Mesoscopic Evacuation Modeling for Small- to Medium-Sized Metropolitan Areas

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ABSTRACT

Modeling and developing different evacuation scenarios gained significant interest in recent years, where the management of the transportation system in support of evacuation efforts proved to be critical in mitigating the impacts of regional emergency events. However, most of the evacuation modeling efforts focused on large urban areas due to the recurrence of the regional emergency event, resources availability, and data availability. For urban areas that are classified as small- and medium-size metropolitan areas, confusion still exists at the metropolitan planning organization (MPO) level on how to develop effective and practical evacuation plans.

This study aims to develop a methodology for supporting effective decision making and testing emergency scenarios while taking into account various factors and their effect on public safety. The focus of this study is on developing an evacuation model for urban areas utilizing the resources available to MPOs and obtaining local evacuation data, which include human behavior data from a local household survey.

A case study is developed using Fargo-Moorhead Council of Government's travel demand model integrated with DYNASMART-P software. The modeling approach provides direct connectivity with the regional model, and the hybrid model incorporates a traffic generation component into the regional model along with dynamic supply.

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1. INTRODUCTION

Evacuation is among the major protective actions used in cases of regional emergencies (28) and it is defined as “the withdrawal action of persons from a specific area because of real or anticipated threat or hazard” (23). Modeling and developing different evacuation scenarios have gained significant interest in recent years, after the terrorist attacks of September 11, 2001, hurricanes Rita and Katrina, and the California wild fires (33). The management of the transportation system in support of evacuation efforts proved to be critical in mitigating the impacts of these events.

An essential element of any evacuation plan is a carefully prepared transportation plan, where accurate preplanning adds to the effectiveness of the evacuation process. Evacuations in cases of regional emergencies result in drastic shifts in the demand for travel over the transportation system. Therefore, the evacuation travel times are greatly affected by the available capacity of the roadway links. The plan needs to address both the response and recovery stages, deal with hazards, and communicate the information to the public.

The main objectives of evacuation planning are to identify the best evacuation routes, and provide estimates of the time needed to evacuate the at-risk population. Decision makers need to know the evacuation time estimates (ETEs) associated with different scenarios to provide sufficient warning to the population and reduce their vulnerability to the hazard. This knowledge helps them to better assess the danger and reach a balance between the last possible time before they issue the evacuation orders to avoid costly unnecessary evacuation while having enough time to evacuate without risking loss of life (14).

An evacuation plan must conform to the criteria set by federal, state, and local agencies with jurisdictional authority and require the coordination among these agencies. There is a great need to establish coordination and communication among different agencies to promote security and safety while enabling the transportation system to deal with the public demand for travel. Congress recognized the importance of this coordination and legislated requirements for transportation planning agencies to address security issues in their plans, including evacuation planning (31). Metropolitan planning organizations (MPOs) have an advantage when it comes to technical analysis, local transportation system planning, and coordination of emergency management efforts.

The Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) was introduced in 2005 (41). One of the major changes introduced by SAFETEA-LU was the separation of the “Safety and Security” planning factor into two stand-alone planning factors for MPOs. Transportation security refers to both personal and homeland security, with the focus on the vulnerability to intentional attack or natural disasters and associated evacuation procedures that should be incorporated in the project selection process. Safety refers to reducing the number of crashes and accidental deaths or injuries associated with the operation of surface modes.

At the MPO level, the inclusion of security in the transportation planning process is in its early stage and confusion exists regarding how the federal legislation can be implemented (12). Most of the applications of security planning are on the operational level of the transportation infrastructure with modest consideration of the security aspect in the development of transportation improvement Plans (TIPs). In a survey of the MPOs conducted in 2002, 78% of the surveyed MPOs introduced changes to their planning process because of security concerns. Also, 25% of the MPOs reported an increase in the costs associated with the planning process due to the increase in technical considerations and the number of stakeholders involved in the process (12).

1.1 Problem Statement

The development of evacuation plans should be done well in advance of the emergency and be revised during the emergency itself based on the details and actual conditions of the event. Emergency officials usually report traffic problems during regional emergency evacuations, such as inadequate roadway signage, uncoordinated traffic lights, and inadequate traffic control (37). The ability to effectively respond to or recover from an emergency situation is strongly related to how actively the transportation system can be managed. For example, the region-wide evacuation traffic management plan developed by department of transportation and emergency management agencies in the state of Louisiana was considered to be the primary factor contributing to the effectiveness of recurring hurricane evacuation events (6).

The effectiveness of an evacuation process is measured by the estimate of the time required for evacuation. This is defined as the time required to evacuate the at-risk population to a farther, safer area (53, 11). Basic traffic engineering principles are used to develop ETEs and estimate the transportation system's ability to accommodate the evacuation demand.

Most of the evacuation modeling efforts were focused on large urban areas (especially in hurricane regions) due to the recurrence of the regional emergency event, resources availability, and data availability. For urban areas that are classified as small- and medium-size areas, there is still confusion at the MPO level on how to develop effective and practical evacuation plans that could be included in their long range transportation plans. Because federal requirements include security as a factor to be considered in transportation planning processes at the metropolitan level, those MPOs need to address emergency relief and disaster preparedness plans, strategies, and policies that support homeland security (54).

Several modeling approaches have been utilized to address the performance of the transportation system and estimate evacuation times. However, simulation-based models are among the most powerful tools that could be applied for accurately and realistically capturing driver-network interactions. Nevertheless, some challenges face the current simulation-based modeling efforts. These challenges include the high cost associated with obtaining the software, training staff, and updating the models to reflect changes on the ground. Also, the availability of data needed for evacuation simulation modeling, which is not usually covered in the transportation census database, continues to be an obstacle. The main focus of the research related to evacuation modeling was on developing simulation models to estimate the clearance times associated with different emergency scenarios. In addition, this study aimed to generate the data needed for evacuation model development which was not available in the literature or the transportation census.

Evacuation models need to address not only the transportation aspects of the problem, but also the human behavior aspects associated with emergency evacuations. Also, these models require evacuation traffic demand data as input, but there was little effort made to incorporate travel demand estimation in those models (50). Many of the developed evacuation simulation models ignored the actual human behavior aspects on the ground during emergency evacuations. Human behavioral analysis is critical to obtain effective and accurate evacuation models and develop reliable estimates of the time needed for evacuation. It is a major factor in identifying the demand for travel and the demand loading rates on the transportation system during an emergency evacuation scenario, and there is a great need for more human behavior data that could be used to develop simulation models.

1.2 Study Objectives

This study aims to develop a methodology for supporting effective decision making and testing different emergency scenarios while taking into account the various factors and their effect on public safety. The focus of this study is on developing an evacuation model for urban areas utilizing the resources available by MPOs. In addition, this study aims to develop the human behavior data needed for evacuation modeling and identify the effect of using those data instead of data developed for hurricane regions to model regional evacuations. Specifically, the main objectives of this study include the following:

1) Identifying the different local data and population parameters needed for estimating evacuation trips generation, trips distribution, and trips loading rates using local surveys
2) Developing an emergency evacuation model that is capable of predicting traffic conditions during regional emergency evacuations recognizing MPOs resources and data availability
3) Evaluating the effects of different traffic operations measures on the performance of the transportation system during emergency evacuation events
4) Evaluating the effects of using the emergency evacuation data generated for medium size MPOs compared with using national evacuation data in developing evacuation models on the performance of the evacuation model

The approach may be applied to the different stages of the emergency response and preparedness: disaster scenario analysis and mitigation preparedness. The output measures of effectiveness (they include the predicted traffic volumes, delays, average speeds, and ETEs) associated with different traffic management options for an emergency evacuation scenario will be used to identify the effect of traffic management options implemented for the emergency scenario.

Evacuation plans will allow for the evacuation of the population under the safest possible conditions within the least amount of time. Additionally, the methodology developed in this study has the ability to account for network and traffic dynamics with reasonable data requirements. Also, it provides connectivity with the four-step travel demand model by integrating it within the regional travel demand model, reducing the complexity associated with updating and maintaining the evacuation model.

1.3 Report Organization

This report consists of five sections, including this introduction. Section 2 provides a review of the literature and the fundamentals of evacuation planning and existing evacuation models. Section 3 provides a detailed description of the research approach and a discussion of the methodology and data analysis. Section 4 details the case study used for this study, in addition to the model development. The summary of the results and conclusion of this study is provided in Section 5.

2. LITERATURE REVIEW

This section provides a review of the fundamentals of evacuation planning. It describes the evacuation modeling process, modeling parameters, simulation tools, and human behavior during emergency evacuations. Also, it provides a background on the study framework, which includes identifying travel demand, trip loading rates, and selection of evacuation destinations and modes.

2.1 Fundamentals of Evacuation Planning

Regional emergency events could be categorized according to the source of the threat (natural or man-made) and the availability of warning time (long or short). Natural disasters include hurricanes, tsunamis, floods, earthquakes, and fires. Man-made threats include hazardous material spills, malfunctions of nuclear plants or chemical facilities, and terrorist attacks. Hurricanes and floods are usually associated with extended warning times before the danger threatens the safety of the population while hazardous materials (hazmat) spills, terrorist attacks, and earthquakes have very little warning time to the public, if any. Different transportation related measures are associated with different phases of the emergency event, which include the following (48):

1) Pre-disaster
   a) Data collection
   b) Infrastructure assessment
   c) Disaster scenario analysis
   d) Mitigation preparedness
2) During disaster
   a) Disaster assessment
   b) Traffic network assessment
   c) Traffic management
   d) Evacuation preparation
   e) Evacuation deployment
3) Post-disaster
   a) Infrastructure assessment
   b) Post-disaster traffic management

Evacuation planning was originally required for the nuclear power industry following the partial meltdown of a reactor at the Three-Mile Island nuclear power plant in 1979. After that incident, the mandate by the Nuclear Regulatory Commission (NRC) for evacuation plans in the areas surrounding nuclear power plants gave the first momentum to evacuation modeling (2).

2.1.1 Urban travel demand modeling and evacuation modeling

The main purpose for analyzing travel behavior is to design models that reproduce, as accurately as possible, the travel flows generated by users of the transportation system and changes in their travel patterns as a result of changes in the conditions of the transportation system. In areas qualifying for an MPO, existing metropolitan travel demand models enhanced by different traffic simulation tools provide a good base for developing evacuation plans. Traditional transportation planning focuses on the diurnal rhythm travel demands of the average weekday to provide acceptable levels of service throughout the day. Emergency planning is different from conventional planning applications in that it usually involves moving a large number of people over a large geographic area during a limited period of time.

Evacuation simulation models play an important role in planning, analyzing, and understanding the different aspects of emergency evacuations. Most of the modeling and simulation tools used for evacuation modeling are based on the four-step travel demand model. It consists of four major stages that are related to the user's trip decision-making process. The first two steps are related to the nature of the land-use patterns, while the last two steps are dependent on the attributes of the modeled transportation network. The four stages are trip generation, trip distribution, modal split, and traffic assignment.

2.1.1.1 Trip generation models: These models use social and economic data to predict the number of trips produced by and attracted to each zone within the study area. Trip production is associated with residential areas and different attributes of households, whereas trip attraction is related to non-residential area characteristics. Production is estimated using factors such as the number of households in that area, household sizes, income, and automobile ownership rates, along with other variables. Attraction is estimated using variables such as employment levels and floor space (29).

To establish the relationship between trip generation rates and the social and economic data of each zone, trip generation models use historical data to estimate the number of trips generated. The most commonly used reference for that is the trip generation manual developed by the Institute of Transportation Engineers (ITE), which provides the type of data used, trip rates, and other related statistical data (29). However, the data provided in that manual represent national averages, which are not necessarily applicable to the local area of interest. In addition, the rates provided in the manual offer a wide range of values, making it difficult to pick a single value representative of local conditions.

For local area studies, two major types of generation models are used: regression models and category analysis models (29). Regression models involve techniques such as the least-square regression model. They are used to predict the trip rates for spatial units or traffic analysis zones (TAZs), based on the available data for one or more variables, such as the number and size of households in each TAZ. These models are easy to construct and use, but they do not always yield accurate results. Category analysis models classify the households and employment type based on similar social and economic attributes instead of spatial zones. Households with similar attributes are assumed to have the same trends for trip production, and the same applies to employment type for trip attractions.

For evacuation trips, the number of trips produced is based on the number of households, the nature of the threat, automobile ownership, and the number of drivers in the household. As for evacuation trip attractions, they are based on the nature of the threat in addition to the type of destination chosen by the evacuee. Evacuation trip generation modeling started in the 1990s where it typically involved the conversion of the number of evacuees into the number of evacuation trips (44). Later, logistic regression and fixed trip rates were used in several studies (36).

2.1.1.2 Trip distribution models: After the trip production and attraction for each zone is determined in the trip generation step, trip distribution models are used to connect trip ends, that is, to establish the flow of trips from production zones to attraction zones (29). The trip distribution in travel demand models between different trip origins and destinations is based on the purpose of the trip. This is because daily trips are made to participate in the different daily activities where the choice of trip destination is determined by the purpose of the trip. The output from this step is a matrix representing the production and attractions between traffic analysis zones, called the origin-destination (O-D) matrix.

The most commonly used type of trip distribution model is called the gravity model (23). This model is a modified version of Newton's law of gravitation between physical bodies in space. In it, the number of trips between zones is assumed to be based on the levels of activity and relative attractiveness of zones, which is measured by travel time or cost (50). The major criticism of the gravity model is that it is based on observation, and cannot be confirmed scientifically. Also it is unable to account for the behavioral assumptions in predicting trip flows for congested links in the transportation network (27).

The destinations for the trips evacuating the at-risk area are based on the nature of the threat in addition to the type of destination chosen by the evacuee. In modeling evacuation trips, there are three major choices for trip destinations: closest point out of the danger area, destinations pre-specified by the evacuation plan, and a mix of options based on factors such as network conditions. The available literature suggests that most of the evacuees will pick the house of a relative or a friend, followed by hotels and motels, and a small percentage of them will pick public shelters as their evacuation destination (23).

2.1.1.3 Modal split: These models predict the mode of travel that is used for trips. They divide trips among the various transportation modes available for users. If the modal split models are applied after the trip distribution step in urban transportation modeling system (UTMS), then they are called trip-interchange models (29). For the purposes of this study, transit users do not have a significant effect on the overall performance of the transportation system. Hence, the only mode of transportation modeled for the purposes of this study is private automobiles.

2.1.1.4 Traffic assignment: In this step, the predicted traffic flows are assigned to the modeled network links. Traffic assignment follows the main principles of equilibrium stated by Wardrop in the 1950s (42): User Equilibrium and System Equilibrium. In User Equilibrium (UE), users of the system choose the route that would minimize their cost (or travel time) without consideration to the overall average travel time on the system. In System Equilibrium (SE), system users would behave cooperatively in choosing their own route to ensure the most efficient use of the system, thus optimizing the overall average cost of travel on the system.

Static assignment does not represent the traffic flows on the transportation network through time, and all traffic is assigned simultaneously to all network links along their path. This assumption is not realistic, but for long-term regional planning purposes, static methods could produce results with a satisfying degree of accuracy. Dynamic assignment techniques introduce the time dimension into the modeling process and are usually used for short-term applications that require a higher degree of accuracy.

Static traffic assignment determines the traffic loading on the roadway network in a steady state setting, while dynamic traffic assignment (DTA) deals with the same problem in dynamic setting (13). DTA-based models witnessed increasing emphasis due to their potential to address longstanding problems with unrealistic assumptions of static planning methods. This is primarily because DTA-based models depart from the standard static assignment assumptions to deal with time-varying traffic flows, which include the effects of roadway congestion. The data requirements for DTA models are similar to static traffic assignment models; however, DTA models require path-delay based on the time of departure and traffic conditions on the trip route instead of volume-delay functions used in static assignment (13).

The DTA tools are mainly used for short-term planning applications. These tools are based on a dynamic traffic assignment algorithm that can handle both traffic dynamics and travel behavior. In addition, they provide an effective platform for evaluating different operational strategies and analyzing their performance and benefits. There are two major methodological approaches provided in the literature for DTA systems: analytical approaches and simulation-based approaches. Analytical approaches solve the DTA problem using mathematical programming. In 1978, Merchant and Nemhauser were the first to formulate a DTA system as a mathematical program (3). Their formulation represented a deterministic, fixed-demand, system optimization problem. Their efforts were followed by several attempts to model DTA as a mathematical problem, such as Janson who in 1991, proposed a User Equilibrium mathematical solution for a DTA problem.

In 2000, Ziliaskopoulos introduced a linear programming formulation for a system optimal DTA problem (3). His formulation was based on the cell transmission principle which added more response to traffic conditions. Using mathematical programming to formulate DTA was limited by constraints related to a trade-off between mathematical traceability and providing efficient solutions for real world large-scale traffic networks (3).

Several simulation models have developed based on DTA, including DYNASMART-P, CONTRAM, DYNAMIT, and TRANSIMS. These models use established analytical formulation and mathematical programming along with a traffic simulator to reproduce traffic flow dynamics. Simulation-based models are more widely used and accepted because they provide more realistic traffic representation than analytical approaches.

DTA simulation models have a traffic simulator, and have the ability to account for the variations in the O-D trips in real-world networks. DTA simulation models use the current available data to incorporate real-time variations in the O-D demand, while maintaining the procedure computational efficiency (43). They have the ability to model congestion during peak and off-peak conditions, in addition to non-recurrent congestion events by modeling the buildup and dispersion of traffic on network links (34). Also, DTA simulation models can be used to estimate real-time current conditions on the network, and predict short-term future network conditions using the rolling horizon framework. Real-time data from surveillance systems are combined with historical data to estimate the network's real-time current conditions and predict short-term future conditions (39).

Conventional tools do not explicitly model driver behavior patterns on the network. Therefore, they are inadequate for evaluating the effects of operational and traffic management strategies, such as implementing various intelligent transportation systems (ITS) technologies. In evacuation modeling, the principle of minimizing travel time still applies to evacuation trips, but there may be some restrictions by the authorities and roadway conditions that will affect the choice of evacuation trip route.

2.1.2 Evacuation modeling parameters

Evacuation studies have been performed in conjunction with emergency preparedness planning for various types of disasters. Evacuation planning emphasizes the development of scenarios and selection of the most appropriate response to that emergency scenario. During the process of developing an evacuation plan, there are several parameters that need to be understood to develop an efficient plan and facilitate communication among the professionals and decision makers. These parameters include (40):

1) **Protective action recommendation** (PAR) is a recommendation from the technical staff working on developing the evacuation plan to the decision makers. It usually consists of three alternatives for the at-risk population: do nothing, shelter in place, or evacuate the area
2) **Evacuation time estimates** (ETEs) is the time period required to move the at-risk population out of the danger area. These are aggregate measures and are different from individual evacuation times, which are defined as the time period from the actual beginning of the evacuation trip until the evacuees are cleared out of the evacuation area
3) **Emergency warning time** consists of two periods: decision period and dissemination period. Decision period is the time decision makers need before they decide to issue the emergency warning, while the dissemination period is the time needed for the warning to reach the public
4) **Mobilization time** is defined as the time period needed by the evacuee to prepare for evacuation before the beginning of the actual evacuation trip. The time needed to prepare for the evacuation is related to the level of risk and the available warning time. In emergency events with short warning times, the main factor in determining the departure time for the public is when they receive the warning. The time people need to mobilize is the main factor in determining their departure time for emergency events with long notification periods (23)
5) **Clearance time** is defined as the time elapsed from when warning was received to when the evacuee reached the evacuation trip destination. Clearance time is usually short for short warning time events

(less preparation and closer destination) while it is long for hurricane type events (an average of about nine hours for Hurricane Floyd) (23)

Traffic flow modeling deals with traffic assignment to evacuation routes, congested bottlenecks, and trip departure timing. In developing traffic evacuation models, an essential element is defining the evacuation transportation network, link geometry, and capacity. Also, an important issue would be defining the level of detail required for the network and emergency planning zones (EPZ), which are largely dependent on the output precision representation and computational speeds desired by the user (28).

Every EPZ should be determined based on event risk and evacuation risk (28). The defined EPZ should be homogenous in its exposure (vulnerability) to the hazard or event justifying the emergency response for the entire EPZ. Also, the EPZ should be homogenous in its evacuation risk, making the evacuation recommendation valid for the entire EPZ. After defining the EPZ, it could be divided into sectors called emergency response planning zones (ERPZ) based on the population and evacuation route (28). More people are going to respond to evacuation instructions if they know they are in an evacuation zone (28), which is why ERPZ should also be defined by political borders (city or county limits) and well recognized geographic features (rivers) or street networks (the interstate system). If the public is unable to identify the boundaries of the EPZ, that could lead to either people not evacuating when they need to, putting them in danger, or too many people evacuating from zones when they did not need to, adding unnecessary strain on the transportation system and adding more to the ETE.

The EPZ could be based on a single fixed point from which the emergency area radiates, as is the case in manmade emergency events like chemical spills or nuclear power plant related emergency events. Also, it might be variable in size, source, and direction, as is the case in natural disasters like storms or wild fires (7). The shape and size of the evacuation area are determined by the size and growth rate of the source itself, and they could be classified as centralized or regional. Fixed sources that expose the population to danger in their immediate surrounding are labeled as centralized, while evacuation areas that are not only defined by the emergency source are labeled as regional (7). The rate of growth of the evacuation area is mainly a function of the nature of the emergency itself and the speed by which it moves (7). The size and characteristics of the evacuating population are determined by the size of the evacuation area, the social and economic attributes of the population, and the level of danger to the public. The level of threat to the public safety may vary with time or remain constant, but it is a major factor in determining how quickly the population needs to be removed from the danger area (7).

2.1.3 Modeling tools for evacuation planning

In the research related to emergency evacuation modeling, there are two main topics of special interest: human behavior and computer simulation (35). These two main areas of evacuation modeling could be combined at three different levels: evacuation time estimates (ETEs) analysis, collection of background data, and human behavior analysis (28). Computer models provide relatively low-cost, low-risk tools for understanding the influencing factors in emergency evacuations and preparing evacuation plans relative to the cost of not having a plan prepared when one is needed. They are mainly used to test various assumptions and analyze the results for different alternatives.

A limitation in evacuation models is that they were focused on developing new traffic flow models while few of them considered the background data and behavioral aspects analysis. Ignoring the human behavior aspect when modeling emergency evacuation could lead to underestimating ETEs.

Early traffic evacuation models aimed at obtaining the ETEs for different scenarios were mainly based on roadway capacities and traffic demand. In most of the literature dealing with evacuation modeling, the capacity of the evacuation network was determined based on Highway Capacity Manual (HCM) procedures. The limitation to this approach is its inability to account for network capacity changes during emergency events (28). Also, it is generally not suited for use with over-saturated traffic networks, such as during emergency evacuations.

Simulation models based on DTA algorithms can handle both traffic dynamics and travel behavior. In addition, they provide an effective platform for evaluating different operational strategies and analyzing their performance and benefits. Real-time transportation simulation models developed over the past decade enabled traffic managers and engineers to better manage and direct traffic, but those models require more detailed input data and more intensive computer modeling.

Different levels of traffic representation are used by different classes of simulation models. In microscopic simulation models, the interactions of individual vehicles are captured by using algorithms that represent vehicle acceleration and deceleration, passing maneuvers, and lane changing behavior. Conversely, macroscopic simulation models do not capture the movement of individual vehicles on the transportation system. Macroscopic models are used to simulate the traffic flow based on speed, flow, and traffic density relationships, and do not model the interactions between individual vehicles. Mesoscopic simulation models simulate individual vehicles on the transportation system, but capture their interaction using aggregate relationships. In mesoscopic models, the travel times are determined based on simulation average speeds, which are calculated using speed-flow relationships (18).

KLD associates Inc. conducted a comparison between using macroscopic and microscopic models for emergency evacuation in a study for the Nine Mile Point nuclear power station (40). The microscopic model used was WATSim while the macroscopic model used was PCDYNEV. The study indicated that for large roadway networks, macroscopic models provide good practical accuracy and efficiency. In that study, the macroscopic model evacuated 4% more traffic than the microscopic model with 5% less simulated evacuation time. In addition, the microscopic model took 300 times the run-time (7 seconds compared to over 2,100 seconds) of the macroscopic model (40).

Evacuation simulation and modeling tools play an important role in the pre-planning stage, real-time evacuation traffic operations, as well as post-emergency analysis stage. Traffic simulation software has seen an increased use for modeling traffic flow under emergency conditions. Simulation tools assist emergency managers and transportation officials in the decision-making process by providing important information about evacuation traffic conditions.

Several models have been developed and/or used to analyze the transportation system in cases of regional emergencies and to improve the evacuation process; the following is a brief description of some of them:

2.1.3.1 Network Emergency Evacuation (NETVAC): It was developed by Shaffi, Mahmasani, and Powell at MIT in 1982 mainly as a reaction to the Three-Mile Island incident in 1979. It could be used for route selection, lane management, and intersection control analysis (9). The major drawback for using this model in evacuation studies is that it does not model drivers' behavior and it has no travel demand component.

2.1.3.2 Mass Evacuation (MASSVAC): It was developed in 1985, and it has been used to test the operational strategies for hurricane evacuations in Virginia (9). A support system called Transportation Evacuation Decision Support System (TEDSS) was developed by Hobeika et al. for the development, analysis, and evaluation of evacuation plans around nuclear power stations.

The system utilizes a database module to store disaster related information, evacuation rules, and the characteristics of the region and the transportation network. The MASSVAC simulation module includes several traffic assignment algorithms to obtain the initial decision for evacuation. A graphic display module is used to pass the input and output from the simulation module to the user. Finally, a system control module is used to manage the previous modules (2).

In this simulation module, vehicles are loaded onto the network through an assignment-simulation process. The input includes different network geometry parameters, origin-destination (O-D) points, as well as trip productions at each origin. MASSVAC is a macroscopic model based on User Equilibrium algorithm and is designed to operate in realtime. It loads the evacuation demand on the transportation network, determines the best evacuation route, and measures the evacuation time (2).

2.1.3.3 Oak Ridge Evacuation Modeling System (OREMS): It was developed in the mid 1990s by the Oak Ridge National Laboratory (ORNL). It represents a computer-based traffic simulation model that has the ability to estimate the time needed for evacuation under different scenarios.

OREMS has a probabilistic model that includes network characteristics. It consists of a pre-processor for data input, a simulation model, and a post-processor that is linked to GIS for the results output and simulation. It has the ability to account for driver behavior and weather conditions, but it can only assign passenger cars since it does not perform modal split (14). Also, it has the ability to be used for real-time operations, but that requires a large amount of data to be fed into the model and analyzed before the model becomes operational, which is a time consuming and a labor intensive process (9).

The input data are updated automatically, with the ability to perform DTA in real-time. Trip attractions are calculated based on experience due to lack of shelter data (14). OREMS was developed for the Federal Emergency Management Agency (FEMA) to be used in the Chemical Stockpile Emergency Preparedness Program (CSEPP). It can be used for ETEs, identifying traffic bottlenecks, and for the evaluation of traffic management strategies (35).

2.1.3.4 Post, Buckley, Schuh and Jernigan (PBS&J) Model: It was developed in 1999 by PBS&J Inc. as a Web-based evacuation travel demand model (it is also known as an Evacuation Traffic Information System [ETIS]). Its main function is to monitor major congested traffic areas during evacuations for hurricane type events (14). The input for the model consists of evacuation data on the county level while the output represents traffic volumes on the regional transportation network.

The PBS&J model is housed at FEMA's Region IV (Alabama, Florida, Georgia, Mississippi, South Carolina, and North Carolina) regional operation center (14). FEMA considers this model a good tool for evacuation planning. For input data, the model requires roadway network, route, evacuation demand, and external stations data on the county level, leading to less data and processing time requirements. The PBS&J model has the ability to account for human behavior and weather data as input. It can also use real-time traffic data as input to support traffic operations during evacuation (14).

In this model, the trip distribution is performed manually (while most of the models use the gravity model) using percentages based on historical data at the county level, and does not have the ability to perform a modal split step (14). In general, this model requires less input data compared with other models, but its dependence on historical data and manual updates may limit its effectiveness. It has been applied to the pre-planning analysis stage for FEMA's Region IV (14).

2.1.3.5 Dynamic Network Evacuation (DYNEV): It is mainly used for the development of evacuation plans for areas surrounding nuclear power plants, and has the potential to be used for hurricane evacuation planning. It has been a component of FEMA's integrated emergency management information system used by state and federal agencies (14).

Input data consists of network, route, evacuation demand, external station data, and it has the ability to use human behavior and weather data as input. The input data structure is similar to OREMS, with the addition to bus data, but it cannot handle real-time data. The DYNEV model can provide ETEs, but it cannot provide real-time output (14).

2.1.3.6 Personal Computer based Dynamic Network Evacuation (PCDYNEV): It is a macroscopic model which consists of two main parts: integrated TRaffic Assignment and Distribution model (TRAD) and Interactive Dynamic Evacuation (IDYNEV). TRAD is used for the distribution of trips between the zones and their assignment to the different links. The input for TRAD consists of the roadway network, traffic demand and origin points, and the possible destinations for each origin point. TRAD utilizes user equilibrium assignment algorithm (40). IDYNEV is a macroscopic simulation model that has the ability to provide traffic flow statistics at different simulation steps for the links in the roadway network (40).

2.1.3.7 Traffic Estimation and Prediction System (TrEPS): Developed in 1995 as a result of DTA research by the Federal Highway Administration (FHWA), it has the ability to support decision making for non-recurrent congestion events (e.g., accidents and work-zone) through dynamic traffic estimation. This model is capable of supporting transportation planning and operation decisions through two major components: a planning component and a real-time operation component (14). Input data consist of network, route, evacuation demand, and external station data. It can use real-time traffic data as input to support traffic operation during evacuation.

2.1.3.8 Network Simulation Model (NETSIM): Developed by KLD Associates Inc., it represents a stochastic microscopic traffic simulation model (5). This simulation model has the ability to measure the transportation system performance under different traffic control strategies. It can model both personal vehicles and buses on congested traffic networks where the demand is processed and analyzed at each simulation step. NETSIM was applied to estimate evacuation times needed for areas surrounding nuclear plants. The major limitation to NETSIM is that it cannot handle large regional networks, and it does not perform dynamic traffic assignment. In addition, it does not have a travel demand component, which needs to be provided from other sources as input.

2.1.4 Human factors and evacuation modeling

To perform projections of travel demand changes, it is necessary to identify the parameters that influence the travel decisions of each individual. With the increasing need for travel demand models to perform more complex and advanced tasks conventional static planning tools fall short of fulfilling this need. Hence, there is increasing emphasis on enhancing those models by improving their input data in addition to the development of new modeling procedures. These improvements aim to enhance the ability and reliability of the models in providing future traffic forecasts to support the decision-making process in addition to supporting traffic operation analysis.

Actual human behavior patterns, along with the response rates, have major impacts on the effectiveness of the results from evacuation traffic simulation models. A distinctive feature of human behavior in emergency situations is that families tend to evacuate as a unit (35), where the driving members of the family pick up the non-driving members and then evacuate out of the danger area. In evacuation traffic management plans, authorities should discourage certain movements but not prohibit them. The application of the evacuation plan should be flexible because the driver might have a strong reason (to pick up someone or to join family members) to go to a certain destination during an emergency situation (40).

Murray and Mahmassani (35) integrated the household trip-chaining behavior with the evacuation simulation model. In their study, they used linear programming to describe the decision-making process for each household in the model (35). They used trip chaining to model household (HH) behavior, an approach feasible only for small networks with a limited number of zones and HH. However, when dealing with regional networks, user equilibrium will most likely be used for the assignment.

Human behavior is usually used to assist in determining the number of trips generated and the trip departure timing. Many of the reviewed models assumed that everyone who was warned about the emergency is going to evacuate, all registered vehicles will evacuate, or that one vehicle per HH is going to evacuate (28). Due to the different nature of the emergency evacuation trips, most researchers rely on data obtained from travel survey to model emergency evacuations.

2.1.5 Travel surveys and evacuation modeling

Travel demand models utilize data provided by travel surveys to establish trip generation, trip distribution, and modal split relations. Hence, urban areas need travel survey data to estimate and validate models that are used for their planning activities by using those data to identify existing conditions and problem areas in their transportation system. It is very important to develop accurate input data to improve the accuracy and reliability of the model output. However, conducting surveys and updating survey data is usually faced by budget and time constraints, limiting the abilities of different transportation agencies to keep the needed data up to date and acquire the data needed for their expanding modeling needs.

Different methods are used to perform travel surveys. Some of the most commonly used method include household travel and activity surveys, vehicle intercept and external station surveys, workplace and establishment surveys, and parking surveys (53). For evacuation modeling applications, travel survey methods are used to collect travel behavioral aspects in addition to common data about the number of daily trips, their destinations, and choice of travel mode. Travel behavioral data collected are determined based on the modeling need, and could include activity based travel summaries, usage of different vehicles for different trip purposes, and stated response travel behavior.

The process of implementing travel surveys is performed over five major stages: planning, design, field implementation, data preparation, and data analysis (8). The survey planning stage is mainly dependent on the scope of the study and the needed data analysis type. In this stage, the problem that needs to be studied is identified. Also, the hypotheses associated with the relations that need to be examined are identified.

At the survey design stage, the best method to acquire the data needed is determined where the survey method, the associated time frame, and budget requirements are established. The different tasks performed at this stage include collecting background information, survey design, organization, sampling, drafting, and constructing (8). The design of the survey is based on the data analysis needed for the project to provide the most efficient method to achieve the objectives of the study.

After the survey design is finished, the survey is then implemented and data collection from the population sample begins. The results from the survey are coded into the system and the data are tested and cleaned to keep the usable data. Afterward, the data are processed and prepared in an analysis-ready format (8). At the data analysis stage, the relations between the response variable and the other variables are established where the data is tested using different statistical measures. Also, the results and conclusions of the study are presented and applied to the problem under investigation.

Surveys that are designed to collect data describing actual travel behavior are classified as revealed preference (RP) surveys (8). On the other hand, stated response (SR) surveys collect data on how the transportation system users would respond to a hypothetical situation (8). Evacuation modeling usually falls within the emergency planning stage where the incident is hypothetical; therefore, most surveys used for evacuation modeling are SR surveys.

Concerns exist about the reliability of SR data for evacuation modeling because what people say they will do under a specific set of circumstances may be different from what they would do if actually faced with these circumstances (8). A number of studies have been reviewed where the validity of data obtained using SR techniques was checked, and it was concluded that in most cases the SR techniques can provide predictions of choice behavior to a satisfactory degree with the need for additional systematic validity research (8).

There are four general classes for SR survey techniques based on the nature of the questions and the expected behavioral outcome: stated preference, stated tolerance, stated adaptation, and stated prospect (8). Stated preference (SP) surveys represent the most important source for developing evacuation models to capture travel decisions where most of the expected behavioral outcomes and constraints are provided. In stated tolerance (ST) surveys, respondents are asked to provide the travel conditions that would prompt them to take a certain action. Stated adaptation (SA) surveys ask respondents to provide relatively open-ended responses to a set of certain constraints, while stated prospect (SPro) surveys provide respondents with some general scenario to elicit their constraints and expected behavioral outcomes.

Stated preference methods refer to the techniques of collecting and modeling with data collected in the form of preferences as reflected in rating, ranking, or choices among hypothetical alternatives characterized by a set of pre-specified attributes that can take different values (4). SP tools were developed in the early 1970s for marketing research, but it wasn't until the early 1980s before the initial application of SP surveys for transportation planning (8). The basis of these methods is the observation of behavioral choices by confronting respondents with hypothetical situations. SP techniques are most useful in transportation planning to measure perceptions and attitudes, and estimation of policy responses, potential demand, and elasticity for transport-related choice sets, such as different travel modes, vehicle types, or route choice (4). The travel behavior of each individual reveals a utility function which provides a means of forecasting future choices. The use of SP techniques has become increasingly common practice for evacuation modeling studies.

Despite the wide use of SP techniques to support transportation studies, the SP survey designs are still subject to a range of experimental error not found within RP survey designs (4). The debate about the predictive validity of stated preference remains the main obstacle faced when using SP surveys for transportation studies (15). The predictive validity refers to the degree of accuracy a hypothetical response predicts future behavior. It is important to have correlation between the stated behavior and actual behavior for the survey to be useful in the analysis (15). The validity of SP data can be maximized when attention is paid to the hypothetical choice circumstances so they are realistic and relevant to individual respondents (4), meaning that the SP survey design is very often the most important determinant of the internal and external validity of any SP data collected. The objective of using experimental design in SP surveys is to present attributes that are varied independently to the population sample surveyed so that the effect of the different attributes on the respondent's behavior is identified (8). When comparing stated preference data and revealed preference data for the same scenario, they are unlikely to have the same variation. However, the decision-making process is similar and thus the utility functions should be proportional to each other with stated preference data being limited by the hypothesis made (25). Also, well designed SP surveys are capable of producing comparable results with the independent evidence of the RP models because respondents to a hypothetical choice situation behave in basically the same manner as those facing real conditions (4).

2.2 Evacuation Modeling

Good evacuation planning involves an iterative process to estimate the best evacuation routes and their corresponding ETEs for different regional emergency scenarios based on local data. The objectives of this study are achieved in two stages: development of local demand loading rates and drivers' behavior data for different emergency evacuation scenarios and incorporating the data into the evacuation modeling tool.

2.2.1 Evacuation travel demand

A major step in evacuation modeling is identifying the demand for travel on the transportation system. The evacuation model should help the planner estimate the size of the population that needs to be evacuated, in addition to the origins and destinations of their trips (7). By taking into consideration the response rates to evacuation orders and the ability to evacuate, three main categories of the evacuating population are defined: residents who live in the danger area, tourists and visitors who mainly stay at hotels and motels, and special facility population, such as those in jails, schools, hospitals, and nursing homes.

The objective of trip generation is to identify the demand or the number vehicles that are going to be using the transportation network. The demand for travel is mainly based on the number of households (HH) and family size since the HH is the basic unit of evacuation. Many factors influence the public compliance rates with evacuation instructions. Some of them are related to different behavioral aspects, while others are associated with the nature of the emergency itself.

For evacuation participation rates, most behavioral models rely on historical data, especially data obtained from hurricane evacuations (14). Sometimes the population evacuates without receiving the instructions to evacuate from the officials. On the other hand, some segments of the population do not comply with the instructions to evacuate. The public response rates generally increase when the warnings are frequently repeated with conformity and when they are issued from a source the public perceives as credible (23).

Families that have a prepared emergency plan are more likely to comply with evacuation instructions than those without a prepared plan at the time of the emergency. According to Mileti and Sorensen, the sequence of public response to emergency warning include receiving and understanding the warning, believing the warning is credible, personalizing the warning, confirming the warning, and responding by taking protective action (23). Also, Perry and Lindell defined four stages that define the public response to emergency warning, which include risk identification, risk assessment, risk reduction, and protective response (23).

A number of issues have been related to public compliance with instructions to evacuate, such as shadow evacuations, spontaneous evacuations, and the "cry wolf" effect (23). Shadow evacuation is defined as the population evacuating from the emergency shadow regions (regions surrounding the evacuation area). Data from Hurricane Floyd's evacuation indicated high evacuation rates from low risk shadow areas. Spontaneous (early) evacuation occurs when the risk seems imminent even before official evacuation instructions are issued. This is especially noticed in emergencies involving short warning times such as hazmat spills incidents. The "cry wolf" effect is the noncompliance of the public to the evacuation instructions because of responding to false alarm messages in the past, which greatly affects the credibility of the warning messages issued in the future (23).

Different assumptions were reported in the literature regarding evacuation compliance rates. Hobeika et al. (1994) assumed a 100% response rate without any consideration to evacuation from the shadow region surrounding the at-risk area. Lindell et al. (2002) used regression analysis to develop a function for the evacuation response rates for hurricane type events. Based on the category of the at-risk area and the hurricane category (28), he developed the following equation:

$$Y = 33.78 - 19.72X_1 + 2.87(X_1)^2 + 31.39X_2 - 2.84(X_2)^2 \qquad \textbf{Equation 2.1}$$

Where, Y: % compliance with evacuation instructions, and
X_1, X_2: Risk area category and hurricane category.

In the literature, the size and distribution of the transient population within the EPZ was usually estimated using the hotel and motel room average occupancy. A compliance rate of 100% with evacuation orders is usually used for visitors, and there is very little literature available for this population category. An important factor to be considered is the seasonal variations in average occupancy, which are usually reported by month. The demand for this category of the population is usually defined as 1.0 vehicles/room, since they are less likely to have more than one vehicle (1). Also, those who travel on buses are most likely to depart as a group using the same bus, reducing the number of vehicles in the evacuating traffic stream.

The evacuation participation rates also vary greatly for different types of hazards. Compliance rates are usually high (could reach the 90% range) in incidents involving hazmat or in major storm surge areas, whereas for small storms or river floods they are usually low (23). From the literature (primarily from hurricane type events), an average of 1.3 vehicles per HH were used in the evacuation. People who did not have access to private vehicles were usually picked up by family or friends, and only an average of 1-2% percent needed official assistance (23).

Some empirical studies and surveys are available in the literature describing the number of evacuating vehicles per HH from the EPZ. Cora and Johnston (2002) used the Poisson distribution to model the number of evacuating vehicles. The results showed a skewed distribution with a mean (λ) equal to 1 and mode equal to 2 with a range of 2 to 6 vehicles evacuating per HH (28). Ruch and Schumann (1997) estimated the number of evacuating vehicles to be 1.35 based on a behavioral survey for the study area. Also, Prater et al. (2000) reported a rate of 1.34 vehicles per HH for Hurricane Bret (28). As for transit-dependent populations, the size and distribution of that category was ignored in the previous research since it is tough to account for and it should have minimal effect on traffic congestion during evacuation.

2.2.2 Evacuation trip loading rates

Evacuation trip loading rates have a major effect on the transportation system congestion levels, operational conditions, and clearance time. Residential HH departure time distributions determine the demand rate loading of evacuating vehicles onto the available evacuation transportation network. However, data obtained from the nationwide census do not cover all the information needed to develop estimates of the mobilization time, and may not specifically focus on the area to be evacuated. In such cases, telephone surveys have been used to obtain information about families and estimates of the response time to certain threat scenarios (40). Analysts agree that the correct function to describe departure time in emergency evacuations is a sigmoid curve (28). The sigmoid function is a special case of the logistic function (52, 51), which is as follows:

$$P(t) = \frac{1}{1+e^{-t}} \qquad \textbf{Equation 2.2}$$

Where: P(t): Population percentage departing at time (t), and
t: Time elapsed since the beginning of the evacuation process.

The logistic function is the inverse of the natural logit function and it is used to convert the logarithm of odds into probability (52). The curve shows exponential growth for negative “t” that slows down to linear growth near “t = 0” and approaches “y = 1” with an exponentially decaying gap.

Cova and Johnson (2002) used a Poisson distribution to model the overall departure times for evacuating vehicles using five-minute increments (28). Radwan et al. (1985) used a sigmoid curve with the following formula:

$$P(t) = \frac{1}{[1+e^{(-\alpha(t-\beta))}} \qquad \textbf{Equation 2.3}$$

Where: β: median departure time, and
α: slope of the curve.

Also, Tweedie et al. (1986) developed his function based on data obtained from local civil defense officials. He generated a distribution function (28) using the formulation:

$$P(t) = 1 - e^{\left[-0.5\left(\frac{t}{\beta^2}\right)\right]} \qquad \textbf{Equation 2.4}$$

Where: β: Mode of the distribution function.

Hobeika and Kim (1998) used an exponential function to describe departure times (2). Their function was equivalent to the function proposed by Radwan et al. (1985) with β = 45 minutes. Lindell et al. (2002) combined warning and preparation time distribution and analyzed data collected from coastal region residents about the time needed to leave their homes after hurricane evacuation instructions were issued (28). Figure 2.1 illustrates the trip loading curves developed by different researchers for different case studies.

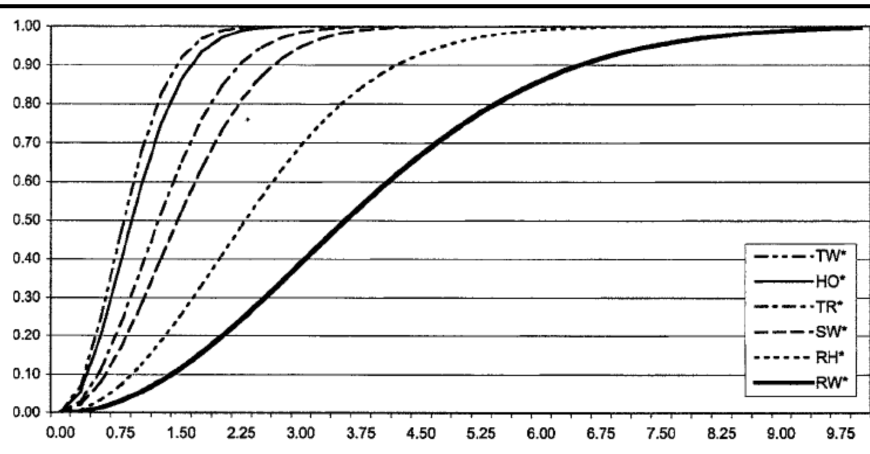

Fig. 1. Departure time curves for Tweedie et al. (1986) (TW*); Hobeika et al. (1994) (HO*); Lindell et al. (2002a) transients (TR*); Southworth and Chin (1987) (SW*); and Lindell et al. residents at home (RH*) and residents at work (RW*)

Figure 2.1 Evacuation departure times curves (28)

Another factor that needs to be considered is the time when the evacuation orders are issued. According to Klepeis et al. (2001), over 90% of the at-risk population is usually at home between 10:00 P.M. and 6:00 A.M., while 30% of the population is indoors between 10:00 A.M. and 3:00 P.M. This indicates that emergency planners need to incorporate additional time during the day for adults to arrive home from work and kids arrive home from school, especially in cases where there is a very short warning time, such as hazmat spills.

2.2.3 Selection of evacuation modes and routes

Data available from literature indicate that the nature of emergency evacuations do not allow for balanced traffic demand where travelers learn from their mistakes. Several factors impact travelers' choice of evacuation route. Evacuees could pick the closest exit point outside the at-risk area, the route with the least travel time, or the route more familiar to them. Most of the population pick the house of a relative or a friend, or a hotel room as an evacuation destination (22, 23). In the literature, it is reported that on average, 13% of the population will evacuate to public shelters based on the severity of the event and income levels (23, 49). Hobeika and Kim (1998) utilized User Equilibrium assignment algorithm in MASSVAC 4.0, where evacuees were assigned to routes that minimize their travel time (2). Cova and Johnson (2002) assigned traffic to routes based on the shortest travel distance to exit the risk area (28).

Several transportation modes are available for evacuating the public, including private vehicles, buses, trains, and air. Most of the available literature focused on private vehicles as the primary mode evacuation since it is the one mode that would significantly impact the surface transportation network. The problem with flying is that airlines may discontinue flights going into the danger zone even if the local airport is still open. Also, if the ground personnel evacuated early, that could stop evacuees' movement through the airport (28). As for evacuation by buses, they are mainly used for the transit dependent (no access to private vehicles) and special facility population. Some members of these populations evacuate with friends or family and it is unclear how that would affect the evacuation of private vehicles. In addition, using buses for evacuation is greatly affected by the availability of buses, time needed to load and mobilize those buses, and evacuate outside the danger area. Using transit might extend the ETE time needed by personal vehicles for two reasons: the need for routes for their return trip may limit the ability to apply contra-flow strategy, and their presence in the traffic stream and their stops may interrupt the flow of the traffic stream.

2.3 Description of Software Tools

This study will mainly use two software packages; Cube-Voyager and DYNASMART-P. These two software packages are used to develop the main features of the model, in addition to other software packages that are used for data compilation, analysis, and other processing tasks. The following sections describe the main features and components of the software.

2.3.1 DYNASMART-P software

In 1992, Peeta and Mahmassani developed a DTA model called DYNASMART (DYnamic Network Assignment-Simulation Model for Advanced Road Telematics) (3). This model has a traffic simulator with fixed departure times for the O-D demand (it assumes a previous knowledge of the O-D demand for the planning period). The rolling horizon approach was used to account for the variations in the O-D trips in real-world networks (43). This approach hinges on the principle of using the current available data to incorporate real-time variations in the O-D demand while maintaining the procedure computational efficiency. It provides an efficient way of handling problems that require knowledge of future demand for the full planning horizon (43). It uses the available information about current and short-term future (5 to 15 minutes) network conditions to determine real-time suitable operations control strategies while preserving computational efficiency.

DYNASMART-P is an analysis tool that incorporates different information supply strategies, route assignment rules, and traffic control measures to best fit the functional requirements of Intelligent

Transportation Systems (ITS) applications. It combines the principles of traffic assignment and simulation to overcome the complexity usually involved with DTA problems, and produces a system with adequate practicality. There are three major components for DYNASMART-P: the simulation component, the user behavior and information supply strategies component, and the path processing component (20).

2.3.1.1 Simulation component: DYNASMART-P utilizes mesoscopic simulation models to represent traffic interactions (38). It efficiently tracks the movement and location of individual vehicles throughout the planning horizon, but it does not monitor microscopic details such as car following (20).

There are two main modules involved with traffic simulation in DYNASMART-P: link movement and node transfer modules. The link movement module processes vehicle movements on network links by evaluating links speeds based on speed-density relationships for each simulation step. The node transfer module determines the link to link (or section to section) traffic transfer based on the control type at the intersection. This module determines the number of vehicles entering and exiting the network, and vehicles still in queue at each simulation step.

2.3.1.2 User behavior and information supply component: Traveler behavior modeling in DYNASMART-P is based on boundedly-rational behavior. That is, drivers are going to alter their trip route only if they experience a gain over a certain threshold perceived to be sufficient for them. Information supply systems will provide drivers with indications of travel times over alternative routes, and sometimes the best route for their trip. Nevertheless, drivers' degree of response to the provided information will vary according to their different user class, indifference band, and resistance to switching routes (20).

2.3.1.3 Path processing: This component determines the impedance of using a specific route using the traffic attributes obtained from the simulation component following the procedures illustrated in Figure 2.2. For multiple user classes, the algorithm for calculating the K-shortest path is combined with the simulation model to calculate the (K) different paths for the O-D pair. To achieve computational efficiency, the (K) shortest paths are calculated at pre-specified intervals instead of every simulation time step. The shortest path calculations in DYNASMART-P are based on generalized link impedance from both travel time and out-of-pocket cost. The user cannot assign more than one cost for different links of the same type in the current version of DYNASMART-P (20).

DYNASMART-P also requires the user to specify the number of shortest paths to be calculated, which is determined by the planning application need to consider alternate paths for it. Usually a single path calculation is used for UE or SE applications, two-path calculations for applications with advanced traveler information systems (ATIS) strategies, and three-path calculations for en-route information planning applications.

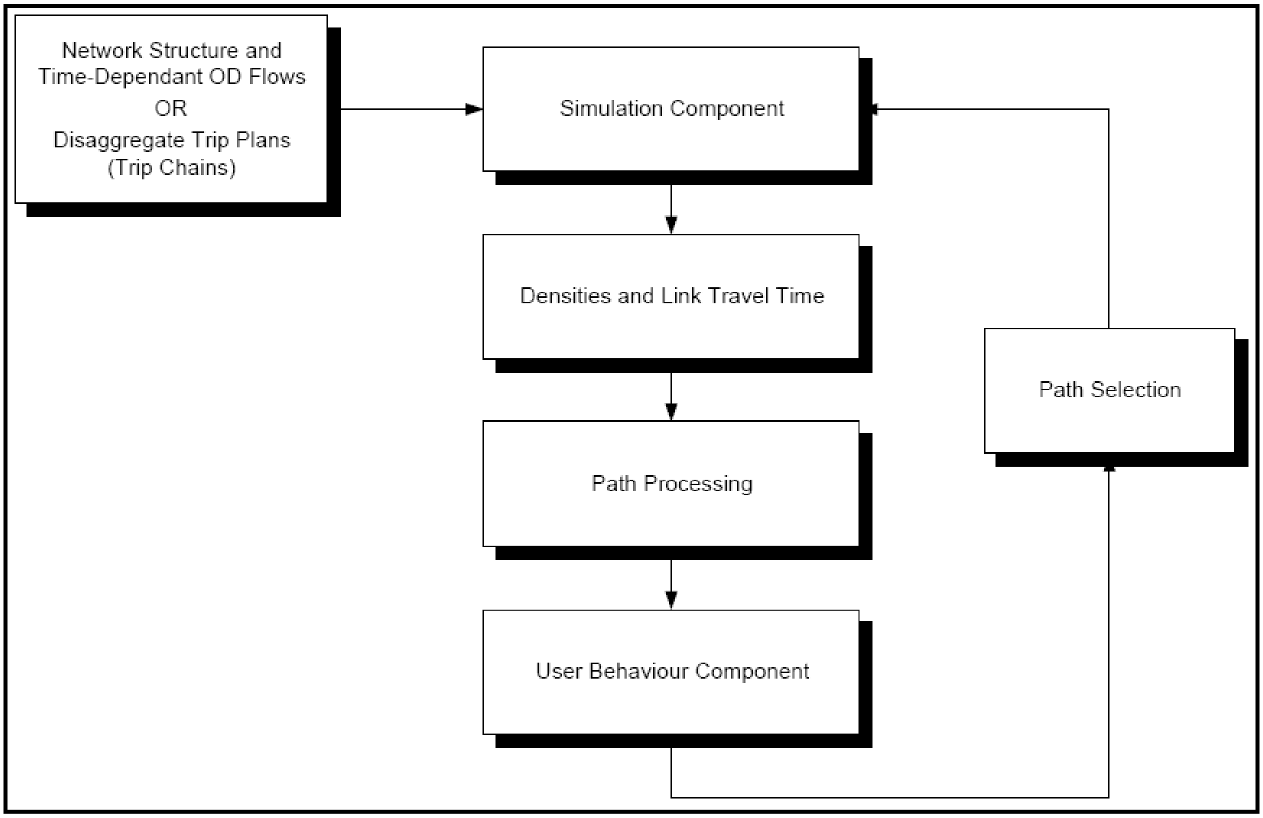

Figure 2.2 DYNASMART-P assignment procedure (20)

2.3.1.4 Model features: DYNASMART-P is capable of handling urban traffic networks with various sizes, up to 89999 nodes (20). In order to achieve a more realistic representation of the network and traffic conditions, DYNASMART-P allows using restrictions on vehicle movements that impact route assignment. These restrictions are used in flow simulation, path processing, and provision of information in the model.

DYNASMART-P can model link intersections with no-control, yield signs, stop signs, and signalized intersections. It can also model different freeway ramp metering strategies. To calculate the number of vehicles that traverse the intersection at each simulation period, DYNASMART-P applies outflow and inflow capacity constraints. Outflow capacity constraints determine the maximum number of vehicles that are allowed to leave each approaching lane at an intersection. Inflow capacity constraints determine the maximum number of vehicles allowed to go into the link through a simulation step. Left turn capacity is based on default values provided in HCM 2000.

Most of the common microscopic simulation models use the critical gap acceptance theory and car following technique to estimate the capacity of an intersection with yield sign control (20). In DYNASMART-P, however, for yield, two-way stop controlled, and all-way stop controlled intersection, vehicles are discharged according to the traffic flow rate on the major approach and the type of turning movement. The user can either specify the discharge rates or use the values from NCHRP (Capacity and Level of Service at Unsignalized Intersections, April 1996), which were used for the purposes of this research.

DYNASMART-P can model pre-timed and actuated signal control, but not at a microscopic level. For pre-timed signals, DYNASMART-P requires the offset, number of phases, and permissive movements for each phase, and the yellow and green times. The user needs to specify the phases and movements associated with each phase, along with the maximum and minimum green times for actuated signal control. DYNASMRT-P is capable of modeling five types of driver classes with different assignment rules based on drivers' knowledge of the network, the availability of ATIS, and how users respond to the provided routing information (20).

2.3.1.5 Demand representation: One of the unique aspects of DYNASMART-P is that it allows the user to specify generation links for each TAZ. These links are used to load the demand and generate vehicles, instead of the conventional method of generating traffic on centroids as in most available planning software. This feature overcomes the problem of generating unrealistic traffic flow patterns around origin and destination nodes (20).

Generation links can be physically contained only in one zone, even if they are on the boundary of more than one zone. However, a generation link may be specified to receive demand from more than one zone. In that case, traffic generated on that link is either proportional to its lane-miles or specified by the user as a loading weight which determines the share of demand a TAZ will provide. A virtual centroid is internally generated for each TAZ or for each aggregated zone. Centroids are connected to the destination nodes where vehicles exit the network. A destination node can be specified for a maximum of two zones (20).

DYNASMART-P provides some flexibility in the way it accepts vehicle generation information (O-D matrices). It offers two options for loading demand information. For entering time interval O-D matrices, the number of loading intervals must be specified along with the start and end of vehicle generation times for each interval. A multiplication factor for demand generation is specified to facilitate the application of different levels of demand loading. The total number of vehicles in the network is obtained by adding up all the entries from all of the specified O-D matrices, and multiplying that sum by the multiplication factor. Truck and high occupancy vehicles (HOV) demand is specified as an independent O-D matrix in the truck demand data file or as a fraction of the demand to be loaded onto the network.

For activity-based O-D matrices, the user specifies the vehicle characteristics and travel plan with intermediate stops and activity duration to model trip chains. It is important to list the vehicles in the vehicle-trip input file in the order of their departure or in the order of their generation links for vehicles with the same departure times. There are no restrictions on the number of intermediate stops that a vehicle makes at intermediate destinations, but DYNASMART-P only reports up to three destinations in the summary statistics file. This type of vehicle loading is needed for evaluating different traffic management strategies that require a specific loading pattern and/or fixed vehicle paths over the planning horizon. If the user specifies the multi-user class (MUC) as a percentage of the vehicle fleet, then this type of loading is not allowed (20).

2.3.1.6 Traffic-flow model: In DYNASMART-P, the traffic flow and traffic relations on the network are described using two types of modified Greenshield's models for traffic propagation (20). For freeways, where the capacity is larger than arterials, DYNASMART-P uses a dual-regime model. A constant free flow is specified for the uncongested free-flow conditions, and a modified version of the model is specified for congested conditions. Figure 2.3 illustrates the functions used in DYNASMRT-P for freeways. The reason for using this model is that freeways can accommodate dense traffic at near free-flow speeds.

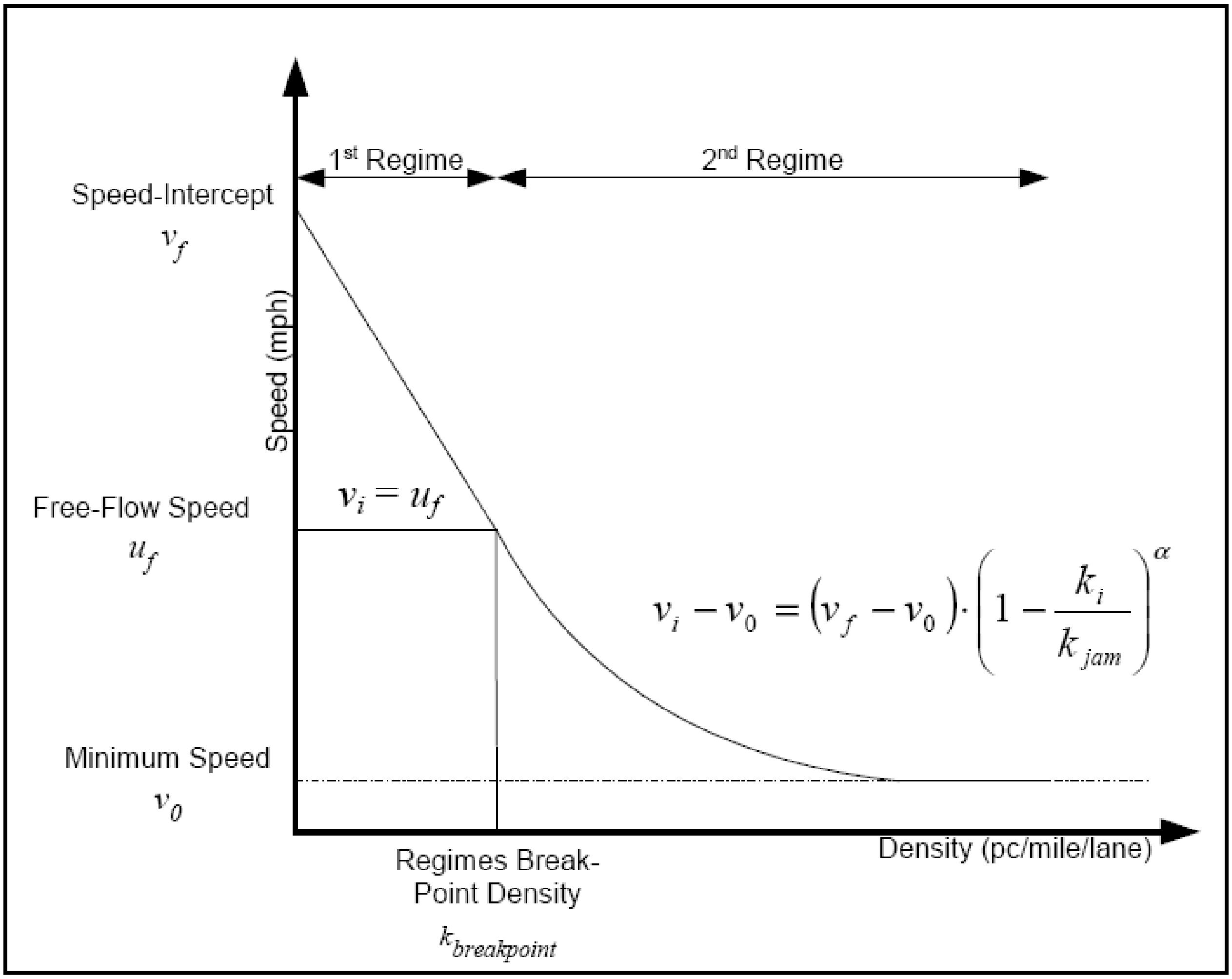

Figure 2.3 Type 1 modified Greenshields' model (20)

A single-regime model is used for arterials, where the presence of traffic control and intersections limit the possibility of free-flow speeds (Figure 2.4). In addition, due to the arterials' limited capacity, any addition to the traffic volume is going to affect the speed over them. Parameters for the dual-regime Greenshields' model in DYNASMART-P were calibrated for the San Antonio (Texas) freeway system. Single-regime parameters were calibrated for the Irvine (California) surface street network (20).

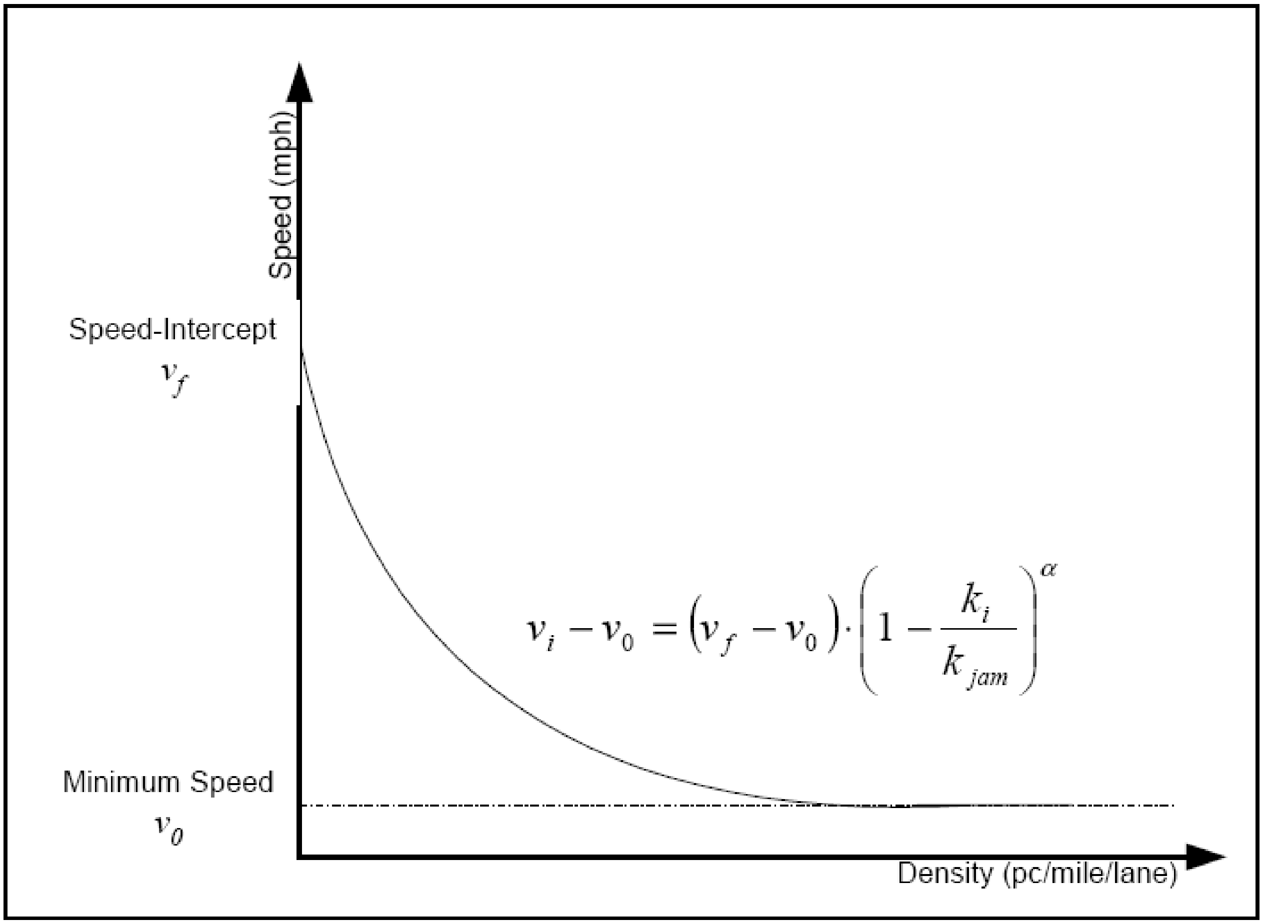

Figure 2.4 Type 2 modified Greenshields' model (20)

Equations 2.5a and 2.5b represent type 1 Greenshields model, and Equation 2.6 represents type 2 Greenshields' model used in DYNASMART-P.

$v_t = u_f$	$0<k_i<k_{breakpoints}$	**Equation 2.5.a**
$v_i - v_0 = (v_f-v_0).\{1-(k_i/k_{jam})$ ^α }	$k_{breakpoint}<_{ki}<k_{jam}$	**Equation 2.5.b**
$v_i - v_0 = (v_f-v_0).\{1-(k_i/k_{jam})$ ^α }		**Equation 2.6**

Where, v_i = speed on link i,
v_f = speed intercept,
u_f = free-flow speed on link i,
v_0 = minimum speed on link i,
k_i = density on link i,
k_{jam} = jam density on link i,
α = power term, and
$k_{breakpoint}$ = breakpoint density.

2.3.2 Cube voyager software

The O-D input matrix for the DYNASMART-P is produced using Cube software, a product from Citilabs. It was used to build the Fargo-Moorhead travel demand model, which is administered by the Fargo-Moorhead Council of Governments (F-M COG), and it is run using the TP+ component.

2.3.2.1 Model features: Cube software represents a transportation analysis and forecasting system that integrates modeling and graphical methods to study the transportation system (10). The graphical representation in Cube is based on Viper (Visual Planning Environment), and together (Cube and Viper) provide the different editors needed to perform the different transportation planning functions (10).

The software also supports some geographic information system (GIS) features, giving the user the ability to build the model network from GIS shape files to better integrate the modeled transportation network with the GIS networks. Cube Base represents the user interface for the Cube system. It provides interactive data input and analysis, GIS, model building, and documentation.

2.3.2.2 Travel forecasting model: Cube software incorporates several algorithms that implement a traditional four-step travel demand modeling process. TP+ is among the most common algorithms used, and is used for the Fargo-Moorhead travel demand model. TP+ may generally be viewed as a processor which implements user-defined travel demand relationships using what Cube refers to as scripts. These scripts, for example, are used to implement trip generation rates in the model using local data and parameters.

To graphically view the transportation planning modeling process, Cube software utilizes a tool called the Application Manager. It provides a flow chart describing the flow of data from one process to another in the system. It also clarifies the different parts of the data that are going to be used as either input or output in those processes. The Application Manager also provides the user with the option of running the whole application or running only specified steps within the application to save time and serve various analyses.

Traffic is assigned in Cube based on a generalized cost function (which is set to be equal to the travel time if no other parameters are used) using the modeled network and the trip matrix as input. The software also offers the option of performing a select-link analysis, which identifies how each O-D pair contributes to the traffic volume using a specific link.

3. METHODOLOGY AND DATA ANALYSIS

This section provides a description of the methodology used to develop the hybrid evacuation model. It provides a discussion of the methodology used to model an evacuation scenario and the different steps needed to achieve the objectives of this study. It provides a summary of the data collection, survey population, and sample selection, in addition to the design of the survey used to collect the data needed for building the model. Also, this section provides a detailed description of the data analysis used for evacuation trip generation, trip distribution, and trip loading data. The modeling approach and data analysis discussed in this section are related to the case study used for this study, which is described in detail in Section 4.

3.1 Methodology

The performance of the transportation system in cases of regional emergencies has a significant effect on public safety. Most of the applications of security planning are on the operational level of the transportation infrastructure with modest consideration of the security aspect in the development of transportation improvement plans (TIPs). To introduce the transportation aspect into the developed evacuation plans, traffic simulation tools are used to model the transportation system performance during emergency evacuation events.

Simulation-based models are among the most powerful tools that could be applied for capturing driver-network interactions. The objectives of this study included developing an evacuation model that recognizes MPO resources and data availability. The developed model should have the ability to address changes in travel demand, perform dynamic traffic assignment, and be capable of evaluating the effectiveness of different traffic operation measures. In addition, this study aimed at generating evacuation related data for small- and medium-size MPOs that could be applied to similar areas.

A major component of this study focuses on the development of a dynamic mesoscopic hybrid simulation. In addition, a public survey was utilized to collect the data needed for developing the evacuation model. The following sections provide a detailed description of the procedure followed in developing the modeling tool and the needed data.

3.1.1 Modeling approach

To satisfy the objectives of this study, the developed modeling approach should have the ability to estimate the evacuation demand, and the time needed for evacuation, and provide system performance measures for different scenarios. The modeling approach utilized for the purposes of this study was developed in two stages: the development of the transportation system and the development of the evacuation modeling tools. The transportation system includes both the demand and supply sides. The characteristics of demand for travel over the transportation system are determined based on the trip generation and distribution data used in the model, in addition to the trip loading rates. The supply is represented by the modeled roadway network and the associated intersection traffic control, lanes, and speeds needed to determine the capacities of the transportation system to accommodate the demand for travel.

Due to the complex nature of evacuation modeling and traffic management during evacuations, both DYNASMART-P and Citilab's Cube software were used. DYNASMART-P (Version 1.3.0) simulation software was selected because it provides connectivity with UTMS, thus making it efficient to obtain the demand for travel and update the models to reflect new conditions in the field. In addition, it is based on DTA, making it suitable for modeling evacuation scenarios which are dynamic by nature. Also, DYANSMART-P represents a mesoscopic simulation class model that could be used to model traffic on a regional level with reasonable input data requirements while providing the needed level of detail for the purposes of this study.

To develop the hybrid approach utilized for this study, Cube software was used in addition to DYNASMART-P. The Cube software provides a graphical view of the transportation model structure through the Application Manager, which represents a flow chart describing the flow of data from one process to another in the system. In addition, it specifies the different parts of the data that are going to be used as either input or output for different scenarios, making it efficient to manage the data. To build the hybrid model, an interface was developed that enabled the exchange of data and output between Cube and DYNASMART-P software.

3.1.2 Model development

The modeling development primarily consisted of integrating a mesoscopic simulation model (DYNASMART-P) with the regional travel demand model developed in Cube software. The modeling approach utilized for the purposes of this study is developed in several stages. They represent the different steps needed for model preparation and calibration before the model could be used to assist in developing evacuation plans. The following sections summarize the different stages of the modeling approach development.

3.1.2.1 Data Collection: Two types of data were needed to develop the evacuation planning model: data for estimating daily travel demand, and data needed for evacuation modeling. The data needed for regional travel demand modeling were provided by the Census for Transportation Planning Package (CTPP), or through local agencies and various data collection efforts. On the other hand, the data needed for evacuation modeling were not available in the census or the literature and had to be collected through a public survey. A more detailed description of the data needed for model development and evacuation modeling is provided in model calibration and data analysis sections.

3.1.2.2 Model Preparation: The study area was divided into TAZs that were homogeneous in their trip generation characteristics. After that, the roadway network was developed as a set of links and nodes and their corresponding number of lanes, speeds, direction, control, capacity, and other properties.

After the regional travel demand model was built to represent daily traffic, a corresponding mesoscopic simulation model was developed. The simulation model incorporated network geometry and social and economic data. In addition, the signal timing plans were also used as input to account for the traffic operations side of the simulation. The two models were integrated to form the hybrid model using an interface developed for the purposes of this study to facilitate the exchange of data between the two models. This interface prepares the O-D matrix from Cube in the desired format for DYNASMART-P input file. It also prepares the output link travel time from DYNASMART-P to be fed back into Cube. The different steps involved in model preparation are discussed in more detail in the hybrid model development section.

3.1.2.3 Model Calibration: The calibration of the model used for the purposes of this study was performed in two stages: calibration of the regional travel demand model and calibration of the hybrid model. The regional travel demand model was calibrated to reflect travel conditions on the transportation system during an average week day. For the calibration of the hybrid model, the travel time over the links was checked to test the stability of the model runs. Several runs were conducted until convergence in link travel times was achieved, and the overall model was checked in terms of the acceptable levels of error, where the O-D matrix loading rates were adjusted to improve the model performance. Next, the number of simulation runs required was determined based on the variance of the performance measures from simulation results.

3.1.2.4 Model Runs: After the hybrid model was developed and calibrated, hypothetical emergency scenarios were incorporated within the model. The hypothetical scenarios selected for the purposes of this study were determined in consultation with local emergency managers and transportation officials. For each emergency scenario, the location, affected area's shape and boundaries and available warning times were determined. To incorporate the hypothetical emergency scenario within the hybrid model, the necessary revisions to the transportation network were made, and the input O-D matrix and travel demand data were modified for each scenario. Also, traffic control parameters were changed to reflect any traffic management plans used for a particular scenario if applicable. After that, selected system performance parameters were calculated to compare the different scenarios and traffic management options if available.

3.1.3 Daily travel demand data

Traditional travel demand modeling utilizes the Urban Transportation Modeling Systems (UTMS) procedures. The inputs for UTMS involve specifying the characteristics of the activities generating vehicle traffic on the transportation system, while the outputs represent the estimated vehicle traffic flows on the system generated by those activities. The data collected were used to develop models and functions that relate travel behavior to attributes that could be directly forecasted. The data needed for modeling daily travel demand were available either through the CTPP, or developed by local agencies.

The data needed consisted of the transportation network data, the different social and economic data of the modeled area, and the data needed for calibrating and validating the developed model. The network data consisted of the geometry of the roadway network in the area, number of lanes, traffic control, speeds, functional classification, and other attributes needed to represent the roadway network. The social and economic data collected represent the data needed to develop trip generation and distribution models, and were grouped for each traffic analysis zone.

The social and economic data for each TAZ included the number of households, household size, school enrollment, number of jobs by category, and population by age group, in addition to other data needed for model development. As for the data needed for model calibration and validation, they included traffic counts on the major roadways, the number of vehicle miles traveled in the area, trip length distribution, and counts of the number of daily trips crossing the screen lines in the modeled area. After the needed data were either obtained or developed, the process of developing a calibrated regional travel demand model began.

3.1.4 Regional travel demand model

Traditional travel demand modeling is based on the UTMS procedures. The UTMS is utilized to predict the number of trips made, their time of day, trips origins and destinations, the mode of travel used, and the routes used for those trips in the metropolitan area (29). In order to model the study area the transportation network was built, and the study area was divided into TAZs. The TAZs represent the basic units used for estimating trip productions and attractions in the regional travel demand model. The TAZs were used to group areas that have similar social and economic attributes related to trip generation in the study area. For the purposes of this research, the modeled area was divided into 543 internal TAZs. The boundaries for these TAZs were defined by major roadways in the modeled metropolitan area in addition to natural barriers prohibiting the movement of traffic. The case study used for the purposes of this research was the Fargo-Moorhead metropolitan area. Figure 3.1 provides a map of the TAZs representing the modeled area.

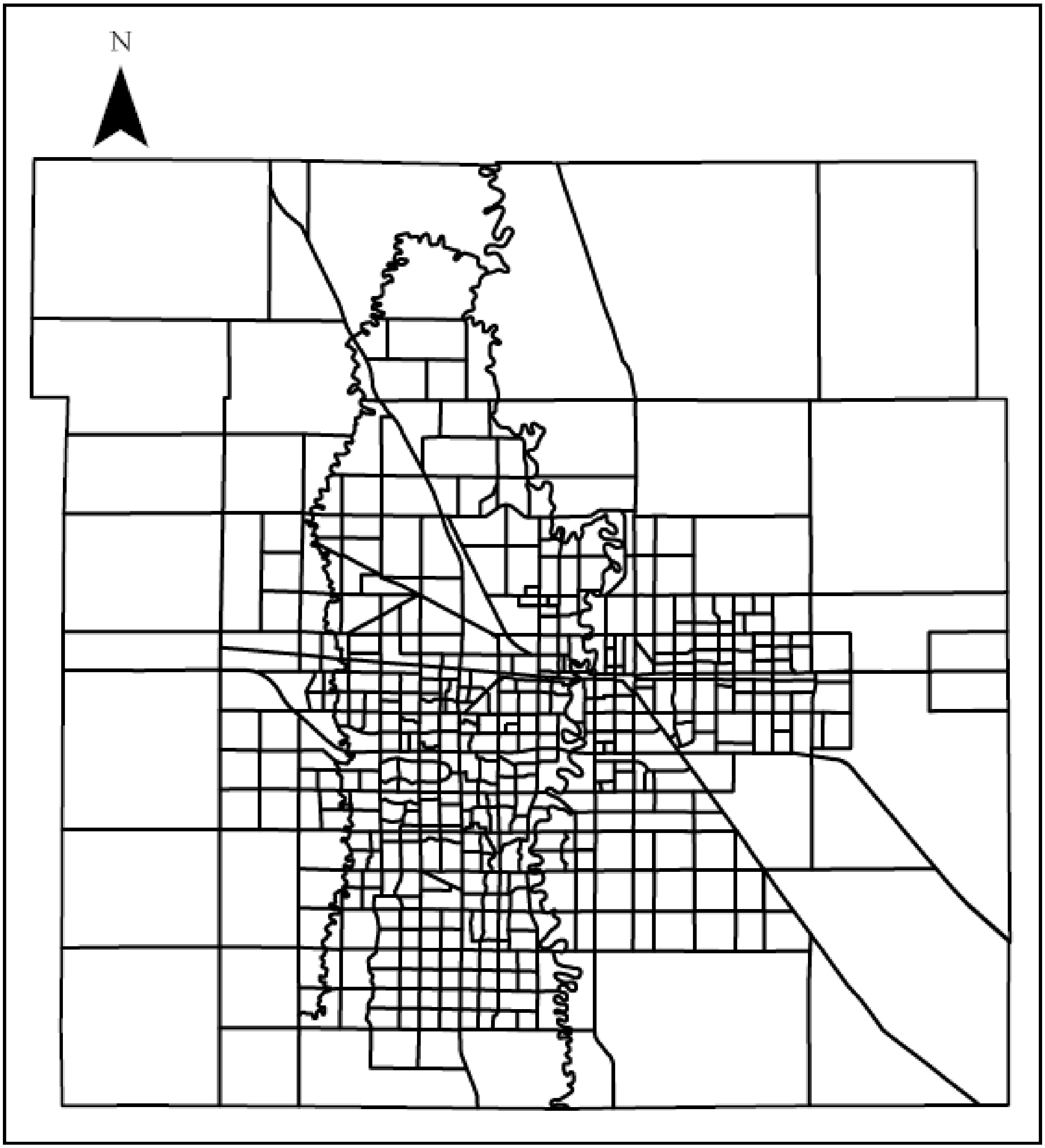

Figure 3.1 The modeled area traffic analysis zones

The transportation network was represented as a set of links and nodes that were assigned different properties, such as number of lanes, speeds, direction, control, capacity, functional class, and turning lanes. There were several steps involved in the process of constructing and calibrating the regional travel demand model; those steps included data preparation, trip generation, trip distribution, mode split, traffic assignment, and model calibration. Figure 3.2 shows the different steps involved in traditional travel demand modeling.

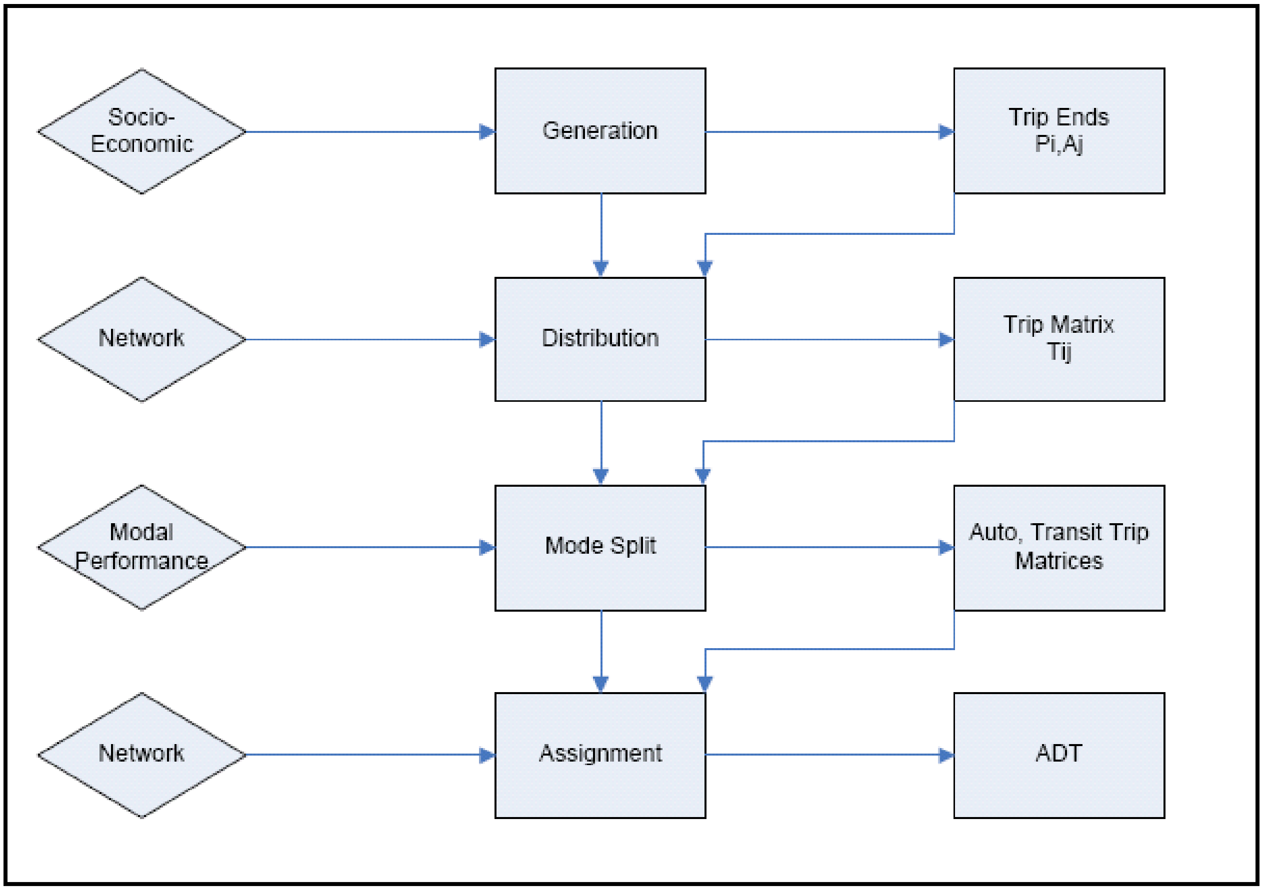

Figure 3.2 The four-step travel demand model

Data preparation was performed before the modeling process started, which included developing the transportation network from geographic information systems (GIS) format and assigning the different parameters to the links, nodes, and TAZs. Another component in the data preparation step was the capacity calculations, where the network links were assigned hourly capacities based on their different attributes. The Highway Capacity Manual (HCM) procedures are usually used in travel demand modeling to determine the capacity and measure travel delays. However, this method has several drawbacks when used for travel demand modeling applications. The HCM procedures depend on the traffic volume and turning percentages for intersection analysis, which are dynamic, making it difficult for the model to converge on a solution (18).

The regional travel demand model utilized HCM capacity equations for rural interstate highways that are based on the number of lanes, percentage of trucks, and speeds (47). For roadways in urban areas, the procedure in chapter ten of the National Cooperative Highway Research Program (NCHRP) report 365 was used (32). The NCHRP capacity calculation are based on the functional class, number of lanes, intersection configuration, left turn lanes, and right turn lanes. Table 3.1 summarizes the capacity values used for the F-M COG travel demand model (1).

Table 3.1 Modeled capacities for urban and rural roads

	Functional Class	One Lane	Multi Lane (Per Lane)	Each Additional lane	Each Right Turn Lane	Each left Turn Lane
	Capacities (Vehicle/Hour/lane)					
Rural	Interstate	-	1,800	-	-	-
	Non-Interstate	1,500	1,700	-	-	-
Urban	Interstate	-	1,700	-	-	-
	Major Arterial/ One-way	1,000	-	800	300	75
	Minor Arterial	675	-	600	200	75
	Collectors/ locals	450	-	400	100	75

After the data preparation step was performed, the next step was trip generation. Trip generation uses social and economic data to predict the number of trips produced by and attracted to each zone within the study area. A trip is defined as the movement between a single origin and a single destination for a single purpose (29). Trip generation rates were based on historical data to estimate the number of trips generated to participate in different activities. The Institute of Transportation Engineers (ITE) Trip Generation Manual provided the needed statistical data and regression models that were used for trip generation (21).

Trip productions in the regional travel demand model were based on the number of single-family and multi-family dwelling units which were obtained from the 2000 census data, in addition to building permit data for the years 2000 to 2005 provided by the F-M COG. The model was used to estimate the number of home-based work (HBW), home-based other (HBO), and non home-based (NHB) trips produced by each TAZ. In order to develop trip attraction estimates, the TAZs were classified as either being within the central business district area (CBD) or within a non central business district area (NCBD).

For university trips generation, major universities in the metropolitan area were treated as special trip generators in the regional travel demand model (1). To account for school trip generation, the population was divided into two different age groups to distinguish between high school- and grade school-aged students for estimating the home-based school (HBS) attraction trips for each category.

In travel demand modeling, the total number of trips produced must be equal to the total number of trip attractions where each production must be coupled with an attraction to form a trip. Trip productions and trip attractions were calculated separately; hence, adjustments were made to make the total productions match the total attractions. Because trip production models provide better estimates of trip rates than trip attraction models, Equations 3.1 and 3.2 are used for trip generation adjustments (29).

$CTP = \sum Pz + \sum Pe - \sum Ae$ **Equation 3.1**

Where: CTP = Control total of productions,
$\sum Pz$ = Trip productions for each zone,

$\sum Pe$ = Trip productions at each external station, and
$\sum Ae$ = Trip attractions at each external station.

$F = CTP / \sum Az$ **Equation 3.2**

Where: F = Adjustment factor,
CTP = Control total of productions, and
$\sum Az$ = Trip attractions at each zone.

The factor resulting from this process for each trip purpose was applied to each TAZ's attraction total to provide the new adjusted attraction values and match the total trip productions and attractions.

After the trip generation step was finished, trip distribution models were used to establish the flow of trips from production zones (trip origins) to attraction zones (trip destinations). The most commonly used type of trip distribution model is called the gravity model. In the gravity model, the number of trips between zones is based on the levels of activity and relative attractiveness of the zones. To account for the impedance to travel, friction factors were used to make shorter trips more desirable than longer ones. Friction factors represent an inverse function of the cost of travel between the trip origin and destination zones.

3.1.5 Regional travel demand model calibration

After the process of developing the regional travel demand model was completed, the calibration and validation of the model began. The calibration of travel demand models is vital for accurately modeling current and future travel patterns in a metropolitan area. In model calibration, the different modeling parameters were adjusted until the predicted travel behavior matched the observed travel behavior for the base case. The process of calibration and error checking is performed at each modeling step to minimize the errors in the overall model. Figure 3.3 illustrates the procedure followed for calibrating the regional travel demand model for the purposes of this research.

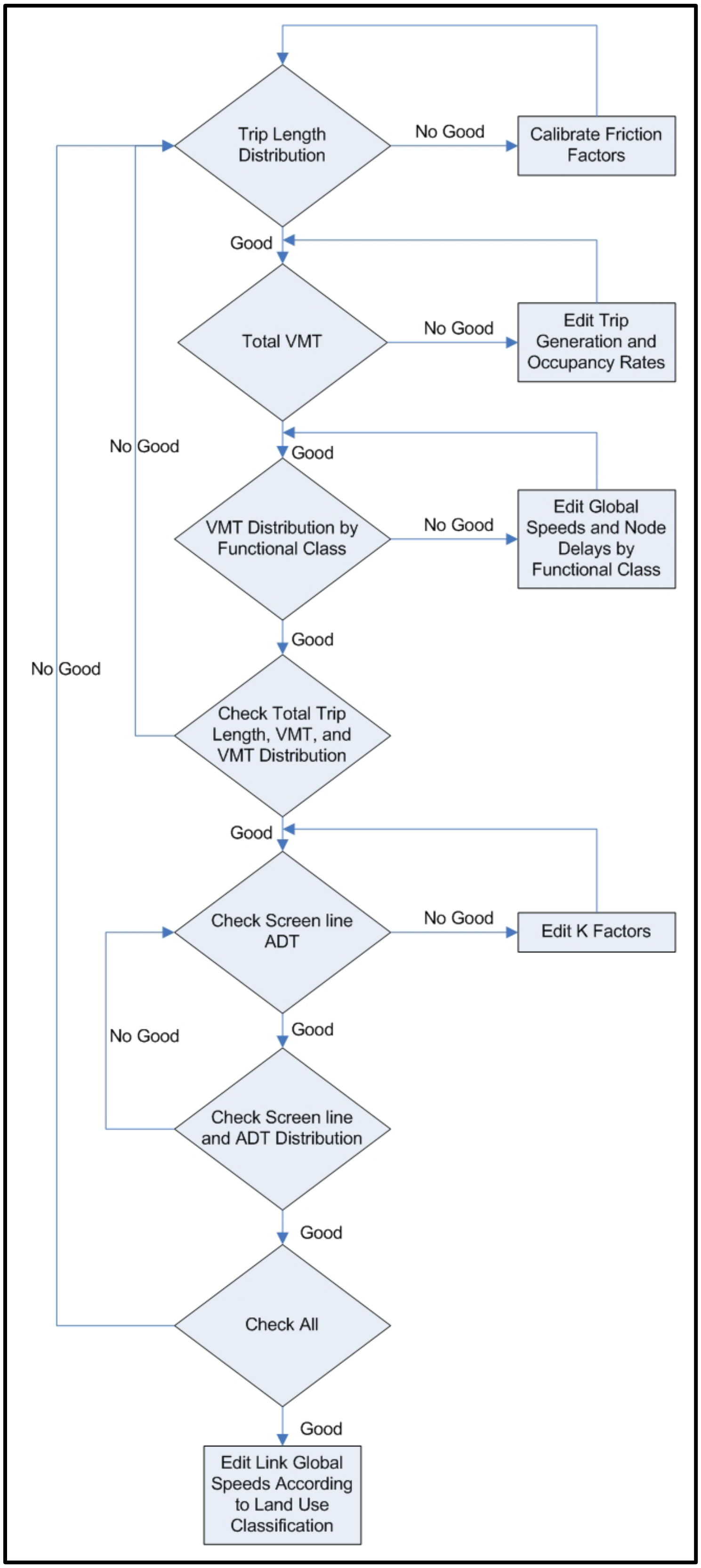

Figure 3.3 Regional travel demand model calibration

The first step in the calibration of the regional travel demand model was to check how the trip length distribution compared with the length of trips provided by the CTPP. The friction factor coefficients were used to make shorter trips more desirable. The length of HBW, HBO, and NHB trips were compared with data obtained from the census, and friction factor coefficients were adjusted until the two data sets matched.

After the modeled trip length distribution matched the census data, the vehicle miles traveled (VMT) were calibrated. The VMT in the regional travel demand model are a function of the number of trips generated in the model and their corresponding trip lengths in miles. To calibrate the VMT values, the total VMT values for the entire metropolitan area were checked against the reported VMT values. The trip generation rates were adjusted to change the total number of trips generated on the transportation system until the modeled and reported VMT values were similar. After the total VMT values were adjusted, the modeled VMT values by roadway functional class were calibrated to match the reported values. If the modeled VMT did not match the reported VMT for a certain roadway functional class, then the global speeds and node delays were adjusted until they were within criteria.

To calibrate for trips distribution between different parts of the modeled area, screenline counts were used. Screenlines are long imaginary traffic analysis lines that bisect the entire modeled region, and they are usually represented by major roadways or geographic barriers. For the case study, the screenlines used included I-29, I-94, the Red River, and the main railroads tracks. If the total modeled traffic screenline volume was above the specified criteria, a lower k factor was assigned to inhibit traffic from crossing the screenline. Similarly, if the screenline had a total modeled traffic volume below the designated criteria, a higher k factor would be applied to the affected zones. This made zonal pairs that cross the screenline more attractive. After achieving an accurate screenline distribution, the calibration process was repeated, starting with checking the trip length distribution, until all the successive calibration components were completed.

The last stage of the regional travel demand model calibration is to check the roadways' modeled average daily traffic (ADT) against the actual traffic count data from the field. If the difference between the modeled and observed traffic volumes was significant, then global speeds were adjusted based on the area's land use characteristics. The root mean square error (RMSE) was then used to determine the overall difference between modeled and observed daily traffic volumes on the roadway links. Also, the coefficient of correlation (R2) was used to check for correlation between modeled and observed roadway traffic volumes.

3.1.6 Development of the mesoscopic simulation model

Following the development and calibration of the regional travel demand model, a corresponding mesoscopic simulation model was prepared for the modeled area. The mesoscopic simulation model (DYNASMART-P) was integrated with the regional travel demand model developed in Cube software. The simulation model used network geometry data, and the demand data represented by the O-D matrix from the regional travel demand model. In addition, the traffic signal timing plans were used as input data to account for the traffic operations characteristics in the modeled area.

The network geometry data included the roadway number of lanes, turning lanes, free-flow speeds, and other attributes. These data were developed earlier for the travel demand model and were exported directly from the GIS data base into DYNASMART-P using the DYNASMART-P editor (DSPED). The control data consisted of the locations and types of traffic control devices in the modeled regional network, in addition to the traffic signal timing plans. The locations and types of traffic control devices were developed from the GIS data base using DSPED, while the signal timing plans were coded manually after being provided by local transportation agencies. The demand data for the simulation model consisted of O-D tables from the regional travel demand model. The traffic volume data from several counting stations were studied to determine the loading rates for the simulation model.

After the simulation model was developed, the model was checked for errors that may occur in the coding of the demand, network data, and model parameters. The process of error checking for simulation models involves checking for software and input coding errors, as well as visual observations from the simulation animation. The error check for input data included checking the connectivity of the modeled roadway links, their number of lanes, functional classification, capacities, traffic controls at the intersections, prohibited movements, and free-flow speeds. For checking the volume-demand data, the trip generation zones were checked, in addition to the origins and destinations of the trips in the modeled transportation network. Finally, the simulation model was run with the required network loading time (seed time) and simulation periods and visually inspected for any errors or unexpected model output.

3.1.7 Development and calibration of the hybrid model

After a functional mesoscopic simulation model was developed for the base year, it was integrated within the regional travel demand model to form the hybrid model used for the purposes of this study. To facilitate the exchange of data between the two models, an interface was developed that allowed for input and output data transfer between the two models. The interface was used to prepare the O-D matrix from Cube in the desired format to be used as input for the simulation model. Also, the interface was used to prepare the roadway link's travel times and traffic volumes from the simulation model to be fed back into the regional travel demand model.

To prepare the O-D matrix from the regional travel demand model that was used in the simulation model, several files were coded using TP+ programming language to extract the required O-D matrices for the AM peak, PM peak, and off peak periods in the desired format for the simulation model. As for the feedback from the simulation model into the regional travel demand model, the travel time over the roadway links from the mesoscopic simulation were prepared in a format that is compatible with Cube software. The travel times were assigned to the network roadway links in the regional travel demand model using several programs that were coded in TP+ programming language. That process included skimming the link IDs from the Cube modeled network, assigning the travel time to each link, and finally producing new travel time and distance matrices for the modeled network. The general structure of the hybrid model is shown in Figure 3.4.

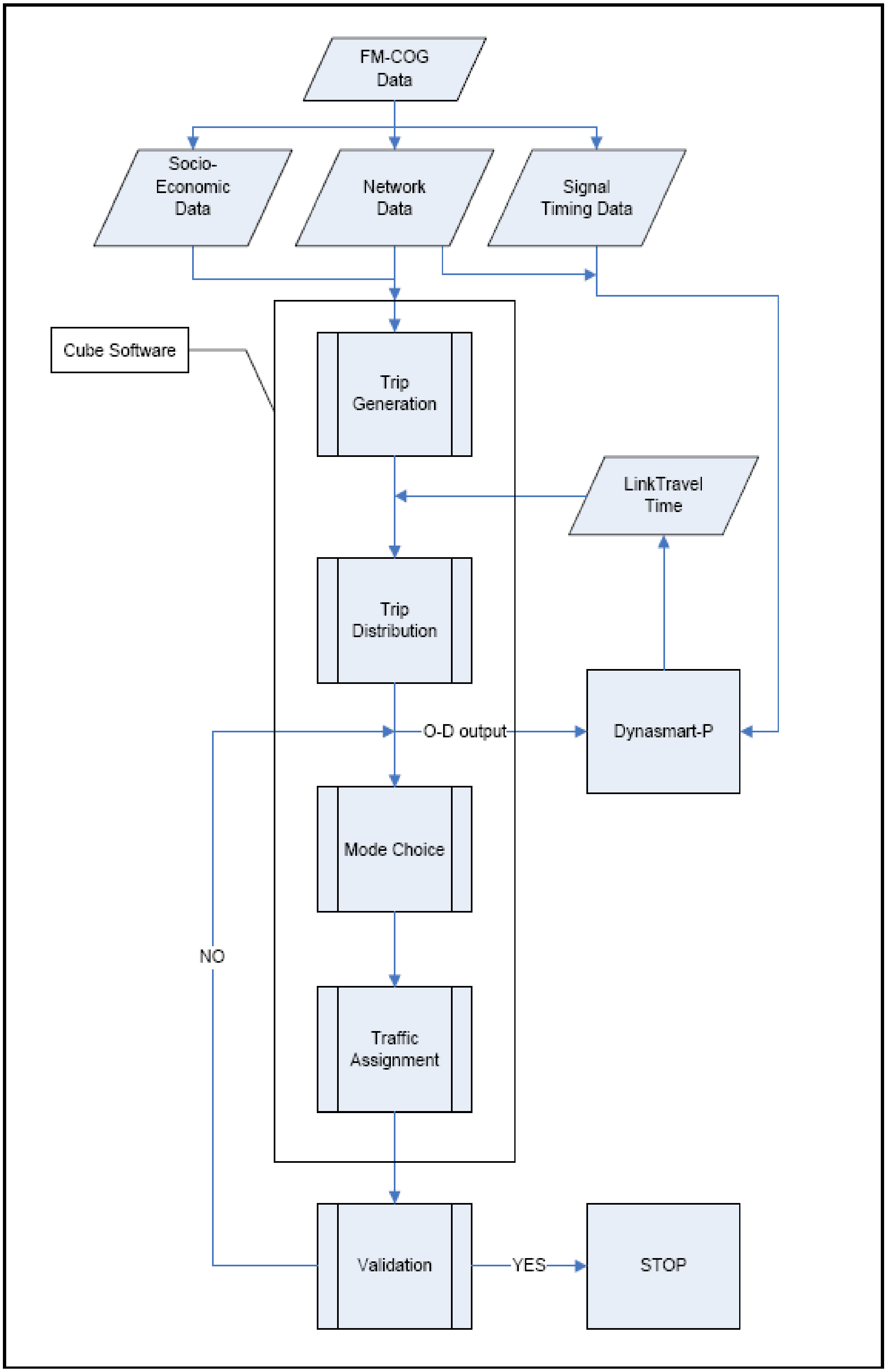

Figure 3.4 The structure of the hybrid model

The feedback from the mesoscopic simulation model into the regional travel demand model was in the form of new travel times over the roadway links based on the output from the simulation. The regional travel demand model used the Bureau of Public Roads (BPR) volume delay functions to estimate the congested travel times over the links. The new travel times are different than those estimated in the regional travel demand model based on static volume-delay functions.

After the new travel times were fed back into the regional travel demand model, the distribution of the trips between O-D pairs was performed based on the new travel times, resulting in an O-D matrix. The new O-D matrix was fed back into the simulation model and a new model run was performed, where the new travel times from that run were fed back into the regional travel demand model again. The process of feeding the new O-D matrices into the simulation model, and the new roadway travel times into the regional travel demand model, was repeated until convergence in the roadway travel times was achieved. After convergence in the travel times between the hybrid model runs was achieved, the model was checked for errors where the average travel times and traffic volumes assigned for roadways were checked against observed values. To check for convergence in the roadway travel times between different iterations, Equation 3.3 was used.

$$\sqrt{\frac{\sum_{l=1}^{L}\sum_{t=1}^{T}(\Sigma Q_i^{l,t} - \Sigma Q_{i-1}^{l,t})^2}{N_l Nt}} < \in \qquad \textbf{Equation 3.3}$$

Where: $\Sigma Q_i^{l,t}$ = Equilibrium travel time over the link,

$\Sigma Q_{i-1}^{l,t}$ = Equilibrium travel time over the link from the previous iteration,

N_{l_t} = Number of links,

Nt = Number of time intervals, and

$\in$ = Critical value to reach convergence.

3.1.8 Emergency evacuation scenario modeling

Following the development and calibration of the hybrid model to the base case conditions, hypothetical emergency scenarios were incorporated within the hybrid model. The transportation system conditions during regional evacuations are complex and different than daily traffic conditions. Hence, modeling hypothetical emergency scenarios requires the collection of travel demand data that is different than what is used for modeling trips made to participate in daily activities. Data were collected for each modeled emergency evacuation scenario to estimate number of evacuating trips and the origins and destinations of those trips. A detailed description of the data collection and analysis efforts are provided in the next section.

To incorporate the hypothetical emergency evacuation scenario within the hybrid model, the necessary revisions to the transportation network were made. Also, the input O-D matrix and travel demand data were modified for each scenario to reflect the population response to evacuation orders. In addition, traffic control parameters were changed to reflect any traffic management plans that were used for a particular scenario if applicable. The process of incorporating the hypothetical emergency evacuation scenario within the hybrid model is illustrated using the case study.

The evacuation trip production and attractions rates were used as input into the regional travel demand component of the hybrid model to obtain the O-D matrix representing the evacuation trips between different zonal pairs. The O-D matrix, in addition to the trip loading rates developed for the evacuation scenario, were used as input for the simulation component of the hybrid model. After that, selected system performance parameters were calculated based on output from the hybrid model runs to compare the different scenarios and traffic management options if available. The system performance data collected consisted of evacuation time estimates, average travel times, and average travel speeds for the different modeled evacuation scenarios. Figure 3.5 illustrates the process used to model emergency evacuations using the developed hybrid model.

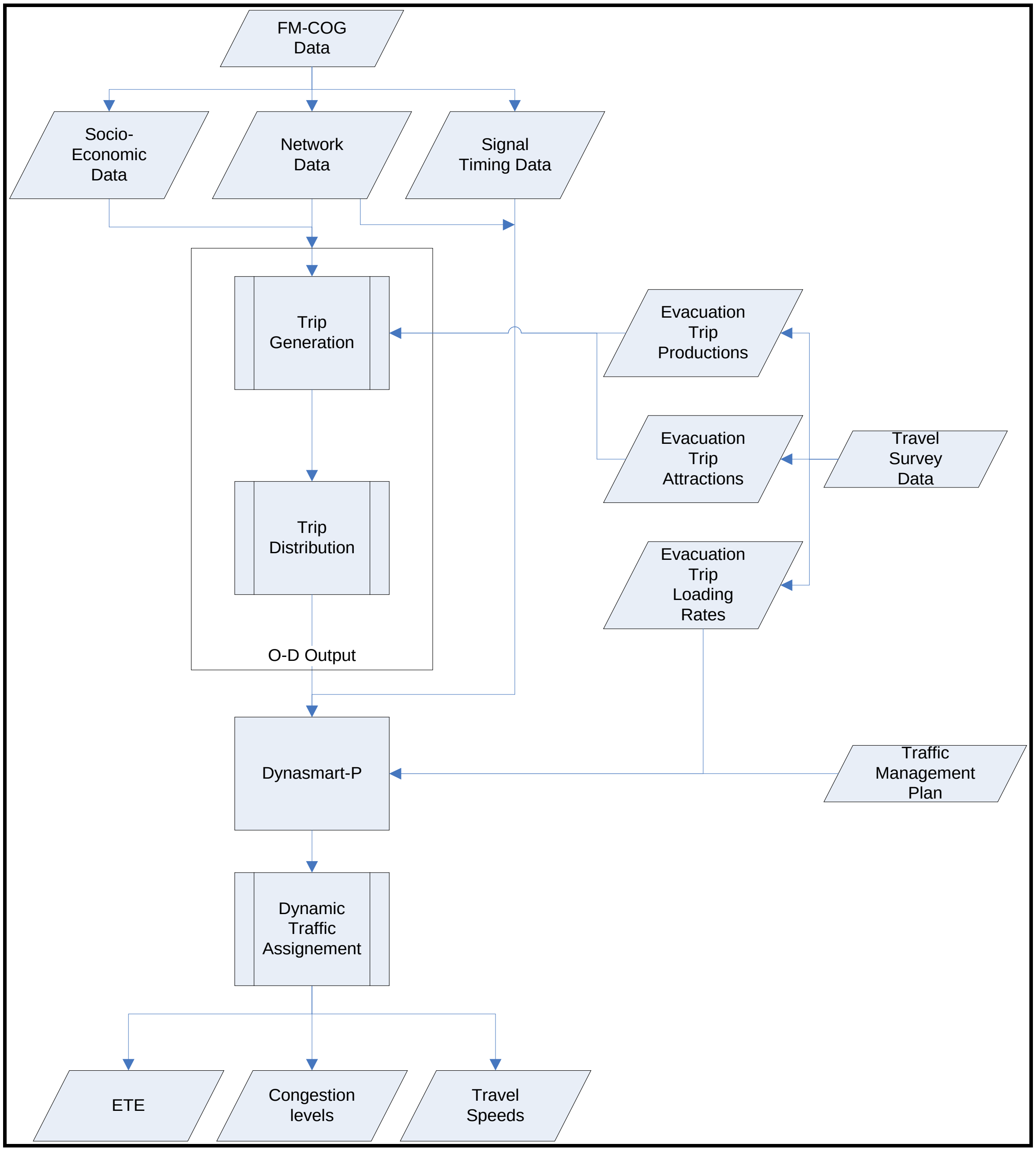

Figure 3.5 Evacuation modeling methodology

3.2 Human Behavior Data Collection

It is vital to identify the different parameters influencing the travel decisions of individuals during emergency evacuations to model the changes in the travel demand over the transportation system. The reliability and accuracy of the output from evacuation models rely on the ability to model the actual evacuee's behavior, and their response rates to evacuation orders. In addition, human behavior data were collected to be used as input for the hybrid model. The data were analyzed and used to develop trip generation rates and travel demand levels, in addition to evacuee's response rates that were not available in the literature and were needed for modeling the evacuation scenario.

This study will evaluate two modeling scenarios. The first scenario will evacuate the Fargodome parking lots and act as an initial test of the hybrid model. The second scenario, which is the primary scenario of this study, will evaluate a regional evacuation triggered by river flooding. After consulting with the stakeholders and to link the modeling efforts to possible local threats, it was decided to model the regional evacuation event triggered by the flooding of the Red River of the North. The scenario represented evacuating the area within the 100-year flood plain in the Fargo-Moorhead metropolitan area triggered by a levee breach or overflow.

3.2.1 Data collection

Faced by the lack of data and performance measures related to transportation security, there was a need to develop accurate input data to improve the accuracy and reliability of the model output. To generate the needed data, a public survey was administered by mail where respondents were asked to mail their responses back in prepaid envelopes (mail-in/mail-back method). The survey was a stated response survey category, which was discussed in detail in Section 2.

3.2.2 Survey population and sampling

The surveyed population included the households located within the 100-year flood plain in the Fargo-Moorhead metropolitan area. After the evacuation area boundaries were identified, the mailing addresses for the households located in that area were provided by the city of Fargo, ND, and the city of Moorhead, MN. Of the approximately 57,000 households in the Fargo-Moorhead metro area (2005), 20,613 were located within the evacuation area, which represents 36% of the households. After the survey population was identified, the sample size was determined using Equation 3.4 (19). Based on Equation 3.4 and using a 95% level of confidence, the needed sample size was determined to be 377 responses. There were 1,500 surveys sent in October 2008, and 454 responses were returned; out of which, 437 provided usable data for the purposes of this study.

$S = [P(1-P)/[(A^2/Z^2\ ) + (P(1-P)/N)]$ **Equation 3.4**

Where: S = Sample sSize,
N = Population size,
P = Estimate of the percentage of people in population interested (50% was used as a conservative estimate,
A = Level of accuracy (0.05 was used), and
Z = Number of standard deviations of the sampling distribution.

3.2.3 Survey design and administration

At the design stage, the survey method, the associated time frame, and budget requirements were established. The design of the survey has a significant effect on the response rates and accuracy of the data obtained. The survey was designed to be as short as possible, keeping the directions and questions simple, clear, objective, and complete. To increase the response rates, the survey included a cover letter to explain the purpose and benefits of the survey, mentioned the partnership with both Cass and Clay County Emergency Management Centers, and a respondent friendly questionnaire and map (note Appendix A).

The final survey used consisted of a two-page (eight questions) questionnaire and a map showing the evacuation area and possible evacuation destinations. The survey questions were designed to provide the following data:

1) Households that will comply with evacuation orders
2) The estimated time needed to prepare for evacuation
3) Number of vehicles used in the evacuation process
4) Evacuation destination category
5) Number of zone that represents their evacuation destination
6) Household category

The data provided by the respondent were used for the following purposes:

1) Trip generation:
   a) % of single-family households that will evacuate
   b) % of multi-family households that will evacuate
   c) Average number of vehicles used in the evacuation trip for each household category
2) Trip distribution:
   a) % of single-family household that will evacuate to each zone
   b) % of multi-family household that will evacuate to each zone
3) Trip loading rates:
   a) % trips evacuating at each time step (mobilization time)
4) General questions:
   a) Does the category of the household affect the probability of complying with evacuation orders?
   b) Does the category of the household affect the time needed for evacuation?
   c) Does the number of vehicles used in the evacuation affect the time needed for evacuation?

3.2.4 Data analysis

After the survey design was finished, the survey was administered and data collection from the population sample began. While the key survey results are located in the following section, Appendix B contains the complete survey results. The results from the survey responses were coded into the system, and the data were tested and cleaned to keep the usable data. Afterward, the data were processed and prepared to be analyzed. The responses were compiled in a Microsoft Office Access database using a form prepared in Visual Basic. The Visual Basic form was designed to reduce the possibility of human errors while compiling the data from the survey.

3.2.4.1 Trip generation: To estimate the demand for travel over the transportation system during emergency evacuation events, the percentage of households evacuating the area and the number of vehicles used by each household were analyzed. For the purposes of this study, special facility population trips were not included in the simulation due to their minimal effect on the performance of the system, where they are evacuated early during the event by air or special transportation. The households were categorized by their size as being single-family or multi-family households. Tables 3.2 and 3.3 summarize the data related to trip generation obtained from the sample response.

Table 3.2 Households Compliance with Evacuation Orders

# Single-Family HH Comply	389	# Single-Family HH Not Comply	25
# Multi-Family HH Comply	23	# Multi-Family HH Not Comply	0
# Total HH Comply	412	# Total HH Will Not comply	25

Table 3.3 Compliance Rates by Household Category

Household Type	% Comply	% Not Comply	Total
Single-Family HH	94.0%	6.0%	100.0%
Multi-Family HH	100.0%	0.0%	100.0%

From Tables 3.2 and 3.3, most of the respondent (94.3%) stated that they will comply with evacuation orders when issued. However, people who live in houses were more reluctant to leave than those living in apartments. The rationale is that some of the single-family household's residents reported they want to stay and protect the property, and minimize the damage as much as possible.

After determining the percentage of households that will comply with the evacuation orders, the number of vehicles used for evacuation per household was determined. From the sample obtained, it was found that the average number of vehicles used in the evacuation was 1.62 vehicles/household. Tables 3.4 and 3.5 summarize the data related to the number of vehicles used during the evacuation.

Table 3.4 Number of Vehicles Used per Household for Evacuation

# of Vehicles Used for Evacuation	Number of Households	% Total
0	0	0.0%
1	189	45.9%
2	192	46.6%
>=3	31	7.5%
Total	412	100.0%

Table 3.5 Number of Vehicles Used for Evacuation by Household Category

# of Vehicles Used	# of Single-Family Households	% of Single-Family Households	# of Multi-Family Households	% of Multi-Family Households
0	0	0.0%	0	0.0%
1	171	44.0%	18	78.3%
2	187	48.0%	5	21.7%
>=3	31	8.0%	0	0.0%
Total	389	100.0%	23	100.0%
Average/HH	1.64	Vehicles/HH	1.22	Vehicles/HH

The data obtained from the survey were classified as categorical where the conditions of multinomial experiments were satisfied (26). Hence, the suitable method for analyzing the data was by using one-way and two-way table's analysis. To check if the household category affected the average number of vehicles used during emergency evacuations, the Chi-Square test was used. The first test was to check if the proportions of people using a certain number of vehicles were significantly different. After that, the test was performed to check if the proportions of people using a certain number of vehicles were statistically significantly different from one household category to the other. The Chi-Square test was performed at a confidence level of 95% (α=0.05) with the following assumptions:

Ho: $P_1=P_2=P_3$
Ha: At least one of them is different

Test statistic: $\chi^2 = \sum [n_i - E_i]^2 / E_i$ **Equation 3.5**
Rejection region: $\chi^2 > \chi^2_{(0.05)}$ with (k-1) degrees of freedom

Where: Ho: The null hypothesis (the percentages of people using a certain number of vehicles for evacuation are the same),
Ha: The alternative hypothesis (at least one of the percentages is different),
P_i: Represents the hypothesized values for multinomial probabilities (percentage using a certain number vehicles for evacuation),
$E_i = nP_i$ and it represents the expected cell count,
n : The total sample size, and
k: The number of categories.

From Table 3.5:
χ^2 = 123.529
Degrees of Freedom (D.F.) = 3-1 = 2

From the Chi-Square tables, with α=0.05 and D.F.=2, χ^2 = 5.99147 (within the rejection region). The null hypothesis was rejected based on the data provided in Table 3.6. Hence, it was concluded that at least one of the proportions of the number of vehicles used during emergency evacuations was significantly different than the others.

Table 3.6 Chi-Square Goodness-of-Fit Test for Categorical Variable

Category	**Observed**	**Test Proportion**	**Expected**	**Contribution to Chi-Sq**
1	189	0.333333	137.333	19.4377
2	192	0.333333	137.333	21.7605
3	31	0.333333	137.333	82.3309
N	N*	DF	Chi-Sq	P-Value
412	0	2	123.529	0

To test if the number of vehicles used for the evacuation was independent from the type of the household, the two-way (contingency) table analysis was used. The test was performed at α=0.05 (95% Confidence Interval) with the following assumptions:

Ho: The two classifications are independent
Ha: The two classifications are dependent

Test statistic: $\chi^2 = \sum [n_{ij} - E_{ij}]^2 / E_{ij}$ **Equation 3.6**
Rejection region: $\chi^2 > \chi^2_{(0.05)}$ with [(r-1)*(c-1)] degrees of freedom

Where: $E_{ij} = (R_iC_j)/n$,
r : The numbr of categories of the first classification, and
c : The number of categories of the second classification

At α=0.05 and D.F.=2, χ^2 = 5.99147 (within the rejection region). The null hypothesis was rejected based on the data summarized in Table 3.6. Hence, the conclusion based on the Chi-Square test was that different household categories use different average number of vehicles for evacuations.

Table 3.7 Chi-Square Test for Number of Cars Used vs. Household Type

HH \ Cars	1	2	3	Total
1	171	187	31	389
	178.45	181.28	29.27	
	0.311	0.18	0.102	
2	18	5	0	23
	10.55	10.72	1.73	
	5.259	3.051	1.731	
Total	189	192	31	412

In Table 3.7, the expected counts were printed below observed counts and Chi-Square contributions were printed below expected counts. The χ^2 value was 10.634 with two degrees of freedom, while the P-Value was (0.005), and one cell with an expected count less than 5. Based on the survey results, Equation 3.7 was used for the evacuation trip generation.

Number of trips = 1.64*(evacuating single-family HH) + 1.22 * (evacuating multi-family HH)
Equation 3.7

3.2.4.2 Trip distribution: After the demand for travel during the emergency event was estimated, the destinations for evacuation trips were determined based on data from the survey responses. The modeled area was divided into 15 possible internal destinations and four destinations outside the metropolitan area. The survey respondents were asked to choose the zone they would most likely evacuate to if the authorities issued the evacuation order for a flood event. Figure 3.6 shows the different possible evacuation destinations.

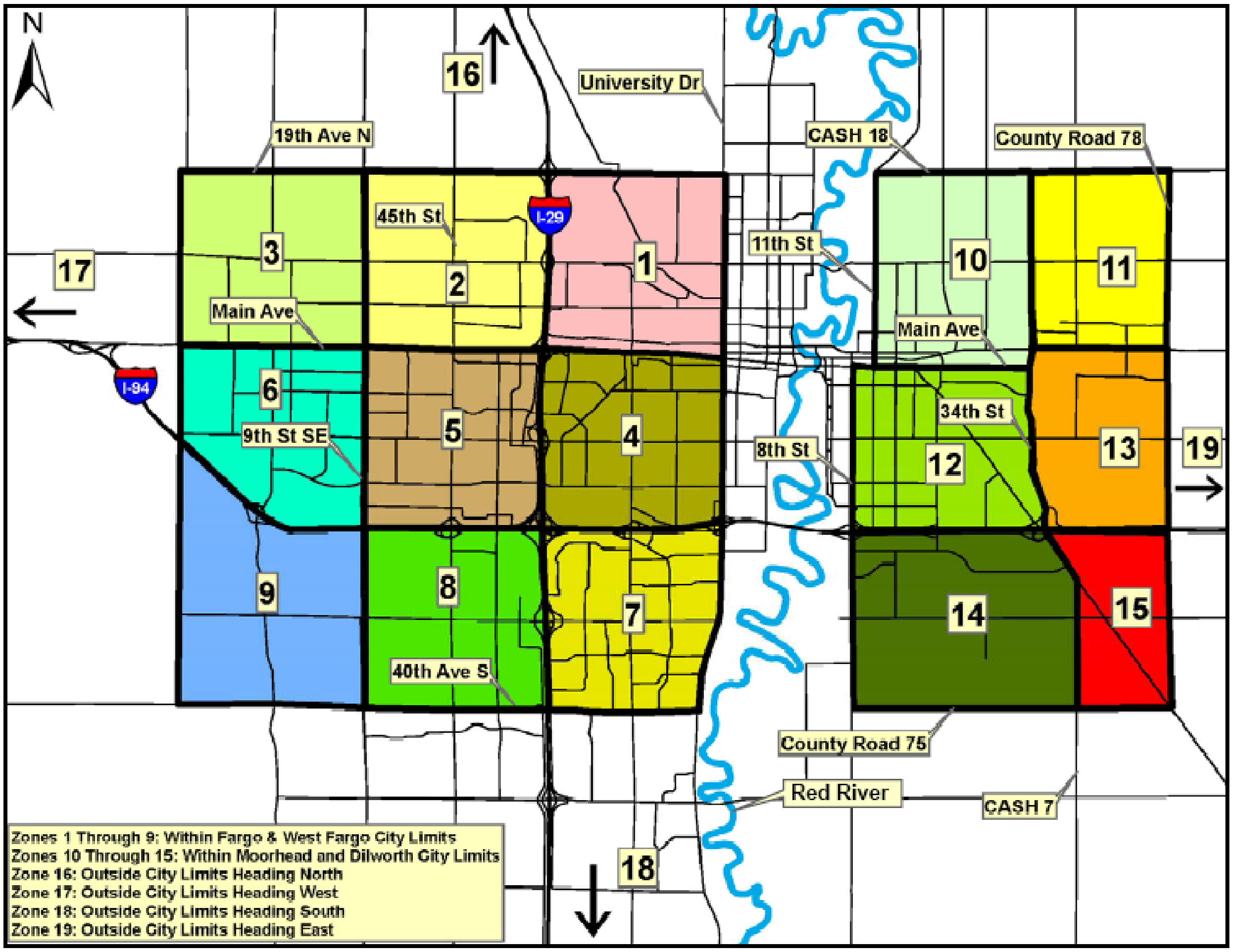

Figure 3.6 Evacuation destinations for a flood event

Some of the evacuation zones were chosen by less than five respondents, however, for statistical analysis purposes at least five respondents need to pick a certain zone. To eliminate zones that have less than five responses, the responses from those zones were added with neighboring zones. Table 3.8 summarizes the survey respondent's choice of evacuation destinations.

Table 3.8 Households Choice of Evacuation Destination (Modified)

Zone Number	**1**	**2+3**	**4**	**5**	**6+9**
Frequency	37	6	27	25	12
Percentage	8.98%	1.46%	6.55%	6.07%	2.91%
Zone Number	**7**	**8**	**10**	**11+13+15**	**12**
Frequency	15	12	7	6	11
Percentage	3.64%	2.91%	1.70%	1.46%	2.67%
Zone Number	**14**	**16**	**17**	**18**	**19**
Frequency	17	52	48	29	108
Percentage	4.13%	12.62%	11.65%	7.04%	26.21%

The data were tested to check if the proportions of the population evacuating to a certain destination were statistically significantly different from one zone to another. Since the data were classified as categorical and the conditions of multinomial experiments applied to it, a one-way table method was used to analyze the data. The test was performed at α=0.05 (95% Confidence Interval) using Equation 3.5. Table 3.9 provides a summary of the results of the Chi-Square test used for this analysis. The hypothesis used for the Chi-Square test includes the following:

Ho: $P_1=P_2=P_3= \ldots\ldots = P_{15}$
Ha: At least one of them is different

From Table 3.8:

$\chi^2 = 363.631$
D.F. = 14

From the Chi-Square tables, with α=0.05 and D.F.=14, $\chi^2 = 23.6848$ (within the rejection region). The test showed that the null hypothesis was rejected, and that at least one of the proportions was significantly different than the others.

Table 3.9 Chi-Square Goodness-of-Fit Test Destination Choice

Category	Observed	Test Proportion	Expected	Contribution to Chi-Sq
1	37	0.0666667	27.4667	3.309
2	6	0.0666667	27.4667	16.777
4	27	0.0666667	27.4667	0.008
5	25	0.0666667	27.4667	0.222
6	8	0.0666667	27.4667	13.797
7	15	0.0666667	27.4667	5.658
8	12	0.0666667	27.4667	8.709
10	7	0.0666667	27.4667	15.251
11	6	0.0666667	27.4667	16.777
12	15	0.0666667	27.4667	5.658
14	17	0.0666667	27.4667	3.989
16	52	0.0666667	27.4667	21.913
17	48	0.0666667	27.4667	15.35
18	29	0.0666667	27.4667	0.086
19	108	0.0666667	27.4667	236.127
N	N*	DF	Chi-Sq	P-Value
412	0	14	363.631	0

Since most of the cells have less than five counts in the “multi-family” household category, no Chi-Square test was performed to check if the category of the household affected the choice of destination zones in cases of regional emergency evacuations. Hence, the percentage of trips made to each destination was used for the evacuation trip distribution. Table 3.10 summarizes the results for the trip distribution step.

Table 3.10 Percentages Evacuating to Each Destination by Household Category

Zone	**1**	**2+3**	**4**	**5**	**6+9**
Single-Family HH	9.25%	1.29%	6.43%	6.43%	2.83%
Multi-Family HH	4.35%	4.35%	8.70%	0.00%	4.35%
Zone	**7**	**8**	**10**	**11+13+15**	**12**
Single-Family HH	3.60%	3.08%	1.54%	1.29%	2.57%
Multi-Family HH	4.35%	0.00%	4.35%	4.35%	4.35%
Zone	**14**	**16**	**17**	**18**	**19**
Single-Family HH	4.11%	12.08%	12.08%	6.94%	26.48%
Multi-Family HH	4.35%	21.74%	4.35%	8.70%	21.74%

From the survey responses, 57.52% of the total evacuees would leave the metro area. Although the destinations differ between household category, 56.53% of the multi-family evacuees and 57.58% of the single-family evacuees would leave the Fargo-Moorhead area.

3.2.4.3 Trip loading rates: Due to the dynamic nature of the emergency evacuation problem, the trip loading rates are very important to achieve realistic representation of the traffic conditions in the modeled area. In the hybrid model, traffic data were examined for 14 major intersections in the modeled area to determine the trip loading rates during daily peak hours. For evacuation trips loading rates, respondents were asked to provide estimates of their mobilization, which is shown in Table 3.11.

Table 3.11 Time Needed to Prepare of Evacuation

1-15 min.	**16-30 min.**	**31-45 min.**	**46-60 min**	**>60 min.**
23	88	80	112	109
5.6%	21.4%	19.4%	27.2%	26.5%

The data from the survey were compared to the estimated data using the Kolmogorov-Smirnov two-sample test. The test statistic (T) represents the maximum difference between the two cumulative distributions being compared to determine if they have the same distribution. The null hypothesis was that both data sets have the same distribution, and the alternative hypothesis was that they are different. The value of the test statistic was 0.15498 and the critical value of (T) at a 95% level of confidence was 0.2935. Hence, the null hypothesis could not be rejected since the two distributions were not statistically different.

3.2.4.4 Data comparison: The data collection and analysis showed that there was a distinct variation in the response and behavior of small- and medium-size urban areas from that of inhabitants of large cities. The data collected for evacuee's behavior provided rates that were different than the averages discussed in Section 2, which were mainly based on data obtained from hurricane regions evacuations and surveys. In addition, the trip loading rates function developed in this study was different than the general function provided in the literature.

Several estimates were reported in the literature of the average number of vehicles used per household during emergency evacuations, where an average of 1.3 vehicles was used in the literature (23). Ruch and Schumann (1997) estimated the number of evacuating vehicles to be 1.35 based on a behavioral survey, while Prater et al. (2000) reported a rate of 1.34 vehicles per HH for Hurricane Bret (28). The data obtained from the survey used in this study showed that an average of 1.62 vehicles per household was estimated to be used in cases of regional emergencies. Also, the survey data showed that multi-family households reported an average of 1.22 vehicles per household, while single-family households reported an average of 1.64 vehicles per household.

The evacuation trips loading rates are determined by the time families need to prepare and leave the household after receiving the evacuation orders. The evacuation trip loading rates have a significant effect on the performance of the transportation system performance during emergency evacuations. Figure 3.7 shows how the curve representing the fitted data from this study compared with the data developed by Tweedie et al. (5). It is shown from the figure that evacuation trips are loaded at a higher rate using the function developed by Tweedie et al. than the function developed from the survey data. The evacuation trip loading rates affect the congestion levels and the clearance time needed by evacuees during emergency evacuations.

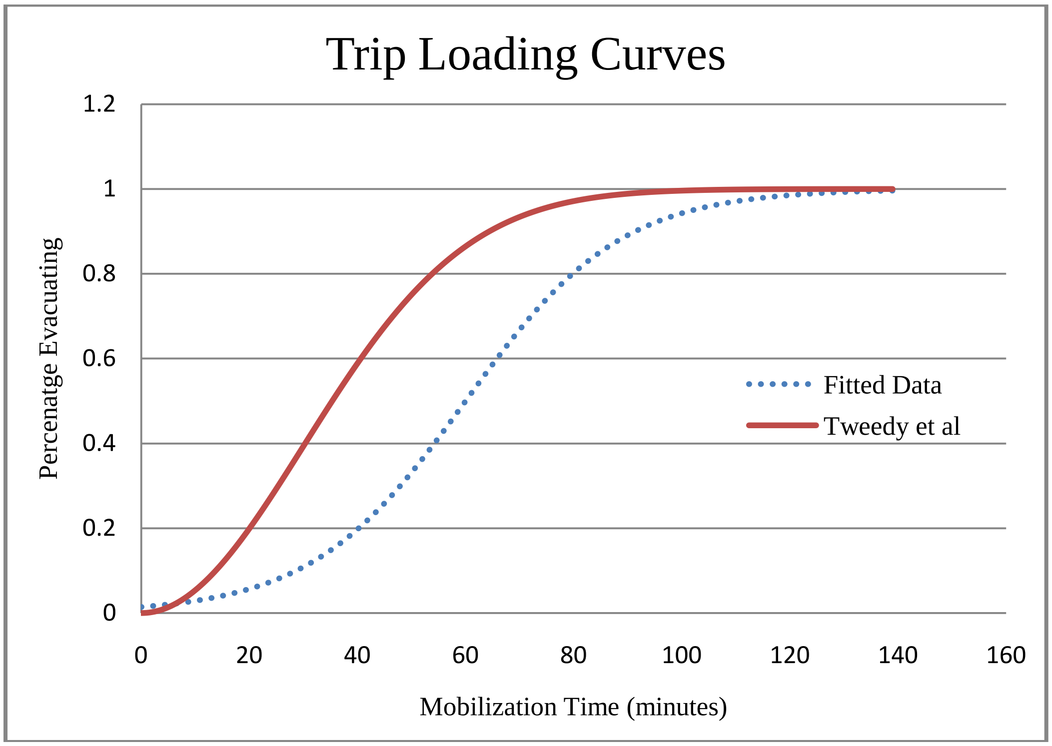

Figure 3.7 Mobilization time curves

4. CASE STUDY AND MODELED SCENARIOS

This section provides a description of the case studies used for this study. It illustrates how the modeling approach was used to develop different emergency evacuation scenarios, and it summarizes the case study results. In addition, this section provides a discussion of the study results and the conclusions based on those results.

4.1 Case Study

For the purpose of this study, the 2005 regional travel model for the Fargo-Moorhead (F-M) area was used. The F-M model consists of 568 Traffic Analysis Zones (TAZs) and a network of 1,709 nodes that are connected by 2,412 links. The modeled area includes four jurisdictions: the cities of Fargo and West Fargo in North Dakota, as well as Moorhead and Dilworth in Minnesota. The total population for the metropolitan area was estimated at 190,500 in 2005 with a projected annual growth rate of 1% over the next 30 years (16). Figure 4.1 shows the modeled area.

The F-M travel demand model was chosen for this study because it provided the adequate size and level of detail that is sufficient for the purpose of this study. In addition, the availability of data, which were provided either through the Fargo-Moorhead Council of Governments (F-M COG) or through the Advanced Traffic Analysis Center (ATAC), played a role in selecting the model.

This study explored the use of DYNASMART-P, which is recognized by the FHWA for evacuation applications in conjunction with the traditional four-step travel demand model. The value of this approach is in utilizing the available data and modeling resources to develop evacuation models that are cost efficient, relatively easy to develop and update, and capable of capturing traffic and drivers' behavior under different traffic management measures.

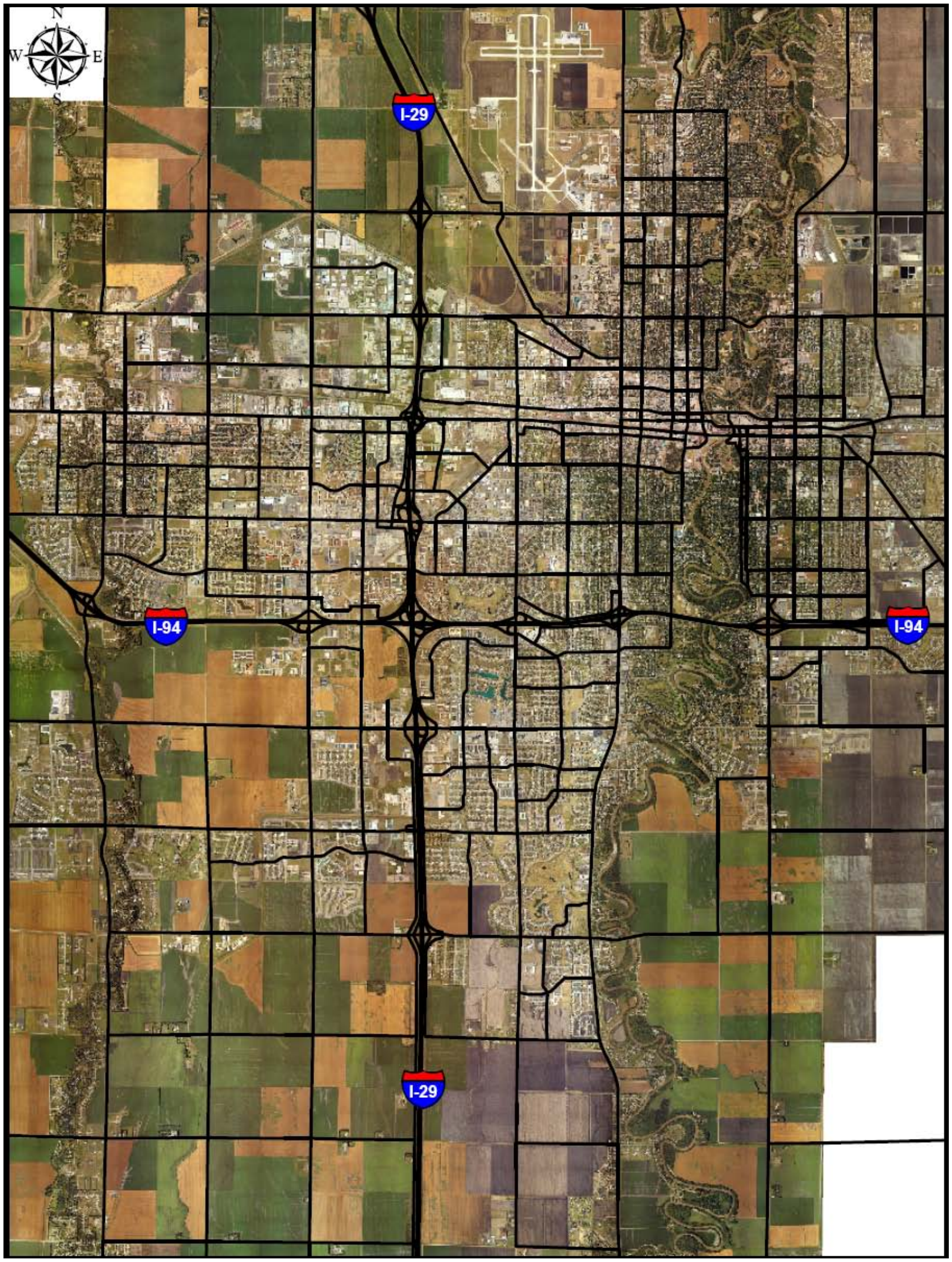

Figure 4.1 The modeled Fargo-Moorhead metropolitan area

4.2 Fargo-Moorhead Regional Travel Demand Model

Several steps were involved in the process of constructing and calibrating the F-M COG's regional travel demand model; those steps included data preparation, trip generation, trip distribution, mode split, traffic assignment, and model calibration. A detailed description of those steps was provided in Section 3. The input data needed for the development and calibration of the regional travel demand model was either provided by the F-M COG or generated from review of the available literature and primary data collection efforts. The F-M COG regional travel demand model was developed using the TP+ modeling system produced by Citilabs within their Cube software system.

4.2.1 Trip generation

Trip generation models estimate the number of trips generated for each TAZ in the modeled metropolitan area using the social and economic attributes for that TAZ. Trip productions were estimated using factors such as the number of households in that area, household sizes, and age groups within the household. Trip attractions were estimated using variables such as employment levels and commercial floor space. Trip generation models utilized the zonal and external trip data as input and generated an array of production and attraction. The values within the array represented the number of trips produced within and attracted to each internal TAZ or to external TAZs.

4.2.1.1 Internal zones trip productions: The number of trips produced by each TAZ was based on the number of single-family and multifamily households in that TAZ. Trip productions were estimated through multiplying the total number of single-family or multifamily dwelling units by the appropriate daily vehicle trip rates. The trips were separated into HBW, HBO, and NHB production trips by multiplying the total vehicle-trips with the percentage of trips by purpose. The vehicle trip rates were adjusted during the calibration process. Table 4.1 is based on NCHRP 365 and it summarizes the trip generation rates used in the F-M COG regional travel demand model.

Table 4.1 Vehicle Trip Generation Rates

		Percentage of Trips by Purpose		
Dwelling Category	Daily Vehicle Trip Rate	HBW	HBO	NHB
Single-Family	9.55	0.20	0.57	0.23
Multi-family	6.47	0.20	0.57	0.23

4.2.1.2. Internal zones trip attractions: To estimate the number of trips attracted to each zone, the TAZs representing the metropolitan area were classified as being within the central business district (CBD) area or within the non-central business district (NCBD). Different trip attraction rates were used for HBW, HBO, and NHB trip attractions for CBD and NCBD zones. Table 4.2 summarizes the trip attraction rates used in the F-M COG regional travel demand model, which were based on NCHRP 365.

Table 4.2 Trip Attraction Rates

Trip Purpose	**CBD Zones**	**NCBD Zones**
HBW	1.45 x TE	1.45 x TE
HBO	2.0 RE + 1.7 SE + 0.5 OE + 0.9 HH	9.0 RE + 1.7 SE + 0.5 OE + 0.9 HH
NHB	1.4 RE + 1.2 SE + 0.5 OE + 0.5 HH	4.1 RE + 1.2 SE + 0.5 OE + 0.5 HH

Where: TE = Total Employment,
RE = Retail Employment,
SE = Service Employment,
OE = Other Employment, and
HH = Households.

4.2.1.3 University trip productions and attractions: Due to the special nature of trip making behavior for university trips, North Dakota State University (NDSU), Concordia College, and Minnesota State University Moorhead (MSUM) were treated as special trip generators. A home based university trip category was included in the F-M COG regional travel demand model. To estimate the number of trips generated by the college campuses and the area directly affected by them, NDSU was used as a model. Data related to trips made from and to NDSU were gathered by ATAC through interviews and parking data, and it was determined that the number of college trips could be predicted based on variables that can be forecasted by the F-M COG. Table 4.3 provides the university trip rates used in the model (1).

Table 4.3 University Trips Generation

			Predicted 2005 Enrollment		
Purpose	Rate	Population Category	Concordia College	MSUM	NDSU
HBW Productions	0.16	On-Campus Students	1,794	1,559	2,876
HBO Productions	0.37	On-Campus Students	1,794	1,559	2,876
NHB Productions	0.17	Total Students	2,608	7,491	11,723
HBS Productions	0.12	On-Campus Students	1,794	1,559	2,876
HBW Attractions	0.30	Total Students	2,608	7,491	11,723
HBO Attractions	0.44	Total Students	2,608	7,491	11,723
NHB Attractions	0.17	Total Students	2,608	7,491	11,723
HBS Attractions	0.72	Off-Campus Students	814	5,932	8,847

4.2.1.4 High school and grade school trip generation: In the F-M COG regional travel demand model, home-based school trips were calculated independently. The initial estimate of HBS trip attractions was set to equal the number of students enrolled in the school zone. Due to the different nature of school trips made by students who may possess a driver's license, the student population was divided into high school and grade school students.

4.2.1.5 Airport trip generation: The Fargo Hector International Airport is located within the areas modeled in the F-M COG regional travel demand model. In 2005, there were 549,209 passengers using the airport (30). The total number of passengers was used to estimate the average daily number of passengers using the airport. The ITE trip generation manual provided the rates used for airport trip generation.

4.2.1.6 External trip generation: Trips with both ends outside the modeled metropolitan area are known as external-external (EE) trips. In the F-M COG regional travel demand model, those trips are assumed to account for 10% of the interstate traffic. If only one trip end is within the modeled area, then it is defined as being an internal-external (IE) trip or external-internal (EI) trip. In the F-M COG regional travel demand model, trip attractions for external zones were estimated by multiplying the average daily traffic with the percentage of trips by purpose at each external zone. To calculate the number of productions for the interstate highways, the total number of through trips was subtracted from the ADT and then multiplied by the percentage of trips by purpose.

4.2.1.7 Trip generation adjustment: Because different factors were used to estimate trip productions and attractions in the F-M COG regional travel demand model, the trip production and attraction totals were unbalanced. In reality, each production must be paired with an attraction to form a trip, and the trip production totals must match the trip attraction totals for each trip type. Equations 3.1 and 3.2 were used to balance the total trip productions and attractions, and the balanced results are summarized in Table 4.4 (1).

Table 4.4 Total Adjusted Productions and Attractions by Trip Purpose

Trip Purpose	Total Trip Productions	Total Trip Attractions
HBW	159,347	159,347
HBO	452,513	452,513
NHB	99,546	99,546
HBS-University	9,942	9,942
HBS-High School	9,027	9,027
HBS- Grade School	20,185	20,185

4.2.2 Trip distribution

The output from the trip generation step was represented by the number of trips produced by and attracted to each TAZ in the modeled metropolitan area. In the trip distribution step, the trip ends are connected to establish the flow of trips from production zones to attraction zones. The output from the trip distribution is a matrix of trips produced and attracted between the TAZs called the origin-destination (O-D) matrix.

The gravity model was used to distribute trips between the TAZs in the F-M COG regional travel demand model. In the gravity model, the number of trips is assumed to be based on the level of activity of the zones and the distance (travel cost) between those zones. The gravity model is based on the assumption that trip interchange between two TAZs is proportional to the number of trips generated at each TAZ and is inversely proportional to the cost of traveling between those two TAZs. Equation 4.1 represents the gravity model used in the F-M COG regional travel demand model (29).

$$T_{IJ} = \frac{P_i[A_i f_{ij} k_{ij}]}{\sum_{n=1}^{m} A_j f_{ij} k_{ij}}$$ **Equation 4.1**

Where: T_{IJ} = The flow of trips from each production zone i to each attraction zone j,
P_i = Total number of trips produced in zone i,
A_j = Total number of trips attracted to zone j,
f_{ij}= Friction factor, and
k_{ij} = Adjustment factor for trip interchanges between zones i and j.

The friction factor in the gravity model is inversely proportional to the travel cost between zones i and j. In the F-M COG regional travel demand model, the friction factors were adjusted until the observed and predicted trip length distributions were similar. The k factor is a scaling factor that is used during calibration and it limits or increases the volume of traffic that crosses sections of the network.

4.2.3 Mode split and temporal distribution

In the F-M COG regional travel demand model, automobiles are the only mode of transportation modeled because of the low percentage of public transit use. The number of trips generated in the model is represented by vehicle trips per day; however, the trips needed to be assigned based on hourly increments.

Based on several hourly traffic counts throughout the metropolitan area the daily traffic was divided into hourly peaks, as shown in Table 4.5.

Table 4.5 Peak Hour Percentage of Daily Traffic

Period	Time	% of daily traffic
AM	7:45 AM - 8:45 AM	7.53%
PM	5:00 PM – 6:00 PM	8.47%
Off Peak	All other times	84%

The production attraction matrix was added to the transposed production attraction matrix and then the trips were divided by two. Using this method, it was assumed that half of the trips go from production to attraction and half of the trips are returning from attraction back to the production. The matrix was then multiplied by the appropriate time of day percentage to obtain three origin destination matrices: AM, PM, and off peak. Also, factors provided by NCHRP 365 were used to produce peak hour directional volumes for HBW, HBO, and NHB trips to allow for peak hour traffic assignment that were representative of the peak hour direction and hourly trip percentage.

4.2.4 Traffic assignment

The last step in the F-M COG regional travel demand model was the assignment of the predicted trip flows between origin and destination TAZs to modeled roadways in the metropolitan area. The assignment step started with three separate O-D matrices: AM, PM, off peak, which contained the traffic volumes to be assigned for each O-D pair. User-equilibrium traffic assignment method was used for this model, and it was implemented using a travel cost (time) function to evaluate the most desirable path for the trip. Travel time was set to the free flow travel time for the first iteration and then changed with iterations depending on congestion levels on the roadway network. This iterative process continued until there was no available path at which the cost could be reduced.

4.2.5 F-M COG regional travel demand model calibration

The final stage in the process of developing the F-M COG regional travel demand model was the calibration and validation of the model to the 2005 base year traffic data. The goal of the calibration process is to have the predicted travel behavior match the observed travel behavior data available. The process of calibrating different parameters and error checking was performed at each modeling step to minimize the errors in the overall model. The calibration process was illustrated in Figure 3.4, and a summary of the different stages of model calibration is provided in the following sections.

4.2.5.1 Trip length distribution: The first task of the calibration of the F-M COG regional travel demand model was to check how the modeled trip length distribution compared with the trip length distribution provided by the census for transportation planning (CTPP) data for the modeled metropolitan area. The modeled HBW, HBO, and NHB trip length distributions were compared with those provided by the CTPP. If the trip length distribution of the modeled trips did not match that provided in the CTPP data, then the friction factors were adjusted until the two distributions were similar. The friction factors were adjusted using Equation 4.2.

$$F_t^{i+1} = F_t^i * \frac{T_t^{obs}}{T_t^i} \qquad \textbf{Equation 4.2}$$

Where: F_t^{i+1} = The friction factor for time interval t for iteration i+1,
F_t^i = Friction factor for time interval t for iteration i,

T_t^{obs} = The observed number of trips in time interval t, and
T_t^i = The estimated number of trips in time interval t for iteration.

Several functions could be used to represent friction factors, but the gamma distribution is one of the best distributions that could be used (32). Equation 4.3 represents the function used for the F-M COG regional travel demand model friction factors (32).

$$F_{ij} = a * t_{ij}^b * e^{c*t_{ij}} \qquad \textbf{Equation 4.3}$$

Where: F_{ij} = The friction factor between zones i and j,
$a, b, and\ c$ = Model coefficients are "b" and "c", while "a" is a scaling factor that could be changed without changing the distribution,
t_{ij} = Travel time between zones i and j, and
e= The base of the natural logarithms.

The factors initially used for the F-M COG regional travel demand model are summarized in Table 4.6, and the friction factors functions used are shown in Figure 4.2.

Table 4.6 Friction Factors Model Coefficients for the F-M COG Model

Trip Purpose	HBW	HBO	NHB
A	1	1	1
B	-0.351	0.548	1.110
C	-0.043	-0.212	-0.280

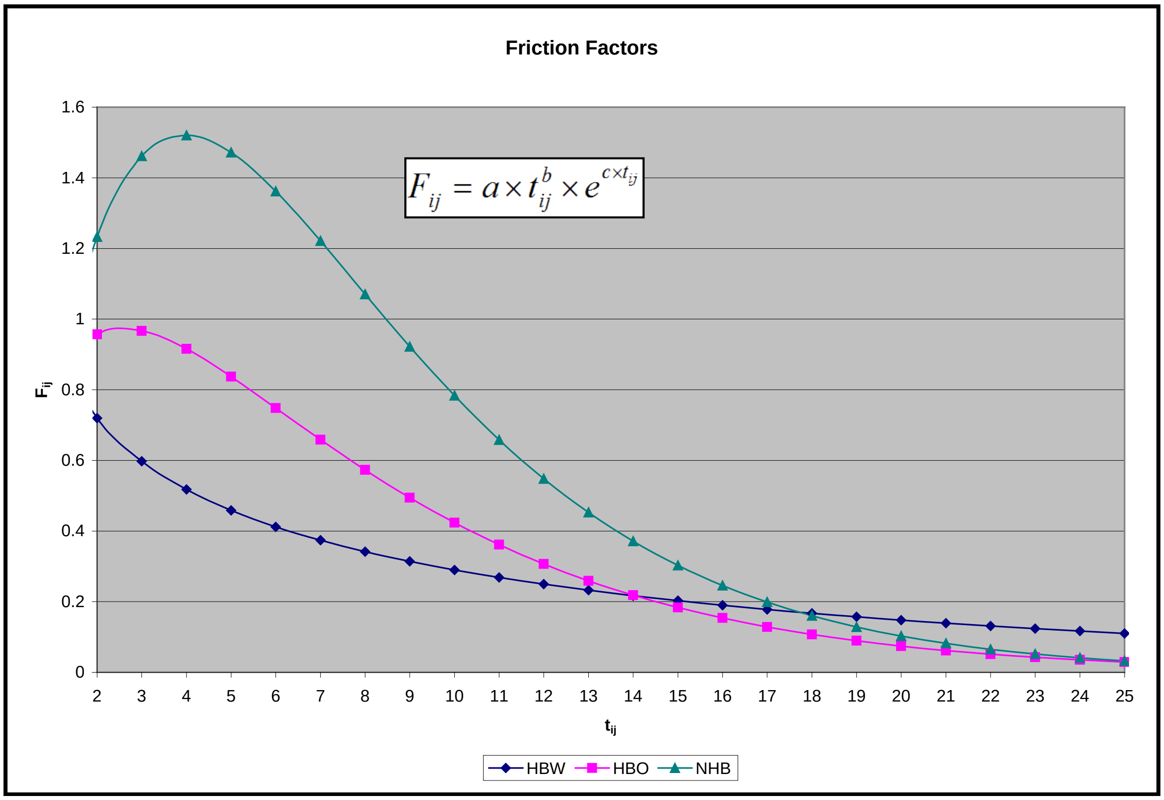

Figure 4.2 Friction factor functions used for the F-M COG model

4.2.5.2 Vehicle miles traveled: The total vehicle miles traveled (VMT) values are based on the number of generated trips in the model and their corresponding lengths in miles. The total modeled VMT values were first compared with the observed total VMT values for both the North Dakota and Minnesota sides of the metropolitan area. If the observed and reported VMT values were different, then the trip generation rates were adjusted to make them similar on a regional level.

After the total VMT values generated by the travel demand model were calibrated on a regional level, the VMT values were checked by roadway functional class. To adjust the modeled VMT values to match the observed VMT values, the global speeds by land use characteristics and node delays were adjusted to make them similar. For the F-M COG regional travel demand model, the overall modeled VMT was within 2% of the observed VMT for the modeled metropolitan area, which is within the 5% difference limit provided in the travel model improvement program's model validation and reasonable checking manual (17). Table 4.7 provides a summary of the observed and modeled VMT values for the F-M COG regional travel demand model.

Table 4.7 VMT Values by Jurisdiction for the F-M COG Model

Jurisdiction	VMT Reported	VMT Modeled	Difference in VMT	% Difference in VMT
Fargo	1,845,042	1,823,416	-21,626	-1.17%
Moorhead	482,413	430,514	-51,899	-10.76%
West Fargo	169,523	172,657	3,134	1.85%
Dilworth	41,029	71,825	30,796	75.06%
ND	2,014,565	1,996,073	-18,492	-0.92%
MN	523,442	502,339	-21,203	-4.03%
Metropolitan Area	2,538,007	2,498,412	-39,595	-1.56%

4.2.5.3 Screenline counts: The screenlines used for the F-M COG regional travel demand model included I-29, I-94, the Red River, and the main railroads tracks. The total ADT values for the roadways crossing the screenlines were compared with the modeled daily traffic volumes on those roadway links. If the ADT values were different from the modeled traffic volumes for those links, the K factors were adjusted to make them closer.

The K factors are trip distribution factors that are used to adjust the utility of making trips between TAZ pairs; they are used in the gravity model to match the modeled trip interchange between the TAZs with the observed trip distribution in the modeled metropolitan area. If the modeled traffic volumes crossing the screenline were above the specified criteria, a lower k factor was assigned to inhibit trips crossing the screenline. Similarly, if the modeled traffic volumes crossing the screenline had a modeled traffic volume below the designated criteria, a higher k factor would be applied to affected zones, making trips between zonal pairs crossing the screenline more attractive.

After an accurate screenline distribution was achieved for the modeled area, the calibration process was repeated starting with checking the trip length distribution until all the successive calibration components were within criteria. Table 4.8 provides a summary of the K factors used in the F-M COG regional travel demand model and the traffic volumes crossing the screenlines in the modeled metropolitan area.

Table 4.8 Screenline Counts and K Factors for the F-M COG Model

Screenline	K Factor	ADT	Modeled ADT	Traffic Volume Difference	Percent Difference (%)
Interstate 29	0.80	96,200	91,500	-4,700	-4.89%
Interstate 94	0.33	135,075	136,400	1,325	0.98%
Red River	0.30	109,950	110,600	650	0.59%
Railroad	0.40	122,875	122,800	-75	-0.06%

4.2.5.3 Network wide adjustments: The final step in the regional travel demand model calibration was to check how the modeled traffic volumes on the roadway links compared with the ADT values obtained from field counts in the metropolitan area. If the ADT values and modeled traffic volumes were significantly different, then the global speeds were adjusted to make them similar. Table 4.9 summarizes the results of modeled and observed traffic volumes comparison for the F-M COG regional travel demand model.

Table 4.9 Traffic Volume Comparison for the F-M COG Model

Volume Range	Above Criteria	Meets Criteria	Below Criteria	% Within Criteria
AADT>25,000	0	18	1	95%
25,000 to 10,000	6	131	23	82%
10,000 to 5,000	35	134	22	71%
5,000 to 2,500	33	129	15	72%
2,500 to 1,000	46	72	13	56%
AADT<1,000	34	27	2	43%
Total	154	511	76	69%

To test for the overall difference between ADT values and modeled traffic volumes, the root mean square error (RMSE) measure was used. The RMSE value was found by averaging the square error for the traffic volume for each link and then taking the square root for the averages. Table 4.10 summarizes the RMSE values for the modeled roadway links by traffic volume range (17).

Table 4.10 RMSE Value by Volume Range for the F-M COG Model

Volume Range	RMSE (%)	Typical Limits (%)
AADT>25,000	14 %	15-20 %
25,000 to 10,000	24 %	25-30 %
10,000 to 5,000	37 %	35-45 %
5,000 to 2,500	55 %	45-100 %
2,500 to 1,000	93 %	45-100 %
AADT<1,000	>100 %	>100 %

4.3 Fargo-Moorhead Hybrid Model

Two types of input files are used for the DYNASMART-P software: simulation input files and graphical input files. The needed files for DYNASMART-P were prepared using the DYNASMART-P editor (DSPED), Microsoft Excel, and Cube software. These files are text based, and each one of them must be prepared in a certain format provided in the user manual (20).

An interface between Cube and DYNASMART-P software was created. Using this interface, the static O-D matrix from Cube was prepared in the desired format for DYNASMART-P to be used as input. Also, the interface was used to feed the output link traffic volumes from the DYNASMART-P simulation runs into the travel demand model in Cube. Figure 4.3 shows the Fargo-Moorhead hybrid model in DYNASMART-P.

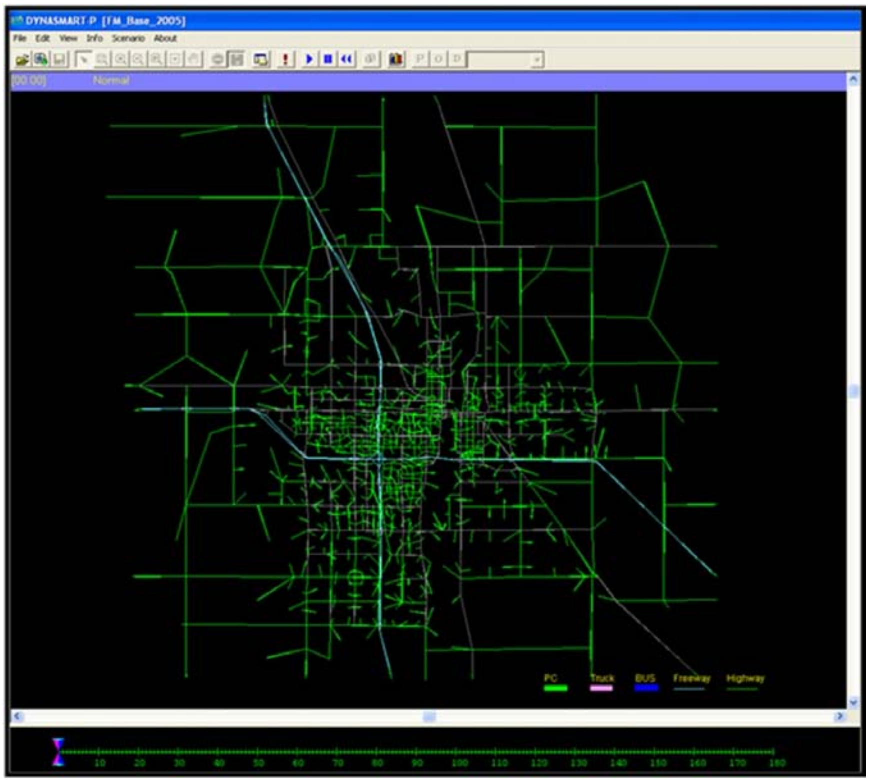

Figure 4.3 Screenshot from the Fargo-Moorhead DYNASMART-P model

4.3.1 Fargo-Moorhead hybrid model calibration

The feedback from DYNASMART-P into the Cube model was represented by new travel time over the links based on the dynamic traffic assignment procedures. The original O-D input matrix for DYNASMART-P was based on the calibrated F-M COG travel demand model. For the hybrid model, traffic data were examined from 14 signalized intersections in Fargo, ND, to determine how the trips are loaded onto the network during daily peak hours (45). These 14 intersections collect continuous traffic volume data and volume variation throughout the day was analyzed for those intersections to determine traffic loading rates during the daily peaks. The traffic volumes were averaged for those intersections during daily traffic peaks, and these averages were used to determine the trip loading patterns into the mesoscopic simulation software. Figure 4.4 shows the locations of the intersections used to study the traffic patterns in the metropolitan area. After the initial simulation runs, the O-D matrix loading rates were adjusted to reflect the actual traffic conditions on the ground.

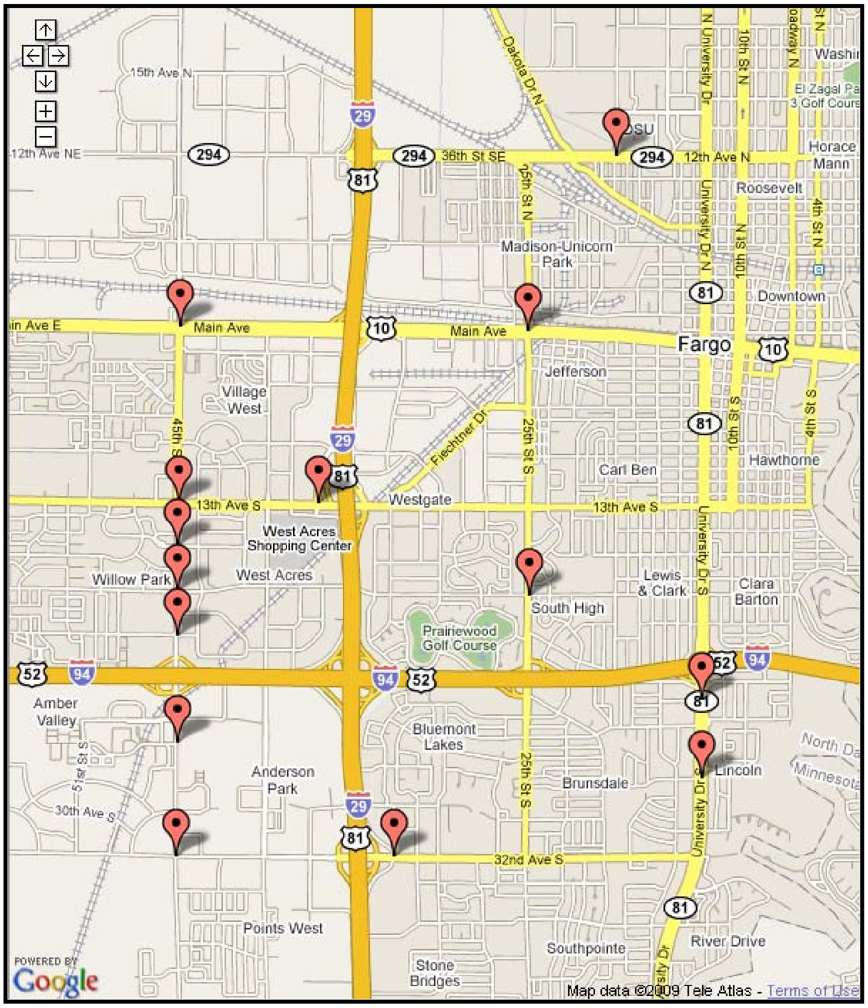

Figure 4.4 Intersection locations used to collect traffic volume data (Fargo, ND)

After providing adequate seed time (traffic loading) and simulation periods for the hybrid model, several runs were conducted until convergence in link travel times was achieved using Equation 4.4 where the value obtained was 0.0217 (42).

$$\sqrt{\frac{\sum_{l=1}^{L}\sum_{t=1}^{T}\left(\sum Q_i^{l,t}-\sum Q_{i-1}^{l,t}\right)^2}{N_l N_t}} < \epsilon \qquad \textbf{Equation 4.4}$$

Where, $\Sigma Q_i^{l,t}$ = Equilibrium travel time over the link,

$\Sigma Q_{i-1}^{l,t}$ = Equilibrium travel time over the link from the previous iteration,

N_{l_t} = Number of links,

N_t = Number of time intervals, and

$\in$ = Critical value to reach convergence (0.05).

For model validation purposes, the overall model was examined in terms of the acceptable levels of error, average travel times, and average trip lengths, it was found to be within the criteria. Table 4.11 summarizes the traffic assignment by volume range from the calibrated hybrid model.

Table 4.11 Model Assignment by Traffic Volume Range

Volume Range	% Within Criteria	Criteria % Deviation
ADT > 25,000	94%	± 22%
25,000 to 10,000	92%	± 25%
10,000 to 5,000	82%	± 29%
5,000 to 2,500	75%	± 36%
2,500 to 1,000	60%	± 47%
ADT < 1,000	59%	± 60 %

The results from the mesoscopic simulation runs will vary due to the difference in the random seed number used for each model run. To determine the number of simulation runs required, the variance of the traffic volumes on roadway links from simulation results needed to be determined. A number of simulation runs were performed to calculate the mean and standard deviation of the traffic volumes of the simulation output. Equation 4.5 was used to determine the number of simulation runs needed (24).

$$N = [t_{\alpha/2}\left(\frac{\delta}{\mu * \varepsilon}\right)]^2 \qquad \textbf{Equation 4.5}$$

Where: N = Number of simulation runs required,
$t_{\alpha/2}$ = The critical value of the t-distribution at confidence level (1-α),
δ = Standard deviation of the performance measure based on simulation,
μ = Mean value of the performance measure based on simulation, and
ε = Allowable error (5%).

For the purposes of this study, a confidence level of 95% was used. The critical value of the t-distribution was (2.77645) and the value of mean was 234.4 vehicles. After applying Equation 4.5, the number of simulation runs required was four model runs.

4.4 Evacuation Scenarios

Several emergency evacuation scenarios were modeled in this study, which were developed in consultation with local emergency managers and interested stakeholders. The methodology was initially tested using a hypothetical evacuation scenario of the Fargodome. After that, scenarios were modeled for evacuation events triggered by flooding of the Red River. For each scenario, the location, threat level, warning times, and the affected area's shape and boundaries were analyzed and determined.

4.4.1 FARGODOME evacuation scenario development

To test the developed methodology, a hypothetical emergency evacuation of the Fargodome was initially modeled. The hypothesized scenario for this study involved the evacuation of a crowd attending a weekday evening event in the Fargodome, which is located north of the downtown business district. The average attendance of a large scale event at the Fargodome is 21,000 people.

The Fargodome has 3,790 parking stalls in the parking lots, and it is estimated that 3,000 cars park in the surrounding neighborhoods and parking lots. The modeled scenario measured the evacuation time estimate for evacuating the Fargodome population to the nearest point out of the danger area and added six new evacuation origins representing the parking lots (shown in red in Figure 4.5) and parking areas surrounding the FARGODOME. It should be pointed out that the ETE does not include the time required to exit the Fargodome building and to walk to the appropriate vehicle. Also, it was assumed that traffic heading into the Fargodome area would be blocked and sent to other areas. In DYNASMART-P, the vehicles generated from the different zones are loaded directly on the roadway network, and it is possible to control the distribution of traffic into the different roadway links. Nevertheless, DYNASMART-P is unable to model the effect of traffic conflict at the exit points of the parking lots on the capacity of those points. The evacuation time estimate for this scenario was 34 minutes.

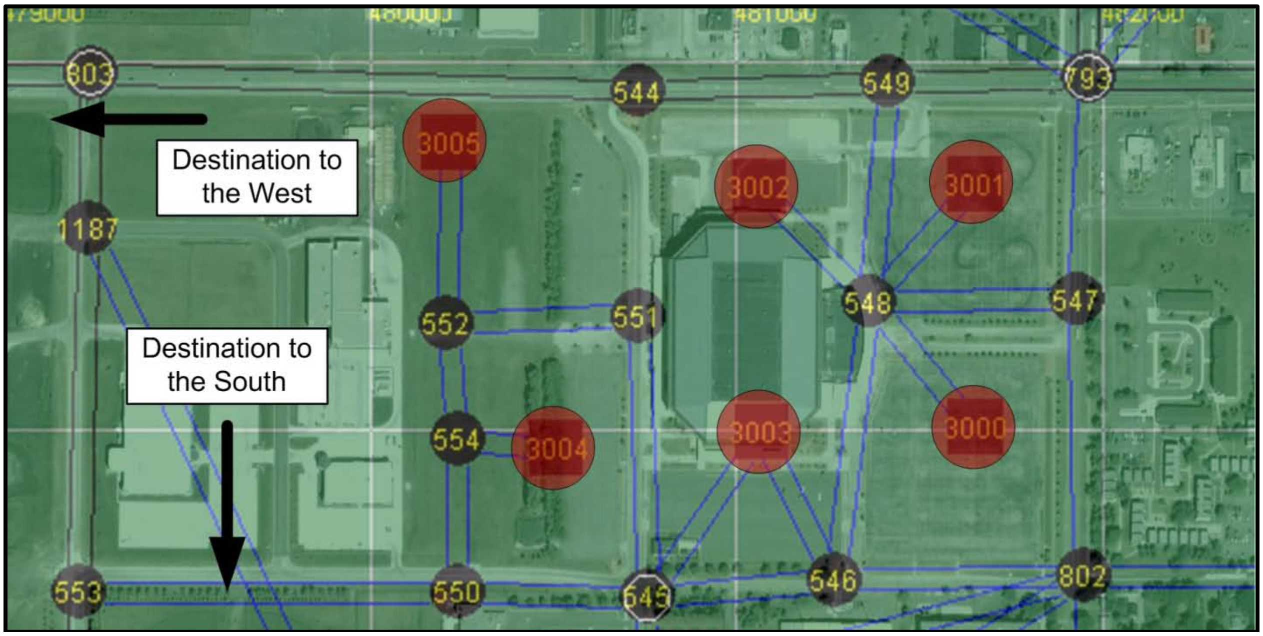

Figure 4.5 Fargodome evacuation DYNASMART-P links/nodes

4.4.2 Emergency evacuation scenario development

The Fargo-Moorhead metropolitan area includes the cities of Fargo, West Fargo, Moorhead, and Dilworth. In 2005, the metropolitan area had a population of 190,500 (16), thus it was classified as a medium size MPO (metropolitan area with a population of 50,000 to 200,000).

The Fargo-Moorhead area can be threatened by flooding from three rivers: Sheyenne River, Wild Rice River, and Red River. The Sheyenne River diversion, which was completed in 1992, provides flood protection for West Fargo, ND. The Wild Rice River is a tributary of the Red River (as is the Sheyenne River) and flows into the Red River just south of the metropolitan area. In the past 112 years, it was reported that the Red River water levels reached flood stage levels 56 times in the Fargo-Moorhead area, exceeding the major flood stage (30 ft) 20 times (46). The Fargo-Moorhead area is the last major metropolitan area on the Red River that remains unprotected from the 100-year (38.2 ft) flood levels (46). In 2009, the Red River had a record crest of 40.84 ft. Due to the extended wet periods over the years, the 100-year flood plain is being revised for Fargo-Moorhead area.

There was interest from the F-M COG and other stakeholders in introducing the security aspect into transportation planning. In the past, the main focus of key stakeholders (i.e., emergency management, law enforcement, fire departments, and transportation agencies) was on general disaster planning and mock drills. However, evacuation modeling would facilitate effective use of the transportation system assets to support emergency management functions, including expedited evacuation and recovery efforts.

The key stakeholders realized the importance of analyzing the redundancies of the transportation network associated with moving a large number of people during emergency evacuations. After consulting with the stakeholders and to link the modeling efforts to possible local threats, it was decided to model the regional evacuation event triggered by the flooding of the Red River. The scenario represents evacuating the area within the 100-year flood plain triggered by a levee breach or overflow. Figure 4.6 shows the metropolitan area and areas within the 100-year flood plain area.

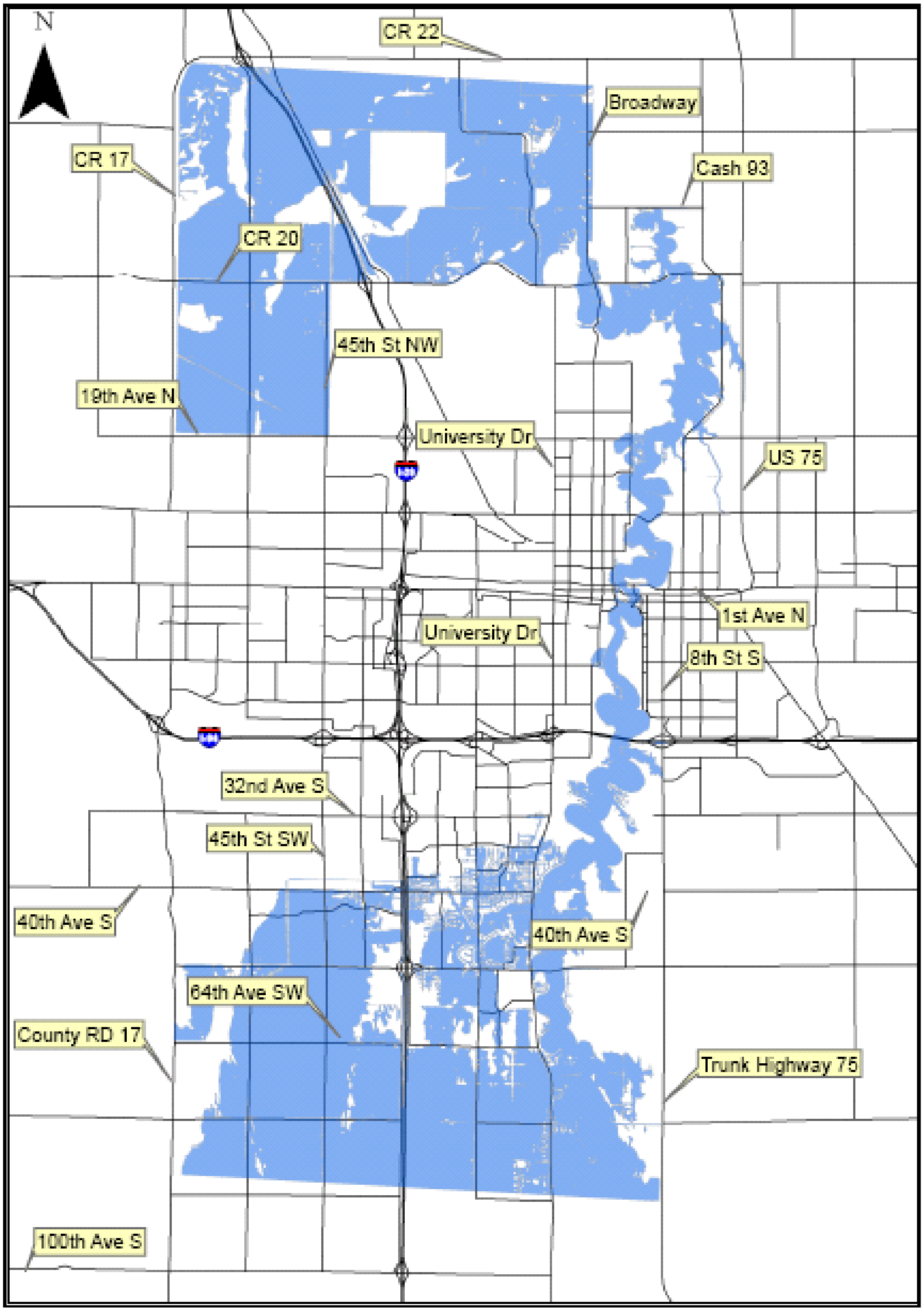

Figure 4.6 The 100-year flood level in the Fargo-Moorhead area (38.2 ft)

4.4.3 Emergency evacuation scenario modeling

Three different evacuation scenarios were modeled: a possible levee breach on the Minnesota side, a possible levee breach on the North Dakota side, and a possible levee breach or overflow on both sides of the river. A fourth scenario was also modeled to measure the effectiveness of modifying the traffic controls to facilitate the evacuation process. In addition, the possible levee breach or overflow on both sides of the river was modeled using data based on the national averages to test how local data are different than national data. In all of the modeled scenarios, it was assumed that the emergency event occurs during the PM peak hour, and that a portion of the population (those who were at work) is allowed to return to their homes before they start the evacuation trip. As the Red River rises during a flood event, several roadways/intersection are closed due to flooding or dike construction. Table 4.12 lists some of the transportation network changes based on the river stage. The closures at the 100-year flood stage were coded into the hybrid model for the five flood evacuation scenarios.

Table 4.12 Traffic Network Changes at Different Flood Levels

River Stage (ft)	Street	Location	Responsibility	Reason
18'	Elm St	14th - 15th Ave N	Fargo	Flooding
24'	N. Broadway	North of 37th Ave	Fargo/Clay Co.	Flooding
25'	9th Ave/N. River Rd	Mickelson Field	Park Board/Fargo	Flooding
28'	12th Ave N.	Red River Bridge	Fargo/Moorhead/Bridge Company	Flooding
30'	County Road 20	10th St - Broadway	Cass Co./Clay Co.	Flooding
30'	2nd St N.	1st - 5th Ave	Fargo	Dike
31'	2nd St S.	Main Ave - 4th St	Fargo	Dike
33'	Lower Terrace	At Elm Street	Fargo	Flooding
34'	Oak St	8th - 11th Ave N	Fargo	Dike
34'	1 Ave N.	Red River Bridge	Fargo/Moorhead	Dike
35'	South Terrace	125 South Terrace	Fargo	Dike
36'	15th Ave N.	At Elm Street	Fargo	Dike
36'	14th Ave N.	Oak - Elm Street	Fargo	Dike
37'	Lindenwood Dr	3rd - 4th St	Fargo	Dike
37'	S University Dr	40th - El Cano Dr	Fargo	Dike

4.3.3.1 Minnesota side evacuation scenario: The input for the hybrid model consisted of the modified street network, the evacuation traffic demand, and the evacuation O-D matrix, in addition to the associated trip loading rates. The output from the simulation consists of different system-wide averages in addition to different performance measures on the traffic network. Table 4.2 summarizes the changes to the traffic network during flooding conditions.

For this scenario, the evacuation population was represented by the people living within the 100-year flood plain on the Minnesota side. The trip generation rates and compliance rates developed in Section 3 were used to obtain the number of vehicles to be loaded onto the traffic network. The evacuation O-D matrix was loaded onto the simulation model using the function described by Equation 3.6. Based on the evacuation area, trip generation, evacuation compliance, and evacuation destination, it would take 180 minutes (3 hours) to evacuate the area of Moorhead, MN, affected by the 100-year flood event (Table 4.13). This includes the time to return home, prepare for the evacuation, travel outside of the affected area, and reach their destination. The results from the Minnesota side evacuation are summarized in Table 4.13.

Table 4.13 Minnesota Side Evacuation Results

Measure	Value
Simulation Planning Horizon (clearance time)	180 Minutes
Number of Vehicles that Reached Destination	16,636 Vehicles
Average Trip Time	14.9 Minutes
Average Trip Distance	8.0 Miles
Average Travel Speed	32.4 MPH

4.3.3.2 North Dakota side evacuation scenario: The input data for the model was prepared in a similar way to what was done for the Minnesota evacuation scenario. The evacuation population was represented by people living within the 100-year flood plain on the North Dakota side of the Red River. The hybrid model estimated that the North Dakota evacuation would take 300 minutes (5 hours), as shown in Table 4.14. The higher evacuation time for this scenario seems logical since the North Dakota side of the Red River experiences more flooding during the 100-year flood event.

Table 4.14 North Dakota Side Evacuation Results

Measure	Value
Simulation Planning Horizon (clearance time)	300 Minutes
Number of Vehicles that Reached Destination	27,459 Vehicles
Average Trip Time	31.2 Minutes
Average Trip Distance	10.3Miles
Average Travel Speed	22.8 MPH

4.3.3.3 North Dakota and Minnesota side evacuation scenario: For this scenario, the population consists of people living on both sides of the Red River within the 100-year flood plain. The input data were prepared using the equation developed in a similar way to the previous two scenarios. The evacuation time estimate for the combined evacuation was 360 minutes (6 hours), as shown in Table 4.15.

Table 4.15 North Dakota and Minnesota Side Evacuation Results

Measure	Value
Simulation Planning Horizon (clearance time)	360 Minutes
Number of Vehicles that Reached Destination	35,725 Vehicles
Average Trip Time	34.5 Minutes
Average Trip Distance	11.0 Miles
Average Travel Speed	21.4 MPH

To compare the traffic movement patterns for the different modeled scenarios, the traffic volumes at several key locations were recorded for each scenario. The results for the previous three evacuation scenarios are summarized in Table 4.16.

Table 4.16 Evacuating Traffic Volumes at Key Locations for the Different Scenarios

Location	Location ID	Traffic Volumes		
		ND Evacuation	MN Evacuation	ND & MN Evacuation
I-94 Red River Crossing EB	1	3,758	321	4,215
I-94 Red River Crossing WB	2	429	3,259	3,777
NP Ave Bridge Crossing EB	3	1,086	150	811
NP Ave Bridge Crossing WB	4	58	836	698
Main Ave Bridge Crossing EB	5	842	145	549
Main Ave Bridge Crossing WB	6	110	836	877
I-94 West of MN 336 EB	7	4,076	1,672	5,339
I-94 West of MN 336 WB	8	8	9	8
I-94 East of Sheyenne St EB	9	238	82	251
I-94 East of Sheyenne St WB	10	1,204	1,122	2,216
I-29 North of 12th Ave N. NB	11	1,851	773	2,546
I-29 North of 12th Ave N. SB	12	1,181	127	1,510
I-29 North of 32nd Ave S. NB	13	437	2	540
I-29 North of 32nd Ave S. SB	14	1,031	687	1,638

The I-94 Red River Bridge crossing served a large number of evacuation trips for all three scenarios. The highest evacuation volume was observed on I-94 eastbound near MN 336, which is on the east side of the Fargo-Moorhead metro area. Based on the household evacuation survey, the external zone to the east of Moorhead had the highest number of responses for a flood evacuation.

4.3.3.4 Evacuation scenario with modified traffic control: To evaluate the effect of traffic operations measures on the performance of the transportation system during emergency events, an evacuation scenario was modeled with modified traffic control data. During major flooding event in recent years, traffic control was performed by personnel from local and state police agencies, National Guard soldiers and airmen, and volunteers of the Cass County Emergency Vehicle Assistance Communication (EVAC) organization. In addition to supporting the movement of emergency and essential service vehicles, traffic control personnel would favor vehicles traveling along the major movements of critical corridors. Local and state traffic engineers could also develop and deploy traffic signal timing plans to assist movement of vehicles during evacuation emergencies. To replicate modified traffic control practices, the green time for the major intersections along several corridors was doubled to facilitate the movement of the evacuation population (Figure 4.7). The results from this evacuation scenario are summarized in Table 4.17.

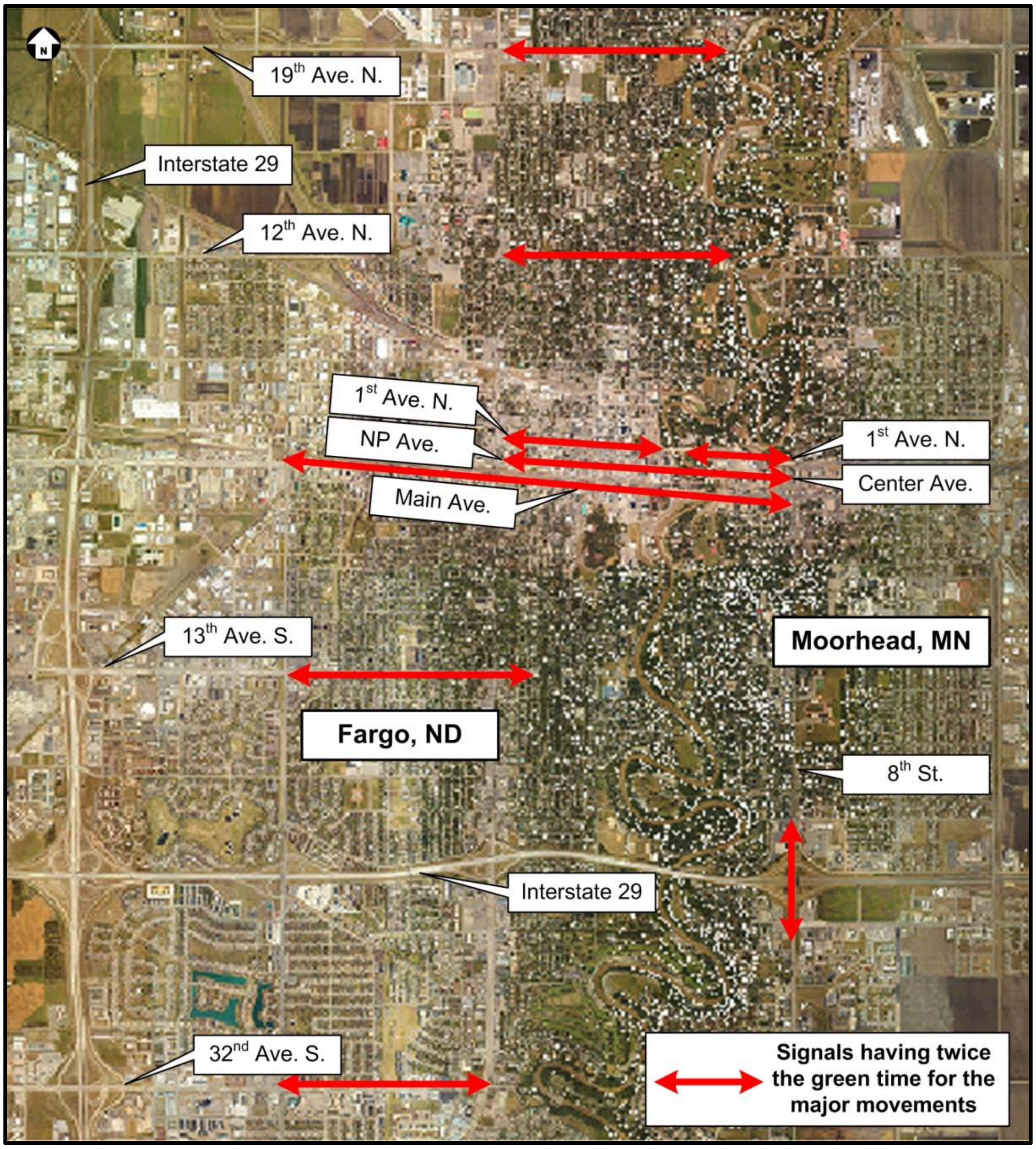

Figure 4.7 Location of modified traffic signal timing plans

Table 4.17 North Dakota and Minnesota Side Evacuation Results (Modified Control)

Measure	Value
Simulation Planning Horizon (clearance time)	330 Minutes
Number of Vehicles that Reached Destination	35,017 Vehicle
Average Trip Time	31.141 Minute
Average Trip Distance	10.629 Mile
Average Travel Speed	22.807 MPH

The output from the model shows that modifying the traffic control during regional evacuation events helps improve the transportation system performance. By comparing the results from Tables 4.15 and 4.17, there was a reduction of more than 8% in the clearance time needed during the evacuation. In addition, the reduction in the average evacuation trip time was almost 10%. These tables illustrate how the developed methodology could be used for testing the effects of different traffic management plans to optimize the use of the transportation system during emergency evacuations.

4.3.3.5 Evacuation scenario using national averages: To evaluate the effect of using data collected for small- and medium-size MPOs compared with using data developed for large cities for developing evacuation models, an evacuation scenario was modeled using national data. The new scenario was a modified version of the flooding on both sides of the Red River, where national trip generation and loading rates discussed in Section 2 were used.

In this scenario, the number of evacuation trips generated per household was 1.3 vehicles. As for how the evacuation trips were distributed, the same trip distribution was used since it is based on local area properties. In addition, the general function developed by Tweedie et al. discussed in Section 2 was used to load evacuation trips onto the transportation system. The results from this evacuation scenario are summarized in Table 4.18.

Table 4.18 North Dakota and Minnesota Side Evacuation Results (National Rates)

Measure	Value
Simulation Planning Horizon (clearance time)	240 Minutes
Number of Vehicles that Reached Destination	32,687 Vehicles
Average Trip Time	34.0 Minutes
Average Trip Distance	9.6 Miles
Average Travel Speed	17.8 MPH

The results from the running the evacuation scenario show a significant reduction (33.3%) in the clearance time needed for evacuation compared with the scenario using the data developed for this study. The main reason for the reduction in the needed clearance time is that evacuation trips are loaded at a higher rate using the functions available in the literature compared with the function developed in this study. The functions were illustrated in Figure 3.7. Also, by comparing the results from Tables 4.15 and 4.18, it was shown that using the average trip generation rates underestimated the number of evacuation trips generated by 8.5%. Hence, the results from this analysis suggest that using human behavior data from hurricane regions for evacuation modeling might result in underestimating the clearance time and demand for travel during medium-size metropolitan areas evacuations.

5. CONCLUSION AND SUMMARY OF THE RESULTS

This section provides a summary of the approach utilized for the purposes of this study. In addition, it provides the conclusions based on the results of this study. It also presents recommendations for possible implementation of the modeling approach as well as suggestions for future research.

5.1 Summary of Model Development

Evacuations in cases of regional emergencies result in drastic shifts in the demand for travel over the transportation system; hence, emergency officials usually report traffic problems during regional emergency events. Estimating the conditions of the transportation system during regional emergency events is critical for emergency preparedness, where the development of evacuation plans should be done well in advance of the occurrence of the emergency event. So far, few studies have addressed evacuation modeling for small-and-medium size MPOs due to the lack of data and resources.

This study aimed at developing a methodological approach for supporting effective decision making and testing different emergency scenarios while taking into account the various factors affecting public safety. The focus of this study was on developing a hybrid evacuation model for urban areas utilizing the resources available for different metropolitan planning organizations (MPOs) and local data. The approach developed in this study utilized the widely available travel demand tools at the MPO level as a modeling basis. These tools were enhanced using simulation class models to provide the required level of details and allow for testing operational level scenarios.

In this model, the traffic simulation side was integrated with the traditional transportation planning side. DYNASMART-P software was incorporated with Cube software using an interface that was developed for this study to introduce traffic dynamics to a traditional planning model. This provided the level of detail needed to analyze the performance of the transportation system under emergency evacuation conditions and develop traffic management plans. To illustrate the capabilities of the hybrid model, a case study was developed using the Fargo-Moorhead metropolitan area regional travel demand model enhanced by traffic simulation tools.

This study also aimed at developing human behavior data needed for evacuation modeling in medium-size MPOs and other areas similar in size. The local human behavior data needed for evacuation modeling were not available in the transportation census or in the literature. That data were needed for trip generation, trip distribution, and trip loading rates, which are critical for developing accurate and reliable evacuation models. In addition, the data obtained were used to identify the population compliance rates with evacuation orders, and the factors affecting the evacuation trip making behavior.

For the purposes of this study, a survey was used to generate the human behavior data needed for developing the evacuation models. The survey revealed that response rates and behavior of the evacuation population were different than what was reported for hurricane regions. The effect of the difference in evacuation behavior between medium-size metropolitan areas and larger cities on the model output was illustrated through the case study.

To illustrate the modeling approach developed for this study, several emergency evacuation scenarios were modeled using the Fargo-Moorhead metropolitan area as a case study. The scenarios included modeling a hypothetical emergency evacuation event of the area within the 100-year flood plain triggered by flooding of the Red River. For each evacuation scenario, the location, threat level, warning times, and the affected area’s shape and boundaries were analyzed and determined.

The modeling results provided estimates of the time needed to safely evacuate the population out of the affected area, in addition to different transportation system performance measures, such as average speeds and travel time for evacuation trips. Also, the developed evacuation model was used to measure the effectiveness of modifying the traffic controls to facilitate the movement of evacuees out of the affected area. In addition, the model was used to test the effect of using national human behavior data instead of the data developed for the purposes of this study on the performance of the modeled transportation system during evacuation. It was shown that using the national average trip generation rates underestimated the number of evacuation trips generated. The results from this analysis suggested that using human behavior data from major metropolitan areas for evacuation modeling might result in underestimating the clearance time and demand for travel during evacuations of medium size metropolitan areas.

5.2 Research Contributions

This study aimed at developing hybrid evacuation models that recognize MPO's resources and data availability to address the need for incorporating the transportation component into their transportation improvement plans. In addition, this study focused on developing the human behavior data needed for developing realistic evacuation models, and comparing that data with national evacuation data. This study demonstrated the possibility of using hybrid models for emergency evacuation planning applications. The modeling approach developed for this study could be applied at different stages of the emergency response and preparedness: disaster scenario analysis and mitigation preparedness. The output measures of effectiveness (traffic volumes, average speeds, and ETEs) associated with different traffic management options for an emergency evacuation scenario were used to identify the effects of a traffic management plan implemented for that scenario.

The developed hybrid model is practical with reasonable input data requirements, and it has the ability to assess regional transportation network performance during regional evacuation events. The modeling approach used for this study provided direct connectivity with the four-step travel demand model, which is standard for all MPOs, in addition to the required level of detail for developing evacuation traffic operations plans. This was achieved by integrating the simulation model within the regional travel demand model, reducing the complexity associated with updating and maintaining the evacuation model. The hybrid model structure incorporated a traffic generation component into the model, where some of the previously developed models didn't have a travel demand component. Also, many of the previous models did not model the transportation network in detail and primarily had static supply; those issues were addressed in this modeling approach.

For the purposes of this study, local human behavior data in response to regional emergency events were developed using household surveys. These data were not available in the transportation census or in the literature for small- and medium-size metropolitan areas. The data obtained from the survey were used to develop evacuation trip generation rates, evacuation trip distribution patterns, and evacuation trip loading rates. The data generated related human behavior during evacuations for both single-family and multi-family households. In addition, the data obtained were used to identify the population compliance rates with evacuation orders and the factors affecting the evacuation trip making behavior.

The human behavior data developed for the purposes of this study showed that response rates and evacuation behavior of populations in medium-sized metropolitan areas were different from those for larger cities populations. The analysis of the results from the case study showed that using human behavior data provided in the literature for large cities in developing evacuation models for medium-size metropolitan areas generated different results. The modeled scenario that was developed using the national average human behavior characteristics underestimated the number of evacuation trips and evacuation time estimates compared with the model developed using local data.

5.3 Recommendations for Future Research

Traffic congestion caused by regional emergency evacuations can be life threatening. The sudden increase in demand will result in excessive loads on roads not typically designed to handle those traffic volumes. The management of the transportation system during regional emergency events is critical to achieve a safe and efficient evacuation. The hybrid model developed for this study could be applied at different stages of the emergency event used to develop traffic management plans to support emergency evacuations. The study could be expanded in the future for the following:

1) With the capabilities of the new hybrid model, it could be used to test other emergency scenarios, such as evacuations triggered by hazmat spills and other major incidents. The methodological approach developed for this study could be applied for different scenarios; however, the trip generation data need to be modified for each modeled scenario. The structure of the hybrid model developed for this study makes it efficient to update the travel demand data needed for different scenarios.
2) There is a great need to generate human behavior data during emergency events for small- and medium-size metropolitan areas. The results from this study showed that human behavior data generated for hurricane regions cannot be used to develop accurate evacuation models for medium size metropolitan areas. The human behavior data could be generated for other metropolitan areas and the results could be compared with the findings from this study.
3) The developed model didn’t include factors such as age and income levels, which could affect the evacuation trip making behavior. Further research is needed to capture more factors that affect the trip making behavior for evacuees.
4) This study didn’t focus on special facilities and transient populations due to their limited effect on the overall transportation system performance. Separate models could be developed for those population categories in the future.
5) This study utilized the User Equilibrium principle to assign traffic to their trip routes. This approach assumes that users have perfect knowledge about traffic conditions on the transportation system and use the route that minimizes their travel cost. During regional evacuations, the evacuees might use the road that is most familiar to them, and the model is not capable of capturing social preferences in traffic assignment. To achieve that, more data need to be collected about the factors affecting the evacuee’s choice of trip route.

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APPENDIX A: Fargo-Moorhead Emergency Evacuation Survey

NDSU RESEARCH STUDY

Emergency Evacuation Survey

Dear resident:

My name is Shawn Birst. I work for the Upper Great Plains Transportation Institute at North Dakota State University, and I am conducting a research project to collect data on residents' response and travel behavior related to a hypothetical emergency evacuation event triggered by river flooding. The results of this study will be used to assist metropolitan emergency management and transportation agencies to improve preparedness in cases of emergencies.

You are invited to participate in this research project. Your participation is voluntary, and you may decline or withdraw from participation at anytime without penalty. If you have any questions about this project please contact me at shawn.birst@ndsu.edu. If you have any questions about the rights of human participants in research or to report a problem, contact the NDSU IRB Office, (701) 231-8980, or ndsu.irb@ndsu.edu.

Emergency Evacuation Survey

<u>Introduction:</u> The Upper Great Plains Transportation Institute (UGPTI) at NDSU in partnership with Cass and Clay County Emergency Management centers is conducting this survey to collect data on residents' response and travel behavior related to a hypothetical emergency evacuation event triggered by Red River flooding. The data will be used to assist metropolitan emergency management and transportation agencies to improve preparedness in cases of emergencies. Your feedback will help improve the safety of your community. It should be noted that all the information provided will be kept confidential. **Please mail back your completed survey using the provided return envelope by November 1, 2008.**

<u>Evacuation Scenario</u>: Immanent (within a few hours) Red River flooding is forecasted (e.g., levee breach and/or overflow) resulting in significant flooding for your area that would not recede for several days. Therefore, evacuation orders are issued by the local jurisdictions. Based on this scenario please complete the following survey.

<u>Please respond to the following eight questions in a manner that best applies to your case:</u>

Q1) If mandatory evacuation orders are issued by the authorities, would you:

☐ Comply with evacuation orders

☐ Not comply with evacuation orders. Please list the reason(s) for not complying:

____

Q2) When the evacuation orders are issued, how much time do you need to prepare before leaving the household?

☐ (1-15) minutes

☐ (16-30) minutes

☐ (31-45) minutes

☐ (46-60) minutes

☐ (>60) minutes

Q3) How many vehicles would you use during the evacuation process?

- ☐ None
- ☐ One
- ☐ Two
- ☐ Three or more

Q4) If you answered "None" to Q3, how would you be evacuated?

- ☐ Relative or friend
- ☐ Local authority/agency

Q5) When the evacuation orders are issued, where would you evacuate to?

- ☐ Relative or a friend's house
- ☐ Hotel or motel
- ☐ Public shelter

Q6) Referring to the attached map, please write the zone number that you would most likely evacuate to?

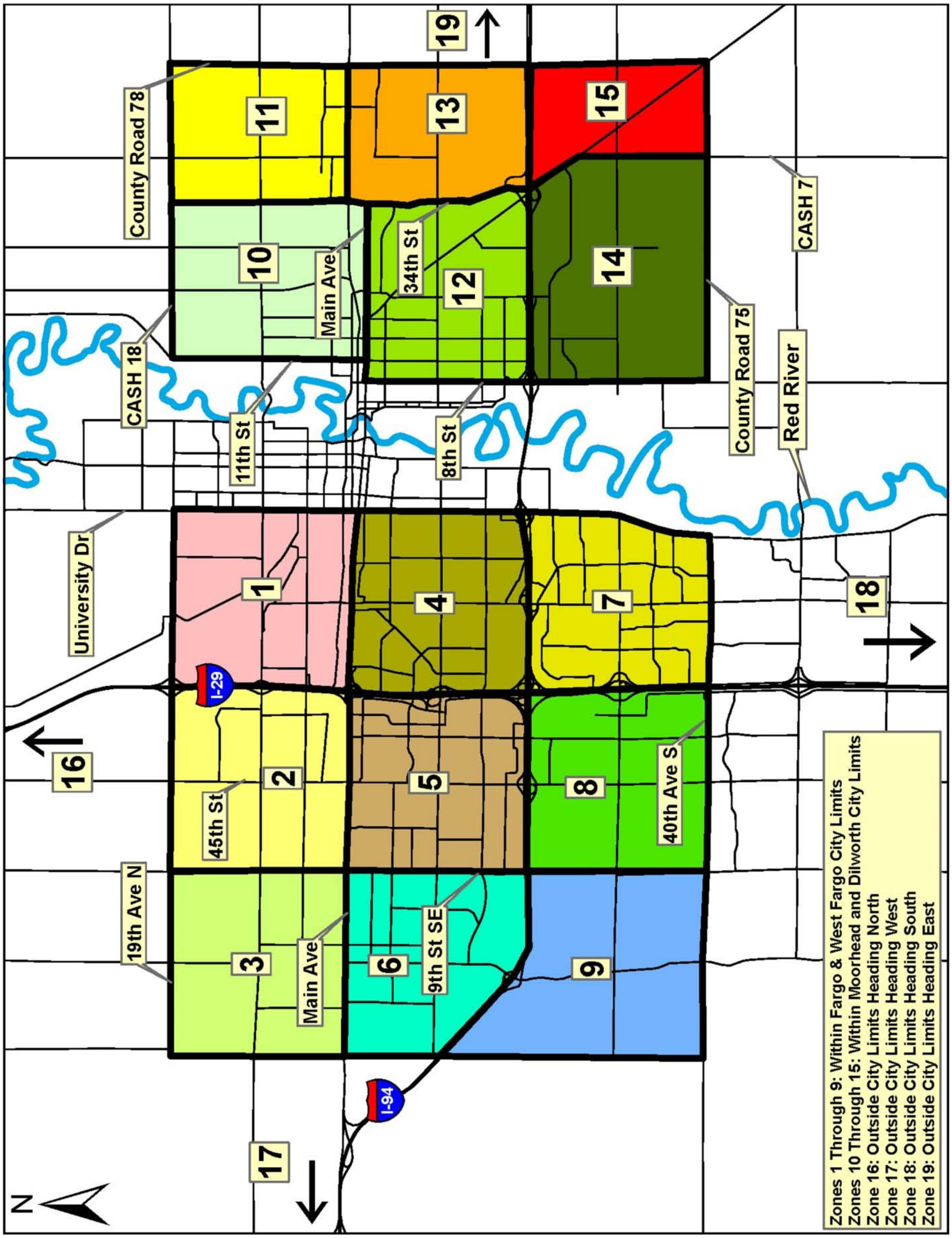
Zone _____

Q7) How would you classify your residency?

- ☐ House (single family dwelling unit)
- ☐ Apartment (multi-family dwelling unit)

Q8) You prefer to be notified about the emergency by:

- ☐ Television alert system
- ☐ Radio alert system
- ☐ Telephone alert system
- ☐ Other


Zones 1 Through 9: Within Fargo & West Fargo City Limits
Zones 10 Through 15: Within Moorhead and Dilworth City Limits
Zone 16: Outside City Limits Heading North
Zone 17: Outside City Limits Heading West
Zone 18: Outside City Limits Heading South
Zone 19: Outside City Limits Heading East
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
County Road 78
CASH 18
11th St
Main Ave
34th St
8th St
County Road 75
CASH 7
Red River
University Dr
I-29
45th St
19th Ave N
Main Ave
9th St SE
40th Ave S
I-94
N

APPENDIX B: Fargo-Moorhead Emergency Evacuation Survey Results

Evacuation Modeling for Small to Medium Sized Metropolitan Areas

Table 1. Households Compliance with Evacuation Orders

# Single-Family Comply	389	# Single-Family Not Comply	25
# Multi-Family Comply	23	# Multi-Family Not Comply	0
# Total Households Comply	412	# Total Households Will Not comply	25

Table 2. Compliance Rates by Household Category

Household Type	% Comply	% Not Comply	Total
Single-Family HH	94.0%	6.0%	100.0%
Multi-Family HH	100.0%	0.0%	100.0%

Table 3. Time Needed to Evacuate

1-15 min.	16-30 min.	31-45 min.	46-60 min	>60 min.
23	88	80	112	109
5.6%	21.4%	19.4%	27.2%	26.5%

Table 4. Number of Vehicles Used for Evacuation by Household Category

# of Vehicles Used	# of Single-Family HH	% of Single-Family HH	# of Multi-Family HH	% of Multi-Family HH
0	0	0.0%	0	0.0%
1	171	44.0%	18	78.3%
2	187	48.0%	5	21.7%
>=3	31	8.0%	0	0.0%
Total	389	100.00%	23	100.0%
Average/HH	1.64	Vehicles/HH	1.22	Vehicles/HH

Average vehicles used = 1.62

Table 5. Evacuation Destination

Destination Choice	# of Households	% of Households
Relative or Friend's House	318	77%
Hotel or Motel	70	17%
Public Shelter	24	6%
Total	412	100%

Table 6. Evacuation Destination by Household Category.

Zone	1	2+3	4	5	6+9
Single-Family HH	9.3%	1.3%	6.4%	6.4%	2.8%
Multi-Family HH	4.4%	4.4%	8.7%	0.0%	4.4%
Zone	**7**	**8**	**10**	**11+13+15**	**12**
Single-Family HH	3.6%	3.1%	1.5%	1.3%	2.6%
Multi-Family HH	4.4%	0.0%	4.4%	4.4%	4.4%
Zone	**14**	**16**	**17**	**18**	**19**
Single-Family HH	4.1%	12.1%	12.1%	6.9%	26.5%
Multi-Family HH	4.4%	21.7%	4.4%	8.7%	21.7%

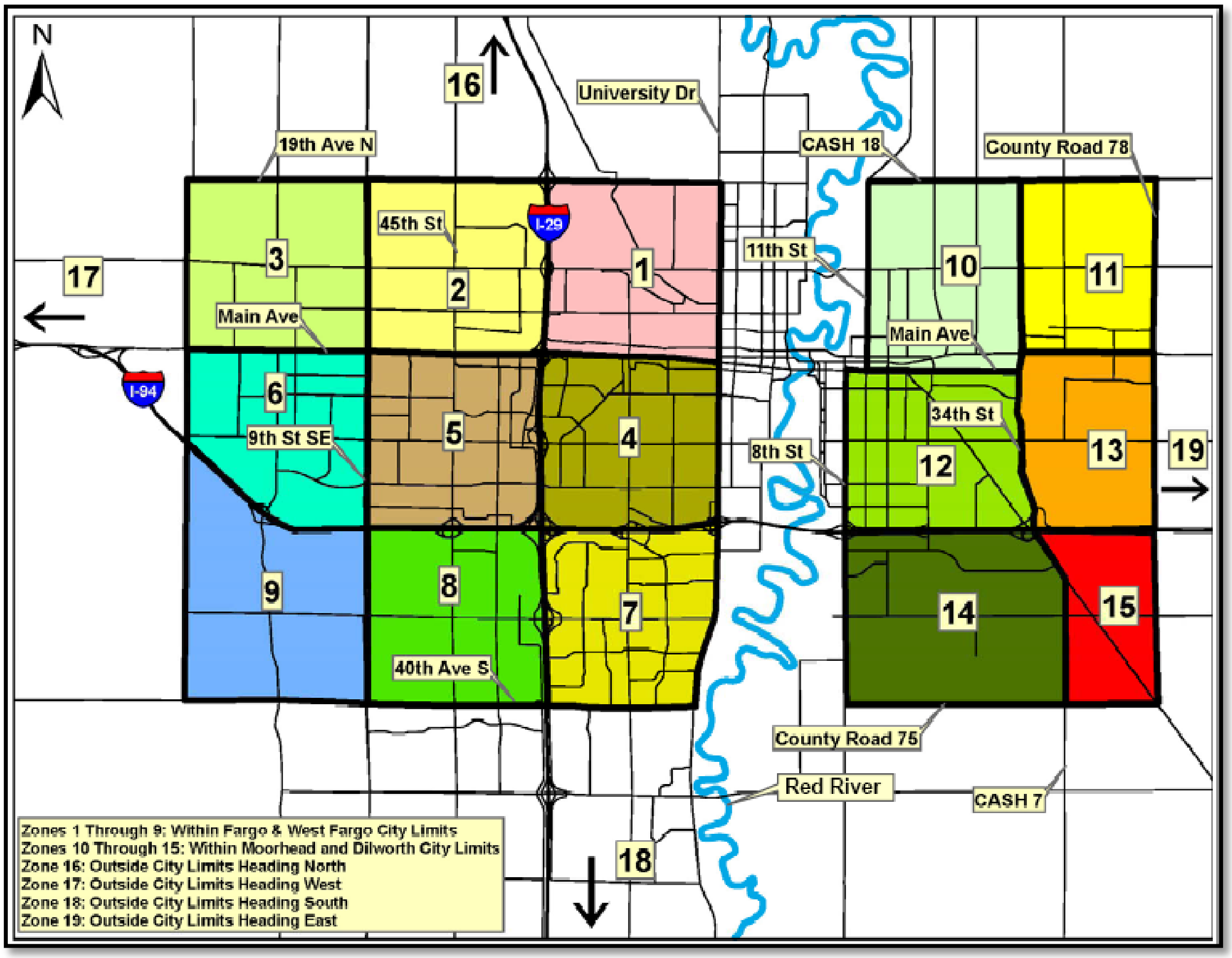


Figure 1. Red River Flooding Evacuation Zones

Table 7. Preferred Method of Notification for Emergency Evacuation.

Destination Choice	# of Households	% of Households
Television alert system	210	49.6%
Telephone alert system	162	38.3%
Radio alert system	51	12.1%
Total	423	100.0%