

1. Report No. SWUTC/09/473700-00057-1		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Computer Simulation-Based Framework for Transportation Evacuation in Major Trip Generator				5. Report Date January 2009	
				6. Performing Organization Code	
7. Author(s) Fengxiang Qiao, Ruixin Ge and Lei Yu				8. Performing Organization Report No. Report 473700-00057	
9. Performing Organization Name and Address Center for Transportation Training and Research Texas Southern University 3100 Cleburne Houston, Texas 77004				10. Work Unit No. (TRAVIS)	
				11. Contract or Grant No. DTRS99-G-0006	
12. Sponsoring Agency Name and Address Southwest Region University Transportation Center Texas Transportation Institute Texas A&M University System College Station, Texas 77843-3135				13. Type of Report and Period Covered	
				14. Sponsoring Agency Code	
15. Supplementary Notes Supported by a grant from the U.S. Department of Transportation, University Transportation Centers Program.					
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17. Key Words Evacuation, Safety and Security, Chemical Spills, Terrorism, Simulation, Computer Science, Traffic Flow Theory, Highway Operations, Intelligent Transportation Systems, Geographic Information Systems, Global Positioning System, Transportation Planning, Traffic Engineering				18. Distribution Statement No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161	
19. Security Classif.(of this report) Unclassified		20. Security Classif.(of this page) Unclassified		21. No. of Pages 117	22. Price

Computer Simulation-Based Framework for Transportation Evacuation in Major Trip Generator

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January 2009

ABSTRACT

Since emergencies including both natural disasters and man-made incidents, are happening more and more frequently, evacuation, especially transportation evacuation, is becoming a hot research focus in recent years. Currently, transportation evacuation study focuses on evacuating people and property from large areas and does not address the problem of transportation evacuation in a small and dense area. This research is intended to identify the study framework of developing transportation evacuation plans in small and dense areas. Texas Medical Center (TMC), Houston, Texas, is selected as case study in this thesis. Incidents are assumed based on potential threats. Traffic information is collected through filed data collections in the TMC area, and evacuation scenarios with incidents and management improvements are coded and simulated in VISSIM, a microscopic traffic simulation model. Genetic Algorithm is one of the calibration methods for searching multiple parameters at the same time and is used in this thesis to calibrate parameters of driving behaviors in VISSIM by using field collected and simulation data. Based on the simulation results, potential improvements and measurement of effectiveness (MOE) of operations such as Reversed Lane (RL) and In-bound Shuttle (IS) are analyzed and evaluated. Simulation results show that the evacuation would be much more efficient if appropriate operational strategies are implemented. Proper management improvements such as Reversed Lane and In-bound Shuttle could greatly maximize the number of persons/vehicles evacuated in the area. The selected operational plan can efficiently evacuate all persons in the Texas Medical Center in suitable simulation scenario under a given incident assumption. The framework of developing transportation evacuation plan is tested and proven to be effective in the Texas Medical Center. The microscopic simulation based study process is targeted on small and dense areas and it can be used in any other similar areas. It is recommended that further work be conducted to form a comprehensive evacuation plan.

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ACKNOWLEDGMENT

The authors recognize that support for this research was provided by a grant from the U.S. Department of Transportation, University Transportation Centers Program to the Southwest Region University Transportation Center.

EXECUTIVE SUMMARY

Transportation evacuation study has become a research focus in recent years since emergency events occur more and more frequently. Generally, emergencies that compel evacuations comprise natural disasters and can be geographically divided into large-scale ones (e.g. hurricanes and radiological incident,) and relatively small-scale ones (e.g. terrorists' bombing threats and toxic material leakage.) The majority of existing transportation evacuation plans are mostly developed for hurricane evacuation and nuclear plant accident purposes and are large enough to cover part or entire city-wide/state-wide areas.

This research focuses on the evacuation study in a small and dense major traffic generator with the hypothetical event of toxic material leakage. Various evacuation scenarios, including various improvement options of Reversed Lane (RL) and Inbound Shuttles (IS), are evaluated by using the microscopic simulation model VISSIM. The proposed evacuation framework includes: (1) study area identification/incident assumption/model selection, (2) data collection, (3) evacuation demand estimation, (4) development of evacuation strategies and evacuation scenarios, (5) network coding, and (6) model calibration and simulation/result analysis.

For demonstrational purpose, the toxic material is assumed to diffuse at typical major traffic generator - Texas Medical Center (TMC) over the entire area in about one hour. The objective is to efficiently evacuate as many persons as possible within the scheduled time period (one hour).

Field data is collected to calibrate the simulation model VISSIM and estimate the base traffic demand in a typical non-evacuation day. O-D is estimated based on observed link traffic flows, link turning movement counts, and link travel times using the software QueensOD by Queens University. The base O-D matrix is then modified by: 1) setting most of the inbound demands to zero except for a few emergency vehicles and Inbound Shuttles, 2) setting the garage-to-garage O-D pairs to zero, and 3) re-distributing the demands which are approaching endangered areas to the nearby safe destinations.

Travel demands from each traffic generator or origin are loaded onto the network through a pre-designed loading curve, which is a function of time providing percentage of evacuees or vehicles to the network. Loading curve reflects the responding speed of evacuees. A Logit-based

loading curve is employed in this research. Seven 500-seconds-long O-D tables are used to represent the speed of evacuees loaded onto the network.

Different evacuation scenarios are developed to evaluate the impacts of different strategies in response to the emergency needs, including the options of RL and different service rates of IS. By following a set of predefined criteria, the relatively optimal evacuation plan for the TMC area is recommended.

RL is an operation of turning one or more lanes of one direction to the opposite direction. It can greatly expand the roadway capacity without building new facilities and is used to address the issue of inadequate outbound capacity. While RL should be placed on the main exiting routes to maximize the outbound capacity, multiple factors need to be concerned. First, the placement should not block the potential inbound vehicles (emergency vehicles, ambulance, inbound shuttles etc.). Also, RL cannot be placed on a street with physical constraints such as the raised medians, along a fire station/police station.

Inbound Shuttle is designed to help when people evacuating exceeds the available vehicles in the area and is useful in evacuating people with special needs. It is assigned based on both the population distribution in different regions of the area and existing bus lines. Shuttle lines should cover most of the places with high demands. Shuttle stops can be located near the exits of the evacuation origins.

Measurement of Effectiveness (MOE) in both network-wide area and in the so-called “core area” are used for the evaluation of different scenarios. Core area refers to the region close to the location where the emergency event occurs. According to the assumption of toxic material leakage in this study, the core area is the most suffered and earlier affected area in the network.

Through simulation, it is found that RL can greatly maximize the roadway capacity, which especially benefits vehicles close to reversed lane. It can be used to quickly evacuate vehicles. Simulation results also show that Inbound Shuttle is a good way to evacuate a large amount of people, especially for small and dense areas where the number of vehicles are usually less than the number of evacuees or areas with a lot of people with special needs.

For further exploration of this research, it is recommended that more evacuation scenarios be developed and simulated. Intelligent Transportation System (ITS) such as advanced surveillance

system should be utilized for more on-line traffic data collection and better model calibration. In this way, evacuation responses could be more automatic, quick, and efficient.

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ABBREVIATIONS

CBD:	Central Business District
DYNEV:	Dynamic Network Evacuation
ETIS:	Evacuation Traffic Information System
FHWA:	Federal Highway Administration
GA:	Genetic Algorithm
GPS:	Global Positioning System
HOV:	High-Occupancy Vehicle
HGV:	Heavy Goods Vehicle
IS:	Inbound Shuttle
LRT:	Light Rail Train
MOE:	Measure of Effectiveness
NRP:	National Response Plan
O-D:	Origin - Destination
OREMS:	Oak Ridge Evacuation Modeling System
RL:	Reversed Lane
SSE:	Sum of Square Error

CHAPTER 1

INTRODUCTION

1.1 Background of Research

Emergency situations are happening more and more frequently in this world (Alsnih, 2004). These include, but are not limited to hurricanes, radiological accidents, terrorist attacks and toxic material leakage. In 2005, Hurricanes Katrina and Rita hit the Gulf Coast causing mass evacuations. Because there were no efficient evacuation plans, traffic was stuck on highways and caused huge life and property loss. In 2007, a gunman made a shocking massacre at Virginia Polytechnic Institute and State University (Report of the Virginia Tech Review Panel, 2007). After the tragedy, universities and high schools paid more attention to emergency preparedness and began to re-consider their evacuation plans.

As emergency situations generally involve serious injury or loss of life and property, it is vital to promptly evacuate people and valuable materials from the affected area. While transportation serves as the most important part to reposition refugees to safe places, it is not easy to operate since transportation evacuation usually involves moving a large number of people over a sizable area in a limited period of time under emergency. The U.S. highway infrastructure permits the movement of large numbers of people over significant distances in a timely and safe manner to suitable shelters away from the hazard zone (NRP, 2004). However, the current situation is that the growth of travel demand is much faster than the expansion of the transportation infrastructure. As a result, the efficient operation and management of evacuation has become very important.

The efficiency of an evacuation depends not only on the ability of the roadway infrastructure along evacuation routes, but largely on the management of evacuation strategies. Based on literature review, the majority of existing transportation evacuation strategies and plans are mostly developed for hurricane evacuations (e.g. Urbana, 2002; Wolshon, 2006; Wolshon, 2001; Hobeika, 1985, etc.) and nuclear plant accident purposes (e.g. NRP, 2004; Han, 2005; Phansak, 2001 etc.) The areas involved are usually huge and could even cover part or entire city-wide/state-wide areas. However, very limited research on transportation evacuations is found for

small and dense area such as the Central Business District (CBD), large commercial centers, and other high density areas where terrorist attacks and unexpected incidents like pipe explosions are happening more and more often all over the world (Katy, 2007). The evacuation plans for large areas may not be appropriate for small locations that are associated with unique characteristics such as high population density, short response time and multiple transportation modes. Therefore, there is a need to identify the methodology of how to develop the effective transportation evacuation plan for small and dense area.

Reoccurrence of catastrophic events has provoked an increased use of traffic simulation software to model traffic flow under emergency conditions (Kevin *et al*, 2007). Simulation-based approach serves as an ideal way to incorporate pieces of information such as roadway networks, traffic controls, demands, supplies, and constraints to the decision-making process. It provides a low-cost, low-risk environment to test various assumptions and alternatives together with the resulted effects vividly. So simulation can be a good tool in developing evacuation plans.

1.2 Research Objective

This research is intended to develop a simulation-based framework to address the transportation evacuation issues in small and dense areas such as Texas Medical Center (TMC) in Houston, Texas. To this end, the following research objectives are developed:

- Develop a microscopic simulation framework to study the transportation evacuation problems in small and dense areas,
- Develop feasible and effective transportation evacuation strategies and evaluate the effectiveness of each strategy, and
- Evaluate the integrated framework with a case study and propose a transportation evacuation plan for Texas Medical Center.

1.3 Outline of Report

This report is organized in the following order. Chapter 2 provides an extensive review of the state-of-the-art of transportation evacuation study. Chapter 3 designs the approaches used in this research in order to fulfill the research objectives. Chapter 4 describes the methodology, the

developed simulation-based evacuation framework, as well as a case study in the Texas Medical Center. Chapter 5 includes the conclusions and recommendations.

CHAPTER 2

LITERATURE REVIEW

Evacuation is a broad topic including multiple functions such as transportation, communication, supply and public awareness, etc. (Texas Evacuation Task Force, 2006). This chapter provides a review of existing research and experiences with the focus on transportation evacuation studies. First, an overview of emergency and evacuation is presented. Then, a summary of current practice on transportation evacuation simulation and evacuation demand modeling is described in details. In addition, current practice model calibration is reviewed. Finally, a summary of the literature review is provided.

2.1 Emergency Preparedness

Emergency conditions may take many forms. Catastrophic events could be the result of not only natural incidents such as hurricanes, floods, and tornados, but also terrorists' attacks, chemical spills, and nuclear accidents. According to the National Response Plan (NRP), a catastrophic incident is defined as "any natural or manmade incident, including terrorism that results in extraordinary levels of mass casualties, damage, or disruption severely affecting the population, infrastructure, environment, economy, national morale, and/or government functions" (NRP, 2004). As emergency situations generally involve serious injury or loss of life and property, it is vital to evacuate people and valuable materials from the affected area promptly. An evacuation is usually "an organized, phased, and supervised withdrawal action" of civilians and their properties from threatened or potentially threatened areas (NRP, 2004). It is one of the most effective and protective methods against severe emergencies (Chang, 2003).

The transportation system plays a key role in evacuation operation through relocating refugees to safe places. Thus, an efficient transportation evacuation plan is very crucial and involves careful planning. As mentioned in the Texas Evacuation Task Force Report, a successful transportation plan needs coordination of multiple functions which include transportation planning, communication, law enforcement and public awareness etc. (Texas Evacuation Task Force, 2006).

According to Federal Highway Administration (FHWA), the transportation roadway infrastructure has the responsibility to keep the public away from dangerous places and evacuate them from affected areas (FHWA, 1998). However, this is often a challenging task given the fact that the demand in evacuation periods is unusually high and can exceed the roadway network capacity. If the studying area is small and with dense population, the gap between the existing infrastructure capacity and high evacuation demand will be even higher. Thus the lack of outbound roadway capacity issues needs to be addressed when planning transportation evacuation activity. In other cases when the transportation system is severely affected, it needs to be able to restore to a minimum level of operations immediately.

Information release is also important and needs to be updated to evacuees and the general public on development of ongoing incidents, official orders and available evacuation options (ITS America, 2002). According to Alsnih, the decisions made by people during an emergency are largely influenced by the information they can get from either officials or media (Alsnih, 2004). Correct and appropriate information helps people acknowledge the developing situation and official recommended actions. It can also give evacuees help on directions of ways out and keep evacuation action in an organized and controlled way.

When planning an emergency evacuation, it is important to know the unique characteristics of both the evacuation and the people in an emergency evacuation situation which are very different from conventional traffic planning. Firstly, the accessibility of roadway networks can be different due to the occurrence of the emergency. Potential situations include: 1) transportation systems affected by the disaster and access routes severely damaged during the disaster 2) certain evacuation mitigation strategies that require shutdown of some of the roadways 3) unusually heavy congestion on existing routes (Han, 2005). Secondly, human behavior can also change significantly under emergency situations which will have a great impact on driving behavior and route choice (Sisiopiku, 2004). Such change in driving behavior and route choice also play an important role in evacuation operation as it directly affects the traffic condition and evacuation results when evacuees are loaded onto the roadway network. Finally, time is the most critical factor under an evacuation operation and the first priority is to evacuate all the people in the affected area in time. All of these characteristics associated with emergency evacuation need to be taken into account when planning an emergency evacuation.

To address the hard emergency evacuation issues, Wolshon pointed out that evaluation of mitigation alternatives for risks during emergency evacuation is necessary (Wolshon, 2002). Different evacuation strategies need to be implemented and different emergency scenarios need to be developed. Based on the performance of the scenarios, the best ones should be selected to form the proposed evacuation plan. After an optimal plan is developed, practice/drill is essential as it can make sure the evacuation plan can be carried out properly. It is important that transportation officials should identify and analyze sectors with high emergency incident potential and address the risk by developing appropriate response including development of evacuation plan (Sisiopiku, 2004).

2.2 Evacuation Operation Plan Assessment

Evacuation plan assessment is to make sure that the evacuation plan developed can achieve the objective of evacuating the people affected from the dangerous area. It can also test different aspects of evacuation performance such as transportation network performance, organization performance and evacuee's response.

Based on literature review, currently two approaches are commonly used for emergency evacuation plans assessment. The first approach is the use of mock-exercises or drills. According to FEMA, it is an event in which volunteers and participants from key agencies are asked to take part in a planned evacuation under hypothetical emergencies (FEMA, 1998). The second approach is to assess the evacuation plan with the help of transportation simulation modeling. Both approaches are aimed at identifying possible flaws and weaknesses of the existing plan and revise it to a satisfactory level.

Through mock exercises and drills, human aspects of the evacuation plan can be better tested. Some of these include using decision making process, information release procedures and coordination among different agencies (Sisiopiku, 2004). The mock-exercises can be conducted in either full-scale or focus on one functional practice (City of New Orleans, 2008). Emergency preparedness administration should coordinate closely with other agencies to train qualified observers to achieve the best assessment. Some limits of this approach are their feasibility and applicability for studying transportation evacuation. This is because it is difficult (sometimes dangerous) to simulate emergency in real life and usually both mock-exercises and drills require a large number of people in the study area. They can be risky and costly; however, they are

necessary and cannot be replaced in evacuation planning. Only through mock-exercise/drills can people gain experience and learn to master the proposed evacuation plan (FEMA, 1998).

Meanwhile, transportation simulation modeling makes it possible to simulate emergency situation and evaluate different evacuation strategies in a controlled way. It is a faster, easier and lower-cost way compared with mock-exercises/drills (Moriarty, 2006).

2.3 Simulation Modeling for Transportation Evacuation

Traffic simulation software has traditionally been used as a tool for evaluating alternative roadway designs, optimizing travel times through route analysis, or retiming intersection signaling. The reoccurrence of catastrophic events, however, has provoked an increased use of traffic simulation software to model traffic flow under emergency conditions (Kevin *et al*, 2007). Traffic simulation serves as an ideal tool to incorporate pieces of information identified above as well as other information such as demands, supplies, and constraints into the decision-making process. Traffic simulation can also provide a low-cost, low-risk environment to test various assumptions and alternatives and to observe their effects immediately. This section discusses the use of different models in emergency situations.

2.3.1 Comparative Review of Traffic Simulation Model for Evacuation

Over the years, several simulation software packages have been developed to model traffic flow in emergency evacuation situations. These include, but are not limited to, the Oak Ridge Evacuation Modeling System (OREMS) (ORNL, 1998), Dynamic Network Evacuation (DYNEV) (KLD Associates, 2004), Evacuation Traffic Information System (ETIS) (PBS&J, 2000), and general-purpose software packages such as VISSIM (PTV Inc, 2005), DYNASMART-P (McTrans, 2007) and MITSIMLab (Yang *et al*, 2000). The software packages possess several commonalities (e.g. they all require route information, evacuee information, and external information), but are also applicable to certain situations on an individual basis.

2.3.1.1 Oak Ridge Evacuation Modeling System (OREMS)

The OREMS model was developed by the Oak Ridge National Laboratories Center for Transportation Analysis in the late 1990's. It is a mesoscopic model used to estimate evacuation time, to develop traffic management and control strategies, and to identify evacuation routes,

traffic control points and traffic operational characteristics for different events or scenarios (Rathi and Solanki 1993).

In OREMS, a network with links and nodes is used to represent the roadway system. The links represent roadway segments and the nodes represent intersections or points along the roadway where the geometry changes (Rathi and Solanki 1993). The input information includes data describing roadway system topology, roadway geometric characteristics, traffic volumes and composition, traffic control devices and their operational characteristics, origin-to-destination trip tables, and vehicle performance characteristics. Human behavior and weather information are also included as inputs to some extent. However, OREMS does not include modal-split in its data processing. In other words, OREMS only considers highways in evacuation planning and does not consider rail, air, or water transportation as possible means of evacuation (Chang, 2003).

OREMS has been proven to have many uses in emergency management. This software has been used to determine the feasibility of evacuation without detailed route planning, to identify bottlenecks that would constrain traffic flow, and to assess the effectiveness of alternative traffic control and evacuation strategies. It has also been useful in estimating traffic speeds on specific portions of road networks, estimating queuing times at traffic lights or bottlenecks, and estimating clearance times for networks or portions thereof (ORNL, 2006).

2.3.1.2 Dynamic Network Evacuation (DYNEV)

The DYNEV model was developed by KLD Associates, Inc. in the late 1970's. It is a macroscopic model used traditionally for simulating evacuation from sites within close proximity to nuclear power plants (Mei, 2002). Enhancements have been made so that it is capable of modeling for regional hurricane planning processes (Chang, 2003). DYNEV has been used to analyze network capacity and evacuation demand (Wolshon et al., 2005).

Similar to OREMS, DYNEV represents the roadway network with a set of links and nodes. The nodes represent the intersection of the link segments. Major inputs to the DYNEV model include the topology of the network, the geometry of each link, the trips to be loaded onto each network link, and the circulation of traffic through the network (Mei, 2002). DYNEV also includes human behavior and weather conditions as inputs. Like OREMS, DYNEV does not

consider modal-split in its data processing, but only bus as a means of evacuation for those without access to private vehicles (Chang, 2003).

DYNEV has an average output, leading it to be considered as a good pre-planning tool and average post-analysis tool in emergency management planning (Chang, 2003). DYNEV presents its output information in both graphical and tabular form. The information includes the speed of evacuating vehicles, the density of the traffic stream, and the total number of vehicles using a particular link (Mei, 2002).

2.3.1.3 Evacuation Traffic Information System (ETIS)

The ETIS model was developed by PBS&J Inc. in the late 1990's. It is a macroscopic model that was primarily developed to forecast large cross-state volumes. The web-based travel demand forecasting system makes it easy for evacuation administrations to access the model online and input data specific to their area. The system is capable of estimating evacuation traffic congestion and cross-state traffic flows. To date, ETIS is used to analyze roadway networks in the southeastern section of the United States (Wolshon, et al., 2005).

A major difference exists between ETIS input and that of OREMS or DYNEV. ETIS input data structure is county-based whereas the input data structure of OREMS and DYNEV are zone-based (Chang, 2003). Therefore, less data is required in the route category. Consistent with the other models, however, ETIS includes human behavior and weather conditions as inputs. PBS&J is currently conducting more research in human behavior analysis to enhance this software package. Additionally, ETIS is capable of modeling contra flow operations and lane closures (PBS&J, 2005).

The ETIS model makes a large number of assumptions based on historical data. Thus, its use is limited in areas where little evacuation historical records exist. As with OREMS, ETIS does not include modal-split in its data processing (Chang, 2003).

According to Chang (2003), the graphical and tabular output of ETIS is average. The model, however, is considered to be a favorable pre-planning tool in emergency management due to its output being largely based on historical data. Specifically, the output of ETIS includes identification of evacuating counties, traffic volumes, shelter capacity, traffic count, destination percentages by city, and estimates of interstate traffic (PBS&J, 2005).

2.3.1.4 VISSIM

VISSIM is developed by PTV Corp (PTV Inc., 2005). It is a microscopic simulation model with parameters describing specific driving behavior. According to PTV Inc, “VISSIM is developed to analyze the full range of functionally classified roadways and transit operations” (PTV Inc., 2005). It is capable of modeling a wide-range of roadway networks as well as various transportation modes including private cars, trucks, buses, High Occupancy Vehicles (HOVs), light rails, heavy trams, pedestrians, and bicycles. It can address the specific geometric design of any transportation network, and also includes a driving behavior model to capture the microscopic driving behavior of vehicles in the evacuation scenario.

VISSIM consists of two different programs internally that constantly communicate with each other and exchange signal status etc. The simulation generates an online visualization of traffic operations as well as offline outputs of statistical data such as travel speed, travel time, average delay and queue lengths. The traffic simulator is a microscopic model with car following and lane change logic in it. The signal state generator is a signal control package that retrieves information through the use of detector. The detector checks the simulator every one tenth of a second. After that, the signal status is confirmed for the following second and related information is transferred to the traffic simulator telling traffic the signal status.

VISSIM uses links and connectors to represent networks requiring intensive inputs. While detailed inputs make it accurate in representing the real world traffic situations, they also make it feasible to evaluate different traffic strategies in an operational level. The multi-modal feature is suitable for traffic studies in areas where complicated traffic composition is involved. The abundant outputs can provide a series of information such as travel time, delay, etc. from which useful information (e.g., time for a certain percentage of people evacuated) can be deduced. Although VISSIM is a general-purposed traffic simulation mode, it could be adopted for traffic evacuation simulation in a small area, given the above features.

2.3.1.5 DYNASMART-P

DYNASMART-P is a relatively new model. It was released by the Federal Highway Administration through McTrans in February 2007 (McTrans, 2007). This microscopic simulation model can be used in transportation network planning as well as traffic operations studying. According to the software manual, the simulation-based dynamic traffic assignment

combines dynamic network assignment models with traffic simulation models. The microscopic feature and dynamic feature make it capable of simulating each individual in the network system seeking routes dynamically. Besides, with the function of modeling driving route-selection behavior under the effects of guide sign/travel information, DYNASMART-P also has the ability of determining time-changing road segment traffic conditions (Mahmassani, 2004).

Compared with other simulation models, DYNASMART-P defines a new generation of planning methods. It is compatible with the traditional four-step process, but with extensions in both range and types of measures (McTrans, 2007).

2.3.1.6 MITSIMLab

MITSIMLab is a transportation simulation model that was developed at the Intelligent Transportation Systems (ITS) Program in Massachusetts Institute of Technology. It was designed to evaluate different traffic management options at the operational level. According to Yang, MITSIMLab can be used to evaluate a wide range of transportation networks with different kinds of traffic management systems (e.g. Advanced Traffic Management Systems) (Yang *et al*, 2000). One unique characteristic of MITSIMLab is that it can model the dynamic interaction between the individual in the simulation network and real time traffic controls and information generated by traffic management systems.

There are three components of MITSIMLab: Microscopic Traffic Simulator (MITSIM), Traffic Management Simulator (TMS), and Graphical User Interface (GUI).

MITSIMlab is a microscopic transportation model. The Microscopic Traffic Simulator (MITSIM) is capable of simulating the behaviors of individual vehicles. The detailed network information and vehicle information are needed in MITSIM to build the simulation network while travel demand, route choice and driving behavior are used to complete the simulation scenarios (User's Guide for MITSIMlab and Road Network Editor (RNE), 2002).

The Traffic Management Simulator (TMS) is the component where the potential traffic control and routing logic are developed. A generic structure is provided in TMS to construct a wide range of different traffic control and routing decisions. The traffic control devices and routing devices in MITSIM are determined by the traffic control and routing decisions generated by TMS. Individuals in the MITSIM then follow the different traffic controls and routing while

interacting with other roadway network users (User's Guide for MITSIMlab and Road Network Editor (RNE), 2002).

2.3.1.7 Comparison of Different Simulation Models

Table 1 compares the different models that have been used to simulate traffic under emergent situations. Although microscopic models require intense data input and may result in longer running time, they have useful features including multi-modal and driving behavior and can provide complete output.

Table 1. Comparison of Different Models

Name	Evacuation Traffic Models			General-purposed Traffic Models		
	OREMS	DYNEV	ETIS	VISSIM	DYNASMART-P	MITSIMLab
Developed Date	late 1990's	late 1970's	late 1990's	2003	2007	1999
Scale	macro	macro	macro	micro	micro	micro
Data Input	Medium	Medium	Small	Large	Large	Large
Data Output	Complete	Average	Average	Complete	Complete	Complete
Multi-Modal	N	N	N	Y	Y	Y
Driving Behavior	N	Y	Y	Y	Y	Y

2.3.2 Current Practice of Transportation Evacuation Simulation

Transportation evacuation simulation has been the research focus recently, covering various areas with different applications.

Pal *et al* (2003) developed a microscopic evacuation simulation model in which GIS was used to define the road network, population, and area being evacuated. The OREMS model was used to model the effect of evacuation on the traffic network in Baldwin County, Alabama.

Jha *et al* (2003) evaluated the emergency evacuation plans for Los Alamos National Lab (LANL) with microscopic traffic simulator MITSIMLab. The study area consisted of the entire region including all Technical Areas (TA) within the LANL and towns of White Rock and Los Alamos. This study considered evacuation during non-peak hours when all employees were

expected to be in the Lab. Five evacuation scenarios were developed in LANL evacuation planning including full or partial closures of various roads and limited access to some special facilities.

Han and Fang (2005) studied evacuation simulation in the event of a major nuclear power plant accident in Tennessee Valley Authority's Sequoyah nuclear power plant with microscopic simulation model VISSIM. Evacuation demand was estimated using the 2000 census data and both static traffic assignment (STA) and dynamic traffic assignment (DTA) were adopted. Operational strategies such as police officers controlling traffic at key intersections and reversing lanes on congested road sections were simulated and assessed. The results showed that operational strategies led to a certain improvement by reducing delay, congestion and evacuation performances under DTA scenarios and was better than that under STA scenarios.

Kwon and Pitt (2005) used model DYNASMART-P to evaluate the effectiveness of alternative strategies for evacuating the traffic in downtown Minneapolis, Minnesota. For this study, the entire southwest portion of the Twin Cities metro area was selected as the study network. Demand data was provided by Metro Council. A set of different network configurations (limited access of inbound traffic, reversed lanes) were evaluated in terms of their effectiveness in coping with a given emergency situation.

McGhee and Grimes (2007) evaluated the Hampton roads hurricane evacuation under different severity of hurricane on traffic operation aspects. Data was directly drawn from the existing traffic control plan (TCP) and abbreviated transportation model (ATM). VISSIM was used to evaluate strategies like ramp metering and reversed lane while issues like temporal distribution of traffic and background traffic were addressed before hand. The authors concluded that, under high volumes of evacuating traffic (more severe categories of hurricanes), on-ramp traffic metering was required to keep evacuating traffic moving at acceptable speeds.

Fang *et al* (2005) explored the relationship between non-compliance with route/destination assignment and evacuation efficiency. Model VISSIM and DYNASMART-P were used as simulation tools to model two real-world network evacuation cases: Sequoyah Nuclear Power Plant Network with VISSIM and a county-wide special-event evacuation operation in Knox County, Tennessee, with DYNASMART-P. Results from both cases suggest that a rate of less than 100% compliance did not compromise evacuation efficiency.

Hakonen (2003) described the structure, functionality, and use of Building Traffic Simulator (BTS). The evacuation of tall buildings was studied by simulations. The simulator had versatile possibilities to define traffic situations, elevator groups, escalators and staircases. The main use of BTS was in elevator planning. It was found that stairs were an inefficient way to empty a tall building and evacuation was also slowed down because of the long distance from the highest floors down to ground level. Reconsideration of the evacuation standards of tall buildings and discussion on improving the fire safety of elevators were needed.

Table 2 is a summary of the recent transportation evacuation studies by comparing their study area, simulation mode, and major work undertaken.

Table 2. Summary of Recent Transportation Evacuation Studies

Name	Study Area	Model	Major Work
Pal <i>et al</i> (2003)	Baldwin County, Alabama	OREMS	Developed a microscopic evacuation simulation model combining GIS with OREMS
Jha <i>et al</i> (2003)	Entire region within the Los Alamos National Lab and towns of White Rock and Los Alamos	MITSIMLab	Evaluated full or partial closures of various roads, limited access to some special facilities
Han and Fang (2005)	Tennessee Valley Authority's Sequoyah nuclear power plant	VISSIM	Evaluated police officers controlling traffic at key intersections, reversing lanes
Kwon and Pitt (2005)	Downtown Minneapolis, Minnesota	DYNASMAR T-P	Evaluated limited access of inbound traffic, reversed lanes
McGhee and Grimes (2007)	Hampton Roads Region, Virginia	VISSIM	Evaluated ramp metering, reversed lane
Fang <i>et al</i> (2005)	Sequoyah Nuclear Power Plant and Knox County, Tennessee	VISSIM and DYNASMAR T-P	Explored the relationship between non-compliance with route/destination assignment and evacuation efficiency
Hakonen (2003)	Tall buildings	Building Traffic Simulator (BTS)	Described the structure, functionality, and use of Building Traffic Simulator (BTS)

It can be concluded from the above literature review that simulation has been used as one of the most important ways to study transportation evacuation. Many existing studies of transportation evacuation are for either a large scale area or for a single building and elevators with the application of different simulation packages and evacuation strategies. However, very limited literatures talked about evacuation in small and dense areas where unique attributes are

different from those large ones and buildings/elevators. Texas Medical Center is one of the typical small and dense areas.

2.4 Demand Estimation for Evacuation Simulation

Accurate estimation of the value and temporal distribution of demand is very important in identifying appropriate evacuation strategies and plans. The following is a review of research and practices on how demands are estimated in current evacuation simulation models.

Lewis (1985) first described a general travel demand forecasting process for hurricane evacuations which is very similar to the urban travel demand forecasting methodology. He addressed some of the critical problems in evacuation transportation planning including the estimation of travel demand.

The up-to-date practice in evacuation demand estimation is a two-step process: the first step is to estimate total evacuation demand and the second step is to estimate the distribution of individual departure time (Mei, 2002).

As said by Mei, the evacuation participation rate method is the most common method of estimating evacuation demand (Mei, 2004). It is the method that estimates the proportion of households in an area that will evacuate based on participation rates. Participation rates are usually developed according to past records of study area including response and actions by local agencies (willingness to issue mandatory vs. voluntary evacuation orders, the policy of disseminating orders door to door vs. via media, etc.), type of housing, population composition (transient versus resident), etc. Wilmot and Mei (2004) pointed out that, typically, no statistical analysis of past data was conducted in establishing such rates, and instead they were established subjectively by experts based on past experience. Based on the estimation of the participation rates and the demographics of the area, the total evacuation demand is established (Fu *et al*, 2007).

The temporal distribution of evacuation trips is usually described by response curves. The curve illustrates the assumed departure time distribution of evacuees. The departure speeds of the evacuees are represented by different steepness of the shape of the response curve. The curve becomes steeper as the response becomes quicker. Selection of a response curve for an emergency is subjective and depends on the analyst's past experience, familiarity with the

affected area, and the anticipated response from the evacuees. Two commonly used approaches to develop temporal distribution of demand are: (Mei, 2002)

- Generation of behavioral response curves from post evacuation surveys, and
- Development of mathematical models based on past reported data from surveys or experiences

US Army Corps of Engineers (2000) proposed three different response curves, for slow, medium, and rapid responses respectively, based on post-evacuation survey and behavioral analysis of past storms. These curves are illustrated in Figure 1. The time point of zero(0) in the figure is when the evacuation order is issued. The value of 10 percent evacuated at the time the evacuation order is issued reflects the average proportion of the population who elected to evacuate before the order was given as observed from past behavior. Simplicity is the advantage of this curve while the weakness is its average response and insensitivity to the changing characteristics or the particular circumstances surrounding each hurricane.

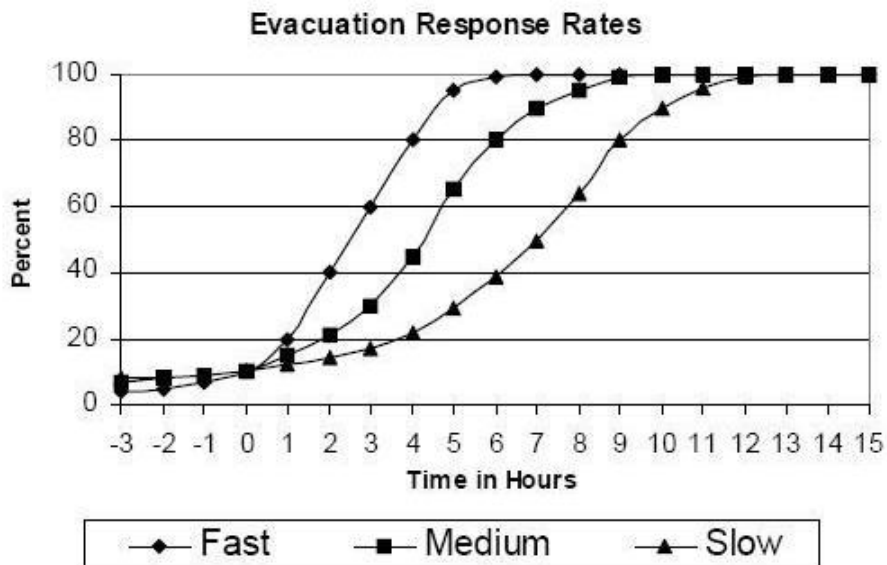


Figure 1. Illustration of Response Curve by US Army Corps of Engineers
Source: US Army Corps of Engineers (2000)

Radwan et al (1985) and Hobeika et al (1998) used a logistic curve to model the loading time of trips onto the highway network during an evacuation from natural disaster in their MASSVAC model:

$$P(t) = 1 / \{1 + \exp[-\alpha \times (t - H)]\} \quad (1)$$

$P(t)$ is the cumulative percentage of the total trips generated at time t . The speed of response of the public to the emergency event is represented by α , which changes the slope of the cumulative traffic loading curve. H is the time at which half of the evacuees in the area have been loaded onto the highway network. H defines the midpoint of the loading curve and can be varied by the user according to disaster characteristics.

The participation rate model and response curve method represent the state-of-the-practice in estimating hurricane evacuation travel demand. Jointly, they provide estimates of temporal evacuation demand by evacuation zone.

2.5 Calibration of Simulation Model

Calibration of a simulation model is critical to obtain meaningful results (Yu *et al*, 2002). The calibration of the traffic simulation model is a process to determine values of the model parameters to make sure that the simulation results are consistent with the field observations, so that the simulation results are reliable.

The parameters that can be used in calibration include driving behavior parameters, signal timing parameters and route selection behavior etc. Microscopic simulation models usually have a driving behavior model which contains many driving behavior parameters (Sisiopiku *et al*, 2004). The driving behavior model determines how the vehicles will behave within the network. These behavior parameters include lane change behavior parameters, vehicle following behavior parameters and lateral behavior parameters etc. There are usually a set of default values of these parameters in the simulation models, however, they only apply to a limited transportation network. When simulating traffic condition, calibration needs to be conducted to obtain the values of the parameters which describe the unique local characteristics of the study area. Calibration makes sure that the simulation network represents the real world situation and thus makes the result reliable.

A lot of research has been conducted on the calibration methodologies. Park and Schneeberger (Park, 2002) developed a detailed calibration procedure for the microscopic simulation model and applied it to calibrate the microscopic model VISSIM for the coordinated actuated signal system in Virginia. Other researchers focused on searching algorithm of appropriate parameters values of the simulation model. Cheu successfully applied Genetic

Algorithm (GA) to find the best combination of parameters that has minimum output difference to real world observations (Cheu, 1998). Hoyer used simulated annealing method in his study to calibrate the microscopic traffic flow model (Hoyer, 1997), and Ben *et al* adopted Complex Algorithm as calibration method (Ben *et al*, 2003).

However, it should be pointed out that it is not practical to reach the point of calibrating all the parameters to represent real world driving behaviors. The first reason is because it is usually very difficult to reach the combination of parameter values which leads to zero difference between the simulation output and real world observation (Ma *et al*, 2007). Instead, researchers aimed to find the optimal set of parameter values that had an acceptable difference between the simulation output and field data. In this case, criteria like Sum of Square Error (SSE) etc. are used as indexes to compare the calibration results. The second reason is that the erratic driving behaviors in the real case are not practical to fully represent by the driving behavior parameters in simulation models. In other words, the current practice of representing driving behavior by parameters is limited (Dittberner, 2002). This is particularly important in evacuation situations, as human behavior can change dramatically under emergencies and disasters. Despite the calibration issue, traffic simulation models' unique advantages make them still the best method currently available to study transportation evacuation.

2.6 Summary of Literature Review

Emergency evacuation study has been drawing more and more attention recently. While different issues in evacuation such as communication, public awareness and flue availability etc. are also essential, transportation evacuation, which relates to the activity of physically evacuating people and property, deserves more value to work with.

There are many traffic simulation models found that can be used to simulate the transportation evacuation. As the traffic during evacuation events in small and dense area is unique in many aspects such as high population density, comparatively low-capacity roadway network and multiple transportation modes, it requires some special characteristics from the simulation model, such as the ability to model very detailed network, ability to represent driving behavior and ease to simulate scenarios with all kinds of evacuation strategies. Also, the simulation model selected for applications must have abundant outputs from the simulation which can be used for further analysis.

While the reviews have shown the existing evacuation study process and strategies available for dealing with the problem of evacuation involving large areas, it is found there's very limited research effort on the simulation of traffic evacuation in small and dense areas. The studies' processes in recent research are tailored for large areas and do not consider attributes of small and dense areas. Therefore, the developed strategies from existing literature are not applicable for small areas.

Evacuation demand modeling and calibration are two issues needed to be addressed during the evacuation study. Evacuation demand modeling is a very important part of transportation evacuation study. Literature shows that the participation rate model and response curve method can be jointly used to estimate temporal evacuation demand. Calibration of a simulation model is critical to the obtaining of meaningful results. Genetic algorithm is a proven, good, and practical optimization technique in identifying best simulator parameters.

In summary, the literature reviews demonstrate that there exists no systematic methodology particularly designed for transportation evacuation in small and dense areas. There is a need to develop an appropriate study procedure addressing this issue with suitable case studies illustrated.

CHAPTER 3

DESIGN OF STUDY

As stated in the previous chapters, the research objective of this thesis is to identify the methodology of how to develop the transportation evacuation plan for small and dense areas with a case study in the Texas Medical Center. To this end, this research is intended to develop a modeling framework for transportation evacuation for small and dense areas, to address the relevant technical issues, and to conduct a case study.

3.1 Framework Development

The first part is to develop a framework for modeling the transportation evacuation situation in small and dense areas. It combines transportation evacuation studies with a traffic simulation model. The framework can be used to evaluate evacuation strategies and evacuations plans under given incident assumptions as well as develop a successful evacuation plan in an iterative process.

Basically, it includes Study Area Identification, Data Collection, Incident Assumption, Simulation Model Selection, Evacuation Demand Estimation, Evacuation Strategies Planning, Network Coding, Network Calibration, Simulation and Result Analysis and Plan Development.

Background information will be collected for the study area. For data collection, the main types of data needed in this framework include roadway and traffic data for network coding, information to determine Origin-Destination Matrices and instantaneous data for the purpose of model calibration. Data collection methods will be identified and data collection plan will be developed.

A comprehensive review will be conducted on existing simulation models that can be used for evacuation study. Based on the unique characteristics of the study area and different features provided by different models, an appropriate model will be selected as the simulation tool in the framework. After evacuation demands are estimated and evacuation strategies are identified, all the information can be coded in the selected simulation model.

Before running the model, it will be calibrated based on the output of the model and instantaneous speed collected in field. Genetic Algorithm (GA) will be used as the core method

of calibration and a total of 10 driving behavior parameters will be calibrated. A computer program will be developed to automatically carry-out the multi-gene calibrating process.

Finally, results will be analyzed based on pre-set criteria. Scenarios are tested and refined if criteria are not meet. In this iterative process, qualified scenarios are selected and final evacuation plans are developed based on them.

3.2 Evacuation Demand Estimation

Demand estimation is one of the key issues in developing a suitable evacuation plan. A test plan is to be developed and hourly flow and link travel time will be collected using GPS devices. GIS model MapleInfo will be used to analyze the data and the results will be served as input to model QueensOD which will generate the Origin-Destination matrices.

A two-step method is identified. Participation rate methods will be used to determine the total evacuation demand and a loading curve will be used to estimate the temporal distribution of the evacuation trips. Then the process of how to transfer normal Origin-Destination matrices to Origin-Destination matrices under evacuation situation will be developed. The common operations include set inbound trips and garage (inside the affected area) to garage trips to zero etc.

3.3 Evacuation Strategies and Analytical Criteria

Evacuation strategies and analytical criteria are two other key issues. The two main problems of a transportation evacuation in a small and dense area are limited roadway facilities with high evacuation demand and a far larger number of people than available vehicles inside the area. Appropriate strategies are to be identified based on the study area and incident assumption to address the issues. Then, the strategies will be implemented and different scenarios are to be developed and simulated.

The results are to be selected based on pre-set criteria that suit the study. And finally, the results will be used to create the transportation evacuation plan for the study area.

3.4 Case study

The last part is to conduct a case study. It is designed to validate the proposed framework. The Texas Medical Center is selected for the case study. Based on the framework, the background of the study is to be identified and data are to be collected to establish the modeling

network, as well as to estimate the evacuation demand and calibrate the simulation model. Different scenarios with various strategies are to be developed, simulated and analyzed. A transportation evacuation plan is to be developed for Texas Medical Center.

CHAPTER 4

DEVELOPING FRAMEWORK FOR EVACUATION PLAN FOR MAJOR TRAFFIC GENERATORS

This chapter presents the development of modeling framework for a transportation evacuation plan for major traffic generators. Several issues are specially discussed such as demand estimation, evacuation strategy development, and analytical criteria.

4.1 Developing Modeling Framework

4.1.1 Development of Modeling Framework

The proposed framework is shown in Figure 2. It integrated the transportation evacuation study with traffic simulation. This microscopic framework can be used for conducting operation analysis of the transportation evacuation in small and dense areas, as well as helping in planning emergency preparation.

The framework includes Study Area Identification, Data Collection, Incident Assumption, Simulation Model Selection, Evacuation Demand Estimation, Evacuation Strategies Planning, Network Coding, Network Calibration, Simulation and Result Analysis and Plan Development.

It is an iterative process that ends only when the proposed evacuation scenario meets the pre-set evacuation requirement. Otherwise, next scenario with different evacuation strategies is to be developed and simulated.

The following sections explain the important components of this modeling framework.

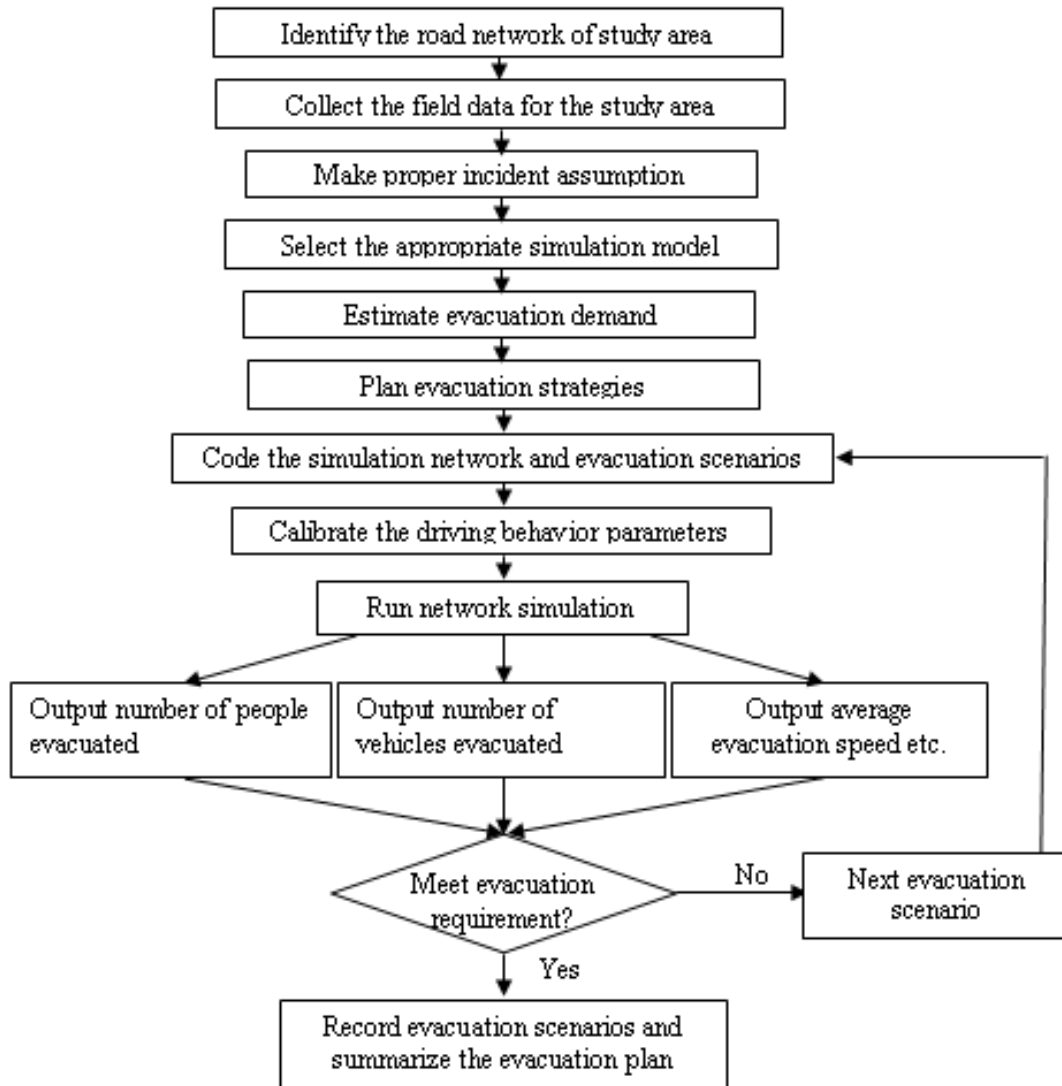


Figure 2. Proposed Study Framework for Developing Transportation Evacuation Plan in Small and Dense Areas

4.1.2 Incident Assumption

Incident assumption is important to evacuation study. Reasonable assumption helps to understand the realistic threat of the study area and thus the evacuation study leads to meaningful results. Besides, different incident assumption creates different evacuation scenarios. For example, the severity factor of the assumed incident will have different impacts on the function of the existing transportation facility. Some may decrease the traffic volume and some may break

down roadway. Besides, different incident assumptions will also affect the evacuation demand estimation.

Incident assumption is closely related to study area. When making the incident assumption, two major factors are taken into account. The first one is the possibility of incident occurrence in the study area, and the second one is whether the emergency event is representative in a transportation evacuation study for small and dense areas. If different severity of incidents and their impacts are beyond the research scope, necessary simplification can be made. Thus, an incident assumption is based on study area and research objectives.

4.1.3 Selection of Simulation Model

Over the years, several simulation software packages have been developed to model traffic flow in emergency evacuation situations. These include, but are not limited to, the Oak Ridge Evacuation Modeling System (OREMS), Dynamic Network Evacuation (DYNEV), Evacuation Traffic Information System (ETIS), and general-purpose software packages such as VISSIM, DYNASMART-P and MITSIMLab.

The unique traffic and vehicle activities in the emergency and evacuation situations are very different from those on daily urban streets. In such a small area, large amounts of different types of vehicles will be loaded onto the roadway network in a limited short time with special driving behaviors. It is required that the selected traffic simulation model be capable of modeling roadway networks in great detail with the various driving behaviors simulated. Also the model should be able to simulate multiple transportation modes including cars, buses, trains etc.

Although microscopic models require intense data input and may result in longer running time, they have useful features including multi-modal and driving behavior and can provide complete output. Most importantly, the microscopic feature makes them more preferable in evacuation study in small areas.

4.1.4 Demand Estimation in Evacuation

A two-step method of Participation rate method and loading curve is used in estimate evacuation demand in this framework. Participation rate method is used to determine the total

evacuation demand and loading curve is used to estimate the temporal distribution of the evacuation trips.

Participation rate method depends on rates which are based on historical data or the results of drills/surveys. Based on the rates, the participation rate method generates the total demand. In case the data are unavailable, the rates are developed subjectively based on experience and literature review. Loading curve is used for represent temporal distribution.

Then a normal Origin-Destination matrix needs to be transferred to Origin-Destination matrix under evacuation situation.

4.1.5 Development of Evacuation Strategies

As evacuation is an extreme situation and can greatly affect the traffic condition, evacuation strategies are essential to ensure efficient evacuation. Small and dense areas like the CBD are usually where roadway facilities are limited compared with dense demand and where the number of people is far more than the number of vehicles inside the area. To address the two problems, Reversed Lane and Inbound Shuttles together with other potential evacuation strategies can be adopted.

4.1.6 Analytical Criteria

In order to evaluate the simulation results and select the appropriate evacuation scenarios, analytical criteria need to be established. The criteria can mainly be divided into two categories. The first category shows the result of evacuation and the second describes the traffic condition of each scenario. The most important criteria are the ones that meet the evacuation objectives.

The common criteria for evacuation include number of vehicles evacuated, number of people evacuated, number of intersections/links congested etc. The common criteria for traffic conditions include travel time, average speed, average delay time and average number of stops etc.

4.1.7 Network Coding

Network coding is to code all the details of networking into the selected microscopic simulation model. This information includes network geometry, local traffic information (traffic

volume etc.), traffic control information (speed limit, locations of stop signs/yield signs/reduce speed areas and signal plans), vehicle information (vehicle composition, speed distribution, driving behavior etc.) and route assignment settings. Analytical measures (data collection points /detectors) also need to be coded in the model to get necessary results.

It is not likely that an incident happens when the network is empty. Therefore, the existing traffic before evacuation (which is called background traffic) was considered in order to eliminate the inaccuracies caused by initiating simulation from an empty network. An initial period when the same network settings (e.g., vehicle inputs, etc.) under normal traffic operation were prepared and traffic during this initial period was simulated during peak hours on a normal weekday. After the initial traffic in the network reached a stable status, evacuation with different vehicle input, traffic control and evaluation options, was assumed to occur. Only the simulation results under evacuation status were used for final analyses.

4.1.8 Network Calibration

The calibration of the traffic simulation model is to determine values of the model parameters to make sure that the simulation results are consistent with the field observations and are reliable.

Driving behavior model is the core of any traffic simulation model. It determines how the vehicles will behave within the network. These behavior parameters include lane change behavior, vehicle following behavior, and lateral behavior etc.

Genetic Algorithm is one of the calibration methods for searching multiple parameters at the same time. Genetic Algorithm is based on the Darwinian survival theory: more fit individuals are evolved from successive generations (Goldberg, 1989). It has a robust ability to find acceptable solutions in complex search spaces. Computer programs can be developed to carry out the calibration with Genetic Algorithm as its core. Traffic information from the field is compared with the simulation output. Indexes, like sum of square error (SSE), can be selected where the calibration program stops when the selected index meets certain criteria. The parameters can then be used in simulation.

4.1.9 Simulation, Result Analysis and Plan Development

Results are to be analyzed based on pre-set criteria after simulation. Scenarios are to be tested and refined if criteria are not meet. In this iterative process, qualified scenarios are selected and evacuation plans are developed based on them.

4.2 Demand Estimation in Evacuation

The up-to-date practice in evacuation demand estimation is a two-step process: the first step is to estimate total evacuation demand and the second step is to estimate the distribution of individual departure time (Mei, 2002). When considering the Origin-Destination matrices, necessary modifications are needed for changing normal weekday O-D matrices to O-D matrices in evacuation

4.2.1 Estimation of Total Evacuation Demand

The evacuation participation rate method is the most common method of estimating evacuation demand (Mei, 2004). It is the method that estimates the proportion of households in an area that will evacuate based on participation rates. Participation rates are usually developed according to past records of study area including response and actions by local agencies (whether or not to order mandatory evacuation), etc. According to literature review, typically, no statistical analysis of past data was conducted in establishing such rates, and instead they were established subjectively by experts based on past experience (Fu *et al*, 2007).

For small and dense areas, except for obtaining the rates from historical disaster records in the area, other alternatives to get the rates are either to call a drill and record the rates or to conduct a survey and ask people:

What they will do?

Whether or not to evacuate?

Where is the destination?

Which route to take?

Which mode to use?

These are relatively easy to do in a small area compared with similar action in large areas. However, both will require the coordination with the authorities in charge of the area. Based on

the estimation of the participation rates and the demographics of the area, the total evacuation demand is established.

Sometimes there's no historical data and no such drill/survey has ever been conducted. In this case, demand data are not available from area authorities and the participation rates need to be established subjectively based on experience and literature review.

4.2.2 *Temporal Distribution*

The temporal distribution of evacuation trips is a distribution of departure time of all the evacuees. It is also important as it shows the evacuees' loading speeds onto the local transportation network. Different loading speeds can have a great impact on the evacuation results.

The temporal distribution is usually described by response curves. The curve depicts the assumed departure time distribution of evacuees. Different steepness of the shape of the response curve show different evacuee behavior. The quicker the response - the steeper the curve. Literature review shows that the selection of a response curve for an emergency is subjective and "depends on the analyst's past experience, familiarity with the affected area, and the anticipated response from the evacuees" (Mei, 2002). Two commonly used approaches to develop temporal distribution of demand are:

- Generation of behavioral response curves from historical records, surveys/drills, and
- Development of mathematical models based on past reported data from surveys or experiences

If historical records of a study area are available, the temporal distribution can be developed based on records or post evacuation surveys. If surveys/drills are feasible in the study area, it's also a good way to develop the temporal distribution.

In case both past records and potential surveys/drills are not available, mathematical models are the only option. The parameters of the model are determined subjectively by experts according to the study area and past experiences. One such model is developed by Radwan et al (1985) and Hobeika et al (1998):

$$P(t) = 1 / \{1 + \exp[-\alpha \times (t - H)]\} \quad (1)$$

$P(t)$ is the cumulative percentage of the total trips generated at time t . The speed of evacuees' response to the emergency event represents α . H is the time at which half of the evacuees in the area have been loaded onto the highway network.

4.2.3 *Developing O-D Matrix under Evacuation Situation*

After estimating the total evacuation demand and temporal distribution, one typical question is how to develop Origin-Destination Matrices under evacuation scenarios. Usually, O-D matrices for normal time periods can be obtained in a normal time period traffic survey. These matrices should be adjusted for use in evacuation scenarios.

The necessary modifications of the base O-D matrix include:

Set most of the inbound demands to zero except for few emergency vehicles and Inbound Shuttles;

Set the garage-to-garage O-D pairs to zero; and

Re-distribute the demands which are approaching to endangered areas to the nearby safe destinations.

Since the demands in normal O-D matrices were far smaller than evacuation times, the O-D matrices were adjusted from the base O-D to evacuation O-D by expanding the total demand in normal period to the evacuation demand. The expansion is conservative and proportion-based in this study. While the demand in a garage during a normal period may not necessary be equal to the garage capacity, we assume the demand of the garage under evacuation equals its capacity to be conservative. The ratios of capacity over normal demand are calculated, and then the value of each O-D pair is multiplied by the corresponding ratio for the value under evacuation.

Figure 3 illustrates the O-D re-distribution in evacuation scenarios. Considering parking garage 6 (O), which is very close to the dangerous point, demands to destinations 1, 2, 3, 4 were re-distributed to destination 5, 6, 7 because 5, 6, and 7 were the nearest destinations and vehicles had to pass those dangerous areas in order to reach 1-4.

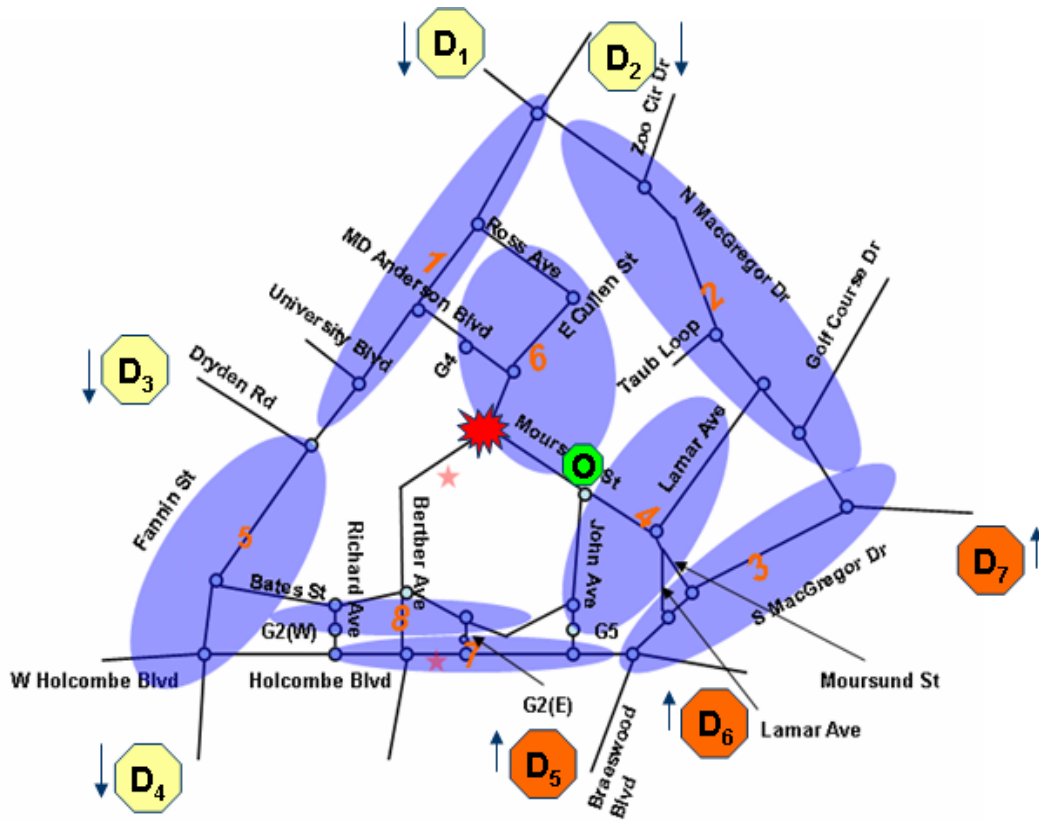


Figure 3. Redistributing O-D Matrices in Evacuation Scenarios

4.3 Evacuation Strategies and Analytical Criteria

4.3.1 Evacuation Strategies

As mentioned in Chapter 4.1.5, small and dense areas are usually the area where roadway facilities are limited compared with dense demand and where the number of people is far more than the number of vehicles inside the area. Reversed Lane (RL) and Inbound Shuttles (IS) are considered in this research to address the problems.

Reversed Lane (RL) is an operation of turning one or more lanes of one direction to the opposite direction. It can greatly expand the roadway capacity without building new facilities. It is used to address the issue of inadequate outbound capacity. While RL should be placed on the main exiting routes to maximize the outbound capacity, multiple factors need to be taken into account. First, the placement should not block the potential inbound vehicles (emergency vehicles, ambulance, inbound shuttles etc.). Also, RL cannot be placed on a street with physical

constraints such as a raised median, and it cannot be placed along a fire station/police department etc.

Inbound Shuttle (IS) is designed to help when people evacuating exceeds the available vehicles in the area. It is also useful to evacuate people with special needs. These two features make it a good tool in evacuation operation in a small and dense area where the number of people is much more than the number of vehicles inside the area and with potential injuries during the incident. The Inbound Shuttle is usually assigned based on both the population distribution in different regions of the area and existing bus lines. The shuttle lines should cover the most places with high demands. The shuttle stops can be located near the exits of the evacuation origins.

Reversed Lane and Inbound Shuttles can be placed in multiple places depending on the need.. The combined use of two strategies can also be adopted to achieve the best evacuation effect. Scenarios with different combinations of these strategies are then tested and analyzed.

4.3.2 Analytical Criteria

The criteria can mainly be divided into two categories. The first category shows the results of evacuation and the second describes the traffic condition of each scenario.

The criteria showing the results of the evacuation include:

Number of people evacuated: the number of people evacuated in the study time period. The larger number of people evacuated should relate to a better performance of the evacuation scenario. The objective is usually to develop an evacuation plan by evacuating all in this region. This is the criterion with highest priority.

Number of vehicles evacuated: the number of vehicles evacuated is similar to the number of people evacuated. Also, the bigger the number is, the better the performance of the evacuation scenario will be. Considering the average occupancy may be bigger than 1.0, the number may not be equal to the demand number.

Number of intersections/links congested: the criterion shows the traffic conditions under evacuation situations. It can be helpful to design the evacuation route as well as improve the infrastructure and management of the locations that are congested.

The criteria for traffic condition include:

Average speed: average vehicle speed during the evacuation period

Average delay time: average delay time of each vehicle during evacuation

Average number of stops: average number of stops of each vehicle during evacuation

These criteria can be used in both the network-wide area and in the so-called “core area” to evaluate different scenarios. Core area refers to the region close to the location where the emergency event occurs. The core area is usually the most suffered and earlier affected area in the network. The criteria targeted on core area are as important as those “global” criteria.

CHAPTER 5

DEVELOPING TRANSPORTATION EVACUATION PLAN FOR TEXAS MEDICAL CENTER

This chapter presents the details of the development of a simulation-based transportation evacuation plan for Texas Medical Center. Different evacuation strategies such as reversed lanes and inbound shuttles are analyzed. Simulation results and evacuation plans are presented in detail.

5.1. Study Area

The selected region for the study is Texas Medical Center (TMC) in Houston, Texas, located to the south of downtown Houston. According to the authority of the Texas Medical Center, TMC is considered the largest medical district in the world given the factor that it has more than 5,000,000 patient visits annually and one of the highest densities of clinical facilities. It has 46 medical institutions, 13 hospitals, and two medical schools (Texas Medical Center Factors and Figures, 2005).

The 0.463 square mile area has approximately 65,300 employees together with 6,500 beds for patients by 2005. On a typical working day, TMC has about 50,000 persons staying in this area. It is a typical small and dense area. The seven internal garages contain 15,000 parking spaces and are considered as major traffic generators in this research. Other commuting options in this area include light rails, shuttles, and car pools. The Houston TMC bus transit center is within walking distance to the study area, and the four arterials surrounding the entire area are major road transportation routes.

Figure 4 and Figure 5 are maps of Texas Medical Center in Houston.



Figure 4. Picture of Texas Medical Center
Source: Texas Medical Center Authority, www.tmc.edu

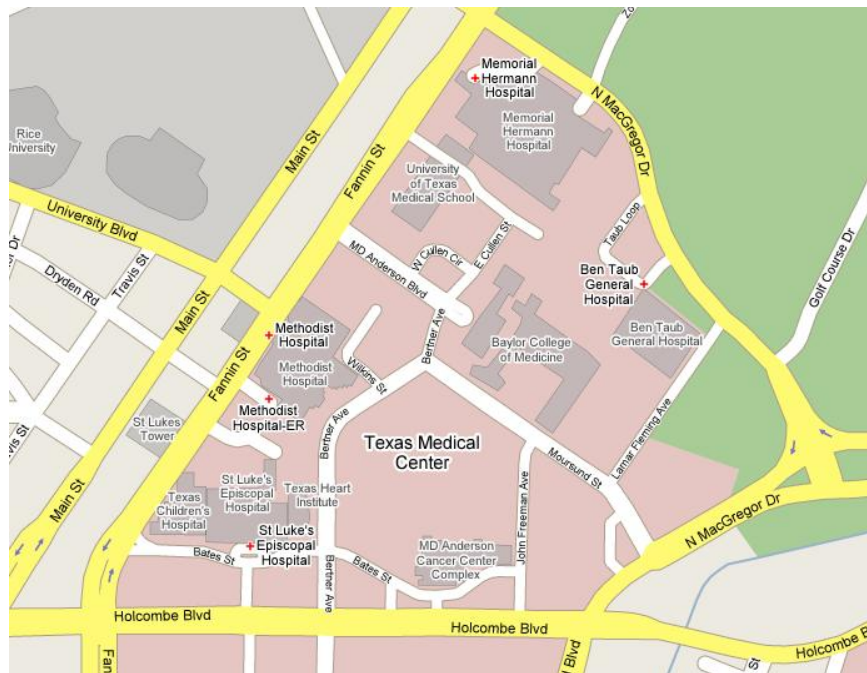


Figure 5. Google Map of Texas Medical Center
Source: Google map, maps.google.com

TMC is a place with a dense population and an abundant history of emergency events. In 2001, TMC encountered serious flooding caused by Tropical Storm Allison. The area was filled with water up to 13 inches deep. Many hospitals were out of power which was deadly to the patients inside. The flooding and lack of an efficient transportation evacuation plan caused severe consequences. Besides flooding, TMC can also be threatened by other emergencies, such as toxic material leakage, pipeline explosion and terrorism attack.

In 1999, a 50 Year “Vision for Growth” Master Plan was completed to guide future development at the Texas Medical Center (TMC, 2001). The principles of this effort were utilized in the development of the Hazard Mitigation Report and act as the guiding force for development activities in the future.

According to this report, Texas Medical Center is not immune to the different hazards. For the protection of the many critical institutions on the campus, multiple mitigation alternatives and projects must be pursued concurrently to maintain the extraordinary level of service the TMC currently provides and reduce the risk of future damage. These include but are not limited to:

- Present a clear understanding of hazards at the Texas Medical Center,
- Develop goals for mitigation activities based on the best available data,
- Develop concepts for future development of access and transportation systems, utilities systems and emergency management techniques, and
- Provide a framework for the timing and prioritization of future hazard mitigation projects.

Currently, Texas Medical Center authority projected several emergency access routes shown in Figure 6.

Types of information needed for the simulation include:

- Roadway network geometry information
- Location of traffic control devices like stop signs, yield signs etc.
- Signal timing plan
- Traffic information such as vehicle composition of the area, hourly volume on arterials
- Information for O-D estimation
- Instantaneous speed for model calibration
- Data collection methods and devices to be used
- Data collection schedules, times and activities

Detailed data collection plans for information to estimation O-D matrices are listed in Appendix A, where a data collection instrument is also attached.

5.2.2 Data Collection

The field data collection was conducted to accumulate information for the development of the model. Information on network geometry and locations of traffic control devices, etc. are used to establish the sketch of simulation network, while traffic volume, signal timing plan, turning ratio and vehicle composition, etc. were collected for the completion of the entire network in VISSIM.

Basically, all the above information was manually retrieved through field studies. The time is in accordance with the incident assumption of this research, which is in a normal weekday afternoon. Hourly traffic volumes on inbound links during the corresponding time period are collected manually. The collected hourly traffic volume is listed in Table 3, which are vehicle inputs in VISSIM.

Table 3. Hourly Traffic Volume for Inbound Links

Name	Traffic Composition	Volume
Garage 1 Exit 1	1	150
Garage 1-E Exit 2	1	150
Garage 2-E Exit 1	1	300
Garage 2-E Exit 2	1	60
Garage 2-E Exit 3	1	270
Garage 4-E Exit 1	1	130
Garage 4-E Exit 2	1	130
Garage 4-E Exit 3	1	200
Garage 5	1	120
Garage 6-E Exit 1	1	160
Garage 6-E Exit 2	1	160
Garage 7	1	30
Garage 10-E Exit 1	1	250
Garage 10-E Exit 2	1	100
Fannin S. St.	2	450
LRT N.	3	20
Fannin N. St.	2	570
LRT S.	3	20
Ben Taub Loop Dr.	1	200
Bertner Ave.	2	216
Braeswood Blvd.	2	991
Hermann Loop Dr.	2	916
Dryden St.	2	200
University Blvd.	2	384
N. Mac Dr.	2	455
Holcombe W. Blvd.	2	1315
Holcombe E. Blvd.	2	726

In Table 3, the values in the column “Traffic Composition” represent three different vehicle compositions. The number one (1) represents 98percent car and two percent Heavy Goods Vehicle (HGV). It’s obtained from field study on vehicles parked in garages. The number two (2) represents 95percent car, 1.3percent HGV and 3.7percent bus. It is the traffic composition on roadway network in TMC. The number three (3) is for Light Rail Train (LRT) only which is 100percent of tram.

As there is no available Origin-Destination (O-D) information under evacuation situations, O-D pairs under this situation are indirectly estimated from traffic counts in the TMC area, including hourly flow and link travel time.

Hourly flow information was collected at two control points and 53 coverage points in the afternoon peak hour on April 27th and 28th, 2007. Control points were used to detect the variations of traffic counts. Data at control points were collected from 14:00 to 18:00 continuously. Coverage points covered each location where traffic counts were needed for O-D estimation. Count data at coverage points were collected for 15 minutes each and expanded and adjusted based on the traffic variation factors from control points. One control point was located along Bertner Ave. near McGoven Complex to monitor traffic variations in TMC-inner traffic. The other control point was located along Holcombe Blvd. to monitor traffic variations on arterials. The stars in Figure 7 represent control points and the filled circles represent data collection groups.

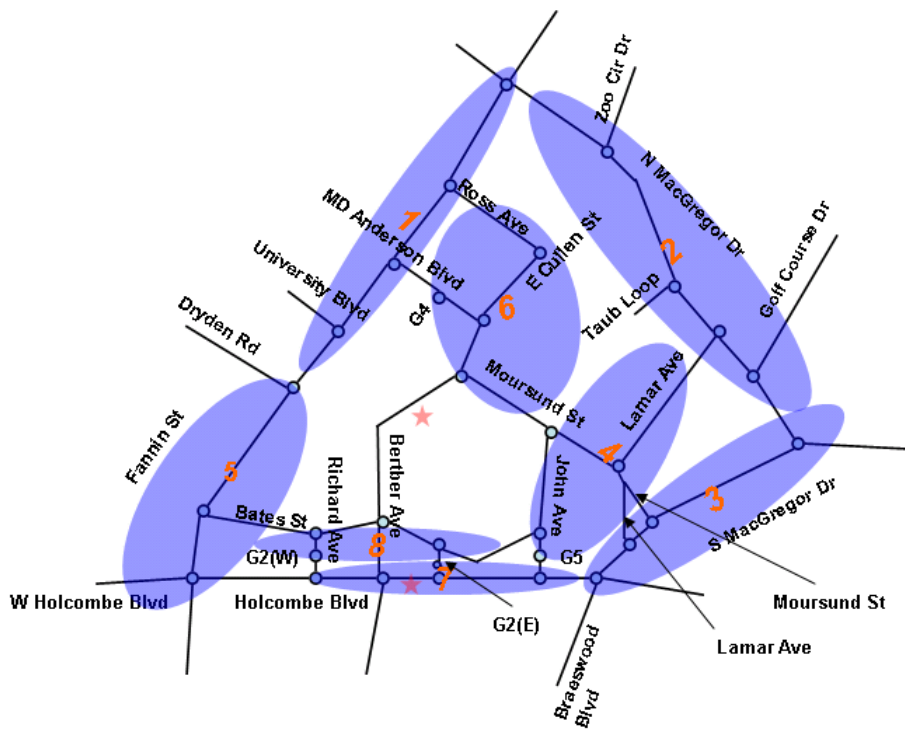


Figure 7. Illustration of Hourly Flow Data Collection in Texas Medical Center

A floating cars data collection method was used to acquire the localized speed and link travel time information on roadway networks. A GPS device, which provides second-by-second vehicle location and speed, was used in the test. The testing vehicle was driven following the traffic flow, and this specific test route for speed survey was illustrated in thick bars in Figure 8.

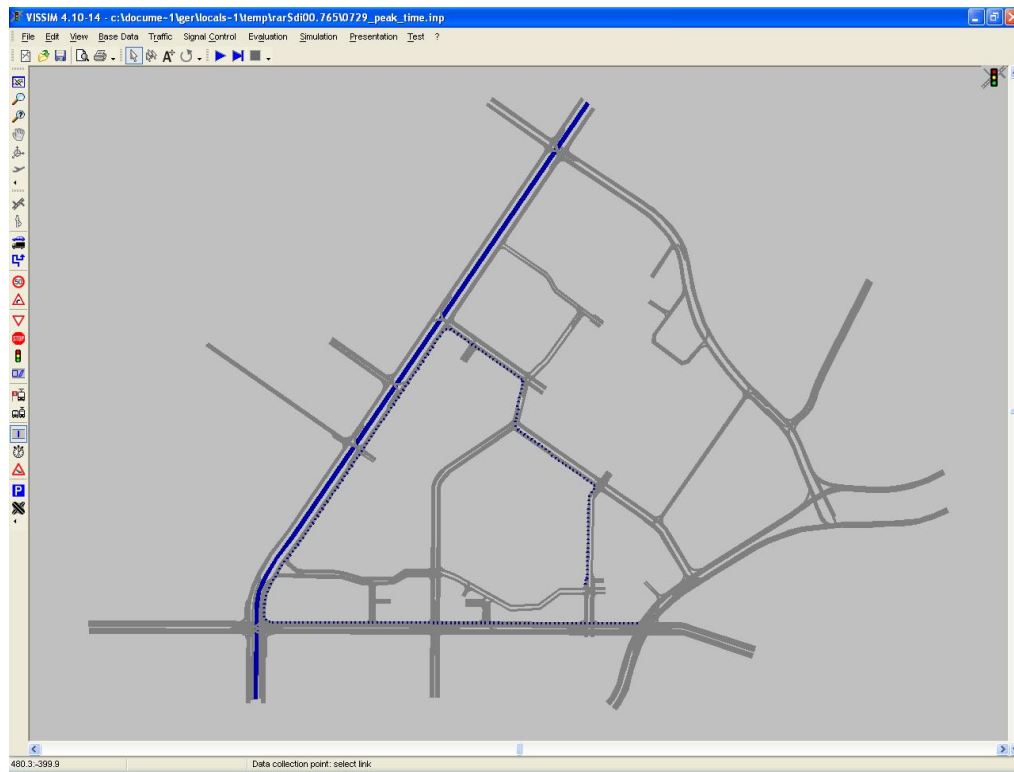


Figure 8. Test Route for Calibration

The test route covered all links on which link travel time is required for O-D estimation. The results were derived by processing the recorded GPS data through the software MapInfo. The detailed procedure is described in the next part.

5.3 Incident Assumption

Considering the factors mentioned in Chapter 4.1, the hypothetical emergency event in this thesis is a truck accident causing hazardous material leakage inside the TMC area during peak hours on a normal weekday. When the presumed hazardous material spreads at the center of the area, a mandatory evacuation is ordered. For demonstrational purposes, the toxic material is

assumed to diffuse over the entire area in about one hour. The goal is to efficiently evacuate as many persons as possible within the scheduled time period.

5.4 Selection of Simulation Model

According to Table 1, OREMS, DYNEV and ETIS should be excluded because they are macroscopic models for even larger area evacuations. A review of the existing traffic simulation models suggests several microscopic traffic simulation models that could meet the needs of the target simulation objectives. One of these models is VISSIM. VISSIM is developed by PTV Corp (PTV Inc., 2005). It is a microscopic, time-step based simulation model with parameters describing specific driving behavior. It is capable of modeling a wide-range of roadway networks as well as various transportation modes including private cars, trucks, buses, High Occupancy Vehicles (HOVs), light rails, heavy trams, pedestrians, and bicycles. It can address the specific geometric design of any transportation network, and also includes a driving behavior model to capture the microscopic driving behavior of vehicles in the evacuation scenario.

Although DYNASMART-P and MITSIMLab are with similar performances, VISSIM is a more matured and widely used simulation model compared with the other two. It can address the specific geometric design of any transportation network including small and dense areas with multiple transportation modes. It also includes a driving behavior model that captures specific driving behavior under evacuation scenarios. VISSIM has the ease to simulate scenarios with all kinds of evacuation strategies with suitable network modifications. These features make VISSIM a useful tool for this study. For most of the transportation evacuation study in a small and dense area, VISSIM is recommended for simulation model.

5.5 Demand Estimation

Different Route Assignments need different forms of demand data. In this thesis, we start with introducing the two route assignments in VISSIM and then estimate the demand for both route assignments.

Dynamic Assignment (DA) and Routing Decisions (RD) are two methods that VISSIM uses in assigning traffic. Generally speaking, RD is simple and efficient in some cases while DA considers dynamic occasions.

Dynamic Assignment in VISSIM is designed to model the route choice behavior when time dependent characteristics exist. Traffic assignment is based on O-D matrices. O-D Matrices can be generated, if not available from survey directly and can be estimated using kinds of algorithms such as are coded in the O-D estimation software QueensOD. O-D estimation normally requires traffic flow and link travel time as inputs

By Routing Decisions method, the paths of vehicle traveling through the road network are determined statically beforehand. Static routes are defined in VISSIM manually with turning ratios collected from the field.

5.5.1 Dynamic Assignment (DA)

Dynamic assignment in VISSIM is conducted by an iterated application of the microscopic traffic flow simulation (PTV Inc., 2005). A modeled network is simulated repetitively while the drivers choose their routes according to the travel cost during the preceding iterations. The “cost” in VISSIM is a combination of travel time, average delay and other factors. The iteration of the simulation runs is continued until the travel times and volumes on the edges of the network do not change greatly between two adjacent iterations. Figure 9 shows the process.

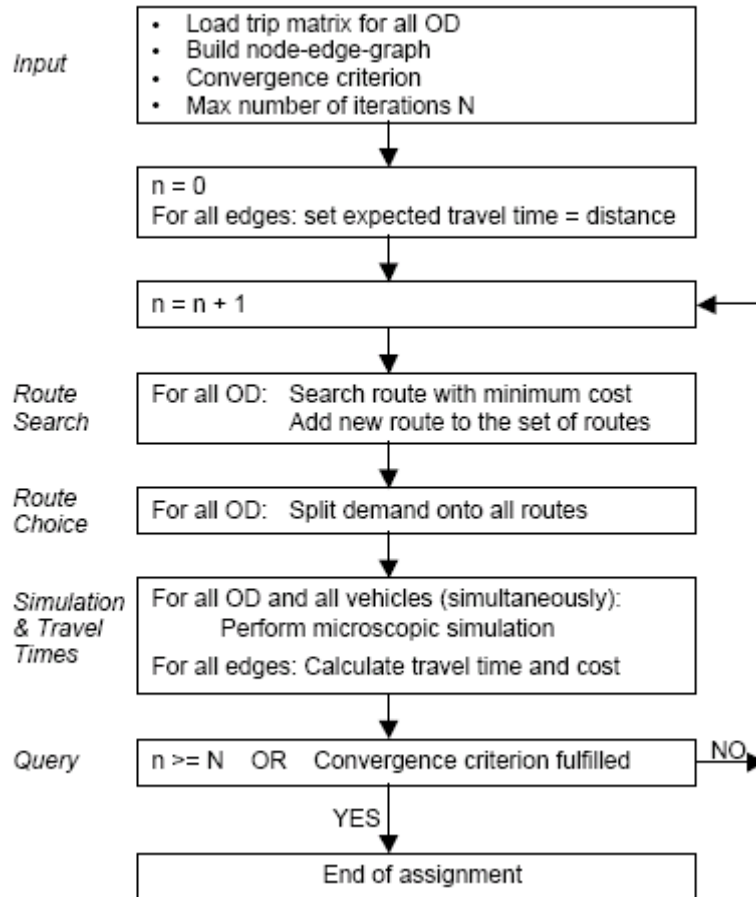


Figure 9. DA Process in VISSIM
Source: VISSIM 4.10 Manual

DA was realized by developing a so-called “abstract network” in VISSIM and employing O-D matrices derived from the output of the O-D estimation software QueensOD.

QueensOD is a model developed by researchers from Queens University (QueensOD Rel 2.10 User’s Guide, 2001). The origin destination traffic demands are estimated based on observed link traffic flows, link turning movement counts, and link travel times. The input files include the master file, node file, link file, signal file, and link traffic flow file. Output files contain the O-D matrices generated from given data.

Node file. Information about each node in the network is needed. One common way is to generate the coordinates from the plotted network in Synchro. Node types are usually one of the two options: ‘both origin and destination zone’ and ‘intermediate node only’.

Link file. Each link is specified using the upstream and downstream nodes. Link length could be obtained through using the ‘transfer’ – ‘data access’ function in SYNCHRO. In this study, turn prohibition indicator was set to zero (0) which means no turns are prohibited. The end controls of each link are identified and coded with signal control, stop sign or yield sign.

Signal file. Signal plan, number, initial cycle length, minimum cycle length, maximum cycle length signal offset, number of phases, effective green time and effective lost time should be inputted into this file.

Link traffic flow file. This file requires inputting hourly flow observed on the link, net link capacity, free flow travel time on link and travel time on link when loaded with observed traffic. Hourly flow is inputted based on the real case, and net capacity is set to 1900veh/h which is the most commonly used value. And for free travel time, the quotient of link length over speed limit is used to calculate the input. The two major difficult parts are hourly flow and link travel time when network is loaded with observed traffic flow.

Two tests are done in order to get the ‘raw’ information. Count data were collected in control points and coverage points. Count data at two control points were collected from 14:00 to 18:00 continuously and Count data at 53 coverage points were collected for 15 minutes each. The hourly variation and daily variation factor were calculated. Based on those, the expansion and adjustment of coverage points were conducted. Arterial and inner street, inbound traffic and outbound traffic, totally four sets of different parameters are calculated to make the results accurate.

For travel time loaded with observed traffic, GPS is used to collect information. All records were then transferred to the computer and converted into Microsoft Access format. Lengths of each attribute are defined in Access and then the Access file was imported into MapInfo. All records were plotted with the loaded map background. Figure 10 illustrates the location plots from GPS records in Excel. Figure 11 shows the plots in MapInfo for obtaining link travel time.

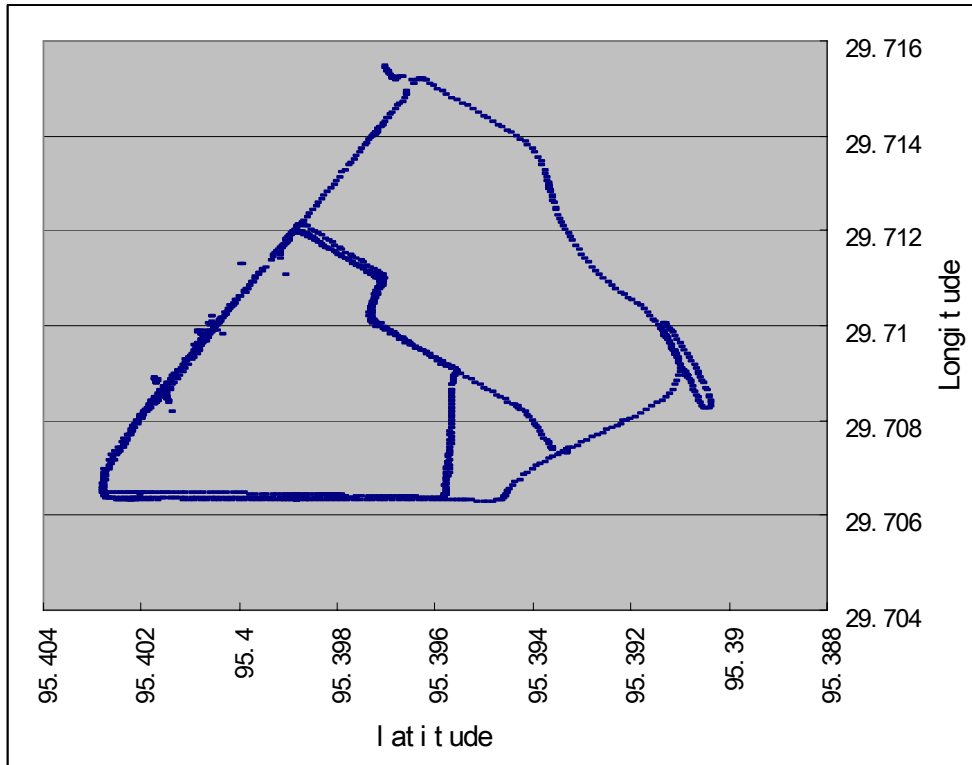


Figure 10. GPS Plots in Excel

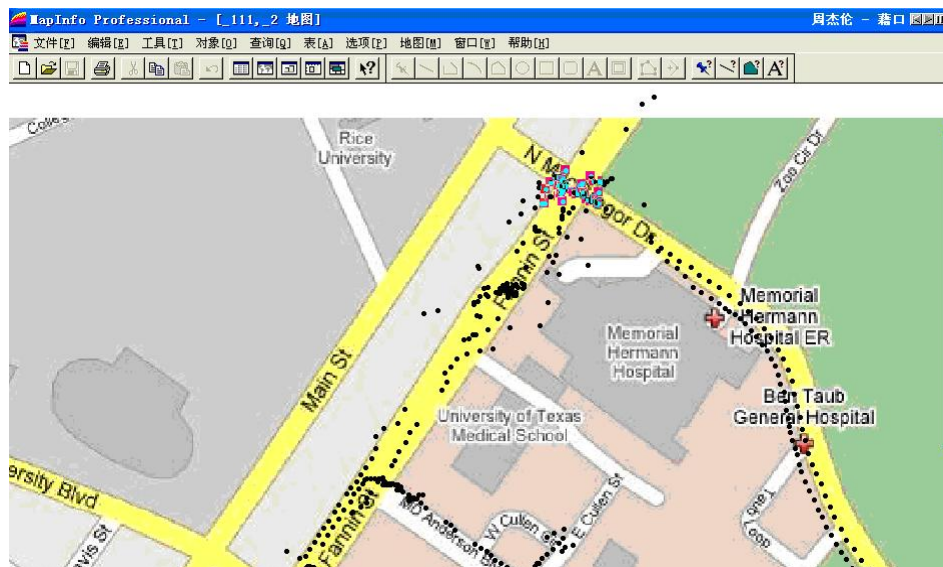


Figure 11. Obtaining Link Travel Time from plotting GPS Data in MapInfo

Master File. The main content in the file is designating the name and directory of each input and out file.

With all the above mentioned input files prepared, O-D matrices can be estimated by using QueensOD. These normal weekday afternoons can be turned into O-D matrices under evacuation scenarios based on the description in Chapter 4.1.3. As no past evacuation records and drills/surveys are available, the participants rates are established subjectively based on experience and literature review. According to the incident assumption, as mandatory evacuation is assumed, the evacuation demand is set as 50,000 people which are the common number of people working inside the TMC area on a normal weekday afternoon.

5.5.2 Routing Decisions (RD)

The evacuation demand for RD is the same as DA. But In VISSIM, RD needs turning ratios as input instead of O-D Matrices. Figure 12 shows one route decision in VISSIM. Under normal situations, the turning ratios are directly based on field data. In evacuation scenarios, turning ratios are different from the normal situations. In this research, we assumed the following way to generate turning ratios for RD in evacuation scenarios.

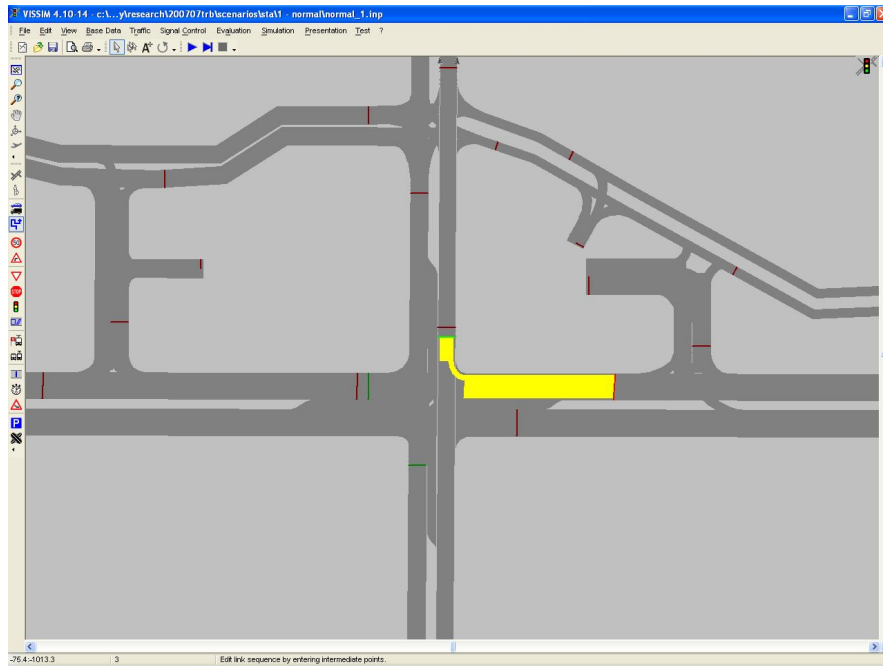


Figure 12. Implementation of Routing Decisions in VISSIM

When evacuation begins, inbound traffic is set to a small number considering that only very limited emergency vehicles and possible Inbound Shuttles are allowed to enter the network

where the emergency occurs. In this case, traffic flows toward the endangered area were split into other directions following the proportion. For example, suppose the traffic flows towards three different directions (through, left-turn, and right-turn) were 750, 150 and 100 veh/hr, respectively. If the right-turning is towards the endangered area, then flow to right turn will be set as zero (0). The original right-turn flow (100 veh/hr) will be assigned to the two remaining directions (through and left-turn movements) proportionally. In this case, the 100 veh/hr right-turn vehicle under normal situation is decomposed, when evacuation occurs, into $100 \cdot 750 / (750 + 150) = 89$ (veh/hr) for through movement, and $100 \cdot 150 / (750 + 150) = 11$ (veh/hr) for left-turn, respectively. Figure 13 shows an example comparing the RD assignment in normal scenarios and evacuation scenarios.

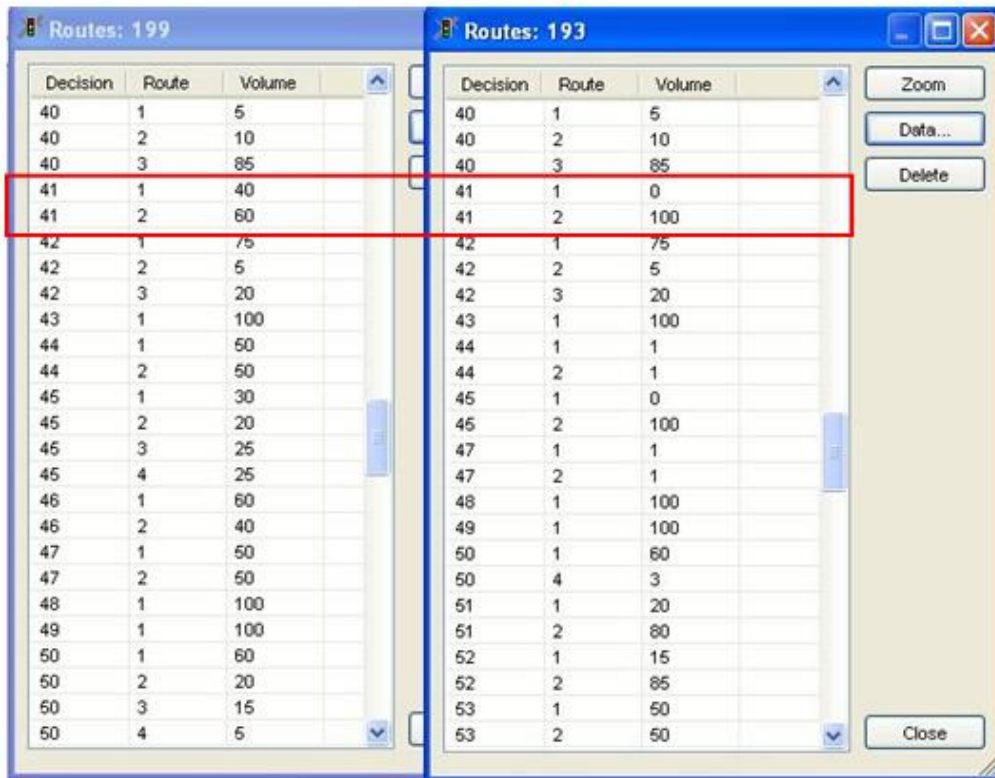


Figure 13. A Comparison of Routing Decisions Assignment in Normal Scenarios and Evacuation Scenarios

5.6 Evacuation Strategies and Evacuation Scenarios

Different evacuation scenarios are developed to evaluate the impacts of different strategies in response to the emergency needs including the options of reversed-lane and different service rate of shuttles. Reversed lane (RL) helps to increase the capacity of evacuation network in the

outbound direction. As the population in the TMC is much larger than the capacity of its parking garages, inbound shuttles (IS) were used to evacuate patients and staff promptly.

Measures of Effectiveness (MOE) in both network-wide area and in the so-called “core area” were used for the evaluation of different scenarios. Core area refers to the region close to the location where the emergency event occurs. According to the assumption of toxic material leakage in this study, the core area is the most suffered and earlier affected area in the network. The location of the core area, parking garages, and reversed lanes are shown in Figure 14.

In Figure 14, the incident broke down the link above the Moursund Street, directly affecting the surrounding area.

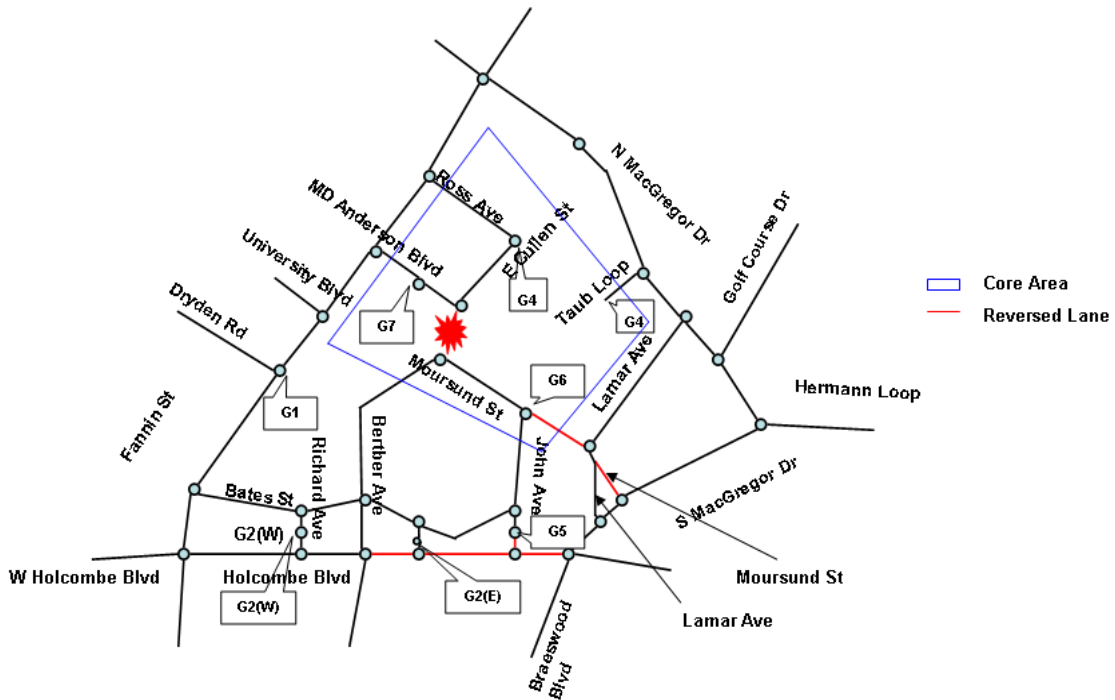


Figure 14. Illustration of Location of Core Area and Reversed Lanes

The designed twenty evacuation scenarios are listed in the following four categories:

1. For base scenario and basic evacuation scenarios:

- Scenario 1-1: normal scenario with no incident,
- Scenario 1-2: evacuation scenario with no improvement,

- Scenario 1-3: evacuation scenario with reversed lane (RL) at Holcombe Blvd between G2(E) and Braeswood Blvd. west bound,
- Scenario 1-4: evacuation scenarios with inbound shuttles (IS) coming into the area with 60 sec interval, and
- Scenario 1-5: evacuation scenario with reversed lane (RL) at Holcombe Blvd between G2(E) and Braeswood Blvd. west bound and inbound shuttles (IS) coming into the area with 60 sec interval.

2. For the evaluation with different combination of RL:

- Scenario 2-1: RL at John Ave between G5 and Holcombe Blvd, south bound,
- Scenario 2-2: RL at Mousund St. between John Ave and S. MacGregor Dr, west bound,
- Scenario 2-3: RL at Holcombe Blvd between G2(E) and Braeswood Blvd. west bound, and
- Scenario 2-4: RL at Holcombe Blvd between John Ave and Bertner Ave. east bound.

RLs are placed on the main exiting routes to maximize the outbound capacity with exception of those places which RL may block the potential inbound vehicles (emergency vehicles, ambulance, inbound shuttles etc.). Also, RL are not placed on Fannin Street because there are physical constraints (raised median and light rail platforms).

3. For the evaluation of different IS service rate with 10 IS lines:

- Scenario 1-4: IS with 60 sec interval,
- Scenario 3-1: IS with 30 sec interval,
- Scenario 3-2: IS with 180 sec interval,
- Scenario 3-3: IS with 60 sec interval and RL at Holcombe Blvd between G2(E) and Braeswood Blvd. west bound,
- Scenario 3-4: IS with 30 sec interval and RL at Holcombe Blvd between G2(E) and Braeswood Blvd. west bound , and

- Scenario 3-5: IS with 180 sec interval and RL at Holcombe Blvd between G2(E) and Braeswood Blvd. west bound.

4. For the evaluation of 20 IS lines at a shuttle interval of 60 sec under different percentage of evacuation demand in the seven parking garages:

- Scenario 4-1: 0% of demand in garages
- Scenario 4-2: 10% of demand in garages
- Scenario 4-3: 30% of demand in garages
- Scenario 4-4: 50% of demand in garages
- Scenario 4-5: 70% of demand in garages
- Scenario 4-6: 100% of demand in garages

For scenarios with IS, the locations of the inbound shuttles were assigned based on both the population distribution in different regions of the area and existing bus lines. As most hospitals were located along Fannin St., Mousund St. and N MacGregor Dr., three groups of inbound shuttle lines were developed passing these three areas. It was assumed that passengers at one stop could occupy the entire shuttle because each shuttle line has only one stop. Figure 15 illustrates the inbound shuttle lines.

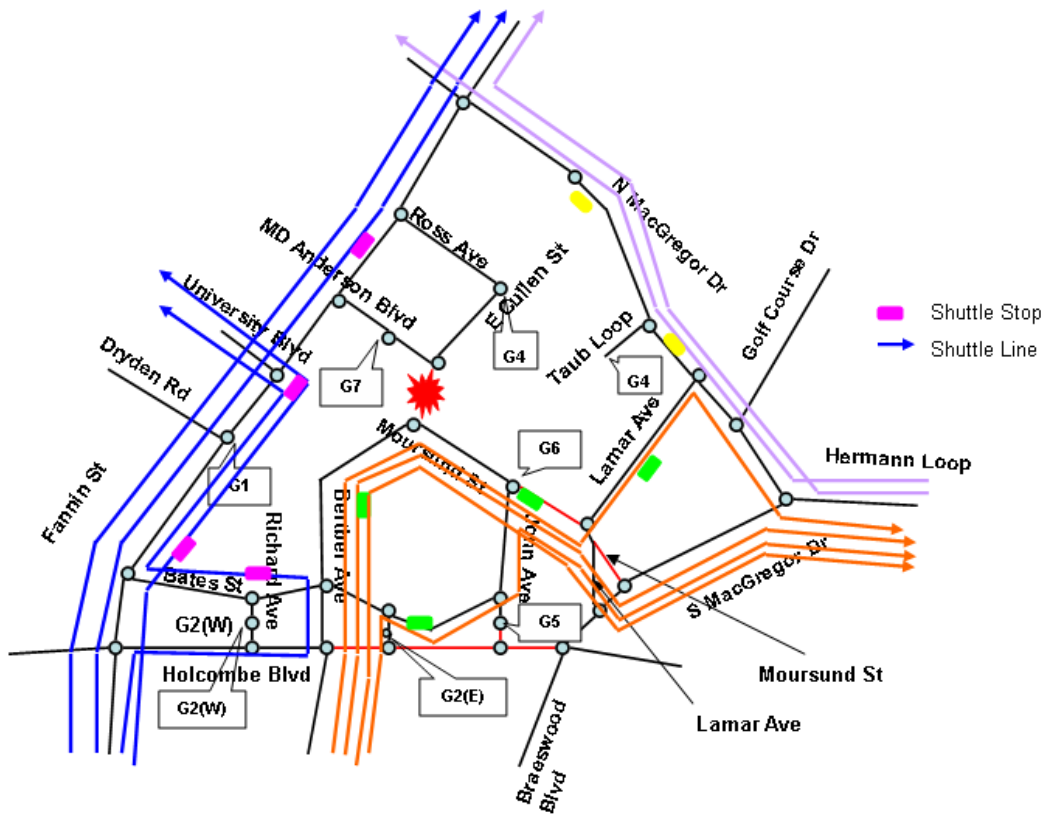


Figure 15. Illustration of Inbound Shuttle Lines

5.7 Network Coding

The purpose of network coding in VISSIM was to simulate the TMC local transportation network and traffic conditions. Microscopic details of network were coded to ensure the quality and accuracy of the study. The network was sketched, while different traffic control devices (stop signs, yield signs, reduce speed areas and signals), vehicle information, and route assignment settings were coded into VISSIM under different layers. Data collection points and other analysis tools were placed in the network to collect simulation outputs. The coding process is shown in Figure 16.

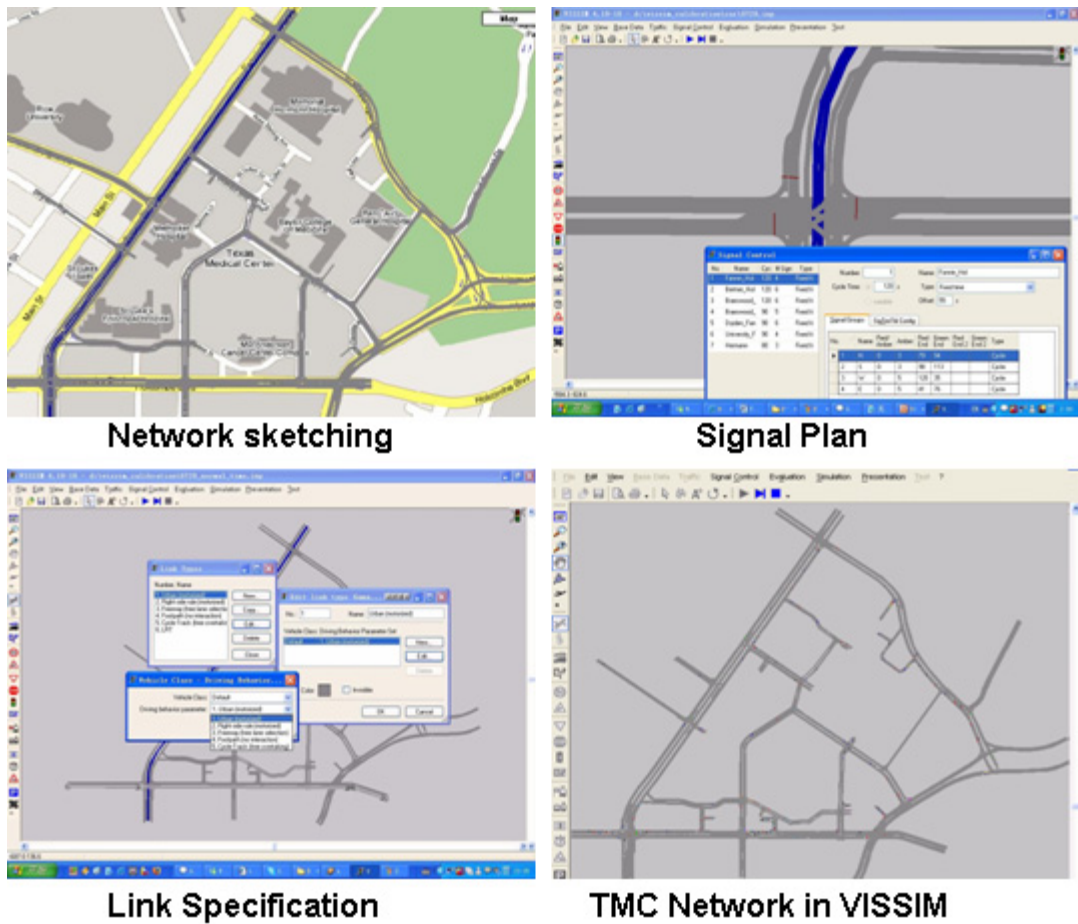


Figure 16. Network Coding in VISSIM

In VISSIM, an “abstract network” is built for DA first. Nodes edges are the physical components of the abstract network. With externally developed O-D matrices, DA can be coded in VISSIM. Routing Decisions traffic assignment was achieved by constructing static routes with turning ratio originated from field survey. Figure 17 shows the DA coded network in VISSIM.

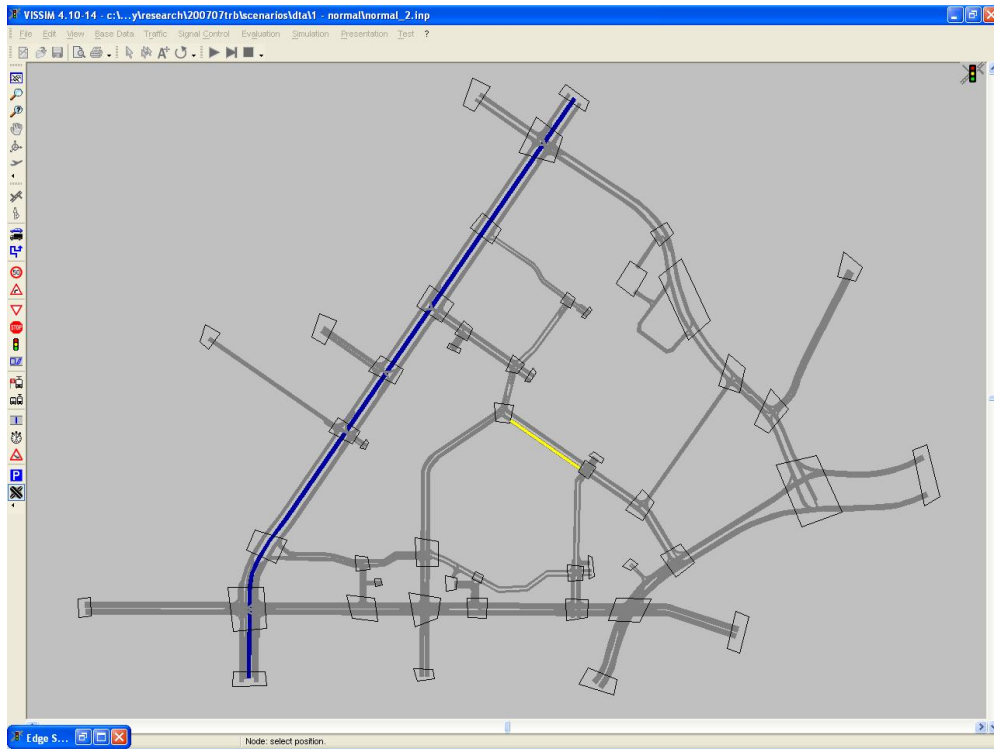


Figure 17. Implementation of Dynamic Assignment in VISSIM

Travel demands from each traffic generator or origin were loaded onto the network through a pre-designed loading curve, which was a function of time providing percentage of evacuees or vehicles to the network. The loading curve reflected the responding behaviors of evacuees. A Logit-based loading curve was employed, which is shown in Figure 18. For scenarios with dynamic traffic assignment, seven 400-seconds-long O-D tables were used to represent the speed of evacuees loaded onto the network. These phased O-D matrices are listed in Appendix C. For scenarios with Routing Decisions traffic assignment, phased vehicles inputs based on loading curve were applied under different simulation time periods.

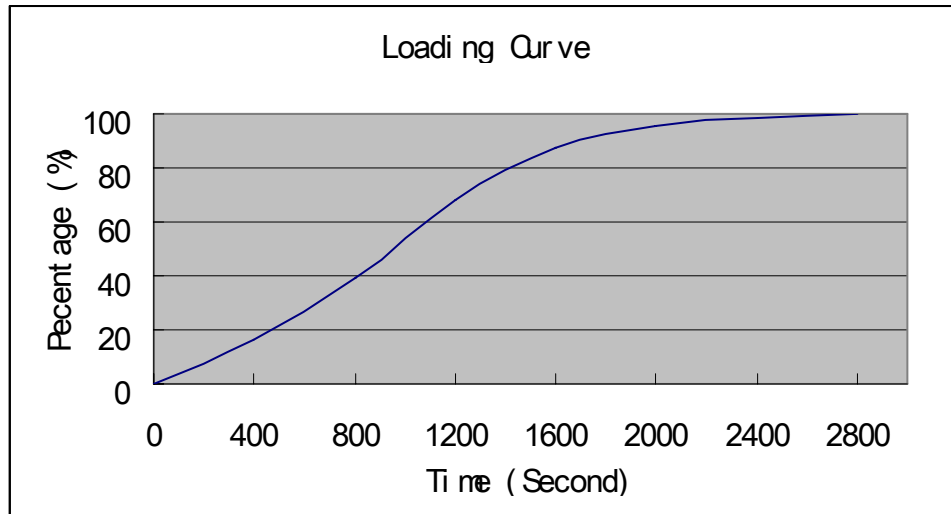


Figure 18. Loading Curve for Evacuation Study in Texas Medical Center

5.8 Network Calibration

The driving behavior model in VISSIM is a psychophysical car following model based on Wiedemann's work on driving behavior (VISSIM Version 4.1 Manual, 2005). The 10 driving behavior parameters need to be calibrated are as follows:

- 1) Lane change behavior:
 - Waiting time before diffusion: (x_1)
 - Min. Headway (front/rear): (x_2)
- 2) Necessary lane change (route) behavior:
 - Maximum deceleration (x_3)
 - $-1m/s*s$ per distance (x_4)
 - Accepted deceleration (x_5)
- 3) Vehicle following behavior:
 - Look ahead distance: min. and max. (x_6)

- Average standstill distance (x7)
- Additive part of desired safety distance (x8)
- Multiple part of desired safety distance (x9)

4) Lateral behavior:

- Distance of standing and distance at 30 mph (x10)

Genetic Algorithm is selected as a calibration method for calibrating multiple parameters at the same time. Genetic Algorithm is based on the Darwinian survival theory: more fit individuals are evolved from successive generations (Goldberg, 1989). It has a robust ability to find acceptable solutions in complex search spaces. Speed data from field is compared with the simulation software generated speed data. Sum of square error (SSE) is calculated and calibration stopped when SSE meets certain criteria (Yu *et al*, 2005).

The computer program “Cali.m” using the Genetic Algorithm Toolbox in programming language MATLAB is developed and used to carry out the calibration process automatically. The VISSIM network file named “TMC.inp” is served as one of the input files for “Cali.m”. The other input file is named “gps_speed.txt”. It contains a list of instantaneous speeds collected in field using GPS receiver. The output contains the calculated SSE, VISSIM generated speed and calibrated parameters for each generation of gene. In this study, a termination criterion is identified as when either 10 consecutive genes have the same SSE, or the differences between SSEs from two consecutive runs are less than or equal to 5% (Yu *et al*, 2005). The flow chart of Cali.m is shown in Figure 19.

The calibration time for one gene ranged from 50 to 80 minutes depending on the amount of traffic on the network on a personal computer equipped with a 3.4 GHz Pentium 4 Processor and one GB of RAM.

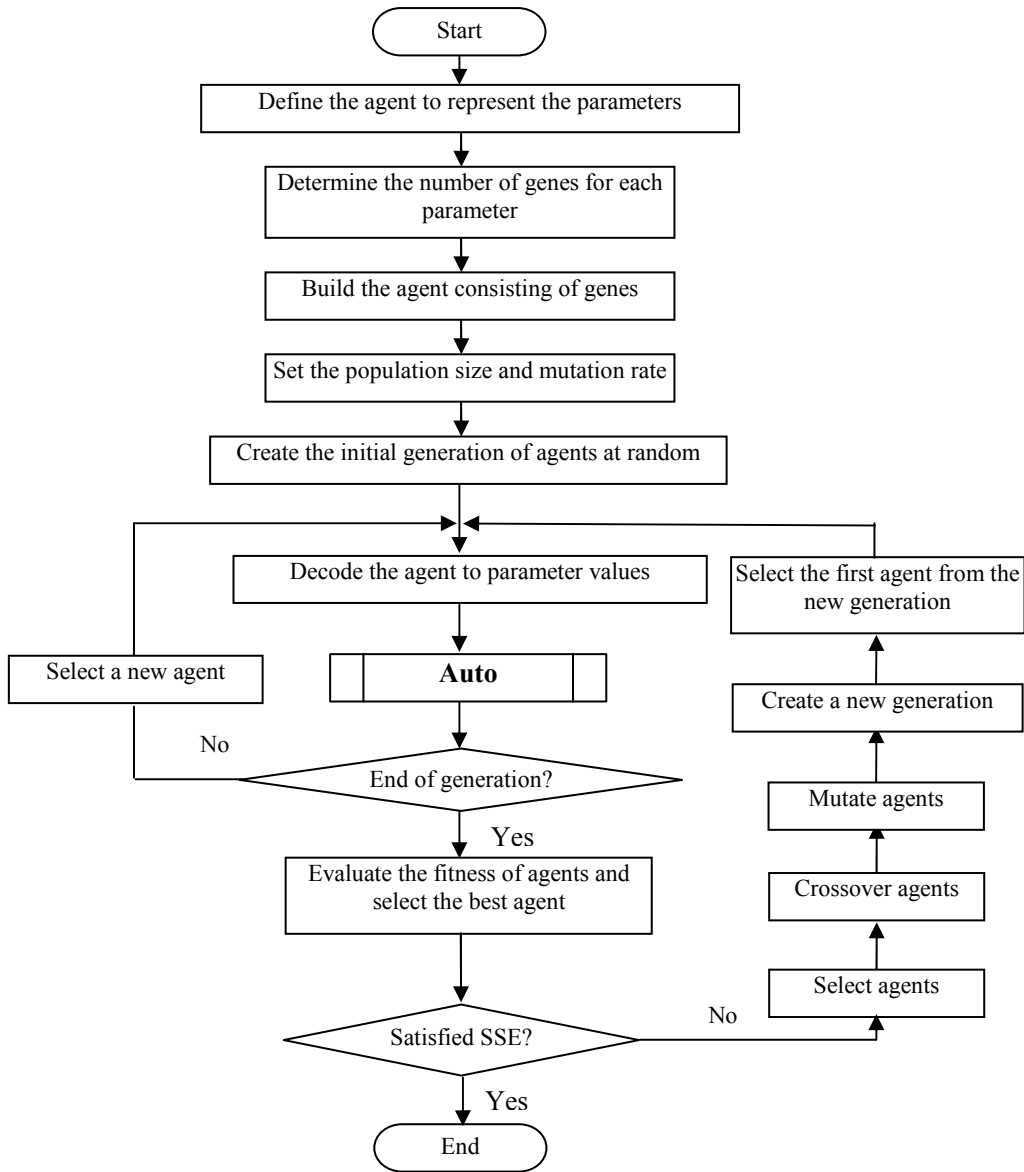


Figure 19. Flow Chart of GA-Based Calibration Program “Cali.m”
Source: TxDOT 0-4317 Research Report: Airport Related Traffic and Mobile Source Emission Implications

Figure 20 shows the result of calibration, and Table 4 lists the Calibrated Parameters for Driving Behaviors. The corresponding SSE for the following genes:

- Gene 1: SSE = 17, 108.12
- Gene 22: SSE = 16,093.12
- Gene 100: SSE = 12,940.20
- Gene 245: SSE = 3,532.53

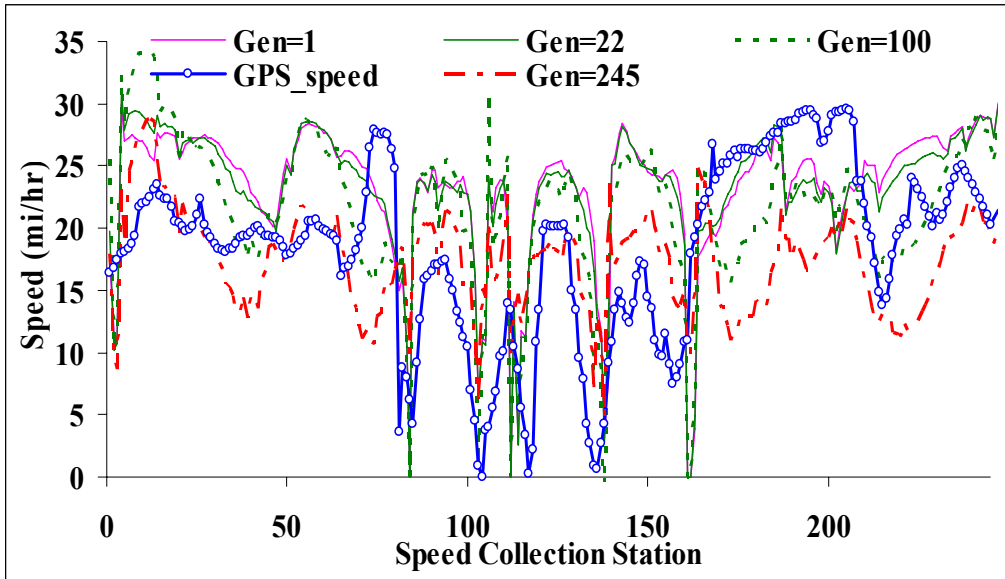


Figure 20. Calibration Result: GPS Field Collected Speed and VISSIM Calibrated Speed Under Different Generation of Gene

Table 4. List of Calibrated Parameters for Driving Behaviors

Parameter	Default Value	Optimal Value
1. Waiting time before diffusion (second)	60	37.6
2. Minimum headway (meter)	0.5	0.46
3. Maximum deceleration (m/s^2)	-3	-1.4
4. $-1m/s^2$ per distance (meter)	50	56.1
5. Accepted deceleration (m/s^2)	-1	-1.7
6. Maximum look ahead distance (meter)	250	233.5
7. Average standstill distance (meter)	2	5.1
8. Additive part of desired safety distance (meter)	2	5.1
9. Multiple part of desired safety distance (meter)	3	6.1
10. Distance of standing and at 30 mph (meter)	1	1.2

5.9 Traffic Simulation

Simulation period was set to be 3800 seconds with background traffic loaded in the first 200 seconds starting from the 201 second the emergency event occurs and mandatory evacuation was initiated. Vehicles would leave their parking garages following the predefined loading curves and when inbound shuttles started to enter the network to pick up passengers. Different evacuation plans corresponding to different scenarios were simulated and tested.

Due to the variations of simulation results, each of the scenarios was simulated for three times under different random seeds. The seeds for different scenarios at each running batch were identical. The output was averaged to avoid random errors.

5.10 Result Analysis and Evacuation Plan Development

5.10.1 Analytical Criteria

In order to evaluate the simulation results, analytical criteria were established and are listed in this section. The criteria are divided into two parts. The first part describes the traffic condition of each scenario and the second one shows the result of evacuation. All criteria are related to the simulation period of 3600 seconds with only one exception in reversed lane scenarios where the simulation period is 600 seconds. As the traffic conditions under evacuation situations were very congested (congested in every intersection and link), criteria such as number of intersections/links congested were not included.

Criteria on traffic condition:

Travel time,

Average speed,

Average delay time, and

Average numbers of stops.

Criteria on evacuation:

Vehicles evacuated,

Shuttles evacuated, and

People evacuated.

5.10.2 Base Scenarios

Table 5 shows the result of network performance for scenarios 1-1 to 1-5 in a simulation period from zero (0) seconds to 3800 seconds. As described before, the first 200 seconds was for loading background traffic. The evacuation occurred after 200 seconds.

Table 5. Simulation Result: Network Performance of Scenarios 1-1 to 1-5

(0 – 3800 s)	S1-1	S1-2	S1-3	S1-4	S1-5
Travel time [s]	87.54	169.05	152.90	184.31	163.12
Avg. speed [mph]	15.77	11.05	11.33	10.55	10.66
Avg. delay time [s]	38.03	105.88	88.8	116.18	98.4
Avg. number of stops	1.39	4.22	3.5	4.5	3.69
Vehicles evacuated	8340	5466	6061	6240	6628
Shuttles evacuated	0	0	0	480	511
People evacuated	16680	10932	12122	36480	38806

The scenarios in Table 5 and Table 6 are as follows:

- Scenario 1-1: normal scenario with no incident,
- Scenario 1-2: evacuation scenario with no improvement,
- Scenario 1-3: evacuation scenario with reversed lane (RL) at Holcombe Blvd between G2 (E) and Braeswood Blvd. west bound,
- Scenario 1-4: evacuation scenarios with inbound shuttles (IS) coming into the area with 60 sec interval, and
- Scenario 1-5: evacuation scenario with reversed lane (RL) at Holcombe Blvd between G2 (E) and Braeswood Blvd. west bound and inbound shuttles (IS) coming into the area with 60 sec interval.

It can be seen that the base scenario (S1-1) performed the best, and the incident scenario with no improvements (S1-2) performed the worst, which is reasonable. The increase of average speed in scenarios with reversed lane (S1-3, and S1-5) was not very significant; however the number of evacuated vehicles increased greatly. The number of vehicles evacuated increased from 5,466 to 6,061. The use of inbound shuttles in (S1-4) resulted in longer average travel time, slower average speed, and larger number of stops. But S1-4 with inbound shuttles reached the

objective of evacuating more people inside the network. Number of people evacuated was calculated as follows:

$$\text{number of people evacuated} = 2.0 \times \text{number of vehicles evacuated} + 50 \times \text{number of shuttles evacuated}$$

2.0 is the average vehicle occupancy during evacuation and 50 is the average shuttle occupancy.

5.10.3 Reverse Lane (RL) Analysis

A close study was conducted to investigate the various effects of different locations of reversed lanes. The results are shown in Table 6 and Table 7.

Table 6. Simulation Result: Network Performance of RL Operation

	S1-2	S2-1	S2-2	S2-3	S2-4
Travel time [s]	273.94	270.35	252.37	254.29	259.10
Avg. speed [mph]	5.58	5.92	6.11	6.02	5.87
Avg. delay time [s]	217.3	213.2	202.33	210.50	214.81
Avg. number of stops	3.11	3.11	3.02	3.18	3.17
Vehicles evacuated	4173	4197	5356	5915	5762
People evacuated	5634	5666	7230	7985	7779

Table 7. Simulation Result: Core Area Performance of RL Operation

	S2-1	S2-2	S2-3	S2-4
0 – 600s after evacuation				
Number veh left area	1210	1238	1323	1419
Delay [s]	29.6	33.2	25.1	28.7
Number stops	0.93	1.09	0.82	1.04
600-3600 after evacuation				
Number veh left area	1883	2201	1551	1853
Delay [s]	28.9	29.6	32.9	29.1
Number stops	1.0	0.9	1.1	1.0

The scenarios in the table are as follows:

- Scenario 2-1: RL at John Ave between G5 and Holcombe Blvd, south bound,
- Scenario 2-2: RL at Mousund St. between John Ave and S. MacGregor Dr, west bound,
- Scenario 2-3: RL at Holcombe Blvd between G2(E) and Braeswood Blvd. west bound, and

- Scenario 2-4: RL at Holcombe Blvd between John Ave and Bertner Ave. east bound.

In Table 6, each scenario with reversed lanes performed better than S1-2 which is the case when no any action was taken during the evacuation. S2-3 and S2-4 provided the biggest numbers of vehicles evacuated from entire network. In both scenarios, reversed lanes were placed on arterials. The increase of evacuated numbers did not affect the performances such as speed, travel time and delay. In core area (Table 7), it is found that most vehicles evacuated during 0-3600 seconds in plan S2-2. Reversed lane in S2-2 was placed closer to the core area and was the major evacuation route within the core area. Reversed lanes could greatly maximize the roadway capacity, which could especially benefit vehicles close to reversed lanes.

5.10.4 Inbound Shuttle (IS) Analysis

As the increase of vehicles evacuated using RL still could not meet the needs of the area, different effects of different service rates for inbound shuttles were further studied. Figure 21 and Figure 22 show the number of vehicles evacuated in network wide and in core area, respectively.

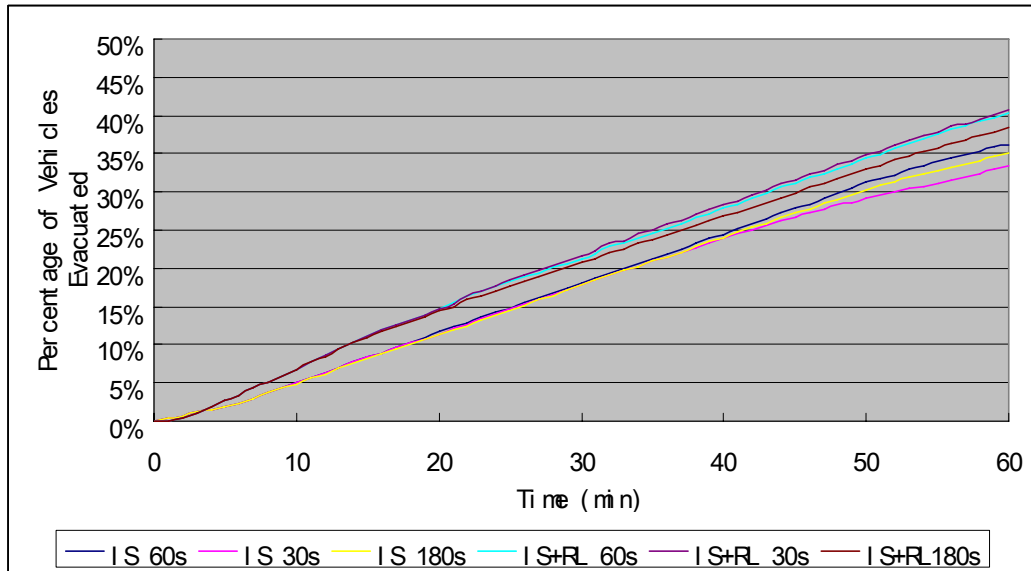


Figure 21. Percentage of Vehicles Evacuated Network-wide

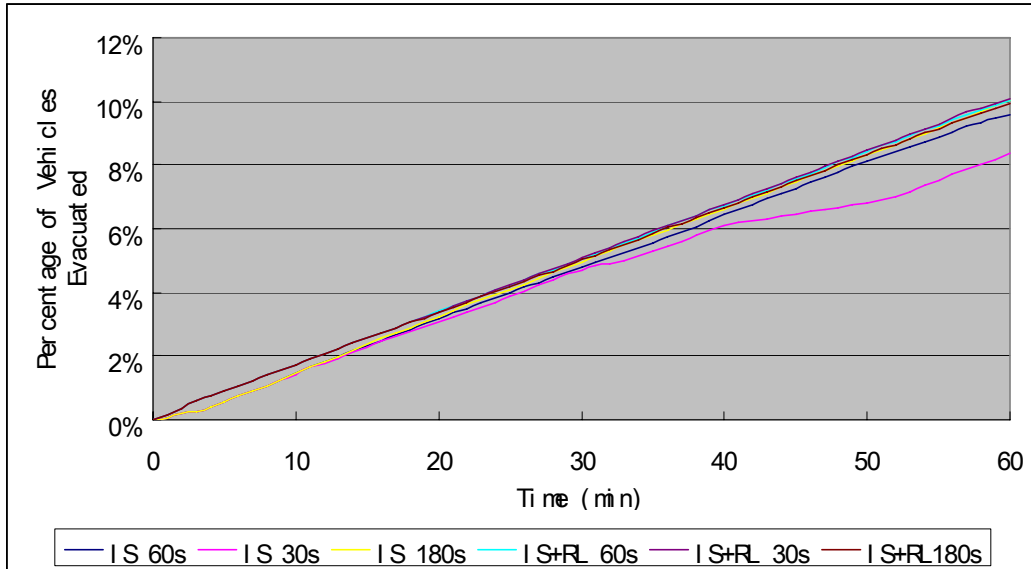


Figure 22. Percentage of Vehicles Evacuated in Core Area

The scenarios in the Figure 21 and 22 are as follows:

- Scenario 1-4: IS with 60 sec interval,
- Scenario 3-1: IS with 30 sec interval,
- Scenario 3-2: IS with 180 sec interval,
- Scenario 3-3: IS with 60 sec interval and RL at Holcombe Blvd between G2(E) and Braeswood Blvd. west bound,
- Scenario 3-4: IS with 30 sec interval and RL at Holcombe Blvd between G2(E) and Braeswood Blvd. west bound , and
- Scenario 3-5: IS with 180 sec interval and RL at Holcombe Blvd between G2(E) and Braeswood Blvd. west bound.

The shuttle intervals of 30 sec, 60 sec and 180 sec were selected to compare with each other for scenarios with and without RL. From Figure 20, the 60 sec shuttle interval is the best in IS group. The interval 60 sec and 30 sec are almost the same in IS+RL group. The evacuation speeds are steady as the curves are almost linear. This is because the area is small, the traffic filled the network in a very short time and demands were constrained by garage gates and capacities of outbound routes..

In IS group, scenario with interval 30 seconds loaded too many shuttles and departure was too quickly from outbound so that the traffic congestion occurred early and fewer vehicles could evacuate. In IS+RL group, since reversed lanes increased the capacity of the evacuating route to some extent, the number of vehicles evacuated in the scenario with 30 second intervals increased. As scenarios with 60 sec and 30 sec shuttle interval almost had the same number of vehicles evacuated, shortening the intervals for inbound shuttle would not greatly affect the number of evacuees.

It is noticeable that the difference in the numbers of vehicles evacuated of IS 60/IS 180 and IS+RL60/IS+RL 180 is very close to the difference of numbers of shuttles entering the network. This indicates that under both situations, the bottleneck was not on the road network; a close examination reveals that the bottleneck was at the exits of parking garages. The outbound capacity of parking garages could not meet the needs under evacuation situations. This is typical in transportation evacuation within a small and dense area.

Table 8 shows the number of shuttles/vehicles/people evacuated using different service rate of IS.

Table 8. Simulation Result: Number of Shuttles/Vehicles/People Evacuated using Different Service Rate of IS (0 – 3800 s)

	S1-4	S3-1	S3-2	S3-3	S3-4	S3-5
Number of shuttle evacuated	405	531	411	352	348	140
Number of vehicles evacuated	5432	5001	5265	6052	6100	5763
Number of people evacuated	31114	36552	31080	29704	29600	18526

5.10.5 Analysis of IS under Different Percentage of Vehicle Evacuation Demand

The number of people evacuated in Table 8 is not satisfactory since the evacuated persons are far from what is expected (there are about 50,000 persons to be evacuated in one hour). Additional improvements were needed. It was assumed that the number of vehicles inside the parking garages which were loaded to the network during evacuation could be restricted by certain management tools at the exit of the garages. The relationship between percentage of vehicle demand and number of people evacuated were then explored in this study.

Table 9 and Figure 23 show the number of shuttle/vehicle/people evacuated when expanding the IS lines from 10 to 20 with 60 sec interval under different percentage of evacuation demand in the parking garages inside the area.

Table 9. Simulation Result: Number of Shuttle/Vehicles/People Evacuated under Different Percentage of Vehicle Demand

	S4-1	S4-2	S4-3	S4-4	S4-5	S4-6
% of vehicle demand	0%	10%	30%	50%	70%	100%
number shuttle evacuated	856	848	840	833	811	405
number vehicles evacuated	438	1531	3433	4020	4320	5027
number people evacuated	43,676	45,462	48,866	49,690	49,190	30,304

The scenarios in the table are as follows:

- Scenario 4-1: 0% of demand in garages
- Scenario 4-2: 10% of demand in garages
- Scenario 4-3: 30% of demand in garages
- Scenario 4-4: 50% of demand in garages
- Scenario 4-5: 70% of demand in garages
- Scenario 4-6: 100% of demand in garages.

From Table 9, when there's no restriction on vehicle demand in the garages inside the area (S4-6, demand is 100%), the network could evacuate the least number of people. In scenario S4-1 with full restrictions at the exit of the parking garages, where the vehicle demand was set to zero (0), the number of shuttles evacuated was the highest. When vehicle demand was reduced to 50%, the number of people evacuated, 49,690, was the greatest.

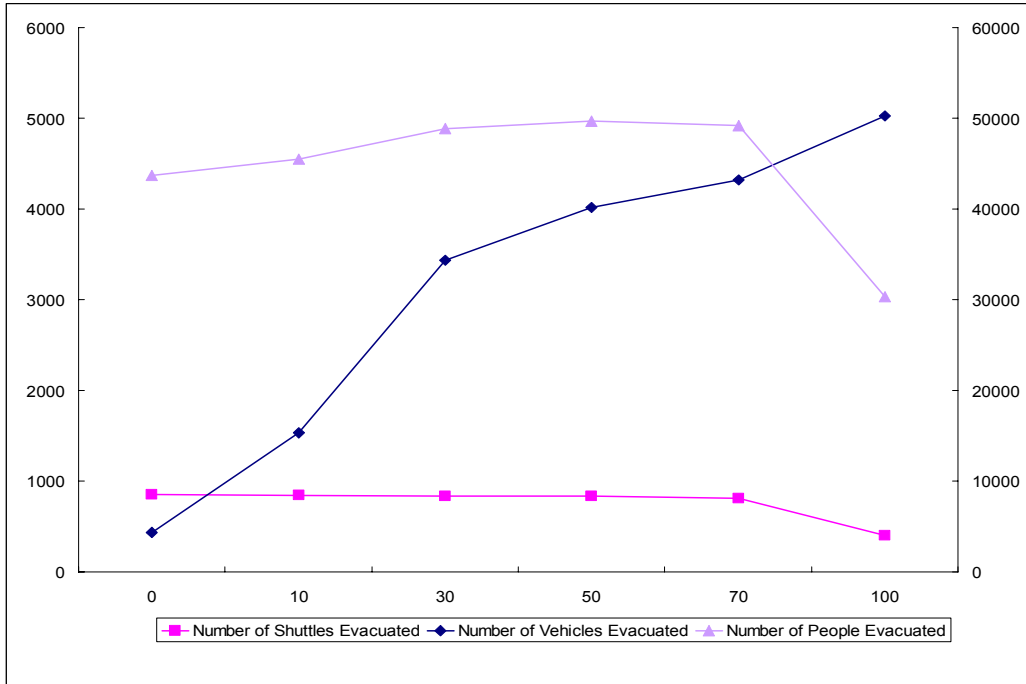


Figure 23. Number of shuttle/vehicles/people evacuated under different percentage of vehicle demand.

In Figure 23, the largest number of people evacuated appeared when vehicle demand was set to a value of around 66percent after curve fittings to the simulated points. Under this case, the number of people evacuated reaches the maximum (around 51,000.) Considering the fact that additional pedestrians may take light rail or run away to evacuate from the area, this is a feasible evacuation plan to evacuate as many people as possible in one hour for Texas Medical Center.

5.11 Transportation Evacuation Plan for Texas Medical Center

When Texas Medical Center is under an emergency situation of truck accident causing hazardous material leakage inside the TMC area during peak hours on a normal weekday, the following plan makes sure that all the people are properly evacuated according to the result analysis in Chapter 4.2.7.

- Implement the Reserved Lane operation in the locations shown in Figure 18
- Implement the Inbound Shuttle operation in the locations shown in Figure 19. The number of shuttle lines is 20 and the interval is 60 seconds.
- Limit the outbound demand of vehicles inside the garages of TMC to 66 percent

For Texas Medical Center Authority, multiple issues need be addressed based on simulation results. For Reversed Lane, operations like putting real-time guide signs and broadcasting need to be conducted in order to quickly deploy the Reversed Lane under emergency situations. For Inbound Shuttle, coordination with METRO is essential for dispatching the shuttles. As Texas Medical Transit Center is very close to TMC, it can be used as storage spaces for emergency shuttles. When the outbound vehicles inside the garages are limited, TMC Authority should make plans beforehand on which categories of vehicles are allowed under such situations. Successful evacuation requires practice. It is recommended that organized exercises/drills be conducted regularly by TMC Authority.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This research proposed a framework to develop the transportation evacuation plan for a small and dense area with consideration of attributes of small and dense area evacuation.

The Texas Medical Center is selected in case study, with the hypothetical event of toxic material leakage using microscopic simulation model VISSIM. Demands under evacuation are estimated in a two-step process. The total demand is identified first and then temporal distribution is estimated. Finally, normal O-D is transferred into O-D during evacuation using a four-step process. Various evacuation scenarios including different improvement options of reversed-lane and inbound-shuttles are evaluated using pre-set analytical criteria. The results show that the framework works for developing transportation evacuation plans for Texas Medical Center.

Reversed Lane (RL) can greatly maximize the roadway capacity, which especially benefits vehicles close to the reversed lane. It can be used to quickly evacuate vehicles.

The simulation result shows that Inbound Shuttle (IS) is a good way to evacuate a large amount of people especially for small and dense areas where numbers of vehicles are usually less than the number of evacuees or areas with a lot of people with special needs.

If the number of vehicles waiting for evacuation can be restricted by certain management tools, then the relationship between IS and the percentage of allowed vehicles needs to be studied. Optimal balance on these factors will result in more efficient evacuation plans.

Finally, a transportation evacuation plan is developed for Texas Medical Center and related issues were suggested.

6.2 Recommendations

It is recommended that a comprehensive study be conducted given the condition of sufficient manpower and time. For example, the combination of Reversed Lanes at more links can be tested and analyzed. The future research on this issue should include the following:

- Management improvements at more locations, e.g. combination of Reversed Lanes, and
- More improvements analysis, e.g. signal optimization etc.

More evacuation scenarios need to be developed and simulated for better evacuation strategies. A database with evacuation scenarios and evacuation strategies should be developed. Intelligent Transportation System (ITS) such as surveillance camera should be utilized for better and more on-line field traffic information. With the real-time traffic data from the field and database containing evacuation information, corresponding evacuation strategies can be obtained from database and applied immediately when the real situation fits one simulated scenario in database. In this way, evacuation responses could be more automatic, quicker and efficient.

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APPENDIX

A. DATA COLLECTION PLAN FOR HOURLY FLOW

Survey Instruction

Data needed: Traffic flow:

- a) at specific links
- b) both directions
- c) car, truck, bus percentage needed

When:

- a) Date: 4-26-2007 Thursday; 4-27-2007 Friday
- b) Time: coverage point, 20 min each; control point 14:00-18:00

Where:

- a) 2 control points and 53 coverage points (See map attached for detail please)
- b) Collect data in group 1, 2, 5, 6 on 4.25 Thursday and 3, 4, 7, 8 on 4.26 Friday.

Who:

Group	Surveyor	Note	Group	Surveyor	Note
1	Mary, Frank	20min/link	5	Cathy, Eric	20min/link
2	Vivian, Lane	20min/link	6	Reza	20min/link
3	Vivian, Lane	20min/link	7	Cathy, Eric	20min/link
4	Mary	20min/link	8	Frank	20min/link
Ctrl 1	Blain, Richard	4 hours	Ctrl 2	Charlie, Jassica	4 hours

How:

- a) Traffic counting equipment for control points
- b) Drawing tally mark for coverage points and calculate

Documents:

- a) Record forms
- b) Certificate letter

Field Operation:

- a) Please gather at 12:30 in RM 139 and leave together. We'll be in designated location at 13:30,

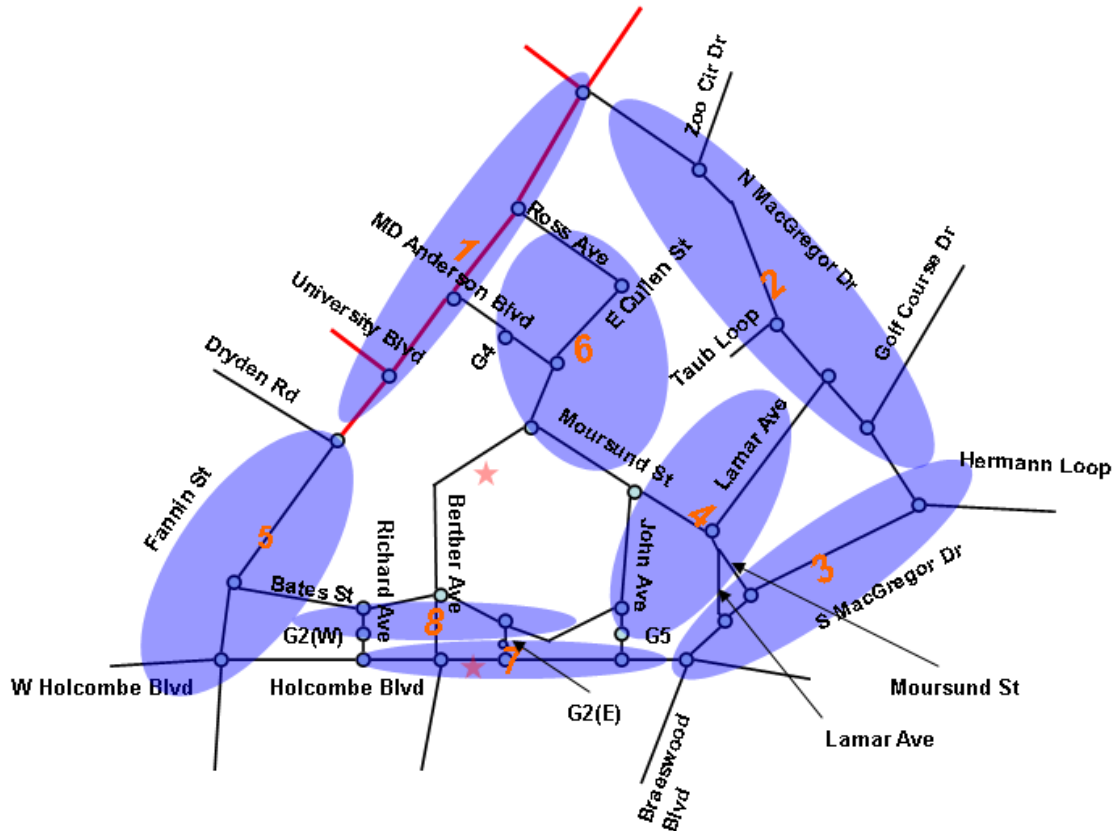
- b) Try to get familiar with the local roadway and traffic condition,
- c) Please be alerted and keep yourself safe,
- d) Start collect traffic flow data at 14:00. For groups with 2 people, you may collect data at the each side of the streets for different direction at the same time; for groups with 1 people, you need collect data for both directions at the same time,
- e) Record data on counting sheet. Please enter every blank precisely,
- f) For group at coverage points, collect data for 20 min and then go to next location. For control points, please keep collecting data for 4 hours, change sheet every 15 minutes, and
- g) Please calculate total counting and return the forms to Richard.

Notes:

- ✘ If administrators come to ask, please show them the certificate letter and explain yourself.
- ✘ For emergencies, call 911 first.
- ✘ For non-emergencies and technical issues, call Dr. Qiao and Richard immediately.

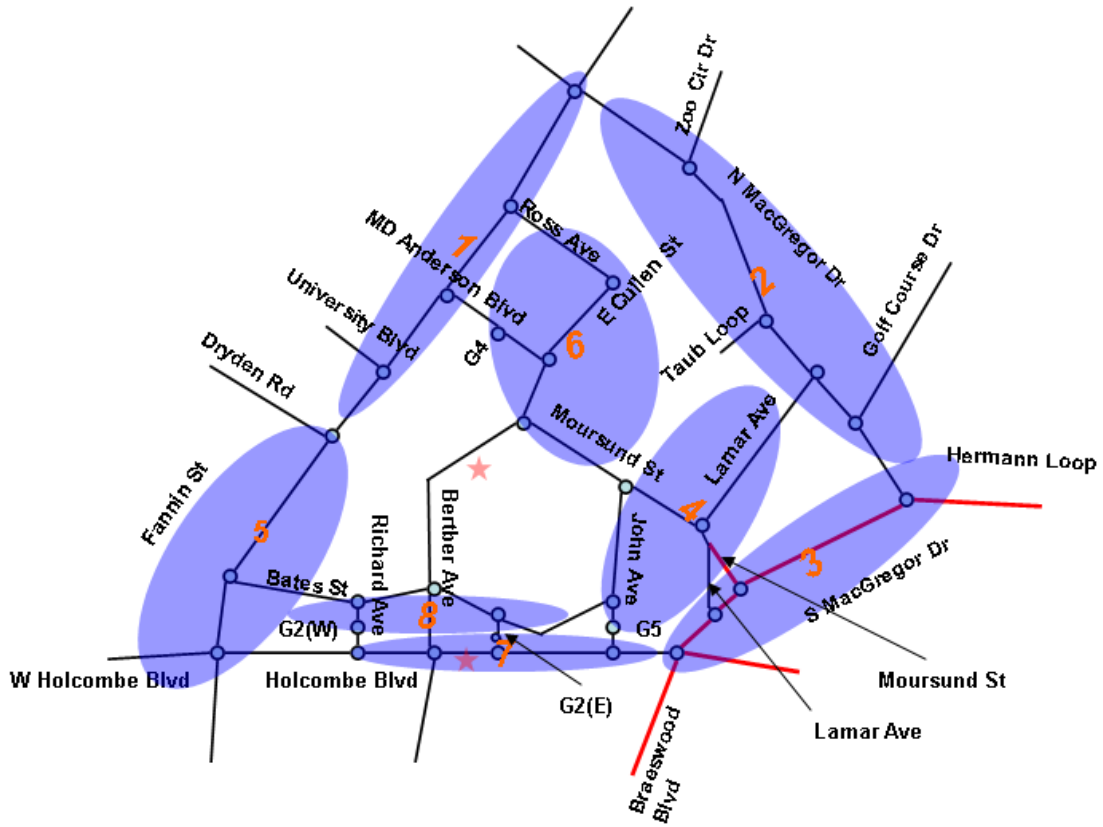
Group Assigning

Group 1: 7 Locations with two persons each.



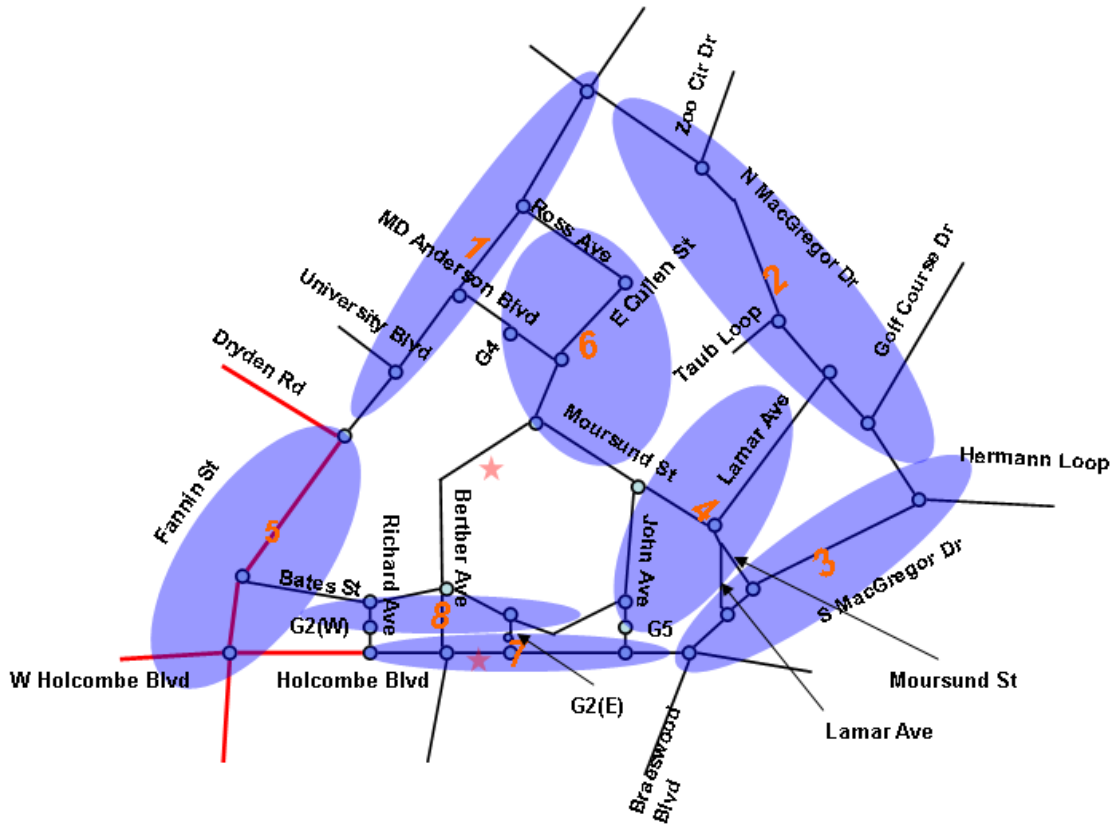
Fannin N. to Fannin @ N. MacGregor
 N. MacGregor W. to N. MacGregor @ Fannin
 Fannin @ N. MacGregor to Fannin @ Ross
 Fannin @ Ross to Fannin @ MD Anderson
 Fannin @ MD Anderson to Fannin @ University
 Fannin @ University to Fannin @ Dryden
 University W. to University @ Fannin

Group 3: 7 Locations with two persons each.



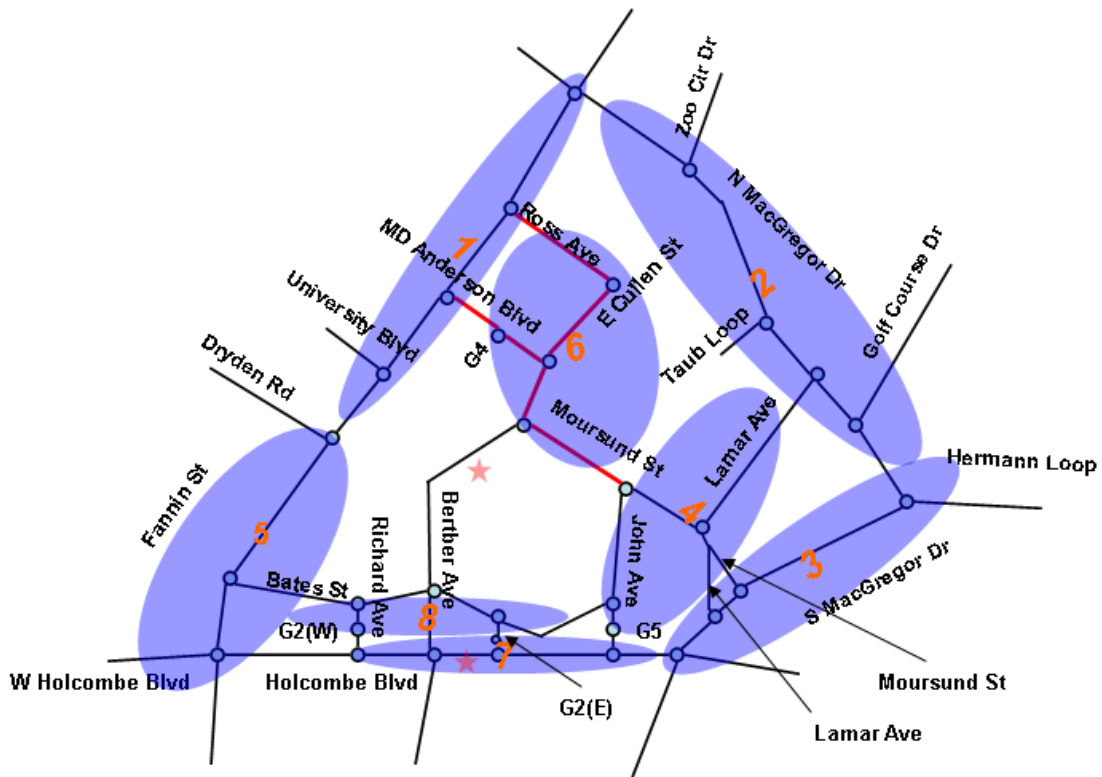
Hermann N. to Hermann @ N. MacGregor
 Hermann @ N. MacGregor to S. MacGregor @ Moursund
 Moursund @ Lamar(N) to Moursund @ S. MacGregor
 S. MacGregor @ Moursund to S. MacGregor @ Lamar(S)
 S. MacGregor @ Lamar (S) to S. MacGregor @ Holcombe
 S. MacGregor @ Holcombe to Braeswood S.
 Holcombe @ Braeswood to Holcombe E.

Group 5: 6 Location with two people.



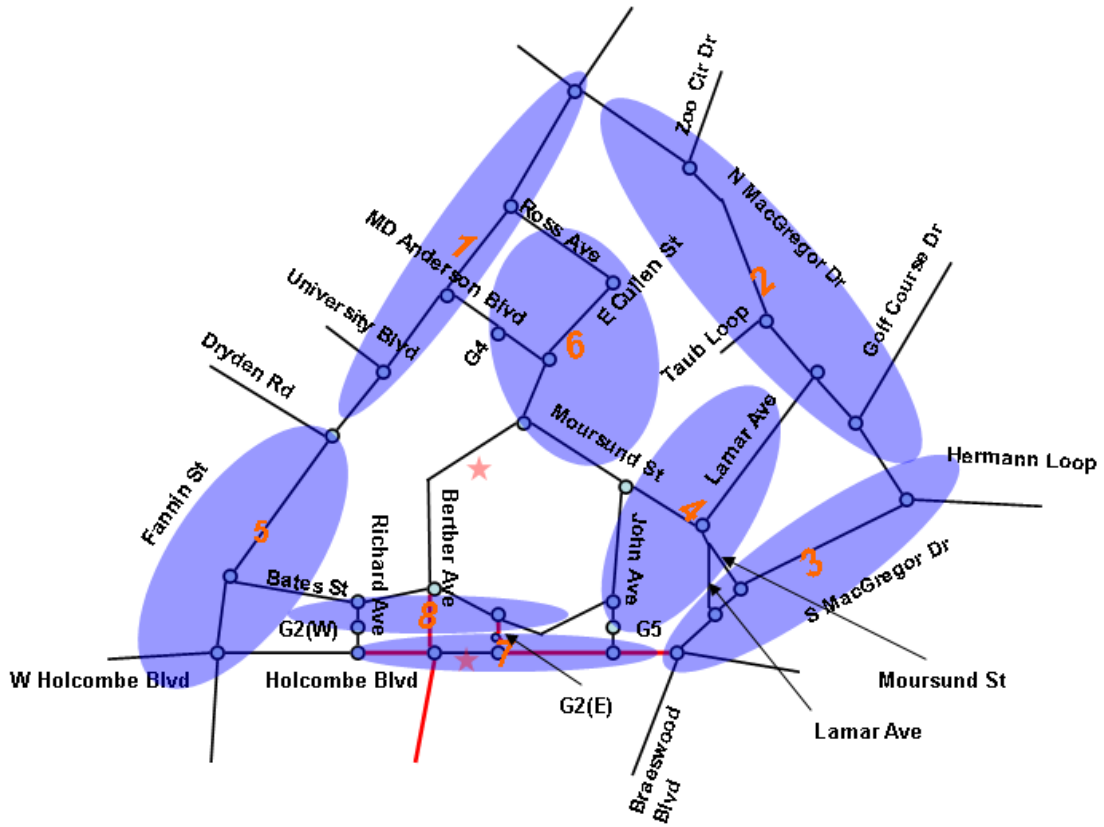
Fannin S to Fannin @ Holcombe
W Holcombe to Holcombe @ Fannin
Holcombe @ Fannin to Holcombe @ Richard
Fannin @ Holcombe to Fannin @ Bates
Fannin @ Bates to Fannin @ Dryden
Dryden W to Dryden @ Fannin

Group 6: 6 location with one person



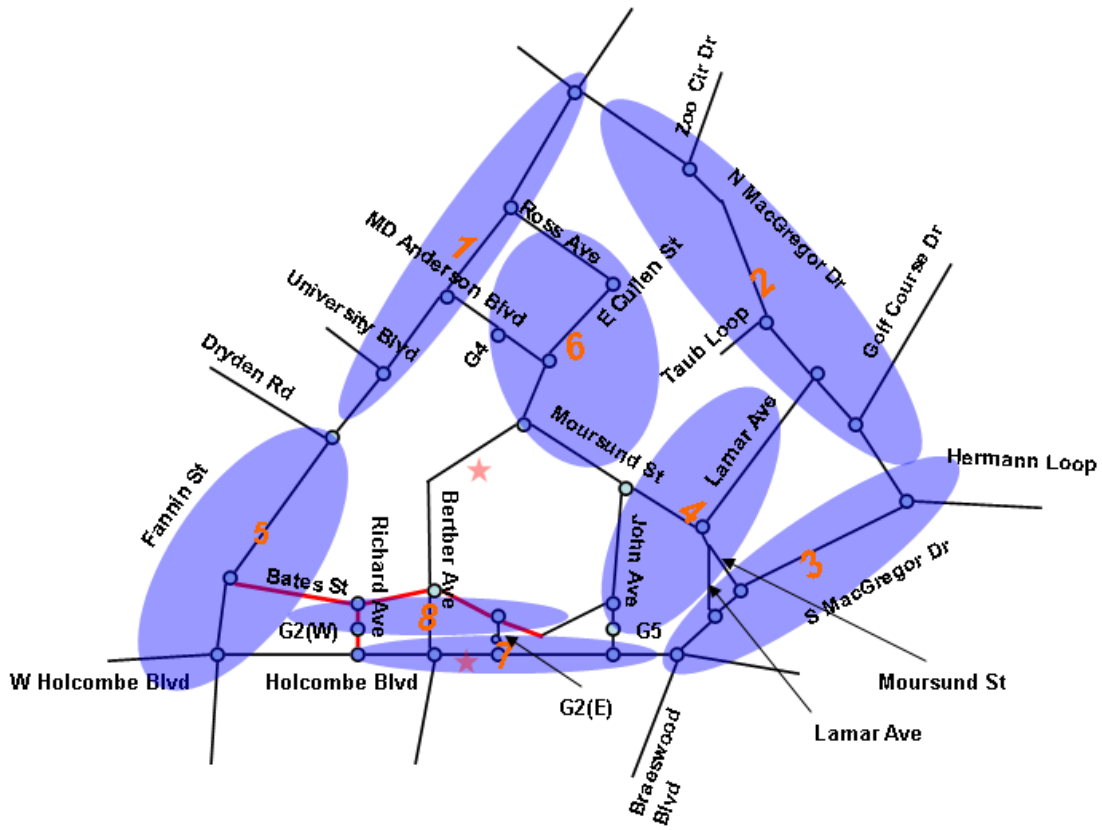
Ross @ Fannin to Ross @ E Cullen
E Cullen @ Ross to E Cullen @ MD Anderson
MD Anderson @ Fannin to MD Anderson @ G4
MD Anderson @ G4 to MD Anderson @ E Cullen
Bertner @ MD Anderson to Bertner @ Moursund
Moursund @ Bertner to Moursund @ John

Group 7: 7 Location with two people



- Holcombe @ Richard to HOLcombe @ Bertner
- S Bertner to Bertner @ HOLcombe
- Bertner @ HOLcombe to Bertner @ Bates
- Bates and G2(E)
- G2(E) and Holcombe
- Holcombe @ G2(E) to Holcombe @ John
- Holcombe @ John to Holcombe @ Braeswood

Group 8: 6 location with 1 people



Bates @ Fannin to Bates @ Richard
 Richard @ Bates to Richard @ G2(W)
 Richard @ G2(W) to Richard @ Holcombe
 Bates @ Richard to Bates @ Bertner
 Bates @ Bertner to Bates @ G2(E)
 Bates @ G2(E) to Bates @ John

B. DATA COLLECTION FORM FOR HOURLY FLOW

	<div style="display: flex; justify-content: space-around; align-items: center;"> <div style="border: 1px solid black; padding: 2px;">*4</div> <div style="font-size: 2em;">←</div> <div style="border: 1px solid black; padding: 2px;">*5</div> </div>
Name*1	
Date*2	
Time*3	
	<div style="border: 1px solid black; padding: 2px; width: 150px; margin: 0 auto;">*6</div>

Direction*7	<i>Car including mini van, pickup trucks</i>	<i>Bus</i>	<i>Truck</i>
	Total:	Total:	Total:

*8			
		Total:	Total:

Note:

*1: Name; *2: Date; *3: Time: starting/ending time; *4: Downstream intersection

*5: Upstream intersection; *6: Street name; *7/*8: Direction: intersection

A → intersection B

C. LIST OF PHASED O-D MATRICES

21*21 O-D Matrix for time period 0-400s

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	2	7	1	0	12	0	10	19	9	1	1	4	1	1	2	2	3	4	0	2	0
7	7	2	5	0	7	6	0	3	19	12	14	14	4	4	9	5	5	5	0	0	4
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	9	3	7	0	5	0	3	14	4	19	0	3	7	6	8	2	5	0	6	1	3
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	8	3	5	0	6	0	0	4	1	4	0	0	7	0	0	0	0	5	3	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	5	0	4	14	4	0	0	8	0	3	0	8	1	1	0	3	0	0	0	2	0
17	0	0	0	0	3	0	0	8	0	0	0	0	4	4	2	0	0	0	0	0	0
18	26	0	22	0	0	0	0	0	0	3	0	5	0	0	0	3	0	3	0	0	0
19	3	2	0	0	9	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	1
20	7	0	5	14	4	0	0	8	0	2	0	7	3	2	5	0	1	0	0	4	2
21	8	1	6	0	14	0	7	0	3	0	5	0	0	0	0	0	0	0	0	0	0

21*21 O-D Matrix for time period 400-800s

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	3	10	1	0	17	0	15	27	13	2	2	5	2	2	3	3	4	5	0	2	1
7	9	3	8	0	10	8	0	4	28	17	20	20	6	6	13	7	7	7	0	0	5
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	12	4	10	0	7	0	5	20	5	27	0	4	10	8	11	3	7	0	9	2	4
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	11	5	7	0	9	0	0	6	2	6	0	0	10	0	1	0	0	8	4	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	8	0	5	20	5	0	0	11	0	4	0	12	2	2	0	4	0	0	0	3	0
17	1	0	0	0	5	0	0	11	0	0	0	0	6	5	3	0	0	0	0	0	0
18	37	0	31	0	0	0	0	0	0	4	0	7	0	0	1	4	0	4	0	0	0
19	4	3	0	0	13	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	1
20	10	0	7	20	5	0	0	11	0	3	0	9	4	3	7	0	2	0	0	5	2
21	12	1	9	0	20	0	10	0	4	0	6	0	0	0	0	0	0	0	0	0	0

21*21 O-D Matrix for time period 800-1200s

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	0	25	79	11	32	9	15	15	6	16	5	20	27	21	17	12	12	4	51	13	14
2	26	0	23	0	65	0	7	11	0	5	0	8	10	10	9	1	1	4	0	16	0
3	63	18	0	0	24	3	8	10	1	9	1	13	9	7	7	5	5	0	33	2	6
4	17	0	11	0	2	0	0	0	0	1	0	5	0	0	0	18	16	0	0	0	13
5	31	58	28	0	0	6	24	17	1	8	0	11	15	13	12	5	5	9	0	25	3
6	4	12	1	0	21	0	19	35	17	2	2	6	2	2	4	4	5	6	0	3	1
7	12	4	10	0	13	11	0	5	35	22	26	26	8	7	17	9	8	9	0	0	6
8	3	0	1	0	0	3	0	0	35	2	0	6	1	1	2	3	0	4	0	0	0
9	13	4	10	0	8	0	4	24	0	4	2	42	9	8	11	1	4	0	9	1	1
10	11	5	10	0	12	18	6	51	8	0	2	26	11	10	12	6	10	13	0	2	7
11	15	5	12	0	9	0	6	26	6	34	0	5	12	11	14	4	9	0	11	2	6
12	20	7	12	0	13	0	0	9	3	9	0	1	16	1	3	1	2	12	8	0	2
13	14	6	8	0	11	0	0	8	2	7	0	0	12	0	1	0	1	10	6	0	1
14	13	6	8	0	11	0	1	18	3	11	1	17	0	2	2	3	3	0	6	0	4
15	10	1	6	31	7	0	1	16	1	1	0	8	1	0	1	4	6	0	0	4	0
16	10	1	7	26	6	0	0	14	0	5	0	15	2	2	0	5	1	0	0	3	0
17	1	0	0	0	6	0	0	14	0	0	0	0	8	7	4	0	0	0	0	0	0
18	47	0	40	0	0	1	0	0	0	6	0	9	0	0	1	5	0	5	0	0	1
19	5	4	0	0	16	0	0	0	0	0	0	0	0	0	0	4	4	0	0	0	2
20	13	1	9	26	6	0	0	14	0	4	0	12	5	4	8	0	2	0	0	7	3
21	15	2	12	0	25	0	13	0	5	0	8	1	1	0	0	0	0	0	0	0	0

21*21 O-D Matrix for time period 1200-1600s

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	0	17	53	7	22	6	10	10	4	11	4	13	18	14	12	8	8	3	34	9	10
2	18	0	16	0	44	0	5	7	0	4	0	5	7	6	6	0	1	3	0	11	0
3	43	12	0	0	16	2	5	6	1	6	0	9	6	5	5	3	3	0	22	2	4
4	12	0	8	0	1	0	0	0	0	1	0	3	0	0	0	12	11	0	0	0	9
5	21	39	19	0	0	4	16	12	0	5	0	7	10	9	8	3	4	6	0	17	2
6	3	8	1	0	15	0	13	24	11	1	1	4	2	2	3	3	3	4	0	2	1
7	8	3	6	0	9	7	0	3	24	15	17	17	5	5	11	6	6	6	0	0	4
8	2	0	1	0	0	2	0	0	24	2	0	4	1	1	1	2	0	3	0	0	0
9	9	3	7	0	5	0	3	16	0	3	1	28	6	5	8	1	3	0	6	0	1
10	8	4	6	0	8	12	4	35	6	0	2	17	8	7	8	4	6	9	0	1	5
11	10	4	8	0	6	0	4	17	4	23	0	4	8	7	10	3	6	0	7	1	4
12	14	5	8	0	9	0	0	6	2	6	0	0	11	1	2	1	1	8	6	0	1
13	10	4	6	0	8	0	0	5	1	5	0	0	8	0	1	0	0	7	4	0	0
14	9	4	5	0	7	0	1	12	2	7	1	11	0	1	1	2	2	0	4	0	3
15	6	1	4	21	5	0	0	11	1	1	0	5	1	0	1	3	4	0	0	3	0
16	7	0	5	17	4	0	0	9	0	3	0	10	2	1	0	3	0	0	0	2	0
17	1	0	0	0	4	0	0	9	0	0	0	0	5	5	3	0	0	0	0	0	0
18	32	0	27	0	0	0	0	0	0	4	0	6	0	0	1	3	0	3	0	0	0
19	3	3	0	0	11	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	1
20	9	0	6	17	4	0	0	9	0	3	0	8	4	3	6	0	2	0	0	5	2
21	10	1	8	0	17	0	9	0	3	0	5	0	0	0	0	0	0	0	0	0	0

21*21 O-D Matrix for time period 1600-2000s

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	0	7	23	3	9	3	4	4	2	5	2	6	8	6	5	4	4	1	15	4	4
2	8	0	7	0	19	0	2	3	0	2	0	2	3	3	3	0	0	1	0	5	0
3	18	5	0	0	7	1	2	3	0	3	0	4	3	2	2	1	1	0	9	1	2
4	5	0	3	0	1	0	0	0	0	0	0	1	0	0	0	5	5	0	0	0	4
5	9	17	8	0	0	2	7	5	0	2	0	3	4	4	4	1	2	3	0	7	1
6	1	4	0	0	6	0	5	10	5	1	1	2	1	1	1	1	1	2	0	1	0
7	3	1	3	0	4	3	0	1	10	6	7	7	2	2	5	3	2	3	0	0	2
8	1	0	0	0	0	1	0	0	10	1	0	2	0	0	1	1	0	1	0	0	0
9	4	1	3	0	2	0	1	7	0	1	1	12	3	2	3	0	1	0	3	0	0
10	3	2	3	0	3	5	2	15	2	0	1	7	3	3	4	2	3	4	0	1	2
11	4	2	4	0	3	0	2	7	2	10	0	2	4	3	4	1	3	0	3	1	2
12	6	2	4	0	4	0	0	3	1	3	0	0	5	0	1	0	1	3	2	0	1
13	4	2	2	0	3	0	0	2	1	2	0	0	4	0	0	0	0	3	2	0	0
14	4	2	2	0	3	0	0	5	1	3	0	5	0	1	1	1	1	0	2	0	1
15	3	0	2	9	2	0	0	5	0	0	0	2	0	0	0	1	2	0	0	1	0
16	3	0	2	7	2	0	0	4	0	1	0	4	1	1	0	1	0	0	0	1	0
17	0	0	0	0	2	0	0	4	0	0	0	0	2	2	1	0	0	0	0	0	0
18	14	0	11	0	0	0	0	0	0	2	0	3	0	0	0	1	0	1	0	0	0
19	1	1	0	0	5	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1
20	4	0	3	7	2	0	0	4	0	1	0	3	2	1	2	0	1	0	0	2	1
21	4	1	3	0	7	0	4	0	1	0	2	0	0	0	0	0	0	0	0	0	0

21*21 O-D Matrix for time period 2000-2400s

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	0	2	8	1	3	1	2	1	1	2	1	2	3	2	2	1	1	0	5	1	1
2	3	0	2	0	6	0	1	1	0	1	0	1	1	1	1	0	0	0	0	2	0
3	6	2	0	0	2	0	1	1	0	1	0	1	1	1	1	0	0	0	3	0	1
4	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	1
5	3	6	3	0	0	1	2	2	0	1	0	1	1	1	1	0	1	1	0	2	0
6	0	1	0	0	2	0	2	3	2	0	0	1	0	0	0	0	0	1	0	0	0
7	1	0	1	0	1	1	0	0	3	2	2	2	1	1	2	1	1	1	0	0	1
8	0	0	0	0	0	0	0	0	3	0	0	1	0	0	0	0	0	0	0	0	0
9	1	0	1	0	1	0	0	2	0	0	0	4	1	1	1	0	0	0	1	0	0
10	1	1	1	0	1	2	1	5	1	0	0	2	1	1	1	1	1	1	0	0	1
11	2	1	1	0	1	0	1	3	1	3	0	1	1	1	1	0	1	0	1	0	1
12	2	1	1	0	1	0	0	1	0	1	0	0	2	0	0	0	0	1	1	0	0
13	1	1	1	0	1	0	0	1	0	1	0	0	1	0	0	0	0	1	1	0	0
14	1	1	1	0	1	0	0	2	0	1	0	2	0	0	0	0	0	0	1	0	0
15	1	0	1	3	1	0	0	2	0	0	0	1	0	0	0	0	1	0	0	0	0
16	1	0	1	3	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
17	0	0	0	0	1	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0
18	5	0	4	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
19	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	1	0	1	3	1	0	0	1	0	0	0	1	1	0	1	0	0	0	0	1	0
21	1	0	1	0	2	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0

21*21 O-D Matrix for time period 2400-2800s

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	0	1	3	0	1	0	1	1	0	1	0	1	1	1	1	1	1	0	2	1	1
2	1	0	1	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
3	3	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0
4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1
5	1	3	1	0	0	0	1	1	0	0	0	0	1	1	1	0	0	0	0	1	0
6	0	1	0	0	1	0	1	2	1	0	0	0	0	0	0	0	0	0	0	0	0
7	1	0	0	0	1	0	0	0	2	1	1	1	0	0	1	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
9	1	0	0	0	0	0	0	1	0	0	0	2	0	0	0	0	0	0	0	0	0
10	0	0	0	0	1	1	0	2	0	0	0	1	0	0	1	0	0	1	0	0	0
11	1	0	1	0	0	0	0	1	0	2	0	0	1	0	1	0	0	0	0	0	0
12	1	0	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
13	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
14	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
15	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
18	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	1	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
21	1	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0