EMERGENCY EVACUATION AROUND NUCLEAR POWER STATIONS - A SYSTEMS APPROACH

by

Uday Shankar Kari

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APPROVED:

Dr. Antoine G. Hobeika, Chairman

Dr. Hanif D. Sherali

Dr. Antonio A. Trani

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(ABSTRACT)

Prior to this work, MASSVAC (MASS eVACuation) had evolved as a micro-computer simulation model for analysis and evaluation of areas facing natural disasters (hurricanes and floods). Conceptual and technical enhancements have been made to procedures within MASSVAC to deal with the special problems of evacuating around nuclear power stations. Its incorporation into TEDSS-3 (Transportation Evacuation Decision Support System) has resulted in a powerful tool to assist development of evacuation plans for nuclear power plants. The computer package comprehensively provides for all functions related to evacuation planning such as development of a socioeconomic and highway network database, estimation of evacuation time and development/evaluation of traffic management strategies to reduce network clearance times and to improve highway network performance during evacuation.

Primary focus is on the new features incorporated into MASSVAC, especially in the trip distribution and traffic assignment procedures. Significant improvements have been made to the software implementations of the Dial traffic assignment and other key algorithms used in MASSVAC. The information content of the model's output has been enhanced for better understanding of the evacuation process and presentation of results.

The above revisions resulted in MASSVAC3.0, which, as a part of TEDSS-3, was applied to compute network clearance times, delineate evacuation routes, estimate exit-point volumes and develop traffic management strategies for the Emergency Planning Zones (EPZs) of the Surry and North Anna nuclear power stations in Virginia.

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1.0 Introduction

Soon after the fissioning of the uranium atom was announced, scientists, engineers, politicians and even the popular press regarded nuclear power as the ultimate technical answer to man's energy problems. Finally, humanity seemed to be within inches of unlimited, cheap power. Since 1970, many countries realized that the "nuclear option" bestows electrical, political and military power. Nuclear power stations were designed and built with great enthusiasm as outstanding examples of peaceful uses of nuclear power. Reactors were provided with many levels of accident prevention systems and were considered infallible.

However, the Three-Mile-Island (TMI) accident of 1979 and later a much more serious one at Chernobyl (USSR) in 1986, shattered public faith in safe and economical production of nuclear power. Before the TMI accident, provisions made by the Nuclear Regulatory Commission (NRC) for licensing of nuclear power plants with respect to general public safety were :

- Reactor Siting

- Off-site radiological emergency planning

Reactor siting stage of the NRC licensing process consists of determining feasible locations for power reactors. Whether a reactor is built in an earthquake or flood-prone area, for example, directly affects its prospects for continued safe operation. Whether it is built near population centers directly affects the feasibility of protective actions in the event of an emergency as well as the extent of threat to public health an accident might create.

The second set of postulates detailed radiological emergency planning activities to be taken by off-site organizations at all levels of government.

However, there is ample evidence to suggest that both, reactor siting and emergency planning were low priority functions in the NRC and its predecessor, the Atomic Energy Commission (AEC), largely as a result of the agencies' complete confidence in the designed reactor safeguards for public protection. Another factor was typical of the media-dominated American democratic environment : that emphasis on the radiological emergency planning would serve only to arouse public concern and to stifle the development of nuclear power. Apart from these attitudes, the role of regulatory bodies in assisting the state in planning was largely advisory. They did not have the authority to require radiological emergency planning by off-site organizations.

The TMI accident, however, forced a re-examination of emergency planning requirements. The U.S. congress passed legislations that required specific findings on the adequacy of state, local and utility emergency planning before the NRC could issue operating licences for a nuclear power plant. The Federal Emergency Management Agency (FEMA) and the NRC drafted a Memoranda Of Understanding (MOU) which provided a rationale for the size of the area in which emergency planning should occur and the response times. A guideline of 10-miles was set as the appropriate size for the ***plume*** emergency planning zone (EPZ)[1] and 50-mile for

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1 Plume Emergency Planning Zone refers to the area for which plans are made for minimization of whole body or inhalated exposure from airborne radioactive material.

the ***ingestion pathway*** [2]. These guidelines were based on a combination of considerations including estimates of accident probabilities and severities, off-site consequences and public concern. Later studies indicated that Emergency Planning Zones (EPZs) of 5-miles and 2-miles also were justifiable for certain types of incidents. Since radio-active plumes are wind-directed, it was postulated that evacuation of sectors or quadrants may be more pragmatic than entire ten-mile area evacuation . The latest theory is that of a **graded response** (described in Chapter 2), in which evacuation is ordered in specific sectors where actual radiation has been detected. These simplified evacuation strategies are argued to be safer and more effective in terms of saving human life and reducing damage than whole area evacuation. This research, however, focuses on 10-mile, 5-mile and quadrant type of evacuation only. With slight extensions, the theories developed could be used to model other types of evacuation strategies.

Various evacuation studies and guidelines provided by the NRC and other organizations pose an interesting set of transportation related evacuation problems for nuclear power plants. Unlike other disaster types, such as floods and hurricanes, location of the incident is fixed and the evacuation area is well-defined. This gives a relatively stable set of evacuation scenarios. The socioeconomic and road network data can therefore be compiled with great precision. This encouraged most researchers to build microscopic, planning (as opposed to operational) models requiring extremely detailed inputs (CLEAR, DYNEV and NETVAC). MASSVAC [3] on the other hand, is much more operations oriented (owing to its origins in natural disaster

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[2] Ingestion Pathway is the area for which plans are made for minimization of indirect exposure particularly through contaminated food and water.

[3] MASSVAC = MASS eVACuation, a computer simulation model, designed at Virginia Tech, for estimating network clearance times and evaluating highway network performance during evacuation processes

evacuation planning) and is designed to operate on relatively simpler input. As proved in this research, this fact does not compromise analytical results provided to an evacuation manager. As a real-time macroscopic model, MASSVAC presents great advantages in evaluating numerous scenarios and operationally testing alternative traffic management strategies.

MASSVAC requires estimates of trip productions from trip origins in an emergency planning zone. These values depend on evacuation area type, population distribution and evacuation scenario. Most of this pre-processing stage is carried out through another program interfaced with MASSVAC. The combined trip production model (with user-oriented graphics capabilities) provides an integrated Transportation Evacuation Decision Support System (TEDSS) for nuclear power plants.

1.1 Research Objectives

The MASSVAC computer simulation model was designed for modeling evacuation under natural disaster conditions. The trip distribution and assignment options provided were specifically tailored to deal with these type of evacuation scenarios.

The principal objective of this research is to enhance the philosophy of MASSVAC, primarily in the area of trip distribution and traffic assignment, to simulate evacuation around nuclear power plants. A number of changes have been made to the model to address special problems presented in nuclear power plant evacuation.

The overall objective of this work is to devise an improved and revised version of MASSVAC so as to make it a versatile and fully operational model.

Evacuation for nuclear power plants differs from "conventional" disasters by the fact that the objective is to get out of the Emergency Planning Zone (EPZ) as opposed to reaching specifically designated, capacity constrained shelters. Trip destinations are ordinary highway nodes outside the emergency planning zone (EPZ) and are assumed to be of infinite capacity. Evacuation processes within the EPZ are assumed to be unaffected by traffic problems on the highway network outside the 10-mile area. The central feature of trip distribution is that it is dictated not only by considerations of travel time but also the need to travel away from the nuclear incident. These concepts led to development of network space partitioning strategies for each trip producing origin (discussed in detail in a following chapter). However, geometric partitioning alone may not guarantee "close" destinations and therefore the feasible set of destinations include those which are not only **away** from the plant but also **close** with respect to travel time.

Evacuation events typically incorporate heavy and extended congestion over large portions of the network under study. Such roadway restrictions do not inhibit trip production as trips are mandated by the nuclear incident. Thus trip distribution must be sensitive to the varying states of the network especially in the congested portions of the network. For this purpose, this research investigates the application of iterative selection of destinations, based on current travel times, for each trip producing origin.

The traditional stochastic, user-choice, multi-path assignment model (Dial's algorithm) was found to be insensitive to the total length of evacuation routes. This is especially true when only a sector of the EPZ has been ordered to evacuate. Evacuation of sectors provides greater route choice, therefore producing many longer alternative routes to the same destination. This leads to an overestimation of evacuation time. Also, these routes may wind toward the incident through many of its links thereby defeating the purpose of destination identification. An alternative all-or-nothing assignment procedure was developed to provide for sector evacuation and to serve as a benchmark for other types of evacuations.

Further, as part of this research effort, model enhancements and sensitivity testing work were carried out to infer evacuation routes, improve the method of storing trips which could not be serviced during a particular iteration in the Dial's algorithm and a number of other improvements to improve the information content of MASSVAC output.

1.2 Organization of the Thesis

This chapter presented a brief history of the development and application of existing emergency planning regulations as they pertain to the reactor licensing process. We have also discussed how we plan to enhance MASSVAC for its new role as an evacuation model for nuclear power plants. The next part of the section outlines following chapters.

Chapter 2 Literature Review: discusses the general methodology of evacuation planning for nuclear power stations evolved from NRC/FEMA guidelines. Descriptions of other computer models developed specifically for nuclear power plant evacuation also are included.

Chapter 3 Research Methodology : delineates the population data collection and compilation methodologies used to create MASSVAC's data base. The modelling of the transportation network is also discussed in this chapter.

Chapter 4 New Features in MASSVAC3.0 : develops the various network partitioning as well as travel time selection methods for identifying feasible sets of destinations for trip origins in the EPZ. The enhancements to Dial's Algorithm and incorporation of the alternative All-or-Nothing assignment procedure is also discussed along with miscellaneous features provided in MASSVAC to improve information content of output and enhance the understanding of the evacuation process.

Chapter 5 Technical Aspects : The extensive changes to the source code of the MASSVAC model necessitated inclusion of this chapter in the thesis. The functions of all subroutines in MASSVAC3.0 discussed along with their role in the model as a whole.

Chapter 6 Application of MASSVAC to Surry and North-Anna EPZs : This chapter demonstrates the application of MASSVAC3.0 to estimate Network Clearance Times, delineate evacuation routes, compute exit point volumes and to develop/evalute traffic management strategies are presented in this chapter.

Chapter 7 Conclusions : consists of concluding remarks and recommendations for further research.

2.0 Literature Review

2.1 Evacuation Study Methodologies

A number of methodologies have been developed to plan for emergency evacuation around nuclear power plants. These methods primarily differ with respect to the area over which evacuation must take place.

Emergency Planning Zone (EPZ) around a nuclear power plant is considered to include all areas lying within (a circle of) 10 miles of the power station. Census tract information is used to aggregate socioeconomic data over **Protective Action Zones** (PAZ) within the EPZ. Evacuation analysis is usually carried out for three population groups: 1) permanent auto-owning population; 2) transient population; 3) non-auto owning population and 4) institutionalized population (hospitals, prisons etc.).

Evacuation Time is defined as the time elapsed from the beginning of the first alert to the public to the time that that the last vehicle crosses the plume exposure pathway EPZ boundary. However, the most complexly determined and site specific component of evacuation time is *network clearance time* i.e., the time from which the first vehicle loads the system to the time by which all trips clear the EPZ. The other components are *notification time* and *preparedness time*.

The following tasks derived, from NRC and FEMA requirements, outline the general approach to evacuation time analysis for nuclear power plants :

1. Delineate Plume Exposure EPZ and Subareas to be studied : In association with utility, state and local government officials, review the boundaries of the plume exposure pathway emergency planning zone (EPZ).

2. Establish categories of People to be evacuated from the EPZ and its subareas : Identify the categories of people for which evacuation times are to be estimated. The first category is the permanent population which comprises of all people who reside within the EPZ. The second category will include population associated with all "special" facilities. Examples of special facilities are military installations, schools, hospitals, prisons, industrial facilities with large employment, hotels and motels, institutions and recreation areas. The third category of people will include those dependent on public transportation to evacuate the EPZ.

3. Estimate Time Required to Prepare to Evacuate : Preparation time is expected to vary both within and among the population categories. These estimates should include, wherever applicable, work-to-home and school-to-home travel times, and times required to secure homes, farms, businesses and special facilities.

4. Conduct an Assessment of the Transportation Network : In order to estimate evacuation times, identify primary road network to be used by the evacuating vehicles. The network will consist of major streets and intersections within the EPZ and will be be reviewed for feasibility by those who implement an evacuation. Highway data should include both geometric (lanes, shoulders, widths etc.) and operational (traffic controls, parking restrictions, speeds etc.) information.

5. Code the Evacuation Network : If a computer based decision support system is used, all network data must be properly coded. The network is coded directionally and the geometric and operational parameters for each link in the system are input into the model.

6. Develop Vehicle Loading Distribution : Evolve and code the appropriate vehicle loading data for use in the computer model.

7. Estimate Evacuation Time Distribution for General Public : The locational distribution of the public will be used in conjunction with the transportation network data compiled to estimate evacuation times associated with each evacuation scenario mandated by of NUREG-0654. For the area as a whole, and for each subarea, evacuation movements should be modelled. These time estimates should be made for different evacuation scenarios with respect to weekday, weather conditions and rate of escalation of disaster event.

8. Estimate Evacuation Times for the Public Transport Dependent Population This involves estimation of number of people to be evacuated by transportation supplied by local governments. From this number, an estimate of total number of vehicles required to accomplish the task must be made. Typically, evacuation of this segment should be accomplished within the time-frame required for evacuation of the general population.

9. Estimate Evacuation Times for Special Facilities : Special Facility populations include persons with access to automobiles such as trips from major employers and recreational facilities. The second set of special facilities includes schools, hospitals and detention facilities that depend on buses and special emergency

vehicles for evacuation. Evacuation time for this category will include the time required to move these vehicles from their storage facilities, embarking time and travel times from the special facilities to areas outside the EPZ.

10. Estimate Evacuation Time Distribution for Prevailing Wind Directions : In addition to evacuation scenarios outlined in task 7, the computer model should be used to estimate times associated with evacuations that use alternate routing choices to avoid most affected by a wind directed plume.

11. Document Analysis, Results and Presentation : This concerns the reporting the findings of the study in acceptable format. Sources of data will be clearly outlined. The methods used to derive the evacuation time estimates will be explained, including a description of computer models used. The bases for assumptions used in the model calculation will be documented. The presentation will be used as forum for responding to any comments on the methods, procedures, and results of the evacuation study.

Most transportation evacuation models including MASSVAC and those discussed in Section 2.2 address the issues listed above. However, recently (1989), the **Graded Response Strategy** has been proposed as a preferred evacuation strategy for nuclear power plants [19]. The basis of this strategy is that nuclear power plant accidents are far less likely to occur than than non-nuclear ones and would typically evolve slowly, giving ample time for off-site response. It is argued that most leaks at a nuclear power station do not warrant a evacuation of the entire 10-mile EPZ. Not only is this a financial and psychological burden on the public, a massive evacuation would unnecessarily risk populations closest to the plant.

The graded response strategy focuses on members of the public most at risk, tailors protective actions to the specific conditions being faced, and implements them in a logical, manageable sequence. The essence of this methodology is to first evacuate an inner zone near the plant of about 2 miles while advising other people in the EPZ to take shelter and await instructions on TV and radio. Then radiation monitoring teams are sent to determine the direction of the radioactive plume after which the sheltered people in the EPZ are carefully relocated to areas away from the plume. The amount of time required and risk involved in this method is argued to far lesser than a whole-scale 10-mile evacuation.

2.2 Evacuation Simulation Models

Three independently developed computer simulation models specifically developed for evacuation around nuclear power plants are discussed here.

2.2.1 CLEAR

CLEAR (Calculates Logical Evacuation And Response) is a microscopic simulation model developed by Pacific Northwest Laboratory for the NRC [15]. The 10-mile EPZ is divided into 24 zones (45 degree sectors in 3 radial zones : the first from the reactor to the 2-mile radius, the second from the 2-mile to 5-mile radius and the third from the 5-mile to the 10-mile radius). Socioeconomic data are compiled for each of these zones.

This is followed by coding of the transportation network in the 24-zone EPZ in a very special way. *Road segments* are identified by superimposing the 24-zone diagram over the transportation network around the EPZ. A road segment ends and another one begins at every road intersection. Furthermore, one road segment ends at the zone boundary and a new one begins in the next zone. Also, if a road segment continues uninterrupted for a long stretch, it may be divided into two or more road segments.

The entire EPZ transportation network is next divided into evacuation trees. Each evacuation tree is a system of intersecting road segments with at least one exit from the EPZ. Evacuation time estimates made for each evacuation tree may or may not determine the evacuation time estimate for an entire EPZ.

A complex network loading methodology is used to assign vehicle trips to the links and road segments of the highway system. Each evacuation tree is incrementally loaded and link capacity constraints and queueing phenomena forced by congestion are taken into account. Upon completion of this loading sequence, moving vehicles on each road segment are listed in a queue with their specific position on the road segment. Every single vehicle is processed in an attempt to advance it along the network during each interval of time.

The time required to clear all vehicles form the EPZ in this manner is the Evacuation Time Estimate (ETE) for the EPZ.

CLEAR is a microscopic model which traces each vehicle in the EPZ. This makes it unsuitable for use as total population model for high population areas. Also, obtaining accurate data for strictly geometric zones as defined above is difficult. The loading and advancement methodologies are based on very roughly determined mathematical models of link service under different flow conditions making the model very weak in modelling different scenarios of evacuation.

2.2.2 DYNEV

DYNEV (DYnamic Network EVacuation) was developed by KLD Associates, Inc. as an adaptation of TRAFLO a traffic simulation model also developed by KLD Associates.

The study procedure to produce evacuation time estimates for nuclear power plants using DYNEV is summarized below :

1. Socioeconomic data is obtained and aggregated over 160 cells of a polar grid, centered at the power station and consisting of 22.5 degree sectors. This is superimposed on a network representation which is derived from maps and actual physical survey of the network. Capacities of each link is estimated and centroids where trips are expected to be generated during evacuation are located. With this information, the "input stream" for the Traffic Assignment model is developed using PREDYN, a diagnostic software which is used to correct any input stream inconsistencies.

2. When the input stream is free of error, the Traffic Assignment Model is executed and the results are carefully evaluated. A number of "treatments" reflecting actual traffic control measures are available to improve network performance. This step is repeated until a satisfactory assignment pattern is achieved.

3. Step 2 is followed by execution of the Traffic Simulation Model in order to provide the user with detailed estimates, expressed as statistical measures of effectiveness (MOE), which describe the detail performance of traffic operations on each link of the network. Again, the user is given the opportunity to

implement corrective treatments designed to expedite the flow of traffic on the network in the event that results appear to be less efficient than it is possible to achieve.

4. Finally the simulation results are analyzed, tabulated and graphed. to show cumulative vehicle trips leaving/remaining in the EPZ and link performance statistics.

DYNEV has been used extensively to develop evacuation plans for nuclear power plants. An extensive critique of all procedures and aspects of the model can be found in [14]. The Input and Input processing phase of the model is very intricate and extensive thereby making DYNEV "a macroscopic model with microscopic input". This contributes the model's infeasibility for real-time operational applications. More importantly, the greatest shortcomings of DYNEV lie its methodologies of Trip Distribution and Traffic Assignment. The main problem with trip distribution is that it is not an independent procedure as in MASSVAC. The user has no control over this procedure since it is integrated with the traffic assignment. Hence instead of determining traffic assignment, trip distribution is *determined by* it. The equilibrium assignment procedure used to derive link flows during evacuation is not a reasonable assumption since evacuation is a rare event which typically occurs over too short an interval of time for the network to reach a steady, optimized state of operation.

2.2.3 NETVAC

This model was developed exclusively for analysis of evacuation around nuclear power plants by Sheffi, Mahmassani and Powell at the Massachusetts Institute of Technology (MIT).

NETVAC was made to improve upon the use of mainstream microscopic traffic simulation models, particularly NETSIM, in terms of methodology as well as computational efficiency. The basic features of NETVAC1 includes : dynamic route selection, priority treatment of flow at signalized intersections and capacity calculations. The network data input to NETVAC1 consists only of link information which includes :

1. Identification- upstream and downstream nodes.

2. Physical information- link length, number of lanes, lane width, shoulder width and approach width.

3. Traffic Engineering Information- link type, including parking information and area type (using HCM type conventions for both)

4. Routing information- including the preference factor for each link.

5. Turning information- including all nodes that can be reached from the head node of the link under consideration, the green split for each movement on the presence of special turning lanes.

NETVAC includes several types of output reports, some of which are given only on request. These can be grouped into reports, some of which are given only on request. These can be grouped into two categories : pre-execution reports and simulation reports. Pre-execution reports includes the listings which deal with the input data ; they include the following:

1. Echo Listing- lists the network input information as it is read.

2. Network listing- lists the network in an ascending order of upstream nodes.

3. Heading label and a list of options and parameter values.

4. List of signalized intersections.

5. List of source nodes.

6. Network Diagnostics- includes error messages.

The simulation reports include interval reports and post processing reports. The interval includes :

1. Total vehicle report- gives total number of vehicles on the network.

2. Link conditions report- number of moving vehicles on the link, queue length on the upstream node, the current rate of departure, volume/capacity ratio.

3. Summary of departures.

4. Spill-backs at every node.

The post processing reports are given once the execution is terminated and include:

1. Link profile report- The flow on each link at each reporting interval.

2. Simulation completion- the time at which the network cleared.

As it stands now, the model can process up to 1200 links with no bound on the number of vehicles that can be evacuated.

3.0 Research Methodology

The research methodology of evacuation modeling for nuclear power plants can be divided into two distinct phases :

- **Phase I :** Highway data preparation and estimation of trip production for different evacuation scenarios from the socioeconomic and geometric data pertaining to the evacuation areas.

- **Phase II :** The trip productions and digitized highway network data compiled in Phase I were used as input to MASSVAC - a special purpose computer model, to estimate evacuation times and to evaluate highway network performance under evacuation.

The inter-relationships between different modules of these two phases are illustrated in Figure 3.1.

Phase I consists of methodologies which derive three sets of data from the socioeconomic data :

1. Network representation of the highway system to be used for evacuation consisting of highway links (and associated characteristics), trip origin nodes, destination nodes and highway nodes.

2. Trip production at each origin node of the emergency planning zone.

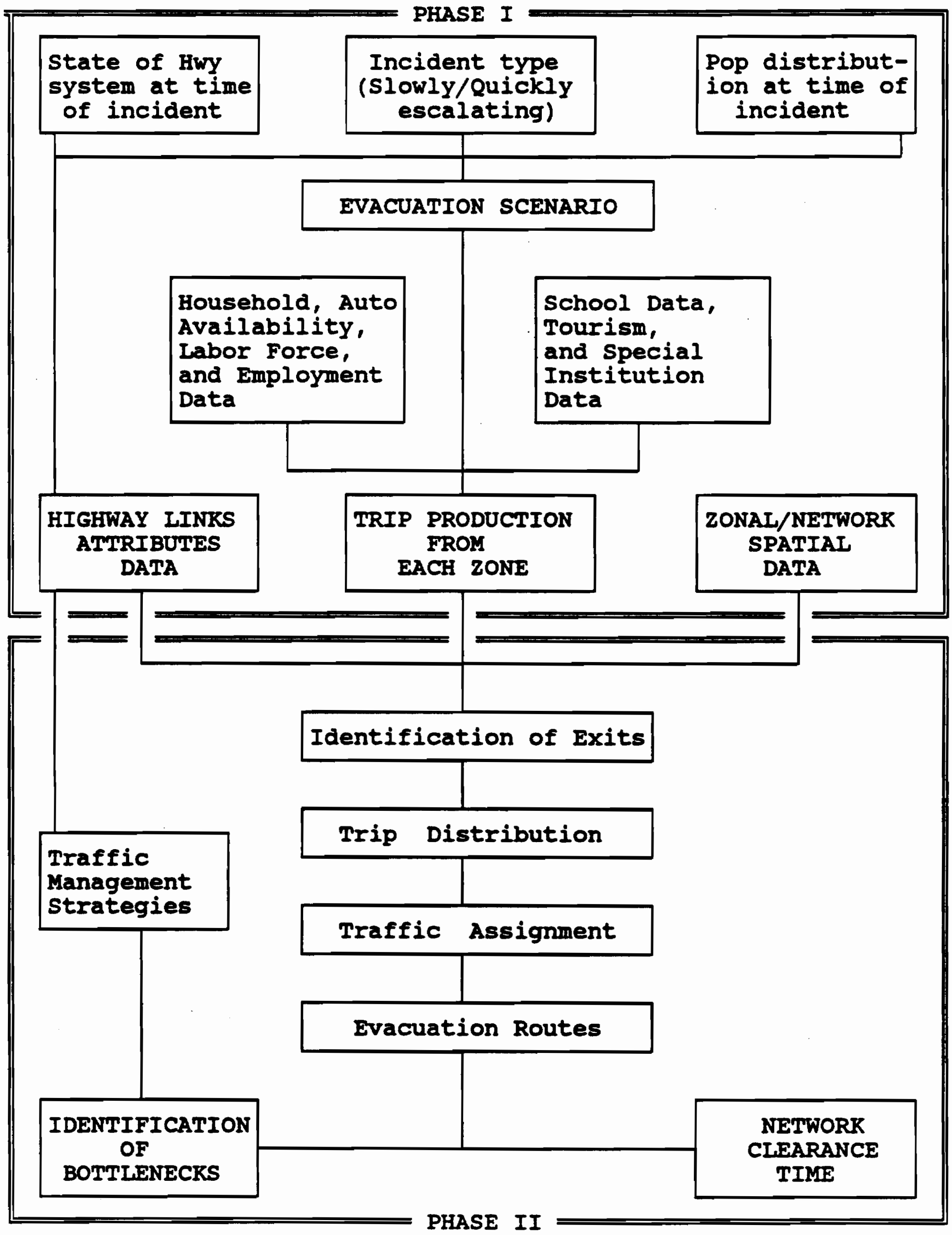

Fig. 3.1 : Framework of Population and Evacuation Study

3. Digitized model of the evacuation area consisting of the highway network, Protective Action Zones (PAZs) and the socioeconomic data - designed for graphical presentation of input and output data to the user(s).

These data are determined primarily from the expected state of the highway network and population distribution at the time of incident and type of incident (slowly/quickly escalating).

The second phase uses MASSVAC, a computer package exclusively designed for evacuation modeling which takes items 1, 2 and 3 described above as input so as to estimate evacuation times and evaluate highway network performance during the evacuation process under different evacuation scenarios. After evaluating different evacuation scenarios, we present results for the worst possible combination of disaster scenarios, taking into account driver behavior during evacuation.

3.1 Phase I : Data Preparation

This phase of evacuation comprises identification of evacuation scenarios, development of population/trip production models and data compilation.

3.1.1 Identification of Scenarios

A specific combination of disaster event, population distribution and highway network configuration is considered as an ***evacuation scenario***. The state of the highway-network/population-distribution system about to undergo evacuation is derived from the socioeconomic characteristics of the emergency planning zones by identifying the most probable set of events necessitating evacuation. Although the number of possible combinations is infinite, it is possible to derive specific set of scenarios by fixing the states of variables affecting evacuation (e.g. type of day : weekend/weekday) and then choose the evacuation scenario as a specific combination of these fixed states.

The number of people present in an area depends on time of day, day of week, and season of the year. Movement of people during different time periods necessitates development of evacuation scenarios. With these scenarios, it is possible to describe expected content of the population to evacuate. Initially population is divided into permanent and transient groups. Permanent population refers to people who live within the study area. Transient population refers to tourists and people employed in the region but not living there.

Both permanent population and transient population groups contain people who do not have access to automobiles. Examples include non-auto owning households in the permanent population and tourists visiting as a part of a bus tour. These people are handled separately in an evacuation. However, it is assumed that they follow similar movement patterns as those having access to a vehicle.

Certain patterns of movement are expected from permanent population. For instance, the majority of people are located at their residence during evening and night time hours throughout the week and year. People employed outside the home are at their places of work on most weekdays throughout the year. During fall, winter and spring, children are at school during the day. During the summer, many children will be at or near their residences.

On most weekends people stay at home or relatively close to home to fulfill shopping and recreational needs. Day trips to recreational areas and vacations are more likely to occur during late spring, summer, and early fall. However, a mass exodus from residential areas on the same weekend is unlikely. In fact, we can assume that at most 10% of the residents leave the study area on any particular weekend.

Assumptions pertaining to transient population behavior may be made. Documentation reveals that there are more tourists in an area during summer months than during winter months. Those tourists staying in hotels are expected to be visiting local attractions during the day time. Although many may be sampling the night life during their visit, generally they will not be too far from their hotels. Tourists using campgrounds can be expected to stay near their campsites throughout the day and night. Transients employed in the evacuation region are expected to be at their place of work during the day and absent from the region at other times.

Identifying population movements is only one element in developing evacuation scenarios. Basically, two types of evacuations may occur based on the type of nuclear incident, namely slowly escalating and quickly escalating emergencies.

During a slowly escalating incident people are notified of a potential problem. All permanent residents return home if they are not already there. School children are reunited with the family if the emergency is classified as "below ALERT" or are sent home if they live outside the ten-mile EPZ [4]. Tourists return to their accommodations although some may elect to immediately leave the area. All other transients leave the area. People are asked to remain sheltered and to await an evacuation order. Because of prior notification, people are ready to evacuate quickly

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[4] This assumes that the level of the incident is below SAE or ALERT. In a General Emergency (highest level), whether slowly or quickly escalating, people may be sheltered or evacuated.

once informed. Consequently, preparation time is minimal if a sufficient amount of time has passed between receiving a warning and being told to evacuate. Further, streets will be relatively empty since most people will be at home waiting for further instructions.

In a quickly escalating incident an order to evacuate is made to the public immediately. People are expected to secure homes and offices and leave directly from their current location. School children are bused directly to Evacuation Assembly centers or are sent home if they live outside the 10-mile EPZ. Tourists leave the area immediately. Preparation time for the permanent population will be more significant in this situation since people take time to close windows, bring in pets, secure facilities, contact other family members etc.. Roads in the evacuation area are initially occupied with typical daily traffic for the time of day and day of week the evacuation order occurs.

Given assumptions on where people are located, three evacuation scenarios exist. Mathematical models describing evacuation populations are found in Section 3.1.2.

3.1.2 Development of Population Models

The equations to determine production of vehicle-trips at each origin are developed from the basics in this section. They are essentially simple mathematical models whose independent variables are raw data pertaining to the evacuation area which are adjusted, if necessary, for each of the scenarios delineated in Section

3.1.2.. The development of these equations is crucial for determining the nature, cost and extent of data collection effort required.

Two mathematical models have been developed to describe the number of vehicles to evacuate during certain events. These two models pertain to people who have access to an automobile. Both models are separated into two parts, one applicable to permanent population and the second applicable to transient population. The sum of these two equations represents total number of vehicles to be loaded from a zone onto a network during relevant evacuation scenarios. Mathematically, this sum is expressed as:

$$TV_i = P_{vi} + T_{vi} \qquad [3.1]$$

where,

TV_i = total vehicles in zone i,

P_{vi} = permanent population vehicles in zone i,

T_{vi} = transient vehicles in zone i.

A third model exists to identify the number of vehicles required to evacuate people not having access to automobiles. Included in this model are school children during a quickly escalating event, hospital patients and public transit dependent people. Each of these models are discussed in detail.

This first evacuation model applies to the following scenarios:

Slowly escalating	*Quickly escalating*
1) week day	1) week night

2) week night 2) week end

3) week end

A mathematically simple expression representing permanent population vehicles for these scenarios is used. Namely,

$$P_{vi} = P_{ai} / VOR_i \qquad [3.2]$$

where,

P_{ai} = auto-owning population in zone i,

VOR_i = vehicle occupancy ratio in zone i.

In these scenarios the majority of auto-owning residents are evacuated from their homes. Family members are together before the evacuation order and leave together in one car. Consequently, vehicle occupancy ratio in equation 3.2 is equal to average household size in each zone.

The second part of equation 3.1, requires an estimation of the number of vehicles used by transients in the evacuation region. For each scenario listed above, most of the non-tourist transients will not be in the area. Therefore, the following equation concentrates on tourists. The number of vehicles used by tourists during an evacuation is:

$$T_{vi} = (H_{ri} * O_{fH})(1 - T_B) + \left[\frac{NH_f * A_r/30 * V_i}{APS} \right] \delta_i + (C_i * O_{fc}) \qquad [3.3]$$

where,

H_{ri} = number of hotel rooms in zone i,

O_{fH} = hotel occupancy factor,

T_B = percent of tourists visiting in bus groups,

NH_f = non-hotel tourist factor (to account for those staying with friends and relatives.),

A_r = monthly attraction rate,

V_i = total yearly visitors to attractions in zone i,

APS = average party size,

$$\delta_i = \begin{cases} 1 \text{ if zone i contains a major tourist attraction,} \\ 0 \text{ otherwise,} \end{cases}$$

C_i = number of campsites in zone i,

O_{fc} = occupancy factor for campgrounds.

The first expression in equation 3.3 determines the number of vehicles used by tourists staying in hotels. From this group must be factored out those traveling in bus groups. It is assumed that one vehicle is available per room for those tourists using private automobile. The second expression applies only to zones with major tourist attractions. According to a Virginia tourism study, thirty five percent of all visitors to Virginia stay with friends and relatives. These people must be accounted for in an evacuation. The vehicle occupancy ratio in this expression is equal to average party size for these types of visitors. The final expression in equation 3.3 determines the number of vehicles used by campers. One vehicle per campsite is assumed. Occupancy factors for hotels and campgrounds depend on the season during which an evacuation occurs.

The second mathematical model applies to a quickly escalating incident occurring on a week day. People are more scattered throughout the zones in this scenario. Also, more people must be accounted for due to those transients who live outside but work inside the evacuation area. The number of people falling into this group is captured by employment figures for each zone. Consequently, these transients are accounted for in the permanent population equation that follows:

$$P_{vi} = \{[P_{ui} + E_i + (P_{ti} - P_{LFi} - P_{si}(SF))] a_i\} / VOR_i \qquad [3.4]$$

where,

P_{ui} = unemployed population in zone i,

E_i = employment in zone i,

P_{ti} = total population in zone i,

P_{LFi} = labor force in zone i,

P_{si} = school age population in zone i,

$$SF = \begin{cases} 1 \text{ if evacuation during school year,} \\ 0 \text{ if evacuation during school holiday,} \end{cases}$$

a_i = percent auto owning population in zone i,

VOR_i = vehicle occupancy ratio

As mentioned above, the employment variable applies to permanent and transient people working in the evacuation area. This model assumes that some transients working in a zone are dependent on public transport. The third expression in the numerator of this equation is intended to estimate the number of people not in the labor force. School age children must be excluded from this group. Housewives are examples of people in this category. The total population determined by summing the first three expressions is factored down to account for those people who do not have access to a vehicle. Finally, a vehicle occupancy ratio adjusts population estimates to total number of vehicles.

The transient population equation used in quickly escalating incidents is the same as equation 3.3. The underlying assumption here is that tourists are within the same zone as their hotel. Given that most hotels are located near large tourist attractions, this assumption should not produce misleading results.

In the computer model developed to simulate evacuations, users input time of day, day of week, month of year and type of evacuation (i.e. slowly or quickly escalating). From this information, the appropriate evacuation equation is utilized to calculate the total number of vehicle trips to load into a network.

A third model is used to determine the number of buses required to evacuate people who not have access to cars and school children. Institutionalized population which includes persons in hospitals, prisons and schools/colleges are evacuated by buses, ambulances and other specially equipped vehicles. The model for a quickly escalating weekday scenario is :

$$B_i = [(SC_i * SF) + (P_{vi} + E_i + (P_{ti} - P_{LFi} - P_{si}(SF)))(1 - a_i)] / B_f \qquad [3.5]$$

where,

B_i = buses required in zone i,

SC_i = students attending school in zone i,

B_f = bus occupancy factor.

(All other variables in this equation retain previous definition)

In the event that the majority of the population are at home when an evacuation order is given, this equation reduces to :

$$B_i = P_{Nai} / B_f \qquad [3.6]$$

where, P_{Nai} = Non-auto owning population in zone i

Tourists are omitted from both equations under the assumption that they will evacuate on the buses that brought them to the area. Consequently no additional buses are required for tourists.

3.1.3 Compilation of Data

This procedure begins by identifying sources and type of data to be compiled based on the preceding steps in Phase I. All socioeconomic data pertaining to the Protective Action Zones (PAZs) which can contribute to quantifying the number of vehicles leaving each zone during an evacuation are listed and evaluated. This is followed by identifying data sources and developing methodologies of updating/adapting the information available to the needs of evacuation planning. The raw data is then processed through the equations and scenarios developed to give the trip production rates under different scenarios.

3.2 *Phase II : Evacuation Analysis*

MASSVAC (MASS eVACuation), a computer simulation model designed for analysis and evaluation of evacuation processes for natural disasters was re-designed and calibrated to include the case of evacuation around fixed point disasters (such as nuclear power plants). The model is designed to take as input the data prepared by Phase I (which is accomplished through an interfacing graphics package) and give as output, the estimated evacuation times and highway performance parameters such as

1. total vehicle-trips serviced by each link during evacuation.

2. times and duration of congestion on highway links.

3. evacuation routes for each trip origin in the network.

The phase II of evacuation planning begins with preliminary runs in which the location and nature of trouble points in the highway network are identified. In subsequent runs, a variety of *traffic management strategies* are introduced to improve the evacuation process under the worst possible combination of disaster events. Once suitable results of evacuation are obtained, the results are displayed graphically on the computer.

3.2.1 Elements of MASSVAC

MASSVAC is a microcomputer model designed to support development and evaluation of evacuation plans. It was originally conceived to simulate natural disaster (Flood/Hurricane/Earthquake) evacuation. A new version of the model was created to include the case of fixed point disasters such as nuclear power plants. We first list the input/output requirements of the model. The actual formats of these elements are illustrated in the User Manual for the TEDSS/MASSVAC[5] computer package.

The outputs of MASSVAC are :

- Estimate possible network clearance time for different values of trip productions (i.e., for different scenarios of evacuation).

- Predict congestion patterns in the highway system : occurrence and duration.

- Determine link usage - total trips serviced, seed volumes, etc..

- Derive Primary Evacuation Routes for each trip origin in the emergency planning zone.

- Apply strategies to improve upon the above results and re-run simulation until the best set of options (leading to lowest evacuation time) are derived.

Inputs are :

---

[5] TEDSS — Transportation Evacuation Decision Support System.

- Network Representation of highway system in the evacuation area. Data required on each link are : link length, free flow speed, capacity, number of lanes, annual average daily traffic and facility type. The cartesian (X- Y-) coordinates of all nodes in the highway system are also required.

- Total number of vehicle trips to be evacuated from each emergency planning zone (EPZ).

Description of Simulation :

The flow chart in Figure 3.2 depicts the operation of the model.

MASSVAC is an iterative, macroscopic and operational evacuation model. It proceeds iteratively (i.e. in fixed intervals of time) by dividing the assumed evacuation time, taken as input, into "simulation intervals". The state of the network and evacuation times for each time interval is recorded and then combined to give the overall results of evacuation.

The key processes in each iteration of evacuation analysis, in order of execution, are :

1. Trip Production

2. Trip Distribution

3. Trip Assignment

4. Determination of evacuation routes

5. Determination of network clearance times

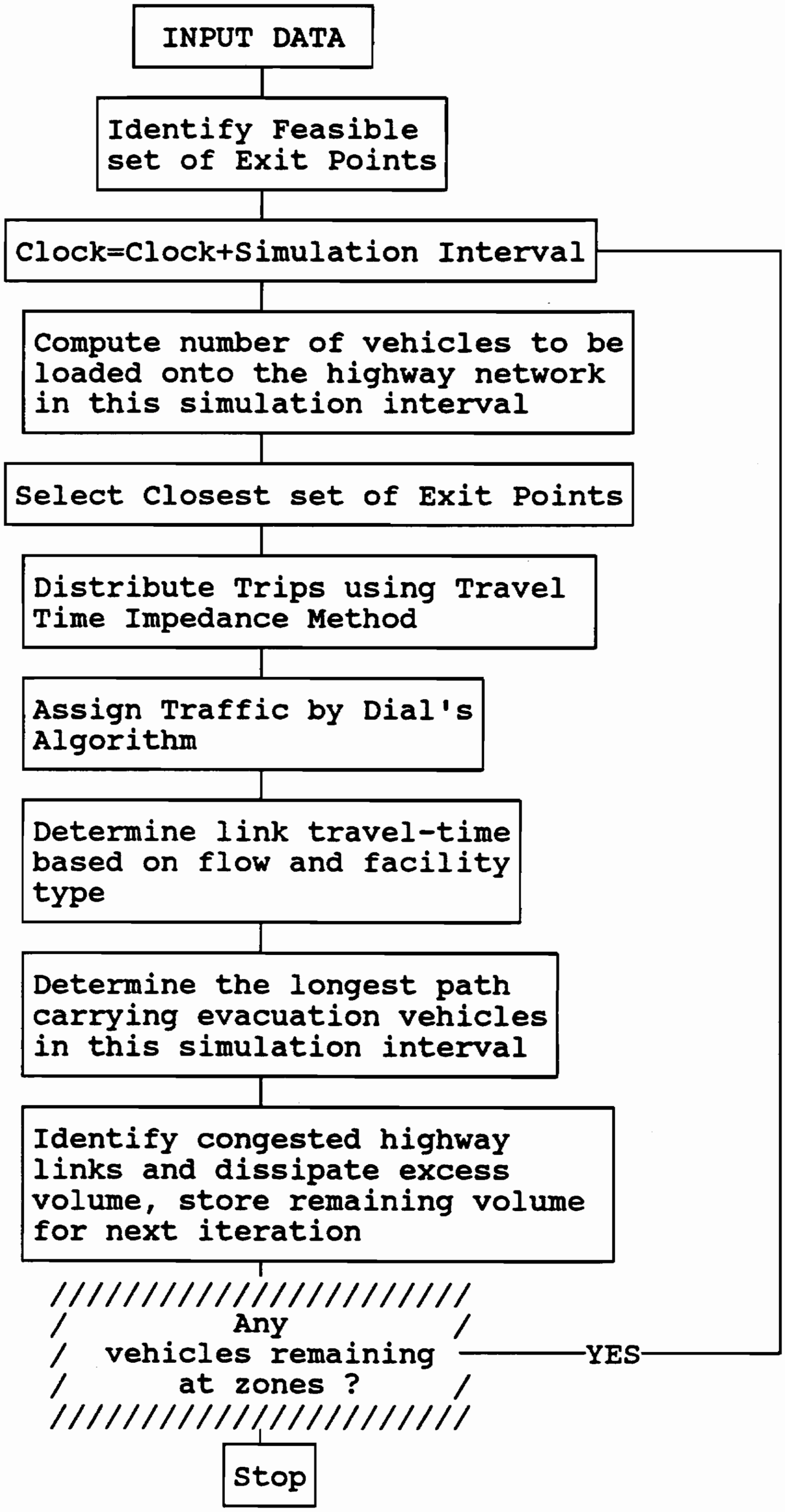


Fig 3.2. Flowchart of MASSVAC

6. Identification of congested links and recording the clock time at which the links were over-capacitated.

The procedures described above are executed iteratively, until all vehicle trips have been cleared from the area. The actual working of each procedure in the simulation model is delineated below.

1. Trip Production : All vehicle trips from an EPZ are aggregated at a "dummy" origin connected to the network by "dummy" links to simulate actual loading of the highway system by people from the zone. The cumulative production at an origin at any time of evacuation is assumed to follow a logit curve. This follows the logic that trips begin to load slowly at the beginning of the evacuation process, reaching a peak rate the assumed half-time and then tapers off towards the last minutes. The number of trips to be loaded in an iteration is computed as the difference of the cumulative trip production of this and the last iteration.

2. Trip Distribution : This step consists of computing the number of trips ending up destinations outside the evacuation area due to trip production at each origin. Zonal trip production is distributed to these destinations based on the status of the network during a particular time interval. Two fundamental assumptions govern trip distribution in MASSVAC:

   - A motorist will not (be permitted to) traverse parts of the highway system closer to the Nuclear Plant than where he or she started out from.

   - An evacuee will always strive (or be directed) to get to the closest exit point(s) in terms of *travel impedance* (distinct from *distance*)

The program, thus, identifies a set of "feasible" destinations for each origin (PAZ) in the network. The methodologies used for determining this feasible set of destinations are discussed in the next section. The Travel Time Impedance Method is then used to distribute trips between each O-D pair after the destination identification process is complete.

3. Trip Assignment : One of two types of algorithms - Dial's or all-or-nothing, are used to translate the trip ends established in the previous step into flows on links. Dial's algorithm is a "two-pass" procedure. The first pass (forward pass) determines efficient links (those which take driver away from origin ***and*** closer to the destination) and assigns probabilistic weights to each of them. The second pass (backward pass) assigns volumes to each link starting from the trip ends (from step 2) at the destinations and working backwards toward the origins. The second type of assignment algorithm is the all-or-nothing assignment which assigns all trips between an O-D pair to the shortest path between them in the current iteration.

4. Calculation of evacuation time :

   The evacuation time is updated during each time interval as :

   EVACUATION TIME = CURRENT CLOCK TIME + TRAVEL TIME ON LONGEST PATH

   The travel time on each path is computed as the sum of travel times experienced on its member links. The travel time on a link is inversely proportional to the flow carried by it. For very small flows, the travel time is equal to link length divided by the free-flow speed.

   The maximum value of EVACUATION TIME computed during the entire simulation is outputted as Network Clearance Time for the area.

5. <u>Location of congested and blocked links :</u> If the volume assigned to a link exceeds its capacity, the link is declared ***congested***. If it exceeds twice of link capacity, the link is deemed unfit for further trip assignment and is, therefore, declared ***blocked***. A study of development of congestion and blocking patterns over the highway network leads to the subjective process of evolving traffic management strategies to reduce evacuation time and improve network performance during evacuation. The volume which can possibly dissipate during the current time interval is computed and the left-over is assigned to the same link in the next iteration.

4.0 New Elements in MASSVAC3.0

A number of enhancements have been made to MASSVAC for its application to evacuation planning around nuclear power stations. Being originally designed for natural disaster evacuation analysis, the trip distribution process in MASSVAC involved capacity constrained destinations. Also, trip distribution was not designed to take the geometry of the network into account since this was not relevant to a natural disaster situation. In the case of evacuation around nuclear power plants, the location of the incident and hence, the emergency planning area, is fixed. The destinations would be nodes outside the Emergency Planning Zone (EPZ), the objective being to evacuate people to these points (which are assumed to have infinite capacity). With existing distribution techniques, some paths would carry trips toward the incident. Hence, methodologies which identify, for each origin, the directions leading "toward" or "away" from the incident need to be incorporated into MASSVAC to realistically simulate the trip distribution during evacuation around nuclear power stations.

Other changes in the source code of MASSVAC have been made to enhance efficiency and to improve content of the output (w.r.t. information on the evacuation process).

This chapter discusses improvements made to the MASSVAC model in the following areas :

1. Trip Distribution.

2. Implementation of Traffic Assignment algorithm.

3. Identification of Evacuation Routes.

4.1 Trip Distribution

Trip Distribution is the process by which, based on socioeconomic and highway data, the volume of traffic between any Origin-Destination (O-D) pair in a highway network is calculated. In this section, we establish the importance of Trip Distribution to MASSVAC in context of evacuation modelling for areas around nuclear power plants. Destinations are highway nodes lying just outside the periphery of the evacuation area. Origins are points in Emergency Planning Zones (EPZs) connected to the highway network with dummy links in such a way that trip loading models real life use of the road network.

All socioeconomic data pertaining to an EPZ is boiled down to the number of trips to be loaded on the network from these origins during evacuation. A portion of these trips are iteratively loaded onto the network. Loading takes place in an iterative, "S-shaped" fashion described in the technical section on the MASSVAC model [10]. The trip production at each origin is distributed to destinations by some procedure (typically an inverse function of the travel time to the destinations). Link usage is determined by a flow assignment algorithm (Dial's algorithm in the case of MASSVAC). Paths are defined as any continuous chain of efficient links between an O-D pair carrying some flow between that O-D pair. Network Clearance Time is the time-length of the longest path plus the clock time of a particular iteration. The travel time of the link is updated according to the flow on it. The Network Clearance Time is the evacuation time for the last iteration.

It is clear that trip loading and link volume assignment are the two most important components in the estimation of evacuation time. If the model predicts these two accurately during each iteration, the rest of its tasks (calculation of travel time on a link, building paths, and estimating clearance time) are, conceptually, straight-forward.

Trip Loading and Link Assignment are relatively well established procedures in MASSVAC. Algorithms for both have been arrived at from extensive research into user behavior and choice under emergency evacuation conditions. Conceptually sandwitched between these two stages we have a rather unresearched and weakly justified stage of *estimation of trip ends*. It is perhaps the most important supporting step in MASSVAC as it completely determines link assignment and hence, all following calculations - including the Network Clearance Time. Traffic Assignment is essentially an expression of Trip Distribution in terms of link and path volumes. An assignment algorithm, however realistically and rigorously established, is therefore no good if its chief input (i.e. Trip Distribution) is inaccurate. Moreover, a logit-based assignment technique like Dial's cannot account for a user perception variance that depends on the length of the path to be travelled [18]. This perception, therefore, needs to be incorporated into trip distribution. An unrealistic trip distribution methodology could result in wrong prediction of link volume assignments and could thereby lead to completely incorrect results. An accurate evacuation model must closely match driver behavior and control strategies employed by the authorities. All the user choice and behavioral assumptions that go into traffic assignment must be incorporated into trip distribution also, if we are to maintain consistency between the two processes. Determination of motorists' choice of destination and the route used to get there is therefore a ***joint*** "distribution/assignment" problem.

In MASSVAC, the question of trip distribution translates into a problem of O-D table generation. In the Section 4.1.1. the O-D table subroutine used in the previous version of MASSVAC is described along with its inadequateness for the problem at hand. Section 4.1.2. deals with the theory of the methodologies developed to fill the vacuum in MASSVAC for evacuation around nuclear power plants. Section 4.1.3 lays out the solution structures and implementation of the methodologies. Notes on the application of all trip distribution options developed in this section are described in Section 4.1.4.

4.1.1 Trip Distribution In Previous Versions of MASSVAC

Trip Distribution was, evidently, quite an undecided procedure in previous versions of MASSVAC. The model had three options :

1. Ask the user for trip table.

2. Input trip productions at the origins and the destination capacities to generate O-D table.

3. Input trip production only, assume unrestrained shelter capacity and apply Travel Time Impedance Method.

Method 2 was tried out extensively on Virginia Beach Hurricane Evacuation Project. An iterative procedure was used to achieve an "optimized" trip table. Each step of trip table estimation was followed by updating of travel times on the links. The updated travel times were used to generate the trip table in the next iteration. After 4 such steps (based on recommendation in the "Traffic Assignment Manual" published by the Bureau of Public Roads) the average of the link's travel times were used to generate the optimized trip table. The shelters (destinations) were capacity constrained and if a shelter was filled up it was not considered in subsequent iterations. If all destinations were capacitated, and trips remain, the capacity of the nearest shelter to the origin with left-over trips was hypothetically increased to complete the O-D table. This step was found to give the lowest evacuation time and total vehicle travel time [10].

The Travel Time Impedance Method, with unrestrained shelter capacities was not relevant to the Virginia Beach Hurricane Evacuation project and was, hence, not implemented.

The most important drawback in these approaches is that the trip table, once determined, was kept over the entire simulation. In each iteration, a percentage of the established trips between each O-D pair was loaded. The Dial's assignment which followed was therefore crippled with a fixed trip-end structure from which a fixed link assignment pattern was derived - the effect of which in no way changed subsequent trip distribution (in following time intervals) to reflect dynamic user behavior during evacuation.

Optimizing the trip table was an inaccurate way to dictate actual assignment in following iterations. This is especially so since it is a standard practice to "push" the model toward minimization of network clearance time thereby causing congestion on many links of the network. Trip distribution should be dynamically sensitive to the high travel times in some parts of the network. The choice of destinations, therefore, should be part of the evacuation model so as to reflect updated travel times of highway links. This could also correspond to simulating a quickly escalating emergency evacuation scenario under intensive traffic management thereby causing dynamic change in the destination choice.

Adaptation of MASSVAC to evacuation around nuclear power stations requires considering the highway nodes just outside the periphery of the boundary as destinations with unconstrained capacity. Among the available options, 3 (Travel Time Impedance Method) is most suitable. The trips are to be distributed from an origin in inverse proportion of travel times to destinations. This distribution must be revised during each interval of simulation so as to reflect changes in destination choice according to change in travel times on links.

In the next section, we shall see why even this solution needs to be modified to best model the combination of driver behavior and evacuation strategies.

4.1.2 General Theory and Objectives

For the purpose of trip distribution, we assume that destinations are not restricted by capacity. This is very much valid, as exit points on the boundary of evacuation will not hinder flow in any way. The only factor of flow impedance which is assumed to affect trip distribution is link congestion and blockage on highway links within the EPZ. The O-D table is, therefore, visualized as describing, quantitatively, the "collective intent" of evacuees (and the evacuation authorities) to cause flow of trips between all O-D pairs in the network. Given a set of exit points to choose from, any realistic model will distribute trips in inverse proportion of the travel impedance (which, in MASSVAC, is expressed in terms of the minimum travel time, i.e. the shortest path label) of the exit point. Since the shelters are unrestrained the most suitable model is the Travel Time Impedance method.

The problem of evacuation around nuclear power stations is not amenable to a straightforward application of the travel time impedance method. This is because the Travel Time Impedance method assigns ***some*** trips to all destinations, no matter how distant they are from the trip origin. This would result in unrealistically long evacuation routes thereby greatly over-estimating Network Clearance Time. More importantly, we would have trips assigned to paths/links which take a motorist closer to the nuclear plant (at the center of the circular evacuation area). In reality, a driver will not (be directed to) proceed in a direction which will increase the danger of exposure to radiation. Therefore, some destinations to which the travel time impedance method assigns trips are unrealistic (i.e., they should not receive any trips). It is clear that for each origin in the network, some destinations are to be **eliminated** based on the orientation of the destinations with respect to the center of the evacuation area.

Another aspect of evacuation around nuclear power stations that is not satisfactorily modelled by the travel time impedance method is the strategy of evacuating the area in the minimum possible time. Even geometrically chosen destinations may not reflect the actual travel times "on the ground". Hence the elimination step must be followed up by a ***selection*** process, based on the "closeness" of destinations.

Since the travel times on the links change with the volumes assigned, and since we would like our trip distribution to be sensitive and to change accordingly, the selection step must be repeated at the beginning of each iteration. This would ensure that the evacuees are constantly directed toward exit points which are closest to them in terms of travel impedance and, at the same time, prevent them from going closer to the disaster than where they started of from. Network configuration is assumed to be essentially constant over evacuation time. Therefore, elimination by geometrical partitioning of network space can be done as a preprocessing stage before commencement of the iterative simulation module. For each origin, we therefore have two sets of destinations - one "flagged" as feasible and the other as infeasible. Both of these sets are maintained as such throughout the simulation.

It may appear that the first step of elimination is superfluous. Due to approximately circular shape of an nuclear power station EPZ, it may be argued that the closest exit point may never involve a route which takes a motorist closer to the nuclear plant. This is possibly true if the loading on the network is "sufficiently" small. But as we have it, in order to minimize evacuation time, the network is often modelled as loaded heavily thereby manifesting congestion in many parts of the network. Hence, ***theoretically***, it is possible that, a destination which was initially close at free flow, would not remain "close enough" with progress of evacuation time due to congestion on links leading towards it. A selection of destination(s) based exclusively on travel time ***may*** therefore, give us a destination which should have been eliminated because of its unfavorable geometric location.

The objectives of this research, derived from the above discussion, thus are :

1. For each trip origin in the network, **eliminate** certain destinations by geometric partitioning of network space if reaching them requires traversal of network areas

closer to the incident (nuclear power plant) than the point of origin. Do this just once before beginning of simulation, and keep a record of eliminated destinations (for each origin) throughout the simulation.

2. **Select** certain destinations from the set of uneliminated destinations based on the most recently revised link travel times. This step is necessarily a part of the evacuation module and should be done at the beginning each iteration.

3. If the number of selected destinations is more than one, apply the travel time impedance method to distribute the production at origin during current time interval.

Thus we have a two stage, composite destination identification technique which controls trip distribution in a way that not only minimizes evacuation time and risk, but also achieves optimal network utilization.

4.1.3 Development and Implementation

The development and implementation of destination elimination/selection procedures involves the following tasks :

- Formulation of specific geometric and travel time techniques.
- Making the required set of algorithms and programs.

- Incorporating them as subroutines in MASSVAC. The Geometrical elimination techniques are contained in the subroutine GEODIT while the travel time selection techniques are in TTDIT.

4.1.3.1 Geometric Destination Elimination Techniques

From the previous section it is clear that for each origin, we need to distinguish between directions leading "toward" the nuclear plant and direction leading "away" from it. This requires a ***geometric partitioning*** of network space into two parts - one containing the incident (power plant) and the other not. The destinations which lie in the space containing the incident are not considered for distribution of trips from the origin for which the partitioning took place.

All the methods discussed below follow a simple "elimination" strategy. First, the shortest path algorithm is executed over each origin in the network. This results in a shortest-path "label" for all nodes (including destinations) in the network. The label for each node signifies the minimum travel to that node (from the origin for which tree was spanned). Then, any one of the methods described below partitions the network space to identify the infeasible destinations for each origin. The shortest-path labels of infeasible destinations are changed to infinity while the labels for the feasible ones are unchanged. The labels of the eliminated destinations stay unaltered throughout the simulation and hence a total "turn-off" w.r.t. trip distribution results.

Three methods of Geometric partitioning (shown in Figure 4.1) have been incorporated into MASSVAC :

- Quadrant Method

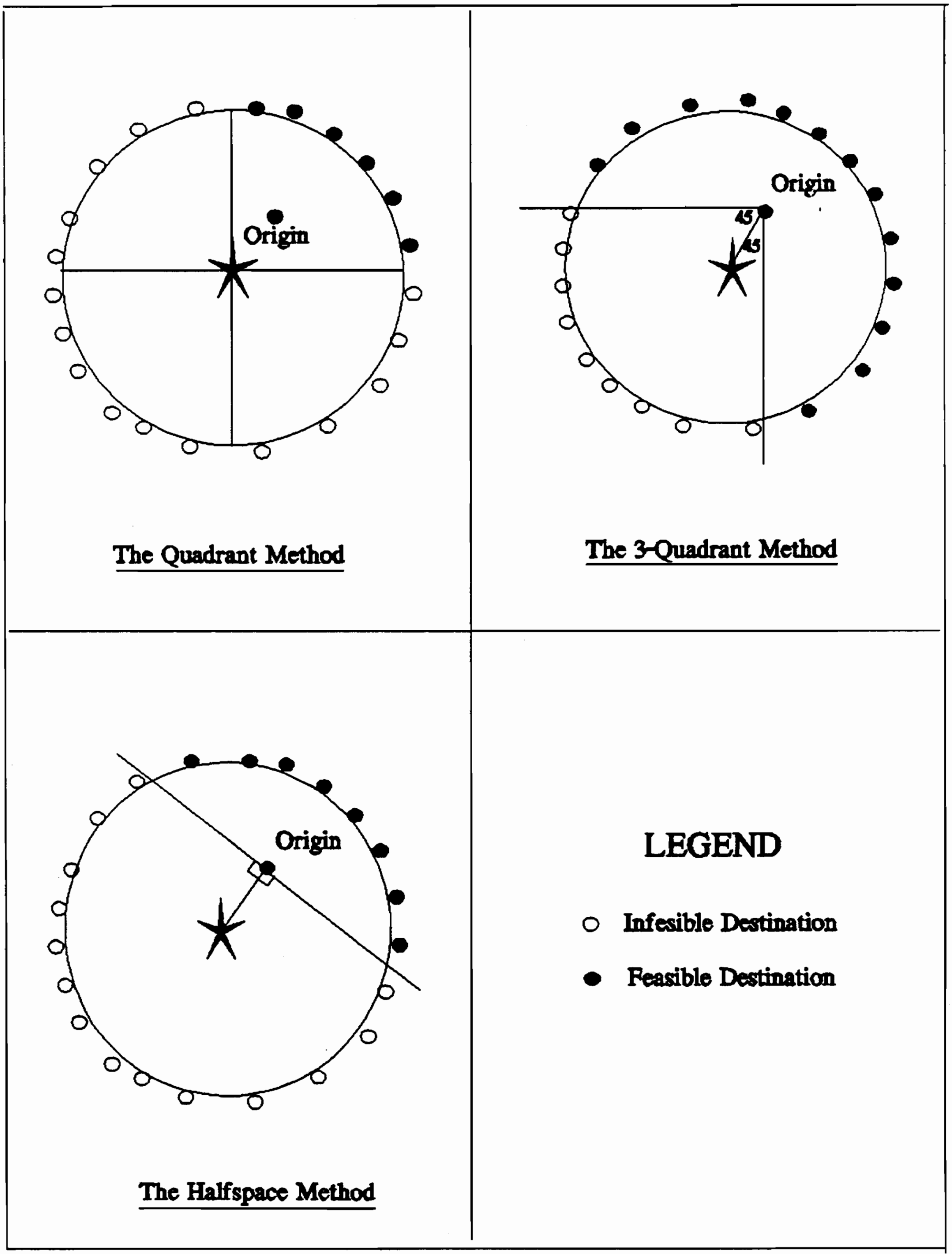


Fig 4.1 : Geometric Destination Elimination Techniques

- Three-Quadrant Method
- Halfspace Method

The Quadrant Method

The evacuation area is divided into four equal parts (quadrants). The origins contribute exclusively to destinations within their respective quadrants. All other destinations are eliminated. Since trips originating from a zone are aggregated at a single point (the zone centroid), production from a zone lying in two or more quadrants will be distributed to destinations in one quadrant only - determined by the quadrant in which its centroid lies.

The inputs required are :

1. X- Y- coordinates of :
   - origins
   - destinations
   - the incident (power plant)
2. the shortest path labels to all destination from this origin.

Note that the radius of circle is not required as we deal with coordinates only. Given the above inputs, the actual implementation of the Quadrant Method is rather simple - it can be wrapped up in a single **block if** statement (See section 5.8)

The Three Quadrant Method

A circle is drawn with the origin as center. All destinations lying in the quadrant containing the center of evacuation area are turned off. The formulation of this method is best explained by Fig and the outline of the code (Section 5.8).

The logic is as follows :

1. Draw a circle of infinite radius centered at the origin (zone centroid).

2. Join the point of incident (the power plant) and the origin with a line segment.

3. At 45 degrees to this line, trace the diameters of the circle thereby forming four quadrants to this circle.

4. Eliminate all destinations lying in the quadrant containing the origin.

The inputs required for this methodology are same as for the Quadrant Method. The implementation as computer source code, follows a different logic :

1. "Draw" two lines - parallel to each axis as ***inferred*** from the X- Y- coordinates of origins, destinations and incident. These lines serve as the diameters (of an circle with infinite radius centered at the trip origin) mentioned above.

2. Eliminate (by changing the shortest path label to infinity) the destinations lying in the quadrant containing the origin.

This method too can be wrapped up in a single **block if** statement (as shown in section 5.8).

The Halfspace Method

A line is drawn through the origin under consideration, perpendicular to the line segment joining it and the center of the evacuation area. This line partitions network space into two **halfspaces.** All destinations lying in the halfspace containing the origin are turned off.

Working in polar coordinates was preferred for implementing this strategy. Conceptualization of the methodology in the Cartesian system is rather more involved.

The inputs required are exactly same as the other methodologies. The radius of the evacuation area is inferred from the given information. The exact radius in the same scale as the X- Y- coordinates is not required.

The implementation of this methodology involves a pre-processing step in the polar subroutine. The X- Y- coordinates of the are converted into **radius** and **angle** vectors with the incident (power plant) as origin. The radius is estimated as the radius vector of the furthest destination. The circle should contain all origins if the evacuation plan is correct. A look at the output of this method is necessary before deciding on this radius. It is possible that the evacuation area is highly unsymmetrical and an origin is located extremely close to the boundary (as decided by the radius vector of the furthest destination). In such a situation, trips at this origin will never be distributed, since all destinations will be eliminated. Hence it must be checked that at least one or two destinations are selected for each origin before finalizing a radius. If necessary, a greater value of radius must be tried out by introducing an "artificial" destination with the desired radius vector but not linked to the network.

Assuming that the angle subtended at the center of the evacuation area by the partitioning line (drawn as described above) is θ and that the polar coordinate angle of the origin is θ_o, the algorithm for this method is

IF

the angle of a destination lies between $(\theta_o + \theta/2)$

and $(\theta_o - \theta/2)$

THEN

retain the Shortest Path label for that destination

ELSE

change shortest path label to infinity

ENDIF

The above solution has to be modified for origins which:

1) lie in the first and fourth quadrant and

2) have radius vector less than or equal to R $\cos\theta$

(R = radius of the circle)

For origins in the first quadrant, the eliminated destinations should have angles between $(\theta_o + \theta/2)$ and $(360 + \theta_o - \theta/2)$. For origins in the fourth quadrant, the eliminated destinations should have angles between $(\theta_o - \theta/2)$ and $(\theta_o + \theta/2 - 360)$.

The derivation of the above is rather intuitive. The problem of altering the simple IF - THEN - ELSE solution comes when one arm of the subtended angle lies in the first quadrant and the other lies in the fourth. A little bit of geometric analysis shows that this is possible only for origins with radius vector less than or equal to R $\cos\theta$ (see Figure 4.2).

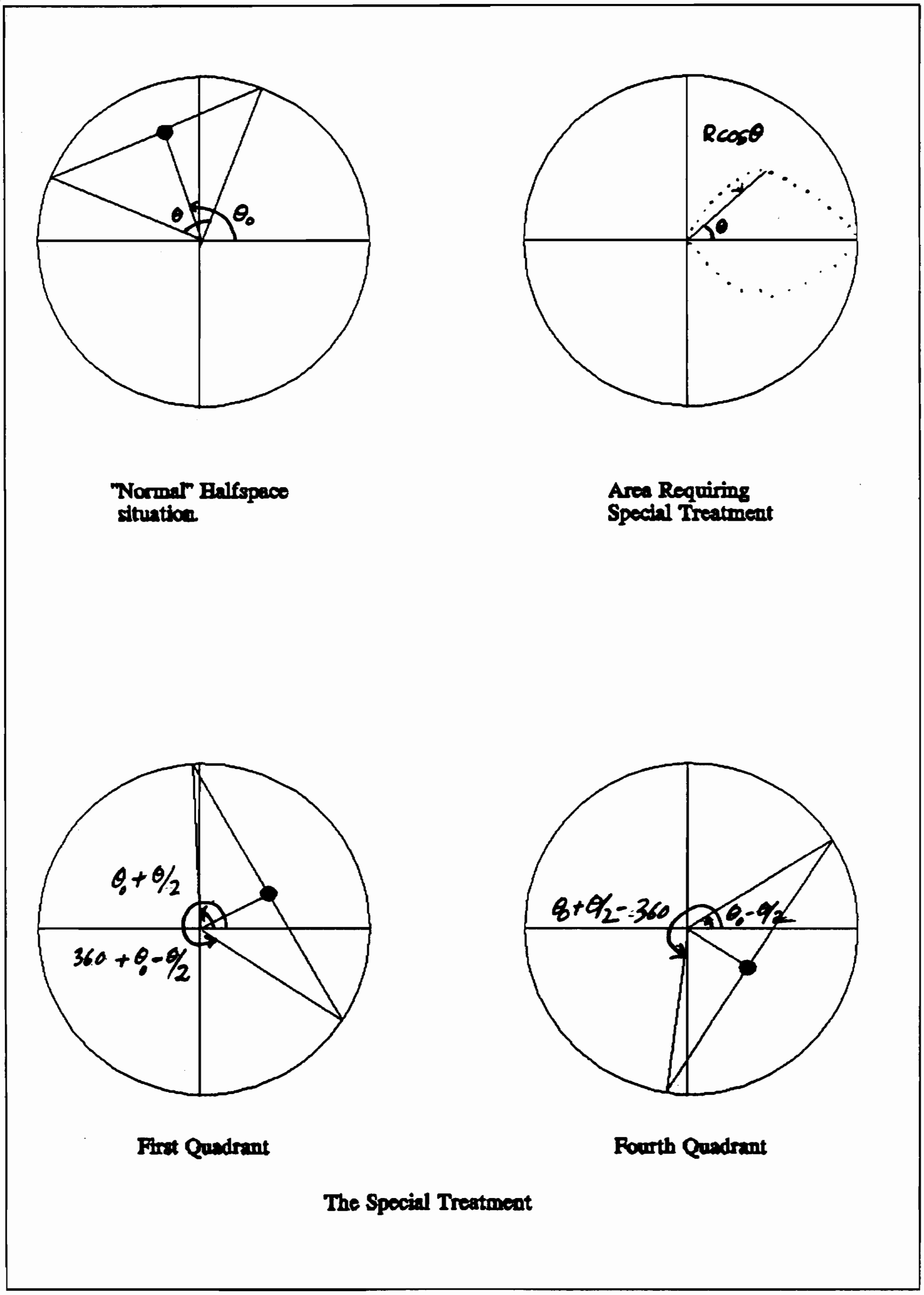


Figure 4.2 : Implementation of the Halfspace Method

4.1.3.2 Selection of destinations based on travel time.

Three strategies of destination selection were evolved. Trips were distributed to the -

- closest exit point.

- three closest exit points

- exit points within 1.5 times the travel time to the closest exit point.

Selecting the "closest" exit point of the evacuation area is perhaps the most natural driver strategy. Now, the closest point as perceived by the driver may not be actually so - especially if the travel times on the links keep changing during evacuation according to the flow at a particular time. Also, loading to the closest exit point will cause excess congestion on some links while leaving the rest of the network unutilized. This would alter the choice of destinations. Hence other ways of modelling the user choice have also been modelled.

The common implementation steps are :

1. For each origin, establish shortest path labels to all destinations (exit points) in the network.

2. Choose the closest exit point(s).

3. Apply the travel time impedance model to distribute the trips from the origin to the selected destinations. The travel time impedance method applied in

MASSVAC distributes trips in inverse proportion of travel times (shortest path labels) in the particular time interval.

The closest point method

A single "loop-check" over all shortest path labels of destinations locates the closest one. We start by assigning a variable to "infinity". Then scan all destination labels one by one. As soon as a lower value of label is found, the variable is given the value of that label and the search is continued until all destinations are checked out. In the end, the variable should contain the closest destination travel time. Another variable is maintained to contain the corresponding destination number.

The three closest points method

The procedure is exactly same as for the closest point. The loop described above is done three times - successively locating the closest, second closest and the third closest exit points. Each time a point is located, it is not considered in the next loop performance.

This procedure can be substituted by a sort routine also. If found to be more efficient, it can be incorporated. First, sort the destinations in ascending order of travel time and pick the "top" three.

The 1.5 method

This method assumes that the exit points chosen will be within one and a half times the distance to the closest point in that time interval (which is based on network loading).

First the closest point is located as in the method 1. Then all destinations within 1.5 times that distance are found by another loop.

4.1.4 Notes on Use of Trip Distribution Options.

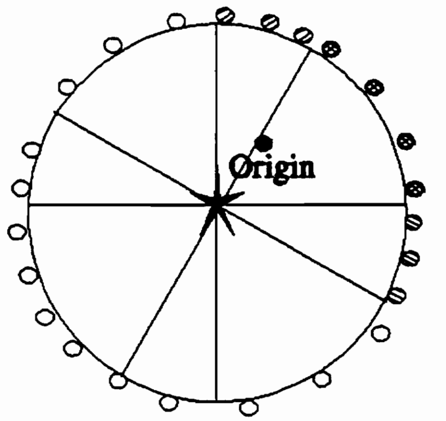
Network Configuration and Evacuation Scenario play a very important role in the selection of the option set determining trip distribution in MASSVAC. Two facts about the geometric destination identification techniques necessitate a purely subjective analysis of these techniques i.e., it is not possible to set any cut-and-dried guidelines of evaluation of these methods. Firstly, unlike destinations whose coordinates are true to their actual position on the map as highway nodes, origins are ***dummy*** nodes which represent an entire Protective Action Zone (PAZ). Thus, trips from a particular PAZ are assumed to start from the geometric location of the respective origin. Secondly, the dummy links connecting these origins to the network do not necessarily represent actual network loading during an evacuation. The truth is that a slight shift in either of the above user-defined representation of the network, could drastically affect the results of the model.

The methods themselves have been evolved to model different evacuation strategy scenarios and are not strictly comparable. The quadrant method is, clearly, dependant on the orientation of the circular evacuation area. Different orientation of quadrants will give different "feasible" sets of destination for the same origin (See figure 4.3). It is obviously not a behavioral model and should therefore be used only to reflect a policy of evacuating quadrant populations in an EPZ independent of each other (as may be necessitated by an evacuation directed towards the location of Evacuation Assembly Centers outside the EPZ).

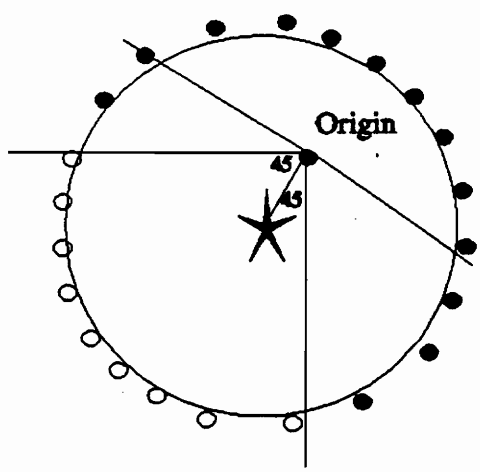
The three-quadrant and halfspace methods are more explicit and elegant in defining directions leading towards/away from the incident. They are independent of the orientation of the frame of reference of the network and are, therefore, more suitable as user-behavioral models. The 3-quadrant method gives the largest set of feasible destinations and is hence, more preferred than others. The set of feasible destinations chosen by the Halfspace method is essentially a sub-set of that given by 3-Quadrant Method (Figure 4.3). Hence, this method should be chosen only when it is felt that 3-Quadrant Method includes "too many" exit points in the feasible set.

Among the 3 Travel time selection options, the Closest Point Method reflects the choice of the closest exit as destination by all trips from a PAZ. Since driver perceptions are not same, this method is not true in a "natural" evacuation processes. Also, it is undesirable to have large populations heading for the same exit points as this may cause congestion on routes leading to that exit point. However, for sparse and well-informed populations with sufficient highway capacity, this method may be a good choice. By the Three Closest Point Method, at most 3 closest exit points, with respect to travel time are chosen as destinations. This is provided as a better alternative to the Closest Point Method and as possible evaluation of the policy of choosing, the 3 closest exit points for each origin. The disadvantage of this method is that all three "closest" points may not be in the "same range" (of distance from the origin) thereby defeating the purpose of Travel Time selection.

The 1.5 Method identifies exit points lying within 50% of the time-distance of the closest destination are chosen. The slight variations in driver perception of closeness of a destination is perhaps best explained by this method. This method,



Different orientation of Quadrants can give different "feasible" sets of destinations



The feasible set of destinations given by Halfspace method is a subset of that given by 3-Quadrant

Figure 4.3 : Notes on use of Geometric Techniques

therefore, has a great advantage over the other two methods in terms of more realistic trip distribution and thereby involving higher network utilization, lower congestion and delays.

Non-Iterative trip distribution (constant percentage distribution of trip ends during all intervals of simulation) is recommended for highway networks in rural or sparse population areas. In such cases, the proportion of drivers who choose to exit the evacuation area at any point remains constant since no delays or traffic bottlenecks are likely to develop, thereby keeping the trip distribution constant through all iteration of simulation (Non-iterative). Highway networks in urban areas are expected to develop traffic bottlenecks and congestion thereby forcing drivers to choose different exit points during different times of evacuation. This results in changing the proportion of trips leaving the area at any given exit point depending on the "current" state of travel times on the highway network. Thus the trip distribution change over different iteration of simulation and hence the iterative option is recommended in these cases.

4.2 Traffic Assignment Procedures

A "single pass" version of Dial's stochastic multipath traffic assignment algorithm has been used in MASSVAC to model route choice mechanism during evacuation. This approach is justified based on the fact that evacuation is a non-recurring phenomena and hence, not all drivers choose the shortest way out of the evacuation area. This results in distribution of traffic between a given origin and destination to alternative efficient routes.

The term "single pass" refers to the method in which efficient (or "reasonable") paths are determined. An efficient path is defined as composed of highway links which take a traveler away from the trip origin. The complete "two-pass" version of the STOCH algorithm requires efficient paths to be composed of links which not only take the traveler away from the origin *but also take him closer to the destination*. However, implementation of the latter would not be practical on large networks since the second pass involves estimation of shortest path labels from every destination (which receives trips from the origin) to all nodes in the network. In the single pass method, the shortest path algorithm needs to be called on the origin only.

Refer to [18] for a complete description of the Dial's algorithm. In this section, we focus on the way Dial's algorithm was incorporated in MASSVAC2.0 and the improvements which were introduced into the implementation of the model in MASSVAC3.0. The execution of Dial's model in MASSVAC2.0 consisted of the following key steps [Jamei, Hwang] :

1. Apply the shortest path algorithm to build the minimum path tree from the origin to each node in the network, thereby determining their minimum impedances.

2. Calculate the "link assignment-likelihood" for each link based on the node labels established in step 1. Hence, all links on the shortest path tree for the origin have likelihood equal to 1 unit. Other efficient links have assignment likelihood equal to less than 1 unit. All inefficient links are assigned zero likelihood of use. A slight modification introduced in this stage is that links which carry flows in excess of double their design capacity (in the previous iteration) are also

assigned zero likelihood of usage, because at that level of flow, the links are in a **blocked** state and therefore cannot carry volume in the current iteration.

3. ***Sort all nodes in ascending order of their shortest path labels from the origin.***

4. Starting with the links emanating from the closest node (as determined in step 3) to the origin, calculate link weights for all links in the network (Forward Pass). Stop assigning weights when all trip receiving destination nodes have been scanned.

5. Starting from the most distant node (which, by step 4, has to be a trip receiving destination node) allocate trips to the feeding links of all nodes in the network in a backward manner until the origin is reached (Backward Pass). ***In MASSVAC2.0, this step was modified to stop loading at the origin if trips at any node in the network could not be allocated to its feeding links. This is possible only if the feeding links have zero weights, which in turn is possible only if they receive zero likelihood in step 2 because of being in a blocked state in the previous iteration*** . Instead of storing trips at the origin, the iteration count for the origin was reduced by 1, thereby causing the origin to reload those trips in the next iteration at the same level and increasing the number of overall iterations in MASSVAC. Effectively, this meant that ***all*** vehicles beginning from any origin had to be stopped until the next iteration if even a few trips could not be assigned backwards all the way to the origin due to congested situations.

Changes have been brought into the steps ***highlighted*** above.

Step 4 is probably justifiable in an evacuation for natural disaster with sufficient warning time. In such cases, vehicles starting in a particular zone (origin) can possibly be stopped for some time during evacuation in the interest of relieving congestion in parts of the highway network. However, in the case of nuclear power plants we cannot impose a time-frame for the evacuation process and hence, it is not possible to stop/restrict vehicles starting in any zone because of congestion in parts of the network. The logit curve loading pattern for all origins must, therefore, be uniform over the entire network during all iterations of simulation.

However, it is a fact that some vehicles will not be able to load onto the network even in a forced loading situation because of excessive congestion. To incorporate this feature, it is necessary to record those trips which are blocked at any point in the network during a particular iteration and add this quantity to the trip production at the origin in the next iteration. In MASSVAC3.0, a new variable (HOLD) was created for this purpose. All trips blocked during the backward pass stage of the STOCH algorithm are stored in this variable and added to the trip production variable (PROD) in subroutine ODTAB.

In the current revision of MASSVAC code, the necessity of calling the TREE algorithm on each origin was obviated by storing the shortest path labels established in the trip distribution stage (subroutine ODTAB). This change, however, does not achieve any computational gains in the overall program. Inspite of this, the Dial traffic assignment procedure remained the most time consuming part of each iteration in MASSVAC.

Use of better sorting technique

A time analysis of each step of execution of the algorithm showed that step 3 is was most time consuming part of the algorithm in MASSVAC2.0 (over 90% of total execution time for the Dial's algorirthm). The sorting routine used in MASSVAC2.0 was the Bubble-Sort algorithm which is very slow. A survey of literature of state-of-the-art sorting algorithms [McLuckie] revealed that the Quicksort routine is a better alternative. This is because the speed of the Bubble-Sort algorithm is dependent on the square of the number of elements to be sorted while the number of comparisons in case of the Quicksort algorithm ranges from $1.1n\log_2(n)$ to $1.4n\log_2(n)$. Incorporating this sorting algorithm to implement step 3, dramatically enhances the efficiency of the STOCH algorithm and MASSVAC as a whole. Using the an adapted version of the Hibbard Quicksort algorithm, step 3 involves only 52% of execution time for Dial's algorithm and brings the overall run-time of MASSVAC down by almost 50%.

All-or-Nothing Assignment

The All-or-Nothing algorithm has been added as an extra traffic assignment algorithm to MASSVAC. The user can choose this option in case it is felt that network clearnce times are being over-estimated by the model through use of the Dial's Algorithm. Such a situation can occur if Dial's algorithm is used for assignment of sparse populations to large networks thereby providing greater route choice. This phenomena leads to traffic assignment on a number of unrealistically long routes - the largest of which determines Network Clearnce Time (which is undesirable). This is one of the major drawbacks of the Dial's algorithm : <u>efficient routes can be arbitrarily long.</u>

One method of solving this problem would be to adopt the "two-pass" version of the STOCH algorithm. But this is undesirable because it is inefficient. Another way is to increase the value of the exponent in the Dial's Algorithm. This causes assignment to fewer routes, but the value of the exponent differs for different network configurations. So, to provide a true bench-mark for traffic assignment, the all-or-nothing procedure has been provided. For a large network with few trip origins, this method must be used.

4.3 Identification of Evacuation Routes

The routes to be used by trips starting from a PAZ is important information for evacuation managers. All paths which are assigned vehicle-trips can be considered to be evacuation routes for a particular PAZ. This was indeed the case in earlier versions of MASSVAC where all trip-carrying paths were shown as evacuation routes. This type of display was feasible since the number of origin-destination pairs were small with only 1 or 2 evacuation shelters designated as destinations for each origin, thereby reducing the total number of possible paths carrying vehicle out of the Emergency Planning Zone (EPZ). However, in case of evacuation around nuclear power stations, each trip-origin could be sending trips to a number of exit points of the EPZ and since the network involved is large, the number of distinct paths to which volumes have been assigned is very large. Also, since assignment pattern changes during each iteration of simulation, the idea of storing and plotting all the paths is impractical from computer memory perspective.

Thus the only way to produce an output to the user is through inference. This involves developing a definition for the very concept of Evacuation Routes. The paths with the highest likelihood of usage by majority of the population during evacuation can be called as Evacuation Routes. Naturally, paths leading to the destination with the highest number of trip-ends should be considered as Evacuation Routes. The methodology used in MASSVAC3.0 is to identify the shortest paths leading to the most used destinations during evacuation.

The logic used to determine evacuation routes is as follows :

1. Obtain the "net trip-table" from the record of trip distribution for the simulation of entire evacuation. This table consists of the number of trips travelled between all O-D pairs in the network.

2. For each origin, sort the destinations in descending order of the trips received during the entire simulation.

3. Starting with the destination receiving the highest number of trips, build the shortest path from the origin to the destination until 90% of the trips starting from the origin have been accounted for. The set of paths so obtained are evacuation routes for the particular origin.

4.4 Miscellaneous New Features

Modification to travel time revision methodology

During simulation, link travel times are revised based on facility type and traffic volume (VPH/lane) using equations derived from the travel time vs. volume curves developed by Davidson [10]. These equations are used to determine travel time on all links in the highway network after the assignment procedure in each iteration. The values of link travel time are used to compute the time-length of evacuation paths (which is, any continues series of links joining an O-D pair). Evacuation time is simply updated as sum of the current clock time and the time-length of longest trip carrying path. All links in the highway network are classified into 5 categories. Denoting link travel time by T(l), link volumes by VT(l) and link length by D(l), (for any link l) the equations and logic used for each link category is as follows :

1. **Link Type 0 (Rural Signalized)** :

   If volume is less than or equal to 750 VPH/LANE

   then

   $T(l) = (2.25 + .00077 \times VT(l)) \times D(l)$

   otherwise

   $T(l) = (-30.58 + .0458 \times VT(l)) \times D(l)$

2. **Link Type 1 (Urban Signalized)** :

   If volume is less than or equal to 750 VPH/LANE

   then

   $T(l) = (0.191 + .00077 \times VT(l)) \times D(l)$

   otherwise

   $T(l) = (-30.58 + .0458 \times VT(l)) \times D(l)$

3. **Link Type 2 (Two-Way Stop Sign)** :

   If volume is less than or equal to 900 VPH/LANE

   then

   $T(l) = (1.9036 + .000561 \times VT(l)) \times D(l)$

   otherwise

   $T(l) = (-23.9804 + .029321 \times VT(l)) \times D(l)$

4. **Link Type 3 (Four-Way Stop Sign) :**

   If volume is less than or equal to 1070 VPH/LANE

   then

   T(I) = (1.66355 + .000605 x VT(I)) x D(I)

   otherwise

   T(I) = (-22.8769 + .02354 x VT(I)) x D(I)

5. **Link Type 4 (Expressways) :**

   If volume is less than or equal to 1600 VPH/LANE

   then

   T(I) = (0.9644 + .000333 x VT(I)) x D(I)

   otherwise

   T(I) = (-18.1668 + .012290 x VT(I)) x D(I)

Link Type 5 (Dummy) is not considered in calculation of evacuation times and hence the travel time for these are held constant to the value at free-flow.

The above logic is modified to incorporate realistic upper and lower limits for flow-based travel time estimates on links by the following rules in the new version of MASSVAC. These rules were necessary to "rationalize" travel time revision based (just) on volume.

1. **Lower Limit** : The revised travel time of a link cannot be less than the free-flow travel time (an obviously intuitive rule). This is a very important (new) feature in MASSVAC, since free-flow speed is an user-controlled variable. So, for modelling under adverse conditions we can raise lower limit on revised values of travel time based on lower speeds on the links.

2. An **upper limit** on revised travel time is determined by the V/C (volume/capacity) as follows (TO(I) = free-flow travel time) :

   a. If V/C ratio is less than 1, T(I) = MIN (T(I), 6*TO(I))

   b. If V/C ratio is between 1 and 1.5, T(I) = MIN (T(I), 8*TO(I))

   c. If V/C ratio is greater than 1.5, T(I) = MIN (T(I), 10*TO(I))

Determining the beginning and ending times of link congestion

A link is considered to be congested during an interval if the volume assigned to it exceeds the capacity of the link. The capacity of a link is an user input. MASSVAC2.0 had the capability of determining whether a link is congested at some clock time during evacuation. But to conduct analysis of development and dissipation of congestion on highway links, a time-track of congestion patterns over the whole network is essential. This information is crucial to development and implementation of Traffic Management Strategies for reducing Network Clearance Time.

To achieve the above objective, a new output was created in MASSVAC3.0 containing the beginning and ending times of congestion on each highway link experiencing congestion during evacuation. This information was inferred from the ability of MASSVAC to identify a congested link at any given clock time. A link is considered to be congested for the entire simulation interval following the clock time at which it was identified as congested. Hence, if a link was congested at "K" consequent clock times beginning at clock = ID, the link is considered to congested for K*SI time units (SI = simulation interval) and congestion ends at clock = ID + SI*K.

Modelling Highway service under Normal/Adverse Conditions

Adverse weather conditions such as snow, fog and severe rain are expected to cause an increase in Network Clearance Times. In MASSVAC, this has been modelled by halving the free-flow speeds on highway links during evacuation. This has been supported by modifying the concept of travel time revision equations, as described above, to to facilitate user control of link speeds.

Use of Shoulders and Flashing operation

Use of shoulders and changing signal to flashing operation are important traffic management options to improve the evacuation process. In MASSVAC3.0, shoulder use can be modelled on Expressways (Link type = 4). When this option is set, the number of lanes on the link is increased by 1 and an the capacity of the link is multiplied by the factor (N + 0.8) where, N is the original number of lanes on the link. For modelling the Flashing operation, all signalized links (types 0 and 1) are modelled as Link type = 2.

5.0 Technical Aspects

The source code of MASSVAC was revised and re-calibrated to deal with evacuation around nuclear power plants. Also, new algorithms and subroutines were necessary to enhance the efficiency of the program w.r.t. run-time and memory usage. These objectives resulted in a new version of the model whose subroutines are discussed in the following sections. The program consists of 18 subroutines besides the main program. The structure of the whole model and the relationship of subroutines are illustrated in Figure 5.1. The complete source code for the program is in Appendix C.

Every subroutine is presented in this thesis at two levels of abstraction : a verbal/algorithmic statement of the procedure and a flowchart. The former (verbal accounts) is the subject of this chapter while the latter (program flowcharts) are included in Appendix A. Each level of abstraction serves a specific purpose as an aid to study of MASSVAC source code. While the verbal description of algorithm is the best way to explain the significance of each procedure and its role in the overall program, the flowcharts are necessary to provide an easy-to-read overview of complex logical transfers in the program.

The most important change in MASSVAC3.0 is that subroutine ODTAB, the procedure used to implement trip distribution in MASSVAC has been incorporated within the simulation module of the model. Earlier, it was an independant subroutine which was processed prior to simulation to establish trip ends which were kept

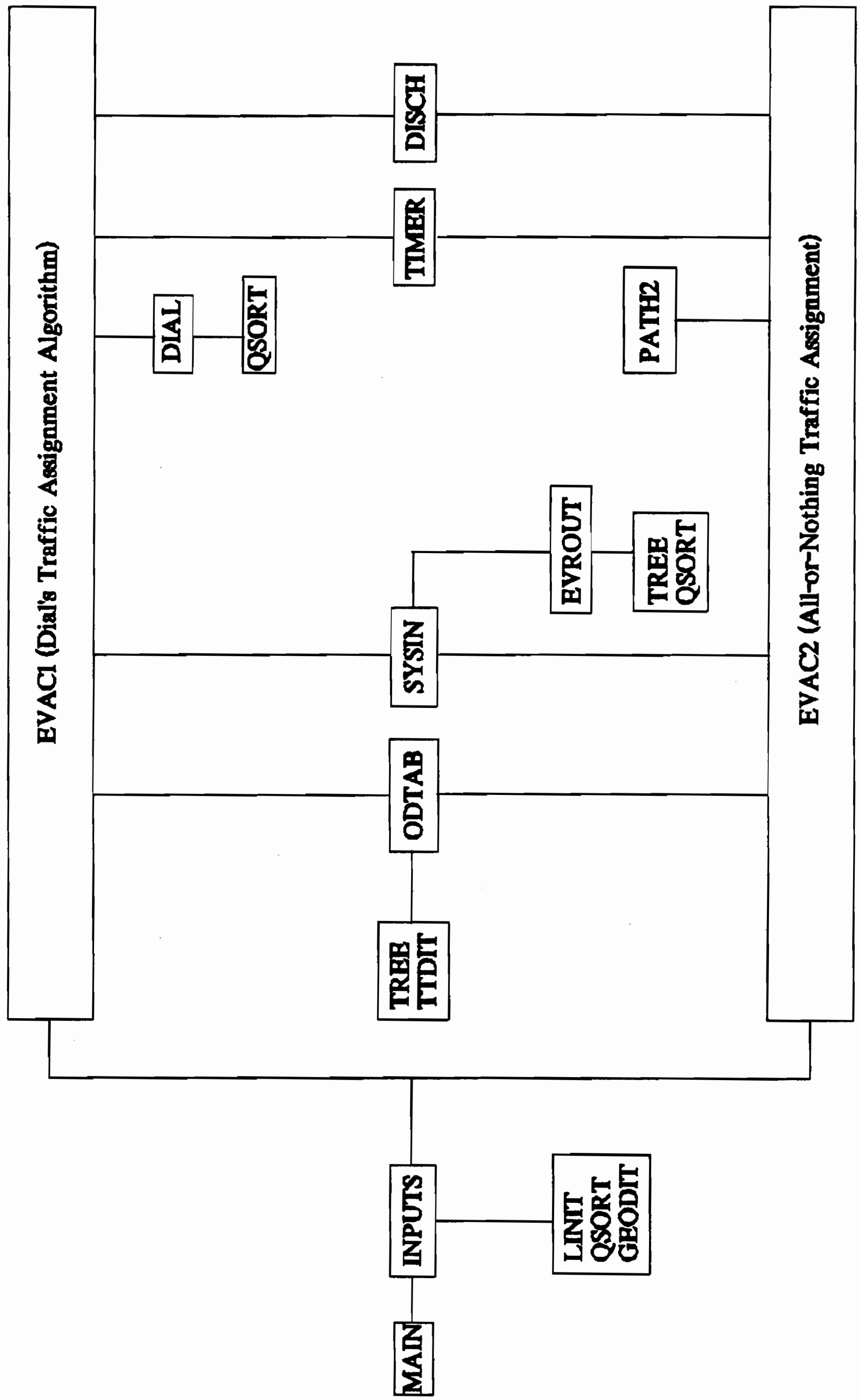


Figure 5.1 : Organization of Subroutines in MASSVAC3.0

constant throughout the simulation. Through supporting subroutines GEODIT (GEOmetric Destination Identification Techniques), TTDIT (Travel Time Destination Identification Techniques) and TREE (Shortest Path Algorithm), this subroutine is now called from the main simaultion module to implement trip distribution at the beginning of each simulation interval. The other major subroutine added to MASSVAC is EVROUT, which is called from SYSIN before the end of the program to establish evacuation routes according to the definition developed in section 4.3. Subroutine DIAL has been changed with respect to the method of dealing with blocked trips. In MASSVAC3.0, subroutine DIAL stores the trips which are blocked at any node during the backward pass and adds them to the trip production for the correseponding origin in the next iteration. Previously, trip loading at the origin was completely stopped and the number of iterations processed for the origin was reduced by 1. The All-or-Nothing traffic assignment procedure has been added to the model to give an extra option of assignment. This has resulted in the alternative simulation control module EVAC2.

5.1 Program MASSVAC

This is the "top-level" control module which first calls subroutine INPUTS to input data and initialize program variables. Then it begins an infinite loop to call either the Dial's multi-path, stochastic assignment module or the all-or-nothing assignment technique. Depending on user choice, one of the modules is repeatedly activated until all vehicles trips are served.

5.2 Subroutine INPUTS

Subroutine INPUTS reads data for MASSVAC and initializes variables as follows

:

1. Input :

   a. the number of exit points (IGN) and the highest node number (IDS) representing a trip-origin in the highway network. The node numbering convention in MASSVAC requires destinations to be numbered first, followed by the origins and then, all highway nodes. Hence, throughout the program, destinations are assumed to be numbered consecutively from 1 to IGN. Similarly, origins are assumed to be numbered consecutively from IGN + 1 to IDS. To facilitate automatic network partitioning by computer image-processing, the model has been designed to accept highway nodes as any number greater that IDS. However, the program runs most efficiently if there is no break in the node sequence.

   b. simulation time-interval and time by which half of the trips are to be loaded (half loading time). From these two inputs, the Z-parameter of the loading function used in trip loading is calculated.

c. flags which activate trip distribution, assignment and network configuration options in MASSVAC.

d. link attributes - beginning, ending & downstream nodes, link length, capacity per lane, number of lanes, free-flow speed, link type (1 = isolated signalized, 2 = two-way stop sign, 3 = four-way stop sign, 4 = expressway, 5 = dummy). Note that links are numbered in the order in which they are read.

e. trip production (i.e., number of vehicles to be evacuated) from each origin in the EPZ.

f. cartesian coordinates of origins, destinations and center of evacuation area.

2. Build the AINDX-AD-ADL data structure for A-nodes of highways links; The AD-ADL array-couple consists of A-nodes and link numbers respectively, sorted in the ascending order of the function (1000*AD + ADL). Hence the links emanating from a single A-node are "bunched" together in ADL. Conversely, such link groups have the same A-node in the AD array. AINDX stores the first occurrence of an A-node in the AD array. This data structure enables easy reference of links (and, therefore, link attributes) which share an A-node. The AINDX-AD-ADL structure is vital for efficient implementation of the shortest path algorithm (subroutine TREE).

3. In a fashion analogous to step 2, build the BINDX-BD-BDL data structure for B-nodes thereby enabling us easily to reference all links sharing any B-node. This data structure is used extensively in MASSVAC to aid the implementation of the Dial's algorithm (subroutine DIAL), the congestion-discharge procedures

(subroutine DISCH), path building (subroutine PATH)and derivation of evacuation routes (subroutine EVROUT).

4. Call subroutine LINIT to initialize dynamic link attributes according to the evacuation scenario and highway network conditions as selected by options in 1c.

5. Call subroutines TREE and GEODIT to accomplish geometric destination identification, thereby deriving the initial feasible set of destinations for each trip-origin. This procedure locates, for each origin, the destinations which would avoid travel toward the nuclear power plant. Since only network geometry is used, this set does not vary during simulation.

5.3 Subroutine LINIT

This subroutine initializes the following link attributes :

1. If the adverse conditions flag is set, then free-flow speed on the links is reduced by 30%.

2. The free-flow travel time is calculated from link length and free-flow speed.

3. The total link capacity is calculated as the product of the capacity per lane and number of lanes

4. The link travel time for the first iteration is set to free-flow travel time if the link is unseeded (off-peak) otherwise, it is revised to higher value based on the seed volume. The seed volume is calculated from the decrementally applied to the links based on the Annual Average Daily Traffic (AADT) for the link.

5.4 Subroutine ODTAB

As the name suggests, this subroutine establishes trip table for each iteration. The trip distribution is either kept constant or revised (according to current state of network). This subroutine is called from subroutine EVAC1 or EVAC2 at the beginning of each iteration.

Since this is the first routine to be called by the evacuation module, the clock time and the iteration counts are incremented by one unit.

Then, for each origin the following procedures are carried out :

1. the cumulative percentage of trips to be loaded at the end of the current and the previous iteration is calculated from the logit curve formula. The trip production for this iteration is computed as the difference of these amounts plus the number of trips blocked (i.e. could not be assigned) in previous iteration (s), if any.

2. the shortest path algorithm (subroutine TREE) is called to establish shortest path labels to all nodes. If a destination is eliminated by geometric methods, then its

travel time is set to infinity (9999.). The time-distance of all other nodes is taken as the shortest path label value.

3. the actual trip distribution is carried out in subroutine TTDIT which implements iterative/non-iterative travel time selection of destinations. The gravity model trip distribution for the region is the output of this subroutine.

Finally, the trip table is printed out to the file ODTAB.OUT and the number of trips receiving non-zero trips from each origin is calculated.

5.5 *Subroutine DIAL*

An adaptation of the probabilistic multipath traffic assignment model suggested by Dial is implemented by this subroutine. For theoretical exposition of this algorithm refer to [18]. Dial's technique is modified in two ways :

1. Traffic is not assigned to congested links whose residual volume (after discharge from previous iteration) exceeds twice the capacity. In this case, the links would be in a congested state in the current iteration also and hence cannot carry any new volume.

2. The method of storing blocked trips for re-assignment has been refined in the new version of MASSVAC. The source code of the previous version indicates that if an evacuation route for an origin is congested, then loading of trips from this origin was stopped completely [Jamei, pp 83]. A new variable (HOLD) has been

created to record the number of trips blocked while processing an origin and this quantity is added to the trip production at this origin in the next iteration. This method allows unblocked traffic to go through normally.

Each call of subroutine DIAL on an origin node O_i results in quantification of the variable V (O_i, L_i) where, V is the volume on link L_i due to trip production at O_i in the current iteration.

The detailed sequence of steps in this algorithm are as follows :

1. ***Assign link likelihoods*** : The likelihood of usage of each link is calculated as recommended by Dial. "Doubly" congested links are given zero likelihood value.

2. All nodes are sorted in ascending order of their shortest path labels determined for the current iteration (in Subroutine ODTAB). This is the most time consuming step in this implementation of Dial's algorithm. An efficient sorting algorithm (such as QuickSort) is, therefore crucial for efficient implementation of this subroutine.

3. ***Forward Pass*** : Beginning at the node closest to the origin (as determined by the sort in the previous step) the weights of all "feeding" links from all nodes are established. Dummy links are given the same weight as their likelihood. To enhance efficiency this process is stopped as soon as the furthest destination node is processed in this manner.

4. ***Backward Pass*** : In this step, the algorithm begins from the furthest node (which has to be a destination node), and assigns trips to the feeding links of all nodes in proportion of the weights established in the previous step. Volume on any link is added to the volume at the A-node of the links. This process continues

recursively until the trips at the origin node (the last node to be processed) is established. *Congestion on all feeding links of a node results in blockage of trips at the node (since feeding links have zero weight). All such trips stored to be loaded in the next iteration.*

5.6 *Subroutine TIMER*

TIMER computes link travel times based on facility type and traffic volume (VPH/lane) using equations based on the travel time vs. volume curves developed by Davidson [10].

These equations are used to determine travel time on a link after the assignment procedure in each iteration. The values of link travel time are used to compute the time-length of evacuation paths (which is, any continues series of links joining an O-D pair). Evacuation time is simply updated as sum of the current clock time and the time-length of longest trip carrying path.

All links in the highway network are classified into 5 categories. Denoting link travel time by T(I), link volumes by VT(I) and link length by D(I), (for any link I) the equations and logic used for each link category is as follows :

1. **Link Type 0 (Rural Signalized)** :

   If volume is less than or equal to 750 VPH/LANE

   then

   $T(I) = (2.25 \quad + .00077 \times VT(I)) \times D(I)$

otherwise

T(I) = (-30.58 + .0458 x VT(I)) x D(I)

2. **Link Type 1 (Urban Signalized) :**

If volume is less than or equal to 750 VPH/LANE

then

T(I) = (0.191 + .00077 x VT(I)) x D(I)

otherwise

T(I) = (-30.58 + .0458 x VT(I)) x D(I)

3. **Link Type 2 (Two-Way Stop Sign) :**

If volume is less than or equal to 900 VPH/LANE

then

T(I) = (1.9036 + .000561 x VT(I)) x D(I)

otherwise

T(I) = (-23.9804 + .029321 x VT(I)) x D(I)

4. **Link Type 3 (Four-Way Stop Sign) :**

If volume is less than or equal to 1070 VPH/LANE

then

T(I) = (1.66355 + .000605 x VT(I)) x D(I)

otherwise

T(I) = (-22.8769 + .02354 x VT(I)) x D(I)

5. **Link Type 4 (Expressways) :**

If volume is less than or equal to 1600 VPH/LANE

then

T(I) = (0.9644 + .000333 x VT(I)) x D(I)

otherwise

T(I) = (-18.1668 + .012290 x VT(I)) x D(I)

Link Type 5 (Dummy) is not considered in calculation of evacuation times and hence the travel time for these are held constant at free-flow.

The above logic is modified to incorporate realistic upper and lower limits for flow-based travel time estimates on links by the following rules in the new version of MASSVAC. These rules were necessary to "rationalize" travel time revision based (just) on volume.

1. **Lower Limit** : The revised travel time of a link cannot be less than the free-flow travel time (an obviously intuitive rule). This is a very important (new) feature in MASSVAC, since free-flow speed is an user-controlled variable. So, for modelling under adverse conditions we can raise lower limit on revised values of travel time based on lower speeds on the links.

2. An **upper limit** on revised travel time is determined by the V/C (volume/capacity) as follows (TO(I) = free-flow travel time) :

   a. If V/C ratio is less than 1, T(I) = MIN (T(I), 6*TO(I))

   b. If V/C ratio is between 1 and 1.5, T(I) = MIN (T(I), 8*TO(I))

   c. If V/C ratio is greater than 1.5, T(I) = MIN (T(I), 10*TO(I))

5.7 *Subroutine DISCH*

Towards the end of processing of each iteration (i.e., after distribution, link assignment, travel time revision and updating evacuation time), subroutine DISCH is called from EVAC1 or EVAC2 to dissipate volumes assigned to links and, therefore, to calculate the remaining volume on congested links in the next iteration. If links are not over-capacitated, they are assumed to serve all trips assigned. The logic of DISCH is explained below [Jamei, pp 89] :

1. If link is an expressway (NTYPE = 4), then use Laporte Regression Equation modified by Kalevela to compute the number of vehicles which the link can dissipate in the current iteration according to the following logic :

    - Calculate the density, DENS, (vehicles per mile per lane) from volume currently assigned to the link (VT) and current speed on the link (which is computed as the link length divided by the revised travel time, T). If DENS exceeds 99, dissipated volume is set to jam density of the link; otherwise the dissipated volume is given by :

$$\text{Dissipated volume} = 74.3*\text{DENS} - 0.75(\text{DENS}*\text{DENS})$$

2. If the links is a dummy, (NTYPE = 5), then the link is assumed to dissipate all volume.

3. For all other link types, the following dissipation logic is used :

a. Using the BD-BDL-BINDX data structure, scan all links sharing the B-node of the congested link. V1 is set to the highest volume entering the B-node through ***any*** of its feeding links. V2 is set to the volume of the link which is not in the same direction as the link with the maximum volume (V1).

b. If no more than 2 links (including the congested link itself) are found to share the B-node of the congested link, then the dissipated volume is simply set to the assigned volume VT. In the calling subroutine EVACx, this dissipation volume is adjusted to MIN [the value returned by DISCH, jam density, capacity.

c. Otherwise the discharge volume is computed as the value of (V1/(V1+V2))*(1800/60) adjusted for the simulation interval.

5.8 *Subroutine GEODIT*

GEODIT (GEOmetric Destination Identification Techniques) is called from subroutine INPUTS to implement the Quadrant or the Three-Quadrant or the Halfspace method of geometric partitioning of origin-destination space. All three methods have a common underlying logic by which a feasible set of destinations are created for each origin. *It is called on one O-D pair at a time.* Depending on the choice of the modeller (as indicated by the value of the variable IGEO, i.e. 1=QUADRANT METHOD, 2=THREE QUADRANT METHOD, 3=HALFSPACE METHOD, 0=NO METHOD), the subroutine implements one of the following methods on each O-D pair and returns control to INPUTS. :

1. **Quadrant Method** :

The X- Y- coordinates of the origin I (variables OX and OY), destination J (DX and DY) and the nuclear power plant (CX and CY) are used to determine if the origin and destination lie in the same quadrant of the EPZ. If they do, then the shortest path label of the destination is retained by simply returning to the calling program without doing anything. Otherwise, the shortest path label of the destination is set to 9999. (infinity), a flag which excludes the destination from consideration for trip distribution. The logic of the program is best illustrated by the portion of source-code actually implementing the method (using the variables referred to above) :

```
IF (((OX(I).GT.CX.AND.OY(I).GE.CY)
+.AND.(DX(J).GT.CX.AND.DY(J).GE.CY))
+.OR.((OX(I).LE.CX.AND.OY(I).GT.CY)
+.AND.(DX(J).LE.CX.AND.DY(J).GT.CY))
+.OR.((OX(I).GE.CX.AND.OY(I).LT.CY)
+.AND.(DX(J).GE.CX.AND.DY(J).LT.CY))
+.OR.((OX(I).LT.CX.AND.OY(I).LE.CY)
+.AND.(DX(J).LT.CX.AND.DY(J).LE.CY)))
+THEN
RETURN
ELSE
TT(I,J)=9999.
```

```
RETURN
ENDIF
```

2. **The 3-Quadrant Method** :

The X- Y- coordinates of the origin I (variables OX and OY), destination J (DX and DY) and the nuclear power plant (CX and CY) are used to determine if the destination lies in the same quadrant as the nuclear power plant when a circle of arbitrarily long radius is drawn at the origin. If so, the shortest path label of the destination is set to 9999; otherwise, the program simply returns. The logic used in this method is very similar to the one used to implement the Quadrant method. The input variables are exactly same. As before, the logic is best illustrated by the FORTRAN IF statement used to implement the method :

```
IF  (((OX(I).GE.CX.AND.OY(I).GE.CY)
+.AND.(DX(J).LT.OX(I).AND.DY(J).LT.OY(I)))
+.OR.((OX(I).LE.CX.AND.OY(I).GE.CY)
+.AND.(DX(J).GT.OX(I).AND.DY(J).LT.OY(I)))
+.OR.((OX(I).GE.CX.AND.OY(I).LE.CY)
+.AND.(DX(J).LT.OX(I).AND.DY(J).GT.OY(I)))
+.OR.((OX(I).LE.CX.AND.OY(I).LE.CY)
+.AND.(DX(J).GT.OX(I).AND.DY(J).GT.OY(I))))
+TT(I,J)=9999.
RETURN
```

3. **The Halfspace Method** :

A line is drawn through the origin under consideration, perpendicular to the line segment joining it and the center of the evacuation area. All destinations lying in the halfspace containing the origin are turned off.

The implementation of this method is more involved than the other methods. Though it can be done with the given information, we could lose out significantly on round off errors. Hence, working in polar coordinates was preferred. If IGEO is given the value 3, the program converts the Cartesian coordinates of all origins and destinations into a Polar system with the center of evacuation area as origin. This involves calling another subroutine and hence this alternative is inevitably the longest.

Assuming that the angle subtended at the center of the evacuation area by the line drawn as described above is θ and that the polar coordinate angle of the origin is θ_o, the algorithm for this method is

IF

the angle of a destination lies between $(\theta_o + \theta/2)$

and $(\theta_o - \theta/2)$

THEN

retain the shortest path label for the destination

ELSE

assign infinite travel time between the O-D pair

ENDIF

The angles of origins and destinations range from 0 to 360 degrees. The above solution has to be modified for the origins which :

1) lie in the first and fourth quadrants and
2) have radius vector less than or equal to R $\cos\theta_o$.

(R = radius of evacuation area)

For the origins of the above type in the first quadrant, the legal destinations should have angles between (θ_o + $\theta/2$) and (360 + θ_o - $\theta/2$). For origins in fourth quadrant, the legal destinations should have angles between (θ_o - $\theta/2$) and (θ_o + $\theta/2$ - 360).

5.9 *Subroutine TTDIT*

TTDIT (Travel Time Destination Identification Techniques) is called on each origin from subroutine ODTAB to distribute trip production at the origin to a feasible set of destinations using travel time impedance method. The destinations to which trips are finally distributed are chosen from the feasible set of destinations created by subroutine GEODIT based on their time-distance from the origin.

The common implementation steps are :

1. Choose the closest exit point(s).

2. Apply the travel time impedance model to distribute the trips from the origin to the selected destinations. The travel time impedance method applied in MASSVAC distributes trips in inverse proportion of travel times (shortest path labels) in the particular time interval.

   The programming logic of the methods is rather simple.

1. **The closest point method** :

A single loop-check over all shortest path labels of destinations locates the closest one. We start by assigning a variable to "infinity". Then scan all destination labels one by one. As soon as a lower value of label is found, the variable is given the value of that label and the search is continued until all destinations are checked out. In the end the variable should contain the closest destination travel time. Another "parallely" maintained variable contains the destination number.

2. **The three closest points method** :

The procedure is exactly same as for the closest point. The loop described above is done three times - successively locating the closest, second closest and the third closest exit points. Each time a point is located, it is not considered in the next loop performance.

This procedure can be substituted by a sort routine also. If found to be more efficient, it can be incorporated. First sort the destinations in ascending order of travel time and pick the "top" three.

3. **The 1.5 method** :

This method assumes that the exit points chosen will be within one and a half times the distance to the closest point in that time interval (which is based on network loading).

First the closest point is located as in the method 1. Then all destinations within 1.5 times that distance are found by another loop.

Then, the travel time selection method is used to distribute trips from the origin to all chosen destinations.

5.10 *Subroutine EVAC1*

This subroutine forms the back-bone of simulation in MASSVAC using the Dial's traffic assignment algorithm. Its main function is to call other subroutines thereby controlling the flow of the entire program. Each execution of this EVAC1 represents one iteration of MASSVAC. The detailed functions of this subroutine are described below :

1. **Call ODTAB Subroutine** to estimate production at the zone centroid of each PAZ (origin) and establish trips between each O-D pair in the network. Since trip distribution is based on the latest values of link travel times in the network, shortest path labels for all nodes from each origin are also established by this step. This information is stored for use in the Dial's algorithm. (See ***Subroutine ODTAB***).

2. **Call SYSIN Subroutine** to check if all trips have been cleared. If so, SYSIN terminates the program after printing the results. (See ***Subroutine SYSIN***). Otherwise, it returns control to EVAC1.

3. For each trip origin in the network, **call DIAL subroutine** to derive link assignments from the trip ends for the origin in this iteration.

4. **Call TIMER Subroutine** on each link in the highway network to revise the travel time on the link based on the flow assigned in the previous step. Vehicle travel time for this iteration is calculated as the sum of the product of link flows and updated link travel times.

5. **Call PATH Subroutine** to trace out the evacuation paths between each O-D pair in the network with more than 1 trip. The longest route traced in this manner determines the updated evacuation time in this iteration in the following manner : Updated Evacuation Time = Clock Time of Current Iteration + time length of longest evacuation route. The maximum value of Updated Evacuation Time over the entire simulation is outputted as the Network Clearance Time for the highway system being analyzed.

6. **Call DISCH Subroutine** on each link which is over-capacitated in this iteration and compute the trip-volume which can be dissipated in this simulation interval. If the flow on the link exceeds the amount which can be discharged, the remaining volume is stored on the link for consideration in the next iteration. For a quickly escalating scenario (ISEED=1), the seed volume for this iteration is computed and added to the remaining volumes on the links.

7. Data for plotting the Loading Curve is outputted at the end of this subroutine in the form of *cumulative trip loaded upto the current clock time.*

5.11 Subroutine EVAC2

EVAC2 is similar in structure to EVAC1 except for the fact that All-or-Nothing traffic assignment procedure is implemented here. It has been coded as a separate subroutine because the method of determining evacuation time, though same in definition, needs to be inferred in a slightly different manner. Hence, it differs from the EVAC1 w.r.t. step 3 only. Instead of a call to Dial, the **subroutine PATH2** is called to assign the trip end between any given O-D pair to the links on the shortest route between them. The shortest path between any O-D pair is inferred from the Back-Node array (FN) derived in the Trip Distribution stage (subroutine ODTAB).

5.12 *Subroutine PATH*

This subroutine has been left unchanged from MASSVAC2.0 and, hence, it is not discussed here. Its function is to identify distinct trip-carrying paths between each O-D pair based on the link assignment in a particular iteration. It is called from EVAC1 only.

5.13 *Subroutine PATH2*

PATH2 implements the All-or-Nothing Assignment option in MASSVAC for the O-D pair on which it is called. It is called from EVAC2 to assign the trip end established between the inputted O-D pair to the links on the shortest path between that O-D pair. The BINDX-BD-BDL data structure is used to backtrace the shortest path using the Back-Node array for each origin.

5.14 Subroutine EVROUT

The function of this subroutine is to trace out evacuation route based on results of the entire simulation. It is called from subroutine SYSIN just before termination of the program. Steps :

1. Obtain "net trip table" from the trip distribution record stored externally by subroutine ODTAB. This table sums up the trips exchanged between each O-D pair in the network during the entire course of simulation.

2. **Call TREE** to set travel times on all links to the free-flow level.

3. For each origin, sort the destination in descending order of trip received. Backtrace the shortest path from each destination using the BINDX-BD-BDL data structure and the Back-Node array until 90% of the trip production at the origin is accounted for. The set of shortest paths so obtained are outputted as evacuation routes for the corresponding origin.

5.15 Subroutine SYSIN

Essentially, this subroutine retains its old structure of MASSVAC2.0. However, new steps involving formation of the final output of MASSVAC have been added. It is called from EVAC1 or EVAC2 to check if all trips have been loaded on to the network. If not, it returns control to the calling subroutine otherwise, the program is terminated by executing the following steps :

1. The remaining volume on links are cleared and evacuation time is updated if necessary.

2. Main Output is printed in the following order :

    a. Network Clearance Time : the maximum value of updated evacuation time obtained during simulation.

    b. Simulation Interval and Half Loading Time used for simulation.

    c. Total vehicle travel time.

    d. Evacuation Time if 20% of trips were loaded before start of Clock - inferred by a method used in MASSVAC2.0.

    e. The total flows, total seed volume and AADT on each link. The output is sorted in descending order of total flows and links are printed in two categories : used and unused links.

f. Beginning and ending times of congestion on all links which experienced over-capacitation at any time during simulation.

g. Evacuation Routes by **calling subroutine EVROUT**.

5.16 Subroutine QSORT

Implements the standard Hibbard Quicksort algorithm discussed in any textbook on computer sorting techniques. The function of this subroutine is exactly same as the Bubble-sort algorithm (Subroutine SORTD) in MASSVAC2.0. The code is a FORTRAN translation of the BASIC code for Hibbard's quicksort recommended on page 93 of [16].

5.17 Subroutine TREE

The structure of this subroutine is exactly same as that in MASSVAC2.0 and hence, is not discussed here. It implements a label correcting variant of the Dijkstra shortest path algorithm described in [11].

5.18 *Subroutine POLAR*

The primary function of this subroutine is to take as input the cartesian coordinates of origins and destinations supplied by the user and return corresponding polar coordinates. This subroutine is activated only if the **halfspace** method is chosen by the user. From the coordinates of the destinations, this subroutine infers the value of RADIUS, a variable in the implementation of the Halfspace method. The significance of this variable and its calibration (if necessary) is discussed in Section 4.1.3.1.

5.19 *Summary of Technical Section*

MASSVAC3.0 is a PC-based FORTRAN computer simulation model. It has been written and compiled using the Microsoft FORTRAN4.1 software development package. The unoptimized size of MASS.EXE (the executable file for MASSVAC) is about 420 kilo bytes and can be used on any IBM/compatible PC with 640K RAM and math co-processor. A network with up to 640 links and 270 nodes (of which the maximum number of destinations = 40 and the maximum origin node number = 80) can be analyzed using the current version of the model. Execution time depends on the size of the network (and the PC used) and varies from 30 seconds on small networks (about 100 links) to 35 minutes on a full-size network on an IBM PS/2 which has the 286 chip and math co-processor.

6.0 Model Application

6.1 Introduction

The TEDSS/MASSVAC computer package was used to develop comprehensive evacuation plans for the 10-mile Emergency Planning Zones (EPZs) of the Surry and North Anna nuclear power stations in Virginia.

Surry Nuclear Power Station is located on the southern shore of the James River approximately 50 miles southeast of Richmond, Virginia. The station is immediately accessible through rural areas. However, the 10-mile Emergency Planning Zone (EPZ) centered at the plant and used in evacuation planning encompasses urban locations including Williamsburg and part of Newport News. Populations of four counties also are considered in evacuation plans for the Surry Power Station. Large sections of Surry County, James City County, and York County and a small piece of Isle of Wight County lie within the 10-mile EPZ. Surry Emergency Planning Zone has been subdivided into 24 Protective Action Zones (PAZs). Thirteen of these zones are located south of the James River. The remaining eleven lie north of this river. The map in Figure 6.1 details jurisdictional and Protective Action Zone (PAZ) boundaries in the 10-mile emergency planning area. Population data pertaining to various jurisdictions are collected for and allocated to each of these protective action zones.

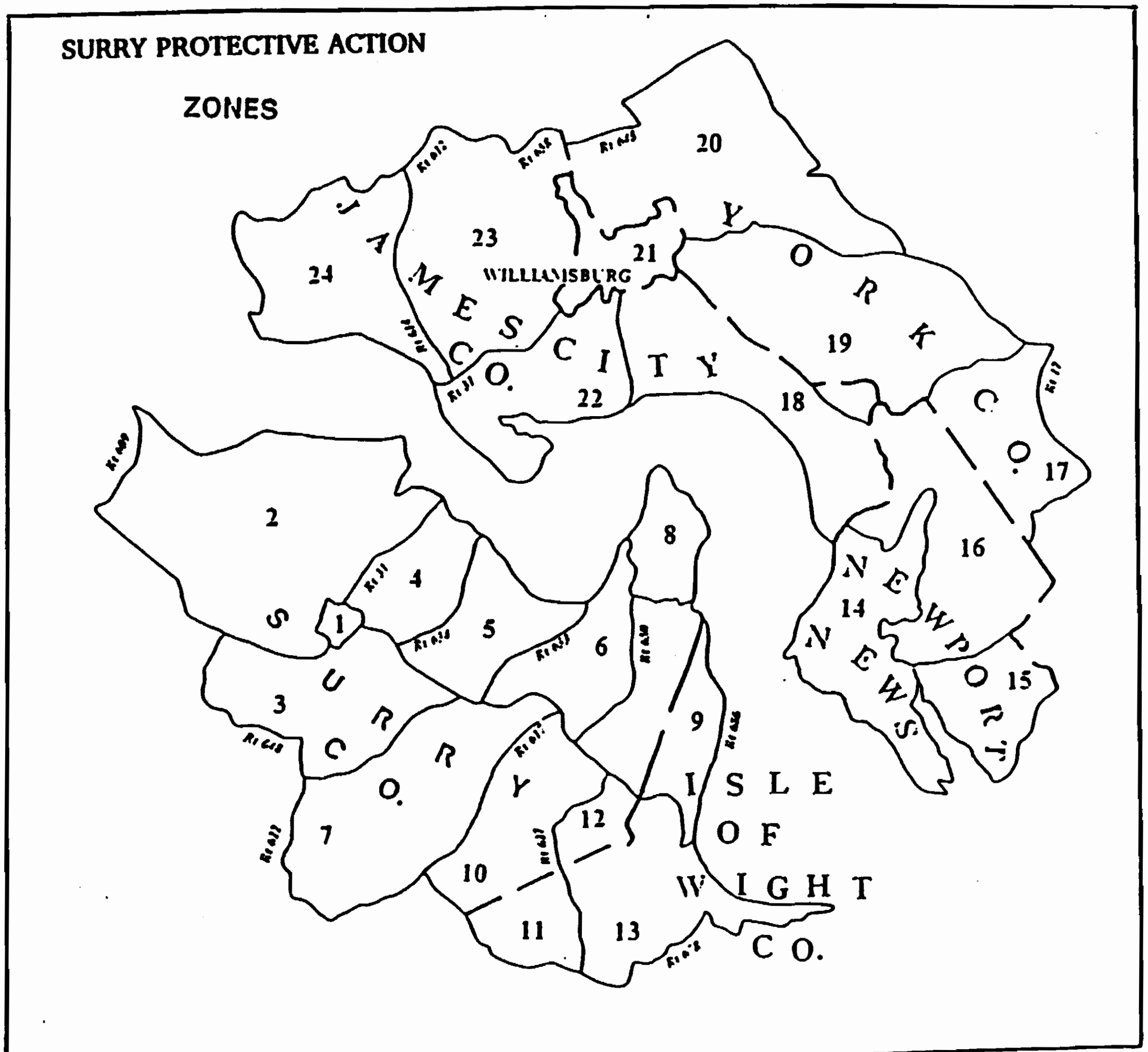


Figure 6.1 : Protective Action Zones for Surry Power Station

North Anna Nuclear Power Station is located in a predominantly rural environment on the shores of Lake Anna approximately 60 miles northwest of Richmond, Virginia. The 10-mile Emergency Planning Zone (EPZ) around this station incorporates large sections of Louisa and Spotsylvania Counties and very small areas in Orange, Caroline and Hanover Counties. North Anna's EPZ has been defined by 26 Protective Action Zones (PAZs). All except 3 of these zones are contained in Louisa and Spotsylvania Counties. The map in Figure 6.2 depicts county and protective action zone boundaries for the North Anna study area.

The research methodology described in Chapter 3 was used to conduct evacuation study for both the EPZs. All socioeconomic economic and highway data pertaining to the two EPZs were reduced to input for MASSVAC using procedures in Phase I (the discussion of which is out of scope of this research). This section focusses on the results obtained through application of MASSVAC to the worst case evacuation scenario derived from the combination of the following :

1. quickly escalating disaster,

2. peak tourist season and

3. weekday

The above scenario was evaluated under normal and adverse weather conditions.

The trip productions from various Protective Action Zones obtained through Phase I for the Surry and North Anna EPZs are shown in Tables 6.1 and 6.2 respectively. For details of the procedures used to arrive at this data refer [1].

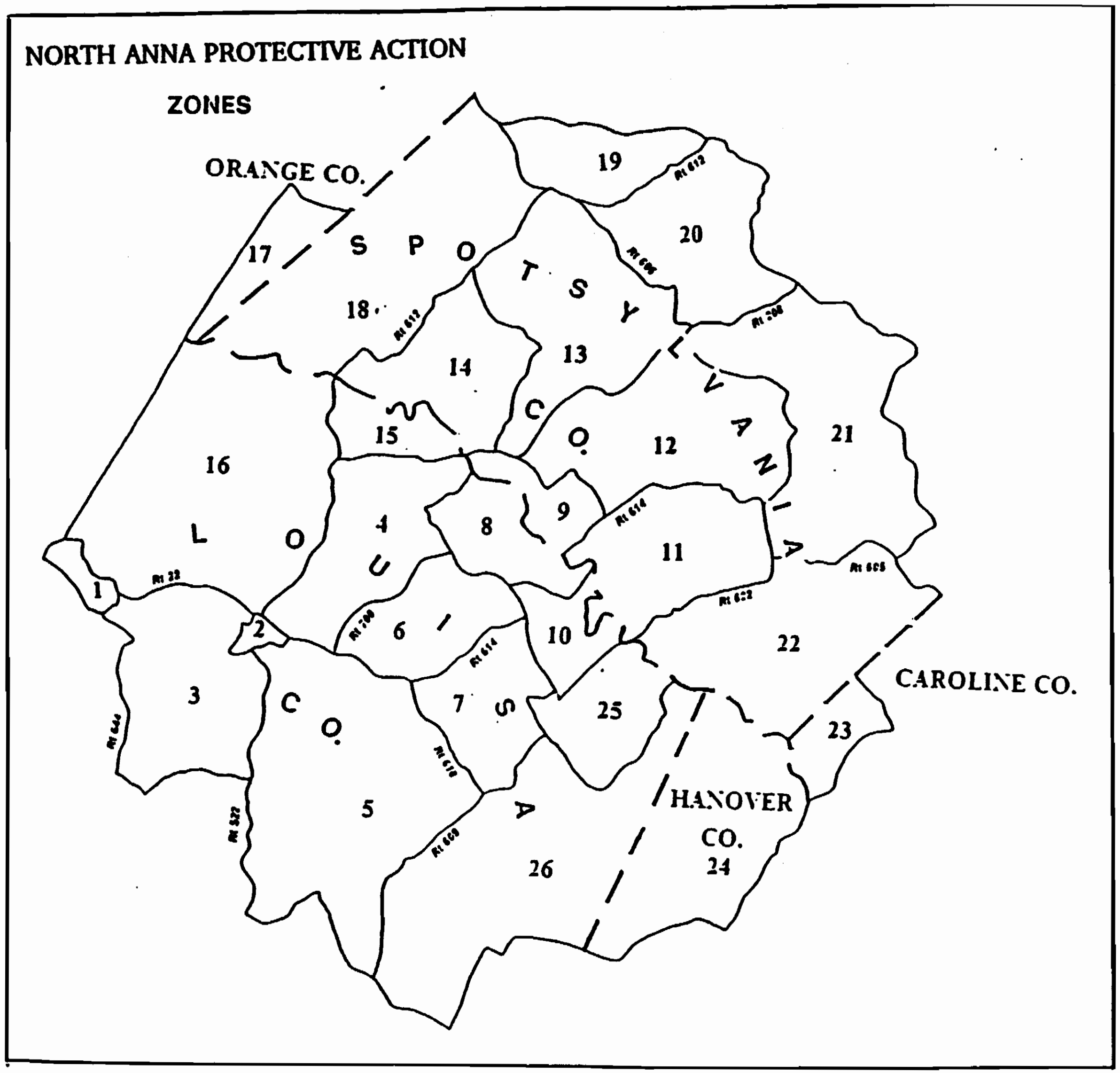


Figure 6.2 : Protective Action Zones for North Anna Power Station

Table 6.1

Surry Number of Vehicles to Evacuate Worst Case Scenario			
Zone Number	Permanent Vehicles	Transient Vehicles	Total Vehicles
1	266	9	275
2	460	0	460
3	413	0	413
4	302	0	302
5	317	0	317
6	238	0	238
7	366	0	366
8	466	0	466
9	168	0	168
10	178	0	178
11	97	0	97
12	77	0	77

contd...

Table 6.1 (continued)

Zone Number	Permanent Vehicles	Transient Vehicles	Total Vehicles
13	774	0	774
14	3528	0	3528
15	12917	0	12917
16	19691	0	19691
17	256	0	256
18	2889	3881	6770
19	1511	1152	2663
20	622	1177	1800
21	9214	5351	14564
22	1636	310	1946
23	3267	918	4185
24	734	0	734

Table 6.2

North Anna Number of Vehicles to Evacuate Worst Case Scenario			
Zone Number	Permanent Vehicles	Transient Vehicles	Total Vehicles
1	435	144	579
2	174	18	191
3	625	0	625
4	125	0	125
5	650	0	650
6	25	0	25
7	100	0	100
8	506	0	506
9	72	0	72
10	19	0	19
11	224	50	274
12	219	35	254
13	251	0	251

contd...

Table 6.2 (continued)

Zone Number	Permanent Vehicles	Transient Vehicles	Total Vehicles
14	523	0	523
15	37	60	97
16	412	20	432
17	55	0	55
18	2042	0	2042
19	151	0	151
20	424	0	424
21	633	0	633
22	280	0	280
23	118	0	118
24	293	0	293
25	195	0	195
26	262	0	262

6.2 Calibration of MASSVAC

Various options need to be resolved and fixed to model the most likely user behavior under evacuation. These parameters are necessarily network and evacuation area specific and, therefore, different set of options should apply for different Emergency Planning Zones (EPZs). MASSVAC's options can be selected through the TEDSS screen shown in Figure 6.3.

Simulation Interval and Half Loading Time

Simulation Interval represents the time-length of "snap-shots" of the evacuation process and, hence, deteremine the degree of accuracy with which aspects such as network performance can be studied. It is, therefore, desirable to load the trips on the network at small time intervals. However, computer execution time is directly proportional to the number of iterations processed and hence, a reasonable limit on the ***ratio*** of half loading time and simulation interval is necessary. This is because the Number of Iterations = (Half Loading Time/Simulation Interval)X2. For all practical purposes, an interval of 15 to 60 minutes is suitable [Jamei]. The simulation interval used in this application was 15 minutes.

Half Loading Time is defined as the time by which 50% of the trip production is loaded on the network. The choice of this paramter in MASSVAC reflects a very important difference between modeling of natural disasters and nuclear power stations. Natural disaster evacuation takes place with much greater warning time than nuclear power plant evacuation. Evacuation in such cases is, therefore, much more regulated and less urgent. Hence network loading is very consistent with level of service available on the network. In terms of modelling, this means that the

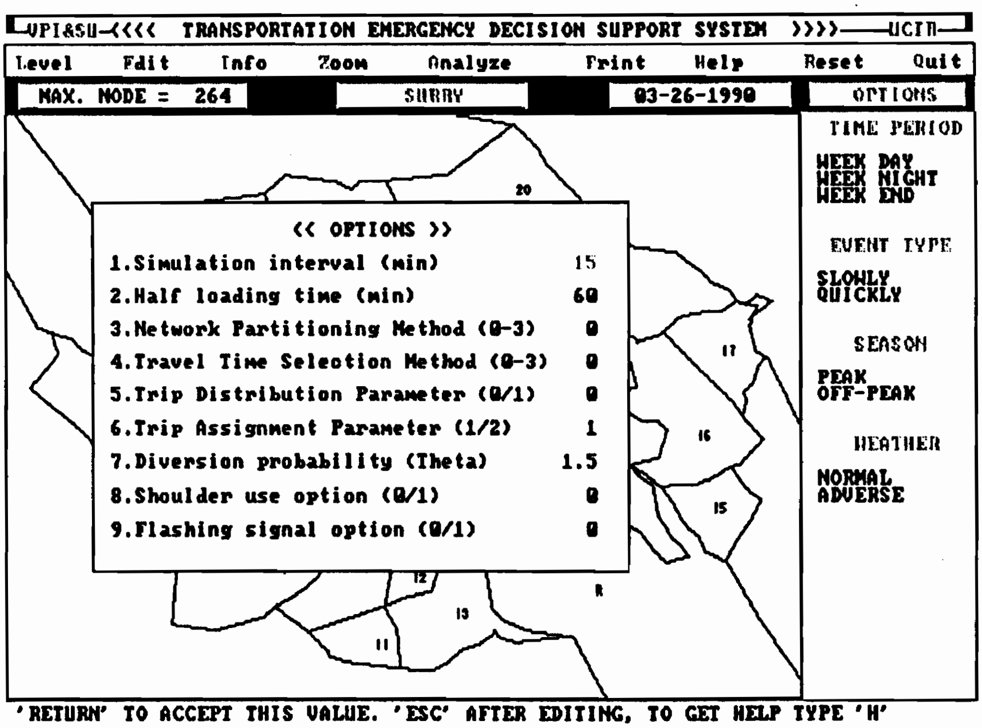


Figure 6.3 : Selection of MASSVAC options in TEDSS

assumed and derived values of Network Clearance Time must converge. In MASSVAC2.0, if the value of Network Clearance Time given by the model was within 50% of the assumed value, it was "accepted" as the "correct" value. However, in the case of nuclear power plant evacuation, loading is necessarily more independant of the network service. This reflects the "getting the hell out" attitude of the public. In this case, loading time is equaivalently called "Response Time". A half loading period of 60 minutes (response time = 2 hours) was used for the high trip loading Surry 10-mile (North) are while 45 minutes was used for all other areas. This reflects a quick response time for evacuees under a quickly escalating, weekday scenario for which results have been presented.

Trip loading in each iteration of MASSVAC is taken as the difference between the cumulative trips to be loaded on the network in this iteration and the last iteration as given by the logit curve formula [10]. Under the worst case scenario, the network is assumed to pre-loaded with peak hour seed volumes which are calculated from the AADTs for the links. Seed volume on each link is calculated as 15% of the AADT for the link (7.5% each way). This volume is decremenetally added to the evacuation flow carried by the link in each iteration.

Trip Distribution

The 3-quadrant method of network partitioning technique was adopted to identify feasible exit points of the EPZ which avoid the direction toward the nuclear incident. The most important criteria used for selecting this geometric technique is that it gives the largest feasible set of destinations. This enhances the second level of selection by the travel time method because of the greater choice available. For the Surry area, no travel time selection method was used because the James River acts as a natural barrier in the EPZ and hence, no amount of congestion in the network would force a "wrong" choice of exit points. For other areas, the 1.5 method of travel time seledtion was used. Again, the Surry (North) area is predominantly urban and hence, the travel times on the network would radically affect the destination choice over differents time-intervals of evacuation and, hence, the destination identification was modeled as Iterative. Other areas were modeled as Non-Iterative.

Traffic Assignment

The Dial's algorithm has been used in all applications of MASSVAC in this study. This is because evacuation over such short times is a rare traffic event and, threrefore, user route-choice tends more toward ***expediency*** rather than ***efficiency***. Since Dial's algorithm is a stochastic, multi-path model which is insensitive to the overall length of the route, it is most suitable for evacuation analysis.

6.3 Application to Surry 10-mile Area

Network Clearance Times reported in this section and Section 6.2 refer to the overall in-vehicle travel time required by all persons to exit the 10-mile Emergency Planning Zone (EPZ) using safe and efficient routes. This represents the most complex component of evacuation time, the other components of which are : *notification time, preparedness time and verification time*. These component times must be added to obtain total evacuation time.

All Network Clearance Times are derived through the MASSVAC computer simulation model for a Scenario 3 type event (quickly escalating disaster on a weekday during the peak season) because this situation reflects the worst case in terms of number of people to evacuate and highway network conditions.

The area surrounding Surry Nuclear Power Station is very diversified. Large concentrations of permanent and transient trips originate in the EPZ north of the James River (Williamsburg, Busch Gardens, Camp Peary U.S. Naval Reserve and parts of Newport News). The southern portion is predominantly rural with a different type of highway network separated from the northern portion by a natural barrier, the James River. Hence, from an engineering perspective, the two areas need to be analyzed separately. These two diverse areas lead to two different sets of evacuation results for the Surry 10-mile area - *Surry 10-mile North* and *Surry 10-mile South*, with the former being more critical for the area as a whole.

6.3.1 Surry 10-Mile (North)

Evacuation of the area north of the James River up to 10-miles from the Surry Power Station involves movement of nearly 67,000 vehicles from 11 PAZs. Network Clearance Time under normal weather conditions is estimated to be **7 hours 30 minutes**.

Adverse weather conditions (snow, heavy precipitation, fog etc.) under which highway speeds are expected to drop to 50% of the normal levels would extend clearance time to **9 hours 40 minutes**.

Through study of network use, congestion and blocking, traffic bottlenecks critical to determination of evacuation time were identified. Based on these observations, a set of traffic management strategies is recommended which, if implemented, would reduce clearance time to **5 hours 45 minutes** under normal conditions and **7 hours 55 minutes** under adverse conditions.

Optimal evacuation routes leading to exit points used by majority (over 90%) of vehicles are listed in Table 6.3. and illustrated in Figure 6.3. The most sought-after evacuation destinations are highway nodes at which I-64, Rt. 60 and Rt. 143 exit the evacuation area. The number of vehicles leaving the 10-mile EPZ at different exit points is an important factor in determining the staffing and inventory needs at decontamination centers located outside the 10-mile EPZ. The traffic volume at all exit points are shown in Table 6.4.

Evacuation of northern part of the Surry EPZ results in excessive ***congestion*** and ***blocking*** in the Surry North area. By congestion we mean that the number of vehicles on a link exceeds its design capacity. Blocking refers to extreme congested or jammed conditions rendering the highways useless for carrying trips. The longest periods of blockage (5 hours) in an uncontrolled evacuation are likely to occur at the following points :

1. Links on RT. 60 near its northern exit point and all feeding links in that neighborhood especially Rt. 612 and Rt. 615.

2. Feeding links for I-64 from the Williamsburg Metropolitan area.

Other important blocked highways lie upstream of exit points in the south-east part of the 10-mile EPZ, specifically on Rts 238 and Rt. 17 leading into the Coleman Bridge, Rt. 105, Rt. 143, I-64 and Rt. 60.

To reduce evacuation times and, more importantly, to improve highway service (by reducing congestion/blocking time) the following generic traffic management strategies are suggested :

1. Cordon off 10-mile EPZ, prevent any trips ***entering*** the area at the boundary on major exit routes. This should be followed by one-way operation of all links immediately downstream of all exit points. This policy would require emergency vehicles, such as buses and ambulances, which may have to make multiple entry during evacuation, to be routed through minor, "non-evacuation" routes.

2. Flashing operation of urban signalized intersections must be considered strongly wherever possible.

3. Permit use of shoulders on expressways (I-64) to enhance evacuation capacity of this critical traffic corridor.

4. Study of link usage reveals that I-64, Rt. 60 and Rt. 143 are major carriers of evacuation trip-volumes. These facilities exhibit satisfactory service levels through most of their lengths in the 10-mile EPZ. However, it is advised that these facilities be used exclusively in the outward direction in immediate proximity of the exit points. Also, partial one-way operation (3 lanes in exit direction) of the links immediately downstream of the last link reduces congestion.

5. A survey of congestion and blocking in the network shows that the most critical links are those feeding the major arterial routes (I-64, Rt. 143, Rt. 60 and Rt. 5). One-way operation of these links (which would result in prevention of trips to exit the major arterial routes into the EPZ) is recommended for improving the utilization of the high capacity facilities.

Specific traffic management strategies suggested for the Surry North area are listed in Table 6.5 and shown in Figure 6.4.

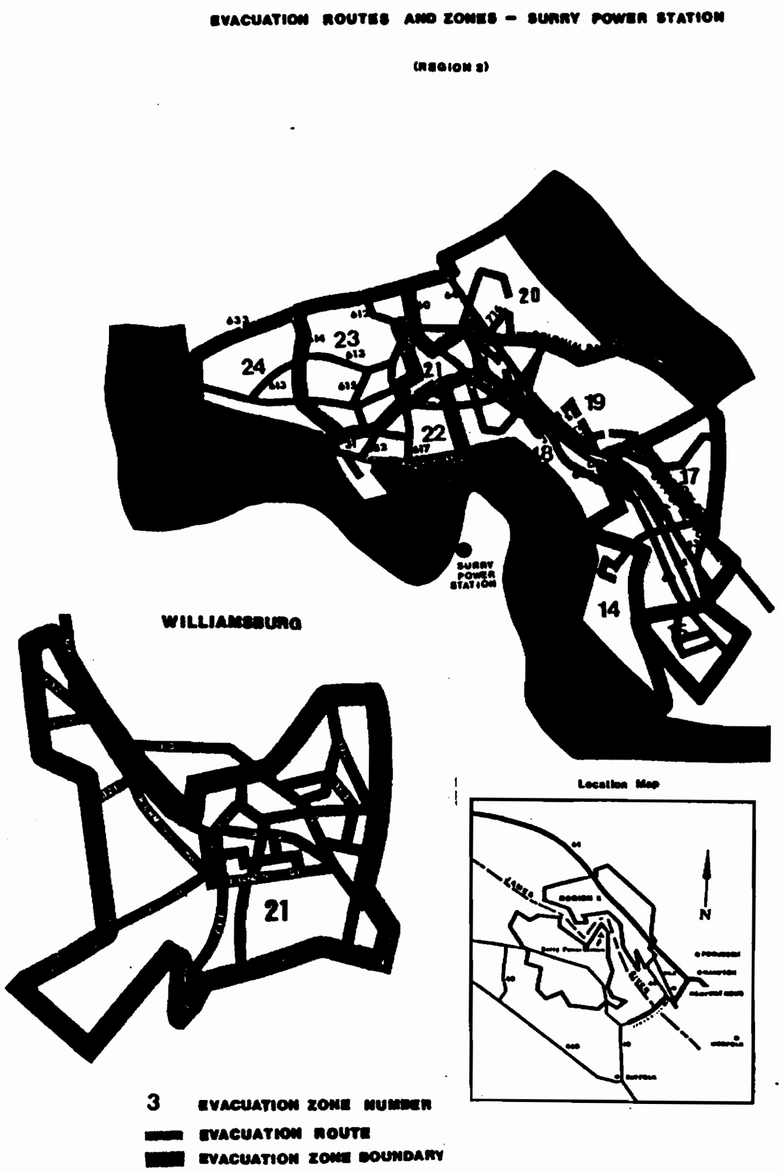


Figure 6.4 : Evacuation Routes and Zones (SPS - Region 2)

6.3.2 Surry 10-Mile (South)

The part of the 10-mile EPZ south of the James River is rural and sparsely populated with the exception of the Town of Surry. The only other trip generator is the Surry Nuclear Power Station itself. Involving movement of only 4000 vehicles, this area also corresponds to Quadrant III (South West Quadrant = sectors JKLM). The maximum network clearance times under normal and adverse conditions are **2 hours 10 minutes** and **2 hours 45 minutes** respectively.

Very few major routes pass through the portion of the EPZ south of the James river. Evacuation occurs primarily in a southerly direction on Route 31 and Route 10 in Surry County. Very little congestion is expected due to low population density and the availability of an adequate highway network.

Evacuation routes for the Surry South area are shown in Table 6.6 and illustrated in Figure 6.5. Expected traffic volume at various exit points in the area are shown in Table 6.7.

Table 6.3

Primary Evacuation Routes for Surry North 10-mile Area

Zone Number	Primary Evacuation Routes
14	1. Use Washington Blvd. to north, turn east on primary route 105 and south on Interstate 64 out of the evacuation area. 2. Use Washington Blvd. to north, turn east on primary route 105 out of the evacuation area. 3. Use Washington Blvd. to north and turn south on U.S 60 out of the evacuation area. 4. Use washington Blvd. to north, turn east on primary route 105 and south on primary route 143 out of the evacuation area.
15	1. Use secondary route to north on Lucas Creek Road and turn east on 173 out of the evacuation area. 2. Use secondary route to east on Eastwood Dr., turn east on Menchville Rd. and south on U.S. 60 out of the evacuation area. 3. Use secondary route to north on Lucas Creek Rd., turn east on 173 and north on U.S 60 and east on primary route 105 to out of the evacuation area. 4. Use secondary route to north on Lucas Creek Rd., turn east on 173, north on U.S 60, east on 105 and south on 143 to out of the evacuation area.
16	1. Use primary route to east on 173 out of the evacuation area. 2. Use primary route to east on 173, turn south on U.S 60 out of the evacuation area Use primary route to east on 105 out of the evacuation area. 3. Use primary route to east on 105, turn south on U.S 60 out of the evacuation area 4. Use primary route to east on 105, turn north on 143 and east on 238 out of the evacuation area.

contd...

Table 6.3 (contd)

Zone Number	Primary Evacuation Routes
17	1. Use 238 east out of the evacuation area 2. Use primary route to west on 238, turn south on 143, west on 105 and south on Interstate 64 out of the evacuation area. 3. Use 238 west, turn south on 143 and west on 105 to out of the evacuation area. 4. Use 238 west, turn north on 143, east on 199 and north on Interstate 64 to out of the evacuation area. 5. Use 238 west, turn south on U.S 60 and out of the evacuation area. 6. Use 238 west, turn south on 143 and out of the evacuation area.
18	1. Use Kingsmill Rd. north, continue north on 637 and U.S 60, turn east on 31, north on 143 and north on Interstate 64 to out of the evacuation area. 2. Use Kingsmill Rd. north, continue north on 637 and U.S 60, turn west on 162 and north on on U.S 60 and out of the evacuation area. 3. Use Kingsmill Rd. south, turn south on U.S 60 and east on 105 and south on Interstate 64 to out of the evacuation area. 4. Use Kingsmill Rd. south, turn south on U.S 60 and east on 105 to out of the evacuation area. 5. Use Kingsmill Rd. south, turn north on U.S 60, east on 105, south on 143 and east on 238 to out of the evacuation area. 6. Use Kingsmill Rd. south, turn south on U.S 60, east on 105 and south on 143 to out of the evacuation area.

contd...

Table 6.3 (contd)

Zone Number	Primary Evacuation Routes
19	1. Use 143 north, turn north on Interstate 64 and out of the evacuation area. 2. Use 143 north, turn south on 5/31 and north on U.S 60 out of the evacuation area. 3. Use 641 south, turn south on 143, east on 199 and south on Interstate 64 out of the evacuation area. 4. Use 641 south, turn south on 143 and east on 199, south on Interstate 64 onto east 105 out of the evacuation area. 5. Use 641 east, turn south on the Colonial Parkway and north on 17 out of the evacuation area.
20	1. Use 143 north, turn north on Interstate 64 out of the evacuation area. 2. Use 716 south, turn west on the Colonial Parkway into Williamsburg, north on 132 and north on U.S.60 out of the evacuation area. 3. Use 716 south, continue south on 641, turn east on 199 and south on Interstate 64 and east on 105 out of the evacuation area.
21	1. Use 5/31 north, continue north on 143 and Interstate 64 to out of the evacuation area. 2. Use 163 west onto U.S 60 north out of the evacuation area. 3. Use 163 west onto U.S 60 north, south on 162, west on 321, south on 615, west on 613 and north on 614 out of the evacuation area. 4. Use 163 west onto U.S 60 north, turn west on 615 and north on 612 out of the evacuation area. 5. Use 163 west onto U.S 60 north, turn south on 162, west on 321, south on 615 and west on 5 out of the evacuation area.

contd...

Table 6.3 (contd)

Zone Number	Primary Evacuation Routes
22	1. Use 617 north, turn west on 199, north on 616 and 615 and north on U.S 60 out of the evacuation area. 2. Use 617 north, turn west on 199, north on 31 through Williamsburg and onto 132, north on 143 and north on Interstate 64 out of the evacuation area. 3. Use 682 south, turn west on the Colonial Parkway, north on 359 and 614 out of the evacuation area.
23	1. Use 612 south and 615 north onto U.S 60 north out of the evacuation area. 2. Use 612 north and out of the evacuation area. 3. Use 612 south and 615 north onto U.S 60 south, turn north on 132 onto 143 north and Interstate 64 out of the evacuation area.
24	1. Use 614 north out of the evacuation area. 2. Use 5 east, turn north on 615 and continue north on U.S 60 out of the evacuation area. 3. Use 5 west out of the evacuation area.

Table 6.4

Expected Traffic Volumes at Surry North 10-Mile Exit Points

Zone Number	Exit Routes	Expected Traffic Volume (Vehicles)
17	Route 238 from 638 to 17	4548
17	& Route 17 from Colonial Parkway to 238	
16	Route 105 from 143 to 17	6140
16	Richneck Rd from 143 to CL	4224
16	Route 143 from Richneck Rd to 173	4833
16	Richneck Rd from 143 to 173	4409
16	Route 64 from 105 to 173	13201
15	Route 60 from Menchville Rd to BNDY	10591
24	Route 5 from 613 to Chickahominy River	2367
23	Route 614 from 613 to 633	2857
23	Route 612 from CL to 658	2714
20	Route 60 from CL to 645	4568
20	Route 64 from 143 to 645	5741

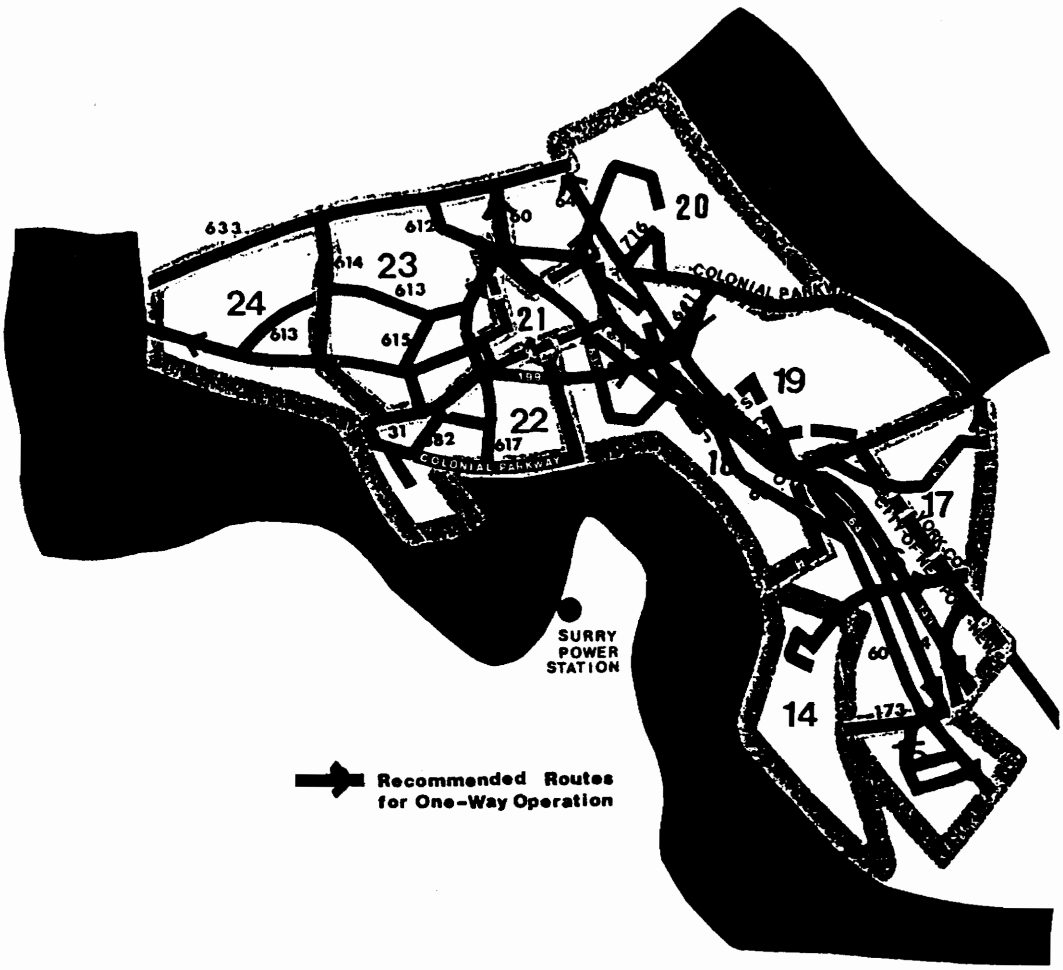


Figure 6.5 : Traffic Management Strategies (SPS - Region 2)

Table 6.5

Highways recommended for one-way operation to improve evacuation
1. Route 5 from 614 to Chickahominy River
2. Route 615 from 321 to 612
3. Route 60 from Richmond Rd. to 645
4. Route 132 from 60 to 143
5. Route 143 from 5/31 to I.S 64
6. Route 64 from 143 to 645
7. Route 199 from 637 to 60
8. Route 199 from 641 to 60
9. Washington Blvd. to Route 60
10. Route 105 from 60 to 64
11. Route 105 from 64 to 143
12. Route 105 from 143 to 17
13. Richneck Rd. from 143 to CL
14. Route 17 from 637 to 238
15. Route 60 from 105 to 173
16. Route 60 from 173 to Menchville Rd.
17. Route 64 from 105 to 173
18. Route 143 from 105 to 173
19. Route 173 from 60 to 64
20. Route 173 from 64 to 143

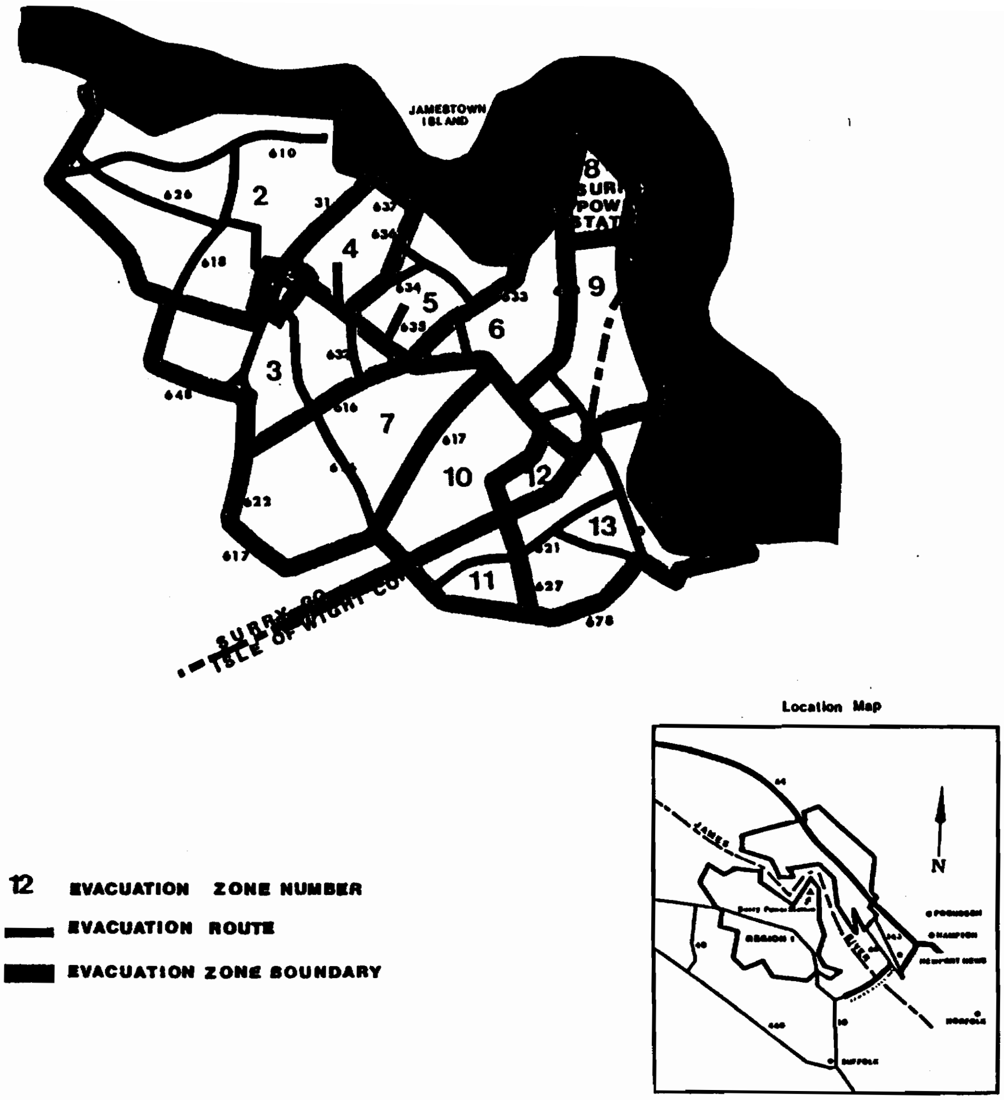


Figure 6.6 : Evacuation Routes and Zones (SPS - Region 1)

Table 6.6

Primary Evacuation Routes for Surry South 10-mile Area

Zone Number	Primary Evacuation Routes
1	1. Use 31 south and onto 622 south out of the evacuation area. 2. Use 31 south out of the evacuation area. 3. Use 31 south and 10 west out of the evacuation area.
2	1. Use 626 north and 618 south out of the evacuation area. 2. Use 626 south, turn south on 31 and onto 622 out of the evacuation area. 3. Use 626 south and turn south on 31 out of the evacuation area.
3	1. Use 10 west, turn south on 31 and south on 622 out of the evacuation area. 2. Use 10 west and 31 south out of the evacuation area. 3. Use 10 west, turn south on 31 and west on 10 out of the evacuation area.
4	1. Use 638 south, turn west on 10, south on 31 and 622 out of the evacuation area. 2. Use 638 south, turn west on 10 and south on 31 out of the evacuation area. 3. Use 638 south, west on 10, south on 31 and west on 10 out of the evacuation area.

contd...

Table 6.6 (contd)

Zone Number	Primary Evacuation Routes
5	1. Use 635 south, turn east on 10 and south on 616 out of the evacuation area. 2. Use 635 south, turn west on 10 and south on 31 and 622 out of the evacuation area. 3. Use 635 south, turn west on 10 and south on 31 out of the evacuation area. 4. Use 635 south, turn east on 10, south on 616 and south on 626 out of the evacuation area.
6	1. Use 617 out of the evacuation area. 2. Use 10 east out of the evacuation area. 3. Use 10 east, turn south on 627 out of the evacuation area. 4. Use 10 west, turn south on 616 out of the evacuation area.
7	1. Use 616 south out of the evacuation area. 2. Use 616 south and 626 south out of the evacuation area. 3. Use 10 west, turn south on 31 and 622 out of the evacuation area. 4. Use 10 west, turn south on 31 out of the evacuation area.
8	1. Use 650 south, turn left on 628, south on 627 and left on 10 out of the evacuation area. 2. Use 650 south, turn right on 617, and south on 617 out of the evacuation area. 3. Use 650 south, turn east on 10 and south on 627 out of the evacuation area. 4. Use 650 south, turn east on 10, south on 627 and west on 621 out of the evacuation area.

contd...

Table 6.6 (contd)

Zone Number	Primary Evacuation Routes
9	1. Use 628 east, turn south on 627 and east on 10 out of the evacuation area. 2. Use 627 south out of the evacuation area.
10	1. Use 617 south out of the evacuation area. 2. Use 10 east out of the evacuation area. 3. Use 10 east, turn south on 627 out of the evacuation area. 4. Use 10 west and 616 south out of the evacuation area.
11	1. Use 627 south out of the evacuation area. 2. Use 621 south out of the evacuation area.
12	1. Use 10 east out of the evacuation area. 2. Use 627 south out of the evacuation area. 3. Use 627 south and turn right on 621 south out of the evacuation area.
13	1. Use 10 east out of the evacuation area.

Table 6.7

Expected Traffic Volumes at Surry South 10-Mile Exit Points

Zone Number	Exit Routes	Expected Traffic Volume (Vehicles)
3	Route 622 from 31 to 644	567
3	Route 31 from 622 to 644	534
3	Route 10 from 31 to 618	461
3	Route 616 from 626 to 622	443
7	Route 626 from 616 to 617	441
11	Route 621 from 627 to 626	111
11	Route 627 from 621 to 626	282
13	Route 673 from 621 to 678	70
13	Route 10 from 621 to 678	1016

6.4 Application to North Anna 10-mile Area

The 10-mile radius Emergency Planning Zone around the North Anna Power Station is comprised of 26 Protective Action Zones. Of these, only a few zones, including the towns of Mineral and Louisa, have a relatively large concentration of people. Zones 14, 18, 20 and 21 contain large populations, too. However, these populations are spread over large areas having ample road systems. Except for Lake Anna State Park, there are no other tourist attractions or institutions of any kind in the 10-mile region. The power station itself accounts for a heavy loading of vehicles onto the road system. Evacuating this region involves movement of nearly 9,000 vehicles to safety. Total network clearance time for all PAZ's within the 10 mile radius under normal conditions is **2 hours 10 minutes**. The evacuation time estimate for adverse weather conditions under which speeds on the highway network fall to 50% of the normal values is **3 hours 5 minutes**.

Three primary routes within the 10 mile radius are Routes 33, 522 and 208. Route 522 receives the heaviest volume of traffic during an evacuation followed closely by Route 33. Most of the heavier populated evacuation zones lie adjacent to the 10 mile radius. Consequently, there is not much interzonal travel.

Congestion occurs only on Route 522 for slightly longer than one half hour, starting one hour after evacuation is initiated. Delays occur near the edge of the 10 mile radius in Orange County on this route. However, there are no serious traffic hold-ups due to blocking i.e. all highway links are expected to be serviceable throughout a normal evacuation process.

Evacuation routes for the 10-mile EPZ are listed in Table 6.8. and illustrated in Figure 6.6. Exit Point traffic volumes are shown in Table 6.9.

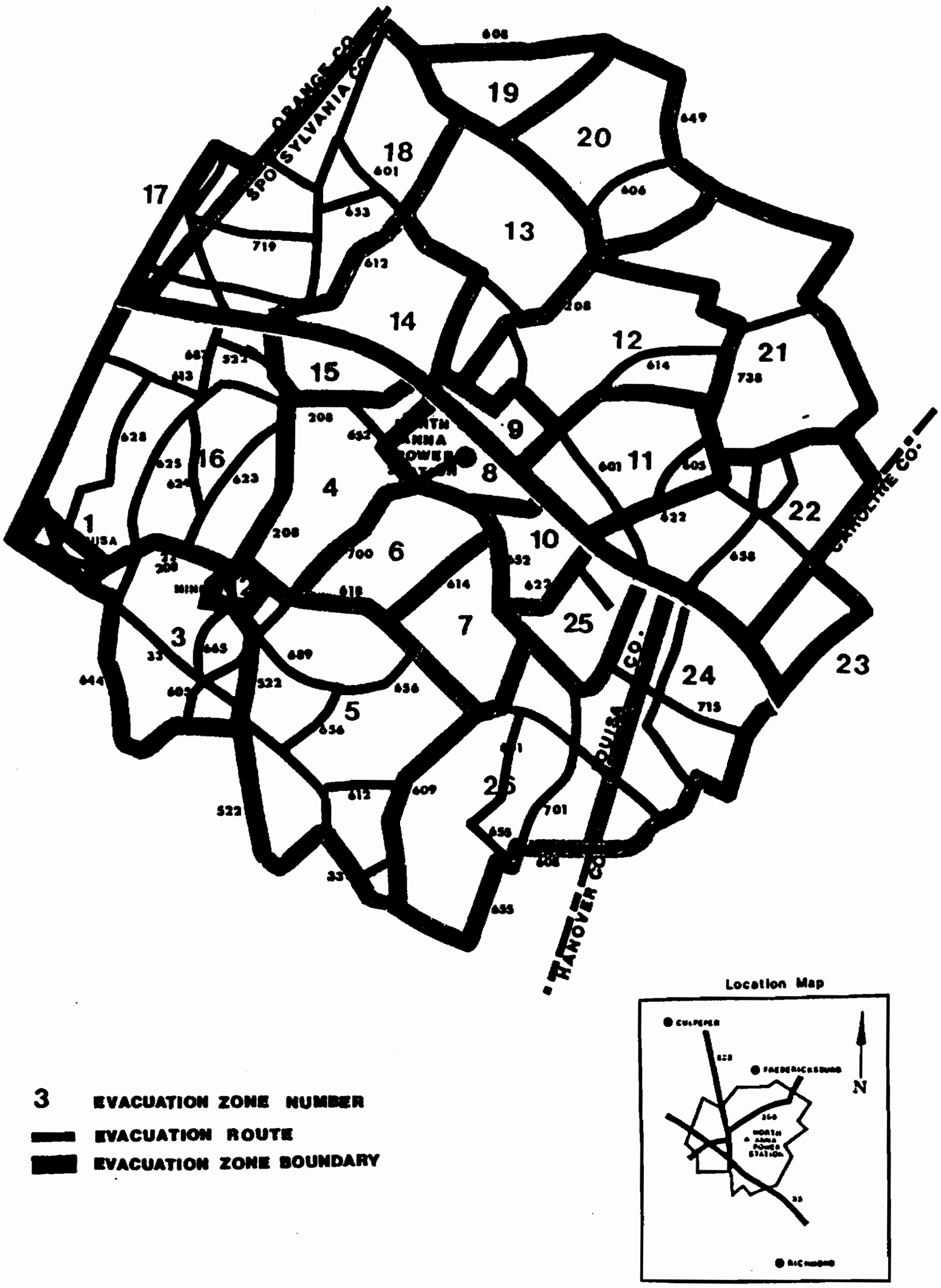


Figure 6.7 : Evacuation Routes and Zones (NAPS)

Table 6.8

Primary Evacuation Routes for North Anna 10-Mile Area

Zone Number	Primary Evacuation Routes
1	1. Use 208 west out of the evacuation area.
2	1. Use 618 west, turn south on U.S 522 out of the evacuation area. 2. Use 208 west, turn south on 767 and west on U.S 33 out of the evacuation area. 3. Use 618 west, turn south on U.S 522 and onto 605 south out of the evacuation area.
3	1. Use 767 south U.S 33 west out of the evacuation area.
4	1. Use 613 west out of the evacuation area. 2. Use 522 north, turn west on 612 out of the evacuation area. 3. Use 522 south onto south 623, turn west on 208, south on 767 and west on U.S 33 out of the evacuation area.
5	1. Use 656 south and U.S 33 west out of the evacuation area
6	1. Use 700 south and U.S 522 south out of the evacuation area 2. Use 700 south, U.S 522 south and 605 south out of the evacuation area. 3. Use 652 west, left on 208 onto 613 west out of the evacuation area.
7	1. Use 650 south, turn east on 618 and south on 701 out of the evacuation area. 2. Use 650 south, turn east on 618, south on 601 and south on 655 out of the evacuation area. 3. Use 650 south, turn east on 618 and out of the evacuation area. 4. Use 650 south, turn west on 618 and south on 609 out of the evacuation area.

contd...

Table 6.8 (contd)

Zone Number	Primary Evacuation Routes
8	1. Use 700 south and continue south on U.S 522 out of the evacuation area. 2. Use 700 south and continue south on U.S 522 onto 605 south out of the evacuation area. 3. Use 700 south, turn west on 618 and continue on west 208, south on 767 and west on U.S 33 out of the evacuation area.
9	1. Use 614 east and 738 north out of the evacuation area. 2. Use 614 east, turn south on 601 and east on 622 and south on 738 out of the evacuation area. 3. Use 614 east, turn east on 657, south on 738 and east on 605 out of the evacuation area.
10	1. Use 622 west, turn south on 652 and 650, east on 618 and south on 701 out of the evacuation area. 2. Use 622 west, turn south on 652 and 650, east on 618, south on 601 and 655 out of the evacuation area. 3. Use 622 west, turn south on 652 and 650, east on 618 and out of the evacuation area.
11	1. Use 622 east and 738 south out of the evacuation area. 2. Use 622 east, 738 north and 605 east out of the evacuation area. 3. Use 601 south, 715 east and turn south on 658 out of the evacuation area.
12	1. Use 208 east out of the evacuation area. 2. Use 614 east and 738 north to out of the evacuation area. 3. Use 208 east, turn north on 650 and east on 606 out of the evacuation area.
13	1. Use 208 east out of the evacuation area. 2. Use 601 north, turn left on 653 west and out of the evacuation area. 3. Use 208 east, 650 north and 606 east out of the evacuation area.

contd...

Table 6.8 (contd)

Zone Number	Primary Evacuation Routes
14	1. Use 612 west out of the evacuation area. 2. Use 612 west, turn north on U.S 522 and west on 719 out of the evacuation area. 3. Use 612 west, turn north on U.S 522 and out of the evacuation area.
15	1. Use U.S 522 north and turn west on 612 out of the evacuation area. 2. Use U.S 522 north and 719 west out of the evacuation area. 3. Use U.S 522 north out of the evacuation area.
16	1. Use 625 south and 613 west out of the evacuation area.
17	1. Use 719 west, 522 north and 651 south out of the evacuation area. 2. Use 719 west and turn north on U.S 522 out of the evacuation area.
18	1. Use 652 north and 653 west out of the evacuation area. 2. Use 601 north and 651 south out of the evacuation area. 3. Use 719 west, 522 north and 651 south out of the evacuation area. 4. Use 601 north and 651 north out of the evacuation area.
19	1. Use 606 east out of the evacuation area.
20	1. Use 606 west out of the evacuation area.
21	1. Use 738 north out of the evacuation area. 2. Use 605 west out of the evacuation area. 3. Use 670 south and 738 south out of the evacuation area.
22	1. Use 738 south out of the evacuation area.

contd...

Table 6.8 (contd)

Zone Number	Primary Evacuation Routes
23	1. Use 671 south out of the evacuation area. 2. Use 669 south out of the evacuation area. 3. Use 671 north out of the evacuation area.
24	1. Use 658 south out of the evacuation area. 2. Use 715 south out of the evacuation area. 3. Use 658 south, turn right on 680 and east on 618 out of the evacuation area.
25	1. Use 622 north, turn south on 652 and 650, east on 618 and south on 701 out of the evacuation area. 2. Use 622 north, turn south on 652 and 650, east on 618, south on 601 and south on 655 out of the evacuation area. 3. Use 622 north, turn south on 652 and 650, east on 618 out of the evacuation area.
26	1. Use 618 east and 701 south out of the evacuation area. 2. Use 618 east out of the evacuation area. 3. Use 618 west, turn south on 601 and south on 655 out of the evacuation area.

Table 6.9

Expected Traffic Volumes at North Anna 10-mile Exit Points

Zone Number	Exit Routes	Expected Traffic Volume (Vehicles)
5	Route 522 from 33 to 643 & Route 33 from 656 to 643	734
3	Route 33 from 767 to 644	708
18	Route 653 from 652 to Bound	675
1	Route 208W from 33 to Bound	614
17	Route 651 from 522 to CP	520
22	Route 738 from 679 to Bound	508
17	Route 522 from 651 to CP	506
20	Route 606 from 650 to 649	479
18	Route 651 from 601 to Bound	456
16	Route 613 from 628 to Bound	450
18	Route 601 from 651 to 608	411
21	Route 738 from 1510 to 647	305
21	Route 605 from 604 to 658	300
24	Route 618 from 680 to 729	209
24	Route 658 from 680 to 729	205
18	Route 606 from 612 to 608	205
26	Route 701 from 618 to 608	160
17	Route 612 from CL to CP	155
24	Route 715 from 658 to 678	149
26	Route 655 from 601 to 701	127
18	Route 651 from 552 to 653	93
21	Route 208 from 650 to 606	89
3	Route 605 from 33 to 643	84
23	Route 669 from 679 to 738	83
1	Route 33 from 208 to Bound	64
5	Route 609 from 648 to 33	53
5	Route 33 from 612 to 657	52
26	Route 609 from 648 to 33	51
23	Route 671 from DMY to 738	44
1	Route 33 from 669 to Bound	33
23	Route 671 from DMY to 738N	32

6.5 *Conclusions of Model Application*

The MASSVAC computer evacuation model was interfaced with the socioeconomic data computer package (TEDSS) to estimate evacuation times and to evaluate (and suggest improvements to) highway network performance for the 10-mile Emergency Planning Zones (EPZs) for the Surry and North Anna nuclear power stations.

The Surry 10-mile area was partitioned into the South (Region 1) and North (Region 2) to reflect the vast differences in area types their mutually independent evacuation processes (since the two areas are disjoint).

The only "problem" areas identified in this study are those sectors involving the Surry North Area. This region has very high trip generating capacity thereby forcing traffic bottlenecks in many parts of the highway network during evacuation. Generic and specific traffic management strategies are suggested for this area based on study of evacuation simulation through MASSVAC. A list of highway links which could experience traffic blockades is also included. For the Surry North area, we recommend that Gloucester High School in Gloucester county be designated as an Evacuation Assembly Center as we expect about 4600 vehicles to exit the 10-mile EPZ using the Coleman memorial bridge.

All other areas in the two EPZs are sparsely populated and therefore generate relatively fewer vehicle trips. In all cases, the highway network is found to have adequate evacuation capacity to carry evacuation flows without development of traffic bottlenecks or serious delays.

7.0 Conclusions

This research has contributed to the successful development of the TEDSS/MASSVAC microcomputer computer software package and its application to evacuation planning around nuclear power stations. With this work, MASSVAC has evolved as an extremely versatile evacuation analysis model capable of estimating network clearance times and evaluating highway network performance for many types of evacuations.

The value of MASSVAC3.0 lies in the plethora of options provided to model user-behavior during emergency evacuation. These considerations greatly influence the Network Loading, Trip Distribution, Traffic Assignment, Determination of link travel times and other critical procedures used by the model. Also, information content of the output has been enhanced for better understanding and reporting of the evacuation process. By interfacing MASSVAC with TEDSS, we have a powerful tool for developing comprehensive evacuation plans for Evacuation Emergency Planning Zones (EPZ). The model provides reasonable estimates of network clearance times using realistic hypotheses and theories of traffic flow characteristics. It is capable of answering what-if type of questions related to evacuation under a variety of scenarios. Using TEDSS, the socioeconomic and highway data pertaining to an EPZ can be compiled and configured to reflect number of evacuation scenarios and highway service conditions possible at the time of the incident. This capability enables development and evaluation of Traffic Management Strategies such as one-way operation of highways, shoulder-use and signal-operations to improve evacuation through lowering network clearance times and traffic congestion/bottlenecks.

7.1 Recommendations for Further Study

Future improvements to the model can be made in both theoretical as well as technical areas. Theoretical improvements pertain to refinements of existing procedures used in MASSVAC and addition of new features to improve modeling and therefore provide better diagnosis of what is most likely to happen during an emergency evacuation. At a number of occasions during this research, it was felt that additional information on the evacuation process would help better reporting of results. But unfortunately, this was beyond the scope of the model since it is macroscopic. Weaknesses in the model lie chiefly in the discharge procedure used for dissipating link flows and estimation of travel times on the links based on current link flows. Due to the "macroscopic" way in which the congestion is identified on links, it is difficult to estimate the number of people actually held up within the network during any simulation interval. Hence, though we can can report trip-loading dynamically, it is impossible to accurately determine how many people actually clear the EPZ at any given time. In addition, practical research on theory and assumptions underlying the network loading and traffic assignment procedures would certainly make the model more realistic. One of the chief areas requiring research is study of driver behavior during evacuation and the corresponding influence on network flows.

Practical improvements lie in better coding of the model itself. A "perpetual" problem in this area is efficiency. Though faster computers and advanced software development environments predominantly influence these matters, it is always possible to make improvements to the code to speed-up runtime. One major step taken in this direction during this research was the reduction in execution of Dial's algorithm through a better sorting technique (Quicksort Algorithm). Another major step would be to incorporate the "longest path" algorithm instead of the PATH subroutine to update evacuation time by finding the length of the longest trip-carrying path in each iteration. Actual enumeration of paths in each iteration is unnecessary primarily because they are too many and it is difficult to determine which one of them represent primary evacuation routes.

Another area of further interest is making the model more user-friendly and informative. In its current form, MASSVAC is a purely "number-crunching" type of program. Any Input/Output must be provided/displayed through interface with another program with graphics capability. This eliminates the possibility of "real-time" simulation thereby depriving the user of visual appreciation of the evacuation process in a dynamic way. In order to achieve this objective, TEDSS and MASSVAC need to be combined into one single program having the capability of displaying the results of each iteration of simulation graphically during real-time operation.

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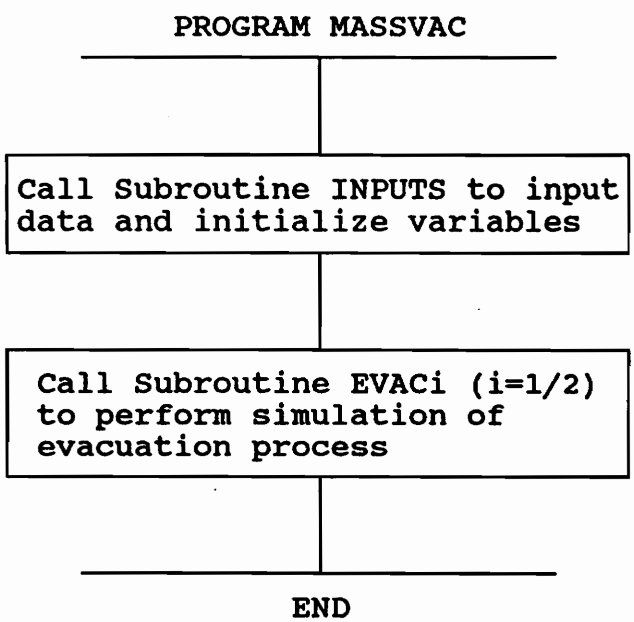
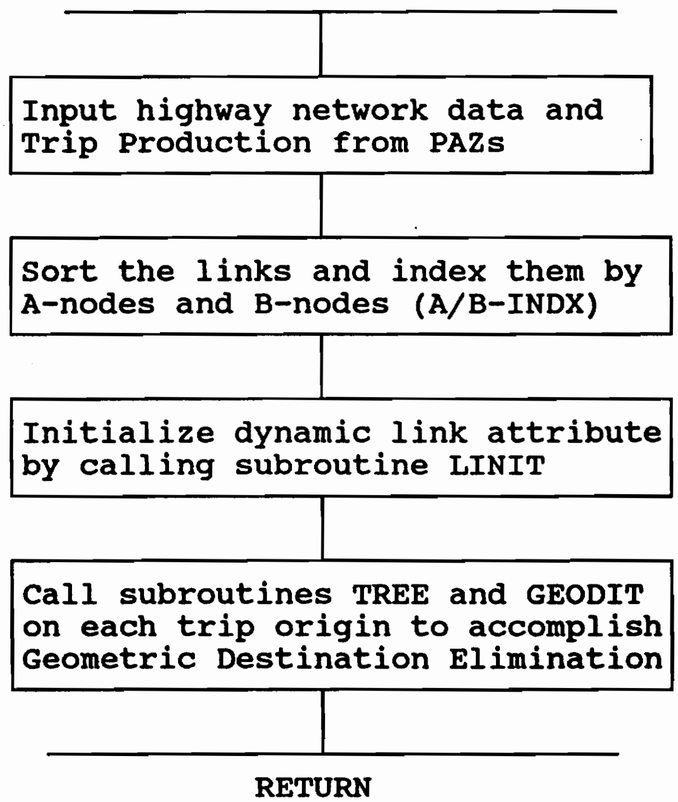
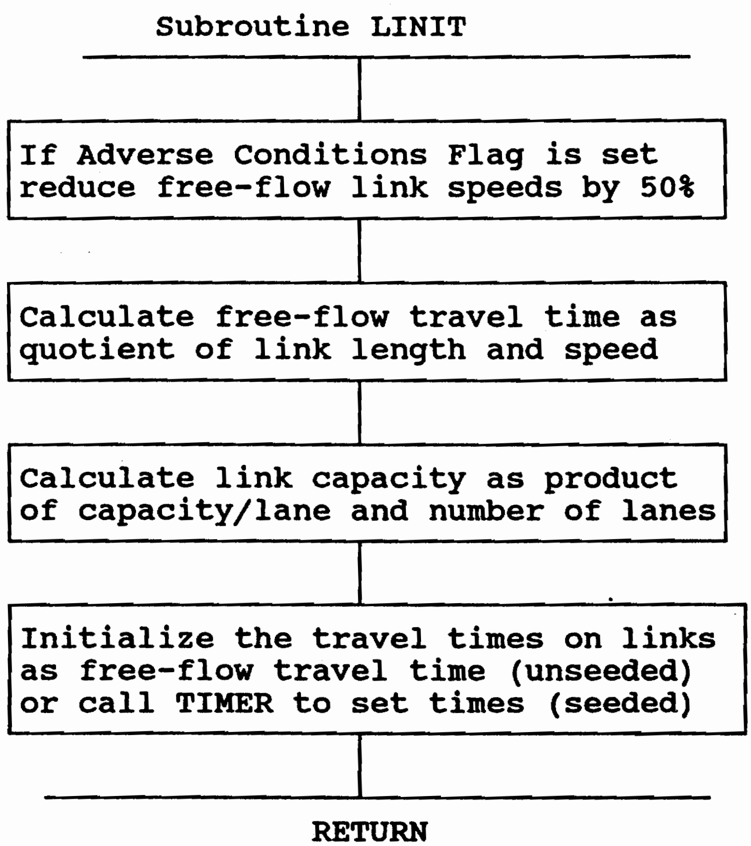
19. Nuclear Management and Resources Council, "Graded Response : The Preferred Evacuation Strategy for Nuclear Power Plants" , February, 1989

Appendix A. Program Flowcharts



Subroutine INPUTS




Subroutine LINIT
If Adverse Conditions Flag is set reduce free-flow link speeds by 50%
Calculate free-flow travel time as quotient of link length and speed
Calculate link capacity as product of capacity/lane and number of lanes
Initialize the travel times on links as free-flow travel time (unseeded) or call TIMER to set times (seeded)
RETURN

Subroutine ODTAB

Compute the trip production in each PAZ for this iteration from the logit curve

Apply the shortest path algorithm on all origins to compute labels for all nodes

Call Subroutine TTDIT to implement trip distribution and print the trip table

RETURN

Subroutine DIAL

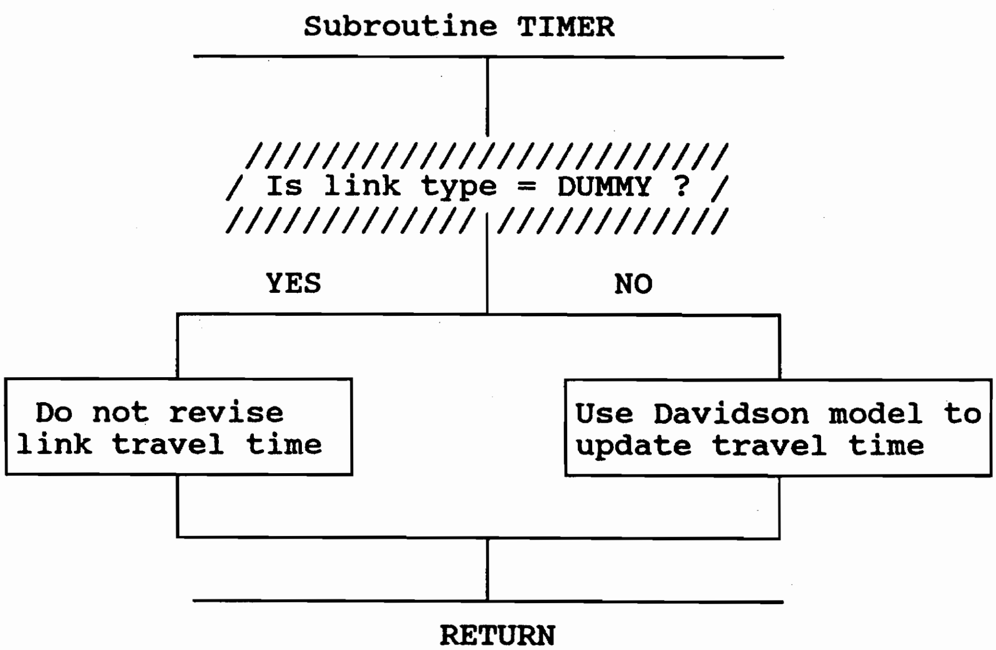
Assign Link Likelihood to all links
Blocked links get zero likelihood

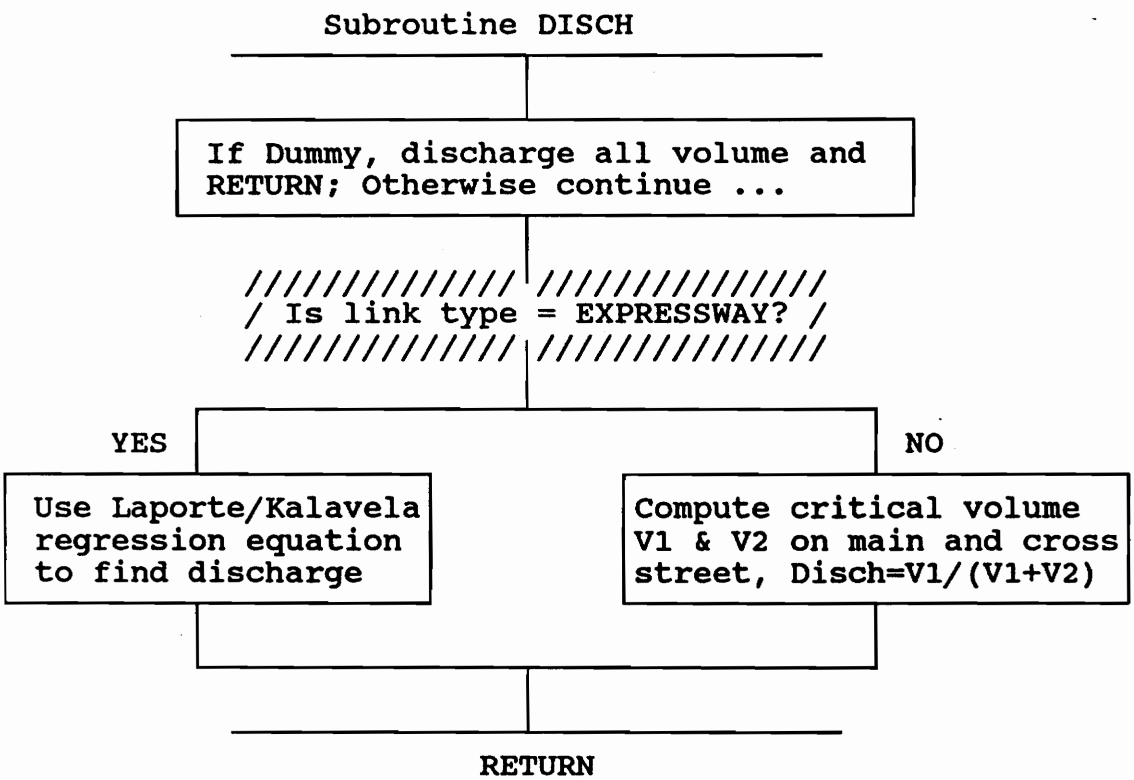
Call QSORT to sort all nodes in ascending order of shortest path labels

FORWARD PASS : Assign "weights" to feeding links of every node in network beginning with closest node

BACKWARD PASS : Beginning with the furthest destination, assign trips to feeding links of all nodes

RETURN


Subroutine TIMER
/ Is link type = DUMMY ? /
YES
NO
Do not revise link travel time
Use Davidson model to update travel time
RETURN


Subroutine DISCH
If Dummy, discharge all volume and RETURN; Otherwise continue ...
/ Is link type = EXPRESSWAY? /
YES
NO
Use Laporte/Kalavela regression equation to find discharge
Compute critical volume V1 & V2 on main and cross street, Disch=V1/(V1+V2)
RETURN

Subroutine GEODIT

Depending on user-choice, implement one of the Geometric Destination Elimination Techniques - Quadrant, 3-Quadrant or Halfspace method to convert the shortest path labels of infeasible destinations to infinity

RETURN

Subroutine TTDIT

Depending on user choice, implement one of the travel time selection methods to choose exits from the feasible set identified by GEODIT

Apply the Travel Time Impedance to distribute trip production from origin to chosen exit pts

RETURN

Subroutine EVAC1

Call ODTAB subroutine to estimate trip production and distribution

Call SYSIN subroutine to stop if all trips are cleared; Otherwise proceed

Call DIAL subroutine to derive link flows from trip ends given by ODTAB

Call TIMER to update link travel time based on link type and current flow

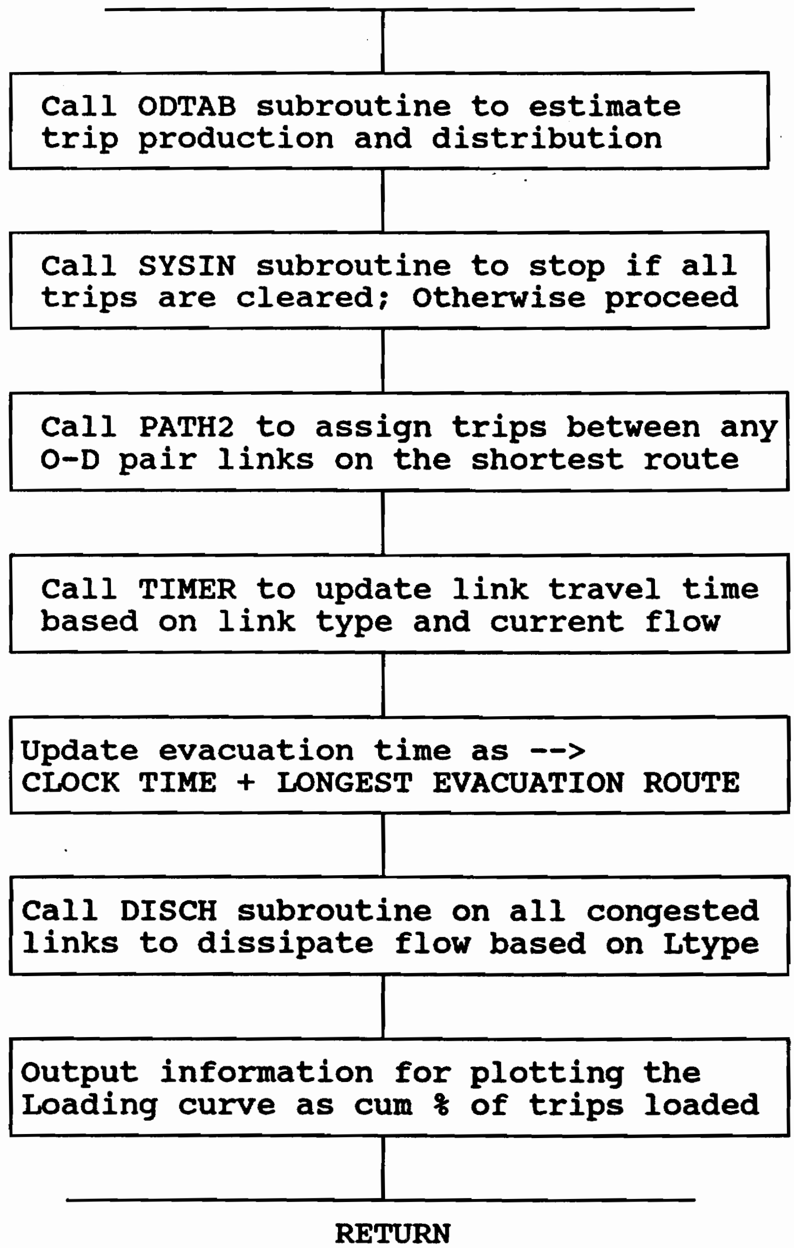
Call PATH subroutine to trace out paths and update evacuation time as --> CLOCK TIME + LONGEST EVACUATION ROUTE

Call DISCH subroutine on all congested links to dissipate flow based on Ltype

Output information for plotting the Loading curve as cum % of trips loaded

RETURN

Subroutine EVAC2



Subroutine PATH2

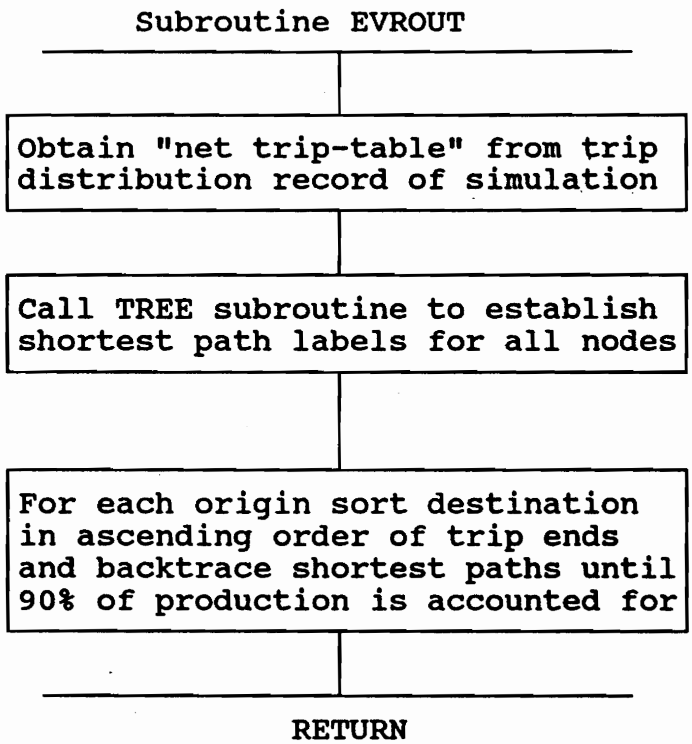
For the O-D pair passed as arg, backtrace shortest path and assign the corresponding trip end

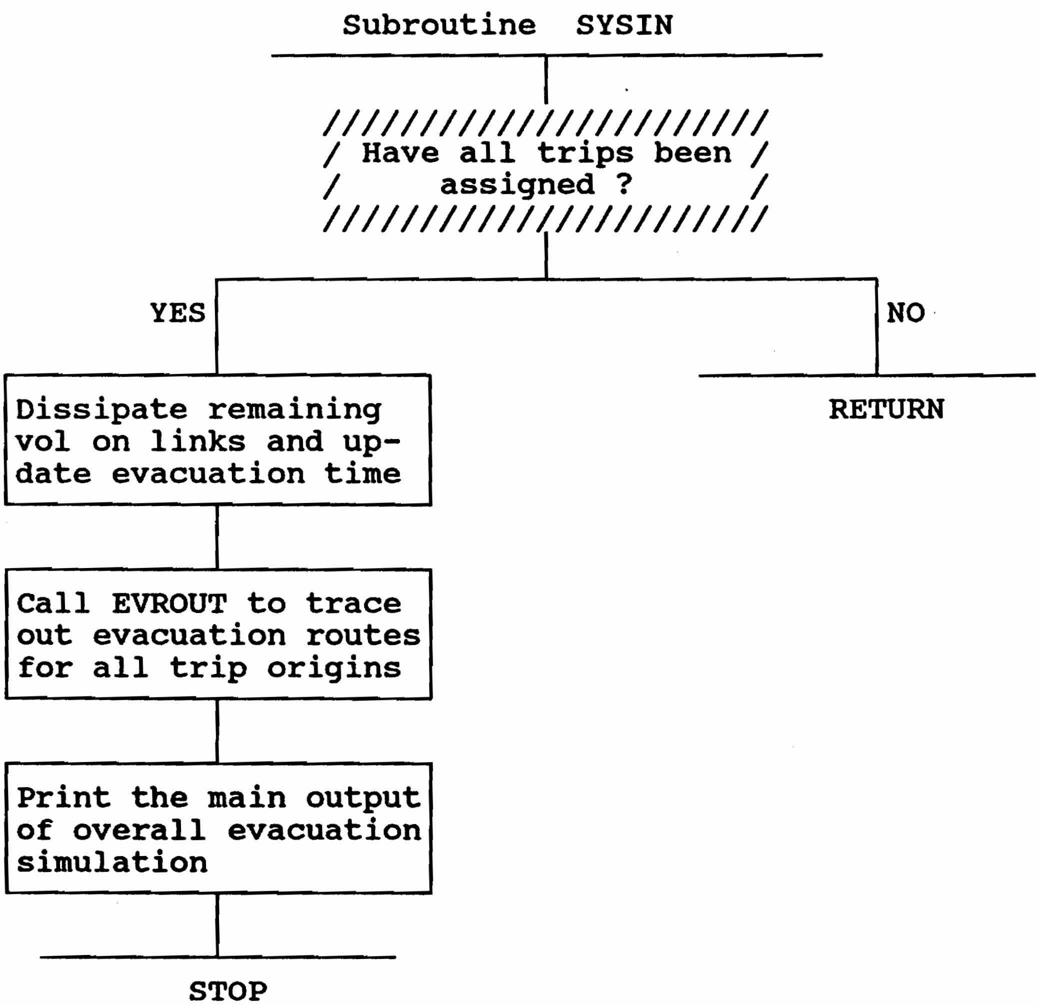
RETURN

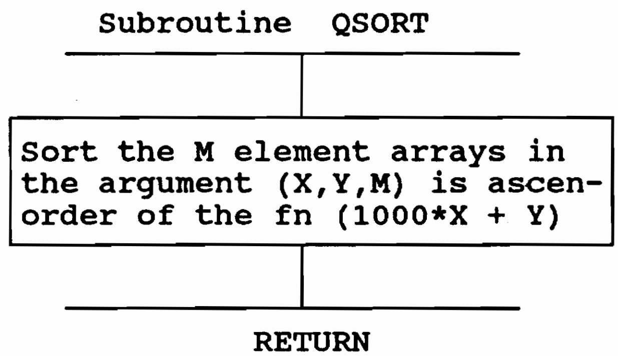
Subroutine PATH

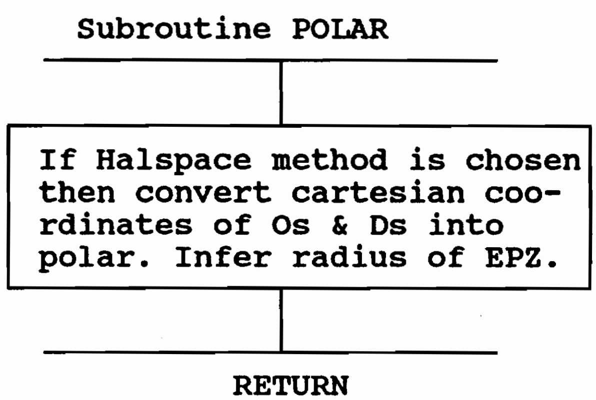
For the O-D pair passed as arg, identify upto 20 paths with a maximum of 25 links each

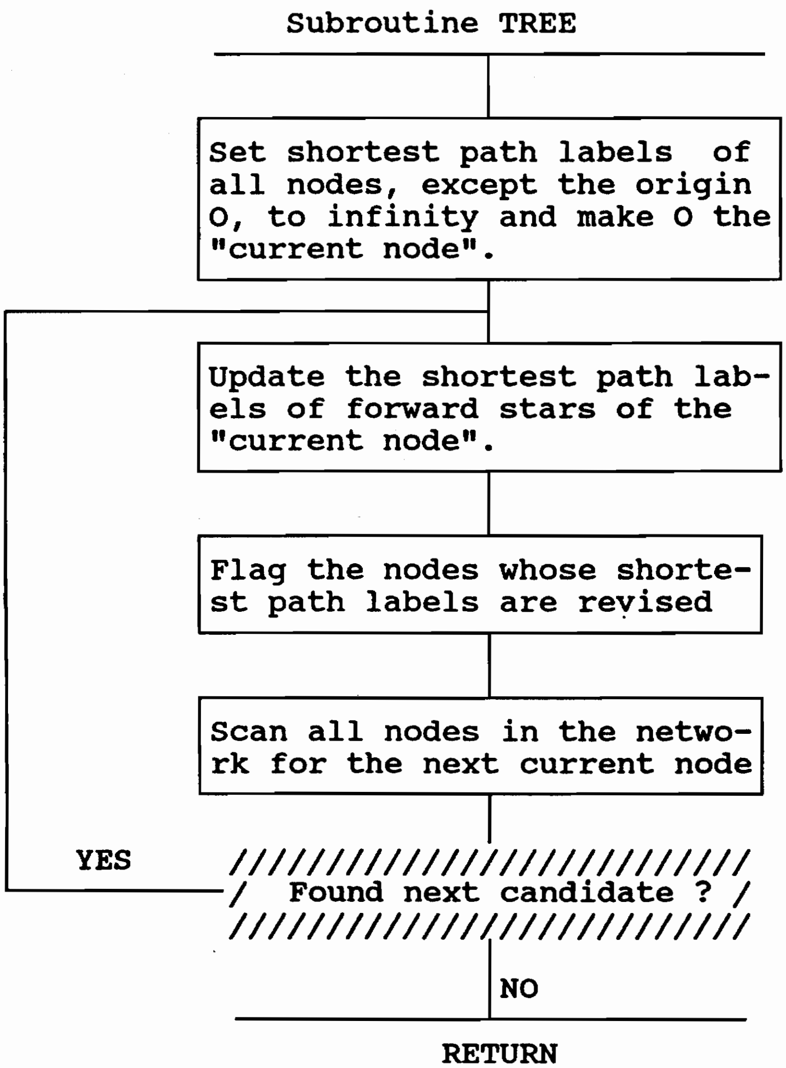
RETURN


Subroutine EVROUT
Obtain "net trip-table" from trip distribution record of simulation
Call TREE subroutine to establish shortest path labels for all nodes
For each origin sort destination in ascending order of trip ends and backtrace shortest paths until 90% of production is accounted for
RETURN


Subroutine SYSIN
Have all trips been assigned ?
YES
NO
RETURN
Dissipate remaining vol on links and up-date evacuation time
Call EVROUT to trace out evacuation routes for all trip origins
Print the main output of overall evacuation simulation
STOP


Subroutine QSORT
Sort the M element arrays in the argument (X,Y,M) is ascen-order of the fn (1000*X + Y)
RETURN


Subroutine POLAR
If Halspace method is chosen then convert cartesian coo-rdinates of Os & Ds into polar. Infer radius of EPZ.
RETURN


Subroutine TREE
Set shortest path labels of all nodes, except the origin O, to infinity and make O the "current node".
Update the shortest path labels of forward stars of the "current node".
Flag the nodes whose shortest path labels are revised
Scan all nodes in the network for the next current node
YES
Found next candidate ?
NO
RETURN

Appendix B. Sample Input

Complete input for the Surry (South) 10-mile EPZ is shown in this section to illustrate the formats of input files used by MASSVAC.

B.1 Links File (LS)

The first record of the file contains the highest detination node number and the highest origin node number. The numbers in the second record denote simulation interval (min), half loading time (min) and Dial exponent respectively. The integers on line 3 are flag values to trigger various options in MASSVAC - IGEO, ITT, ISEED, IDESID, IASSGN, IWEATH, ISHLD, IFLASH (see Appendix B : Variable Description). Line # 4 contains the name of the file containing trip production from all origins (maximum length = 25 characters).

All lines from line # 5 onwards represent one link in the network. MASSVAC's network is stored in the standard arc-oriented format in which the newtork is represented as a list of links. Each line is **link record** reprtesenting a single, one-way link in the highway network. Each link record consists of link attributes in the following order : zone number, beginning node (A-node), ending node (B-node), Downstream node, link length (miles), capacity (VPH/lane), number of lanes, free-flow speed, link type, AADT and link name (25 characters).

```
11 24
15.  45.  1.50
 2 3 1 0 1 0 0 0
jklm.veh
 13   1 146 147 1.71  1000  1  55  2  2137 Route 10 from 677 to 621
 13   2 147 148 2.50  1000  1  45  2    11 Route 673 from 677 to 621
 13   3 148 149 1.70  1000  1  45  3   121 Route 627 from 626 to 621
 11   4 148   3 2.60  1000  1  45  3    45 Route 621 from 626 to 627
  7   5 187   6 3.29  1000  1  55  2    70 Route 626 from 617 to 616
 10   5 159 160 5.69  1000  1  50  2   198 Route 617 from 626 to 10
  7   6 187 186 2.10  1000  1  45  2    60 Route 616 from 622 to 626
  3   7 197   8 0.69  1000  1  45  2   155 Route 622 from 644 to 31
  3   8 197 196 1.00  1000  1  60  2  1052 Route 31 from 644 to 622
  2   9 198 199 2.30  1000  1  55  2    39 Route 618 from 10 to 626
  2   9 196 197 2.58  1000  1  55  2  1892 Route 10 from 618 to 31
  2  10 208  11 0.60  1000  1  55  2    39 Route 610 from 609 to 626
  2  11 208  10 0.70  1000  1  45  2   108 Route 626 from 609 to 610
  1  12 193   0 0.00  9999  1  60  5     0 Dummy Connector
  2  13 204   0 0.00  9999  1  60  5     0 Dummy Connector
  2  13 200   0 0.00  9999  1  60  5     0 Dummy Connector
  3  14 182   0 0.00  9999  1  60  5     0 Dummy connector
  4  15 179   0 0.00  9999  1  60  5     0 Dummy Connector
  4  15 180   0 0.00  9999  1  60  5     0 Dummy Connector
  5  16 175   0 0.00  9999  1  60  5     0 Dummy Connector
  5  16 174   0 0.00  9999  1  60  5     0 Dummy Connector
  6  17 159   0 0.00  9999  1  60  5     0 Dummy Connector
  7  18 172   0 0.00  9999  1  60  5     0 Dummy Connector
  8  19  25   0 0.00  9999  1  60  5     0 Dummy Connector
  9  20 262   0 0.00  9999  1  60  5     0 Dummy Connector
  9  20 155   0 0.00  9999  1  60  5     0 Dummy Connector
 10  21 158   0 0.00  9999  1  60  5     0 Dummy Connector
 10  21 159   0 0.00  9999  1  60  5     0 Dummy Connector
 11  22 148   0 0.00  9999  1  60  5     0 Dummy Connector
```

```
12  23 156   0 0.00  9999  1  60  5     0 Dummy Connector
13  24 151   0 0.00  9999  1  60  5     0 Dummy Connector
 8  25 163 161 1.65  1000  1  50  2  1817 Route 650 from sps to zb9
13 146 147 148 1.80  1000  1  45  2   208 Route 621 from 10 to 673
13 146 151 150 1.57  1000  1  55  2  2137 Route 10 from 621 to 676
13 146   1   0 1.71  1000  1  55  2  2137 Route 10 from 621 to 677
13 147 148   4 1.40  1000  1  45  3   127 Route 621 from 673 to 627
13 147 146   1 1.80  1000  1  45  2   208 Route 621 from 673 to 10
13 147   2   0 2.50  1000  1  45  2    11 Route 673 from 621 to 677
13 148   3   0 1.70  1000  1  45  2   121 Route 627 from 621 to 626
13 148 149 156 1.10  1000  1  45  2    53 Route 627 from 621 to CL
11 148   4   0 2.60  1000  1  45  3    45 Route 621 from 627 to 626
13 148 147   2 1.40  1000  1  45  2   127 Route 621 from 627 to 673
13 149 148   3 1.10  1000  1  45  2    53 Route 627 from cl to 621
12 149 156 155 3.10  1000  1  45  2    68 Route 627 from CL to 10
13 150 151 146 0.51  1000  1  55  2  2137 Route 10 from cl to 676
 9 150 156 157 1.07  1000  1  55  2  1892 Route 10 from cl to 627
13 151 150 156 0.51  1000  1  55  2  2137 Route 10 from 676 to cl
13 151 153 154 0.74  1000  1  45  2  1388 Route 676 from 10 686
13 151 146   1 1.57  1000  1  55  2  2137 Route 10 from 676 to 621
13 152 153 154 0.80  1000  1  45  2   422 Route 686 from END to 676
 9 153 262   0 0.92  1000  1  45  2    40 Route 676 from 686 to END
 9 153 154 155 0.40  1000  1  45  2   946 Route 686 from 676 to cl
13 153 151 150 0.74  1000  1  45  2  1388 Route 676 from 686 to 10
13 153 152   0 0.80  1000  1  45  2   422 Route 686 from 676 to END
 9 154 155 156 0.38  1000  1  45  2   798 Route 628 from cl to 627
 9 154 153 151 0.40  1000  1  45  2   946 Route 628 from cl to 676
 9 155 156 150 1.20  1000  1  45  2    83 Route 627 from 628 to 10
 9 155 154 153 0.38  1000  1  45  2   798 Route 628 from 627 to cl
 9 155 162 161 1.42  1000  1  45  2  1255 Route 628 from 627 to 650
 9 156 150 151 1.07  1000  1  55  2  1892 Route 10 from 627 to cl
 9 156 155 154 1.20  1000  1  45  2    83 Route 627 from 10 to 628
 9 156 157 159 1.11  1000  1  55  2  1892 Route 10 from 627 to 650
12 156 149 148 3.10  1000  1  45  2    68 Route 627 from 10 to cl
10 157 158   0 1.20  1000  1  45  2    29 Route 650 from 10 to End
 9 157 156 150 1.11  1000  1  55  2  1892 Route 10 from 650 to 627
```

```
10 157 159 170 1.02  1000  1  55  2  1892 Route 10 from 650 to 617
 9 157 162 161 1.25  1000  1  45  2   306 Route 650 from 10 to 628
10 158 157 159 1.20  1000  1  45  2    29 Route 650 from end to 10
 6 159 170 171 0.95  1000  1  55  2  1892 Route 10 from 617 to 634
10 159 157 156 1.02  1000  1  55  2  1892 Route 10 from 617 to 650
10 159   5   0 5.69  1000  1  50  2   198 Route 617 from 10 to 626
 6 159 160 161 1.15  1000  1  50  2   894 Route 617 from 10 to 628
 6 160 159 170 1.15  1000  1  50  2   894 Route 617 from 628 to 10
 6 160 161 162 0.15  1000  1  50  2   718 Route 617 from 628 to 650
 6 160 162 161 0.10  1000  1  45  2   208 Route 628 from 617 to 650
 9 161 162 157 0.13  1000  1  45  2  1278 Route 650 from 617 to 628
 9 161 163 164 2.95  1000  1  50  2  1817 Route 650 from 617 to ZB9
 6 161 160 162 0.15  1000  1  50  2   718 Route 617 from 650 to 628
 9 162 155 154 1.42  1000  1  45  2  1255 Route 628 from 650 to 627
 9 162 157 159 1.25  1000  1  45  2   306 Route 650 from 628 to 10
 9 162 161 160 0.13  1000  1  45  2  1278 Route 650 from 628 to 617
 6 162 160 159 0.10  1000  1  45  2   208 Route 628 from 650 to 617
 9 163 161 162 2.95  1000  1  50  2  1817 Route 650 from ZB9 to 617
 8 163  25   0 1.65  1000  1  50  2  1817 Route 650 from ZB9 to SPS
 6 165 166 168 0.07  1000  1  35  2     4 Route 633 from JR to 658
 6 166 168 169 1.52  1000  1  35  2    58 Route 633 from 658 to 634
 6 166 165   0 0.07  1000  1  35  2     4 Route 633 from 658 to JR
 5 166 167 175 1.95  1000  1  45  2    22 Route 658 from 633 to 634
 5 167 168 169 0.96  1000  1  35  2   224 Route 634 from 658 to 633
 5 167 175 184 1.29  1000  1  35  2   182 Route 634 from 658 to 637
 5 167 166 168 1.95  1000  1  45  2    22 Route 658 from 634 to 633
 6 168 166 165 1.52  1000  1  35  2    58 Route 633 from 634 to 658
 5 168 167 175 0.96  1000  1  35  2   224 Route 634 from 633 to 658
 6 168 169 171 0.20  1000  1  35  2   190 Route 633 from 634 to 634
 6 169 170 159 1.20  1000  1  45  2   225 Route 634 from 633 to 10
 6 169 168 167 0.20  1000  1  35  2   190 Route 633 from 634 to 634
 6 169 171 172 1.80  1000  1  35  2    80 Route 633 from 634 to 10
 6 170 169 168 1.20  1000  1  45  2   225 Route 634 from 10 to 633
 6 170 171 172 1.52  1000  1  55  2  1892 Route 10 from 634 to 633
 6 170 159 157 0.95  1000  1  55  2  1892 Route 10 from 634 to 617
 6 171 169 168 1.80  1000  1  35  2    80 Route 633 from 10 to 634
```

5	171	172	186	0.47	1000	1	55	2	1892 Route 10 from 633 to 616
6	171	170	159	1.52	1000	1	55	2	1892 Route 10 from 633 to 634
5	172	171	170	0.47	1000	1	55	2	1892 Route 10 from 616 to 633
7	172	186	187	1.40	1000	1	45	2	143 Route 616 from 10 to 632
5	172	173	185	0.57	1000	1	55	2	1892 Route 10 from 616 to 635
5	173	174	0	1.20	1000	1	45	2	55 Route 635 from 10 to END
5	173	172	171	0.57	1000	1	55	2	1892 Route 10 from 635 to 616
5	173	185	183	1.10	1000	1	55	2	1892 Route 10 from 635 to 632
5	174	173	172	1.20	1000	1	45	2	55 Route 635 from End to 10
5	175	176	177	0.93	1000	1	55	2	110 Route 637 from 634 to 636
5	175	184	183	1.10	1000	1	45	2	182 Route 634 from 637 to 636
5	175	167	168	1.29	1000	1	35	2	182 Route 634 from 637 to 658
5	176	177	178	0.87	1000	1	55	2	365 Route 636 from 637 to 637
5	176	175	184	0.93	1000	1	55	2	110 Route 637 from 636 to 634
5	176	184	183	1.27	1000	1	55	2	198 Route 636 from 637 to 634
4	177	179	202	0.86	1000	1	55	2	110 Route 637 from 636 to ZB4
5	177	176	184	0.87	1000	1	55	2	365 Route 636 from 637 to 637
5	177	178	0	0.32	1000	1	55	2	60 Route 636 from 637 to JR
5	178	177	176	0.32	1000	1	55	2	60 Route 636 from JR to 637
4	179	177	176	0.86	1000	1	55	2	110 Route 637 from ZB4 to 636
4	179	202	201	0.66	1000	1	55	2	145 Route 637 from ZB4 to 31
4	180	181	182	1.34	1000	1	45	2	102 Route 638 from End to 10
4	181	180	0	1.34	1000	1	45	2	102 Route 638 from 10 to END
4	181	182	183	0.27	1000	1	45	2	1892 Route 10 from 638 to 634
4	181	190	193	0.67	1000	1	45	2	1892 Route 10 from 638 to ZB1
4	182	183	185	0.12	1000	1	55	2	1892 Route 10 from 634 to 634
4	182	181	190	0.27	1000	1	45	2	1892 Route 10 from 634 to 638
3	182	188	187	1.50	1000	1	45	2	140 Route 634 from 10 to 626
5	183	185	186	0.57	1000	1	55	2	1892 Route 10 from 634 to 632
4	183	182	188	0.12	1000	1	55	2	1892 Route 10 from 634 to 634
4	183	184	175	1.40	1000	1	45	2	422 Route 634 from 10 to 636
5	184	176	177	1.27	1000	1	55	2	198 Route 636 from 634 to 637
4	184	183	185	1.40	1000	1	45	2	422 Route 634 from 636 to 10
5	184	175	167	1.10	1000	1	45	2	182 Route 634 from 636 to 637
3	185	186	187	1.59	1000	1	45	2	102 Route 632 from 10 to 616
5	185	173	172	1.10	1000	1	55	2	1892 Route 10 from 632 to 635

```
5 185 183 182 0.57  1000  1  55  2  1892 Route 10 from 632 to 634
3 186 185 183 1.59  1000  1  45  2   102 Route 632 from 616 to 10
7 186 172 171 1.40  1000  1  45  2   143 Route 616 from 632 to 10
7 186 187   6 1.60  1000  1  45  2   170 Route 616 from 632 to 626
7 187 186 172 1.60  1000  1  45  2   170 Route 616 from 626 to 632
7 187   6   0 2.10  1000  1  45  2    60 Route 616 from 626 to 622
7 187   5   0 3.29  1000  1  55  2    70 Route 626 from 616 to 617
3 187 188 189 2.40  1000  1  55  2    80 Route 626 from 616 to 634
3 188 182 183 1.50  1000  1  45  2   140 Route 634 from 626 to 10
3 188 187   5 2.40  1000  1  55  2    80 Route 626 from 634 to 616
3 188 189 194 1.01  1000  1  55  2   120 Route 626 from 634 to ZB!
1 189 194 195 0.35  1000  1  45  2   272 Route 626 from ZB1 to 31
3 189 188 187 1.01  1000  1  55  2   120 Route 626 from ZB1 to 634
4 190 181 182 0.67  1000  1  45  2  1892 Route 10 from ZB1 to 638
1 190 193 192 0.64  1000  1  45  2  1892 Route 10 from ZB1 to 31
1 191 193 194 0.41  1000  1  45  2  1160 Route 31 from ZB1 to 10
4 191 201 200 0.61  1000  1  50  2  1160 Route 31 from ZB1 to 620
1 192 193 194 0.42  1000  1  45  2   963 Route 626 from ZB1 to 31
2 192 200 199 1.41  1000  1  45  2   700 Route 626 from ZB1 to 620
1 193 192 200 0.42  1000  1  45  2   963 Route 626 from 31 to ZB1
1 193 194 195 0.57  1000  1  45  2  1160 Route 31 from 10 to 626
1 193 191 201 0.41  1000  1  45  2  1160 Route 31 from 10 to ZB1
1 193 190 181 0.64  1000  1  45  2  1892 Route 10 from 31 to ZB1
1 194 195 196 0.15  1000  1  45  2  1160 Route 31 from 626 to ZB1
1 194 189 188 0.35  1000  1  45  2   272 Route 626 from 31 to ZB1
1 194 193 191 0.57  1000  1  45  2  1160 Route 31 from 626 to 10
3 195 196 197 0.41  1000  1  45  2  1160 Route 31 from ZB1 to 10
1 195 194 193 0.15  1000  1  45  2  1160 Route 31 from ZB1 to 626
2 196   9   0 2.58  1000  1  55  2  1892 Route 10 from 31 to 618
3 196 195 194 0.41  1000  1  45  2  1160 Route 31 from 10 to ZB1
3 196 197   8 1.35  1000  1  60  2  1052 Route 31 from 10 to 622
3 197   7   0 0.69  1000  1  45  2   155 Route 622 from 31 to 644
3 197   8   0 1.00  1000  1  60  2  1052 Route 31 from 622 to 644
3 197 196 195 1.35  1000  1  60  2  1052 Route 31 from 622 to 10
2 198 199 206 0.40  1000  1  55  2   132 Route 618 from 626 to 626
2 198   9   0 2.30  1000  1  55  2    39 Route 618 from 626 to 10
```

2 198 208 10 3.96 1000 1 55 2 98 Route 626 from 618 to 610

2 199 200 201 0.93 1000 1 45 2 189 Route 626 from 618 to 620

2 199 206 205 1.00 1000 1 55 2 61 Route 618 from 626 to 640

2 199 198 9 0.40 1000 1 55 2 132 Route 618 from 626 to 626

2 200 192 193 1.41 1000 1 45 2 700 Route 626 from 620 to ZB!

2 200 199 198 0.93 1000 1 45 2 189 Route 626 from 620 to 618

2 200 201 191 1.20 1000 1 45 2 47 Route 620 from 626 to 31

4 201 202 203 4.00 1000 1 60 2 1160 Route 31 from 620 to 637

2 201 200 199 1.20 1000 1 45 2 47 Route 620 from 31 to 626

4 201 191 193 0.61 1000 1 50 2 1160 Route 31 from 620 to ZB1

4 202 203 0 0.25 1000 1 40 2 1160 Route 31 from 637 to JAMES

4 202 201 191 4.00 1000 1 60 2 1160 Route 31 from 637 to 620

4 202 179 177 0.66 1000 1 55 2 145 Route 637 from 31 to ZB4

4 203 202 201 0.25 1000 1 40 2 1160 Route 31 from JAMES to 637

2 204 205 208 2.94 1000 1 45 2 16 Route 610 from END to 618

2 205 206 199 1.00 1000 1 55 2 62 Route 618 from 610 to 640

2 205 208 10 4.40 1000 1 55 2 40 Route 610 from 618 to 626

2 205 204 0 2.94 1000 1 45 2 16 Route 610 from 618 to END

2 206 205 208 1.00 1000 1 55 2 62 Route 618 from 640 to 610

2 206 207 0 1.05 1000 1 45 2 7 Route 640 from 618 to END

2 206 199 198 1.00 1000 1 55 2 61 Route 618 from 640 to 626

2 207 206 205 1.05 1000 1 45 2 7 Route 640 from END to 618

2 208 198 9 3.96 1000 1 55 2 98 Route 626 from 610 to 618

2 208 11 0 0.70 1000 1 45 2 108 Route 626 from 610 to 609

2 208 205 199 4.40 1000 1 55 2 40 Route 610 from 626 to 618

2 208 10 0 0.60 1000 1 55 2 39 Route 610 from 626 to 609

9 262 153 151 0.92 1000 1 45 2 40 Route 676 from END to 686

B.2 Trip production

Trip production at 13 origins contained in file JKLM.VEH (see line # 4 in the section on links file. Format used is 10F6.0.

```
 275. 460. 413. 302. 317. 238. 366. 466. 168. 178.
  97.  77. 774.
```

B.3 Coordinates of Destination and Origins

The cartesian coordinates of destinations and origins in the format 2F5.1 contained in file XY.

```
163.0 56.0
162.0 54.0
131.0 44.0
108.0 49.0
 91.0 63.0
 59.0 80.0
 59.0 88.0
 52.0 90.0
 40.0108.0
 12.0134.0
 16.0139.0
 72.0111.0
 78.0131.0
 79.0 97.0
 89.0119.0
107.0108.0
130.0101.0
100.0 84.0
```

149.0122.0

148.0 96.0

118.0 77.0

125.0 59.0

137.0 73.0

149.0 70.0

144.0124.0

Appendix C. Sample Outputs

C.1 Trip Table (ODTAB.OUT)

This file contains the Trip table for the entire simulation as shown below. Each line (record) in the file contains information on a single O-D pair. For brevity, the O-D pair with zero trip ends are not printed. The numbers in each line represent the iteration number, clock time, origin number, destination number, number of trips, travel time used in trip distribution equation and shortest path label of the destination in the current iteration.

```
2   30   21   1    6.0310    14.53146    14.53146
```

The sample record (one line of ODTAB.OUT) above shows that second iteration of simulation (clock=30), a trip end of 6.0310 vehicles was establish from origin # 21 to destination # 1. The travel time to the destination is same as its shortest path label in the current iteration i.e., 14.53146.

C.2 Link characteristics

Each record of the files showing link characterics contain the total volume, total seed volume and AADT on a single link on the network.

146 1 1015.125 131.749 2137.000

Sample record : the link (146 - 1) carries 1015 trips during evacuation of which seed volume is 132. The AADT inputted for this link was 2137.

The output for is link characteristics are in two categories - used link (LINKCHAR.OUT) and unused links (UNUSEDL.OUT).

C.3 Congestion (CONGEST.OUT)

Each record contains the A-node, B-node, Beginning time and ending time of congestion on a link experiencing over-capacitation during simulation. Times are expressed in minutes elapsed after beginning of loading. Each record represents one continuous time period of congestion. If the link was congested during n different time intervals of simulation, then this file will have n records for that link.

129	5	180	210
130	123	180	225

133	135	90	180
134	6	45	75
134	6	90	135
134	6	150	165
134	6	180	210
134	130	180	210
134	133	90	105

Above, the link (134 - 6) is congested during four intervals of simulation, (at clock = 45 to 75, 90 to 135, 150 to 165 and 180 to 210).

C.4 Evacuation Routes (EVROUT.OUT)

Contains information for plotting of evacuation routes by TEDSS. Each evacuation route consists of two records. The first contains the Origin and Destination which the path connect along with trips (expressed also as % of total production). The second record is the backward trace of the evacuation route from the destination to the origin.

```
13   9   183. 41.94
 9 198 199 200  13
```

The evacuation route for the O-D pair (13 - 9) as having 183 trip, representing 41.94% of total production (record # 1). The evacuation route is expressed as the backward sequence of the nodes 9, 198, 199, 200, and 3.

C.5 Updating Evacuation Times (EVACTIME.OUT)

This file is an expanded verion of the screen output showing the network clearance time being updated during each iteration. Each record contains the updated evacuation time, clock time, the Origin, destination and the number of the specific path responsible for updating evacuation time, the length of and the flow on that path.

```
25.990   15  13   7   1  10.990    123.332
```

In the example, the updated evacuation time at some point in the iteration Clock = 15 is 25.990. This is due to path # 1 between O-D pair 15-13. The length of that path is 10.990 min (15 + 10.99 = 25.99) and the flow is 123.332.

C.6 Trip Blocking (HOLD.OUT)

This file shows the number of trips blocked at any node by Dial's algorithm due to congestion. It shows the origin from which the trips started and the % of total trip production that the blocked vehicles represent. The sample record shown below is self-explanatory.

CLOCK= 45 59.51 TRIPS BLOCKED AT NODE 3 (O: 21 % = .0896)

C.7 Trip Loading (LOADING.OUT)

This file contains information for plotting the loading curve. Each record of this file contains the clock time and % of trips loaded at the of an iteration.

75 55.224

90 62.322

Two records of the file are shown above. Thus 55.224% of total trips produced by clock time = 75 and 62.322% was loaded by clock = 90.

C.8 Summary of Results (SUMMARY.OUT)

This file contains : network clearance time, simulation interval and half loading time used, total vehicle travel time, network clearance time if 20% trips are loaded prior to beginning of simulation. This information is passed to TEDSS where it is displayed in words to the user.

C.9 Net Trip Table (TRIP.OUT)

This file is basically as summation of information contained in ODTAB.OUT over all iterations. It contains the trip table resulting from overall simulation with destinations sorted (for each origin) in descending order of trip received. Below, each record represents origin #, destination # and trips.

21	6	2467.
21	2	1917.
21	7	1813.
21	4	1622.
21	5	1484.
21	1	1480.
21	3	1423.
21	17	0.
21	16	0.
21	15	0.
21	14	0.

21	13	0.
21	12	0.
21	11	0.
21	10	0.
21	9	0.
21	8	0.
22	6	27263.
22	7	26030.
22	2	10725.
22	4	9597.
22	5	8964.
22	3	8664.
22	1	8564.
22	17	0.
22	16	0.
22	15	0.
22	14	0.
22	13	0.
22	12	0.
22	11	0.
22	10	0.
22	9	0.
22	8	0.

The structure of this file for origins 21 and 22. This file is created and used in EVROUT for determining the destinations which receive highest trips from an origin. Evacuation routes are traced out for destinations accounting for 90% of trip distribution.

Vita

Uday Shankar Kari was born in Madras, India on December 25, 1966. He lived in a number of places in India owing to his father's army postings until he joined Birla Institute of Technology and Science, Pilani, India in August 1983 where he received a Bachelor of Engineering (Honours) degree in Civil Engineering in July 1987. He worked as marketing executive with a computer firm in Hyderabad, before coming to the U.S. in August 1988 to join the graduate program in Civil Engineering (Transportation) at Virginia Tech. He completed all requirements for the Master of Science degree in Civil Engineering in April 1990. Kari has specialized in Transportation Modeling and Planning with a strong orientation toward Computer Applications and Operations Research.