queue accumulates upstream and the outflow of this bottleneck can be used to decide the entire link's performance with regards to the conserved vehicle. The location and time of a detour can also be derived from the optimization algorithm proposed in this chapter. In addition, with the increased application of real-time traffic monitoring technologies through Intelligent Transportation Systems (ITS), traffic management professionals may apply the proposed method directly using on-line traffic data. In real-time traffic monitoring when the density and exit flow rate are captured, the detour trigger time can be obtained automatically which is close to that obtained from the system optimum framework presented in this chapter.

6 Conclusions

This dissertation includes comprehensive methodologies and solutions for long distance city evacuation planning. The methodology starts with data preparation and simulation input design, followed by the introduction of updated Cell Transmission Model solution for a dynamic city evacuation simulation. Following this, different scenarios of dynamic evacuation process are analyzed with different demand level, information refresh rate and effects of active control. The final portion of this dissertation includes a mathematical analysis of a dynamic city evacuation process. This dissertation created several new solutions and methodologies that will help the analysis and evaluation of a long distance evacuation process. In addition, the simulation modeling algorithm and the mathematical DTA analysis algorithms can be utilized in different transportation application areas. The simulation model presented in this dissertation is flexible and efficient for long distance traffic simulation and Dynamic Traffic Assignment analysis.

The work presented in this dissertation could lead to important future research in mathematical modeling and simulation of a traffic network. We recommend the following research as a follow-up to this dissertation:

1) Calibration model for the Cell Transmission Model: This model can be validated with microscopic traffic models to ensure the accuracy and stability of each of the cell under different traffic densities. The length limit for a cell

can also be optimized to avoid the distortion of the data. Sometimes, when a cell is too long, the FIFO principle might be violated.

2) The algorithm in the DTA simulation can be updated with a more flexible route choice mechanism.
3) An interactive decision support system can be used during an actual evacuation. To prepare such a model or system, collected survey data could be utilized to simulate real life decision scenarios. The analysis about people's behavior in an evacuation process, such as start time, detour decision, destination selection and information resources can be updated with the most recent data, thus the simulation model can output more accurate results.

This dissertation provides promising and effective solutions for long distance evacuation from an at-risk area. The presented framework and models can be applied in real world evacuation scenarios. The research presented in this dissertation can assist evacuation planners and decision makers create a more accurate and practical evacuation plan, which will result in saving more lives and properties.

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