

Run Run Shaw Library

香港城市大學
City University of Hong Kong

Copyright Warning

Use of this thesis/dissertation/project is for the purpose of private study or scholarly research only. ***Users must comply with the Copyright Ordinance.***

Anyone who consults this thesis/dissertation/project is understood to recognise that its copyright rests with its author and that no part of it may be reproduced without the author's prior written consent.

A DYNAMIC NETWORK FLOW OPTIMIZATION FOR LARGE-SCALE EMERGENCY EVACUATION

LIN PENG

DOCTOR OF PHILOSOPHY

CITY UNIVERSITY OF HONG KONG

JANUARY 2006

CITY UNIVERSITY OF HONG KONG

香港城市大學

A DYNAMIC NETWORK FLOW OPTIMIZATION FOR LARGE-SCALE EMERGENCY EVACUATION

災時區域性疏散的動態網絡流最優化研究

Submitted to

Department of Building and Construction

建築系

in Partial Fulfillment of the Requirements

for the Degree of Doctor of Philosophy

哲學博士學位

by

Lin Peng

林鵬

January 2006

二零零六年一月

Abstract

The cities in Mainland China and Hong Kong are densely populated. Serious natural or man-made disasters, such as nuclear plant accident, floods, tsunami, wildfire, leakage of toxic gases, tornadoes, earthquake or war may cause huge lost of lives and properties. Evacuation from the hazardous region(s) is commonly used to migrate the ill effects of such disasters. It serves as the last defensive line to protect people by evacuating them from the affected areas so as to reduce the casualties. Despite its importance, the study of evacuation process is still inadequate because it is impossible to perform drill exercise to evaluate the evacuation efficiency. With the recent development of digital computer, some computer programs, such as the MASSVAC, have been developed to evaluate the evacuation plan. However, such programs are mainly concentrated on transportation aspects and in particular the optimization of the traffic system. The evacuation process indeed involves the movement of people and vehicles. A comprehensive study on people and vehicle evacuation is of vital importance. Accordingly, the major objectives of the study are to establish an integrated system for managing large-scale evacuation of densely populated regions by integrating simulation models, visualization tools, GIS, and optimization algorithm.

Firstly, a competitive random walker model has been established by taking into account the cooperative behavior of bi-direction pedestrian flow and uncooperative behavior of evacuees under high time stress. The model has been adopted to simulate the evacuation of a subway and an interesting and counter-

intuitive phenomenon, known as the Braess's Paradox, has been observed in the people's moving network.

Secondly, a capacity constrained evacuation model (CCEM), based on the queue model has been established on a GIS platform to model a regional traffic evacuation. It provides a cost-effective way to evaluate the evacuation planning in real time application. An iterative assignment has been implemented in the model to allocate the evacuees to the quasi-optimal routes.

Thirdly, a time-varying quickest flow problem (TVQFP), based on dynamic network flow, has been developed to optimize the evacuation plan. This algorithm can be adopted to optimize the evacuation shelters, evacuation routes and evacuation schedule simultaneously. It can effectively simulate the effect of unconstrained (unlimited capacity) and constrained (limited capacity) shelters – temporary safe places.

Finally, a hybrid evacuation model, integrating the dynamic network flow optimization approach and simulation, has been established in this study. The optimization model was used to optimize the evacuation routes, schedules, and shelters. The simulation model took the optimized strategies and provided a description about the evacuation behavior under emergency situations. The hybrid model made full use of the advantages of both simulation-based model and dynamic network flow based optimization model.

Acknowledgements

I would like to express my appreciation to a number of individuals who helped make this research possible. In particular, I would like to express my sincere thanks to my advisor, Dr. S. M. Lo, who has always been inspiring and generous in sharing his insights, thoughts and experience with me. He has provided brilliant guidance, encouragement and support and I give my heartfelt thanks to him.

I am also grateful to Dr. L. Chen for his direction and encouragement throughout my studies, and to Dr. K.K. Yuen, Dr. Z. Fang and Dr. W.S. Zhang, who provided valuable suggestions and guidance for my research.

I am indebted to C.M. Zhao and H.C. Huang for providing valuable suggestions on the manuscript of this dissertation.

Finally, I would like to thank my wife, Ling, and my parents for all their love and support.

Contents

Abstract.....i

Acknowledgements iii

Contents iv

List of Figures.....x

List of Tables xvi

Nomenclature xvii

Chapter 1 Introduction 1

1.1 Background.....1

1.2 Emergency Planning and Emergency Traffic 2

1.3 Aims and Objectives 6

1.4 Methodologies 7

1.5 Contributions 8

1.5.1 Establishing a hybrid evacuation model.....8

1.5.2 Identifying the importance of shelter capacity on evacuation analysis 12

1.6 Outline of the Dissertation..... 13

Chapter 2 Literature Review.....14

2.1 Introduction..... 14

2.2 Macroscopic Model 16

2.2.1 Lighthill-Whitham Model 16

2.2.2 Hughes Pedestrian Flow Model 17

2.3 Microscopic Simulation Model 17

2.3.1 Continuous Models 18

2.3.2 Discrete Models 20

2.4 Mesoscopic Models 24

2.5 Emergency Traffic 25

2.5.1 Pre-Movement Time 28

2.5.2 Destination Selection 29

2.5.3 Route Selection 31

2.5.4 Development of Hazards 34

2.6 Existing Evacuation Models 36

2.7 Summary of Literature 65

Chapter 3 A Pedestrian Evacuation Model 69

3.1 Introduction 69

3.2 Random Walk Model 70

3.3 A Competitive Random Walk Model 72

3.4 Uncooperative Behavior of Crowds 76

3.5 Fundamental Diagram of the Model 79

3.6 Spatio-temporal Distribution of Escapes 81

3.7 An improved Model for Bi-direction Pedestrian Flow 89

3.8 Lane Formation and Oscillation in Bi-directional Flow..... 94

3.9 Other Aspects Considered in Evacuation Model..... 100

3.9.1 Evacuation Way-finding.....100

3.9.2 Total Evacuation Time (TET) (Klüpfel 2003).....101

3.9.3 Representation of the Evacuation Network.....102

3.10 Application to Tunnel Evacuation 103

3.10.1 Layout of the Tunnel Evacuation..... 104

3.10.2 Evacuation Scenario I..... 105

3.10.3 Evacuation Scenario II.....110

3.11 Summary 114

Chapter 4 A Capacity Constrianted Model for Regional Evacuation 116

4.1 Introduction.....116

4.2 Meso-Simulation Queue Model.....118

4.2.1 The Link Model 118

4.2.2 The Node Model 121

4.3 Simulation-based Iterative Traffic Assignments..... 129

4.3.1 Destination Selection 129

4.3.2 Route Selection Problem..... 129

4.3.3 Expansion of Evacuation Network 130

4.3.4 Simulation-based Iterative Dynamic Traffic Assignment..... 130

4.4 Evacuation Model Implementation..... 133

4.4.1 Topological Network Representation 133

4.4.2 Vehicle Types..... 135

4.4.3 Mode Choice 135

4.4.4 Traffic Demand Forecasting 135

4.4.5 Evacuation Departure Time..... 136

4.4.6 Integration of Evacuation Model with GIS 138

4.5 Structure of the GIS-based Evacuation Model 140

4.6 Comparision with Field Measurement 140

4.7 Comparision with TEVACS Model 143

4.8 Sensitivity Analysis..... 148

4.8.1 Sensitivity to Population Size..... 149

4.8.2 Sensitivity to the Evacuation Load Time..... 150

4.8.3 Sensitivity to the Closure of One Shelter 152

4.8.4 Influence of Background Traffic 154

4.9 Summary 155

Chapter 5 Evacuation Optimization in Dynamic Networks.....157

5.1 Introduction..... 157

5.2 Static Network Flow Approach..... 159

5.3 Dynamic Network Definitions..... 161

5.4 Multi-source and Multi-sink Problem (MSMSP)..... 164

5.5 Storage at Nodes 167

5.6 Constraints Imposed by Intersections..... 168

5.7 Algorithms 170

5.8 Lexicographically Time-varying Quickest Problem 174

5.9 Case I: Urban Evacuation Optimization 176

5.10 Case II: High-rising Building Evacuation 183

5.11 A MSTVQFP Approach 187

5.12 Summary 192

Chapter 6 Evacuation Planning for a City 194

6.1 Introduction 194

6.2 Shelter-route-schedule Planning 194

6.2.1 Constrained vs. Unconstrained Problem 195

6.2.2 Evacuation Schedule Problem 197

6.3 Case Study 199

6.4 Unconstrained Evacuation Problem 202

6.5 Adoption of Different Load Times (LT) 208

6.6 Constrained Evacuation Problem 121

6.7 Hybrid Evacuation Model 222

6.8 Summary 226

Chapter 7 Conclusion 228

7.1 Summary 228

7.2 Limitations and future Considerations 235

References.....238

List of Figures

Fig.1. 1 Schematic overview of research areas 4

Fig.1. 2 Methodology of the study 7

Fig.1. 3 Structure of the hybrid evacuation model 9

Fig.1. 4 Structure of the Dissertation..... 13

Fig.2. 1 Definitions and notation in the Nagel-Schreckenberg model 21

Fig.2. 2 Cellular automaton model for pedestrian movement 22

Fig.2. 3 General behavior of people in emergencies 27

Fig.2. 4 Methodology adopted in evacuation route optimization..... 35

Fig.2. 5 Classification of evacuation models..... 39

Fig.2. 6 the classification according to the level of detail 43

Fig.3. 1 Possible configurations of a walker on the square lattice 71

Fig.3. 2 More than one person choose one cell 73

Fig.3. 3 Schematic picture of room divided by many districts..... 74

Fig.3. 4 Competitive movement of persons..... 76

Fig.3. 5 Movement of pedestrians through an exit..... 77

Fig.3. 6 Flow rate per step for an orderly evacuation..... 78

Fig.3. 7 Flow rate of orderly evacuation and competitive evacuation 79

Fig.3. 8 Movement of pedestrians through a corridor under periodic conditions 80

Fig.3. 9 Relationship between pedestrian density and walking velocity..... 81

Fig.3. 10 Flow pattern of people out of a hall simulated by Nagatani's model at different simulation times..... 83

Fig.3. 11 Flow pattern of people out of a hall by our improved.....85

Fig.3. 12 Flow rate of area A and B.....87

Fig.3. 13 Cumulative output of persons at area A and B.....87

Fig.3. 14 Flow rate of area A and B.....88

Fig.3. 15 Cumulative output of persons 88

Fig.3. 16 Schematic illustration of the bi-directional flow in a channel 90

Fig.3. 17 Avoidance of collision with left walkers.....91

Fig.3. 18 Adjacent site conditions of right walkers.....91

Fig.3. 19 Lane formation for crowd density of 0.15 94

Fig.3. 20 Lane formation at crowd density 0.3.....94

Fig.3. 21 Lane formation at crowd density 0.35.....95

Fig.3. 22 Occurrence of jamming.....95

Fig.3. 23 Influence of reverse walkers on each side.....95

Fig.3. 24 Lane formation for density 0.2 with initial walkers' positions A1.....96

Fig.3. 25 lane formation for density 0.2 with initial walkers' positions A2 96

Fig.3. 26 Lane formation for density 0.2 with initial walkers' positions A3.....96

Fig.3. 27 Lane formation for density 0.2 with initial walkers' positions A4.....97

Fig.3. 28 Evolution of effective velocity with simulation steps.....98

Fig.3. 29 Unsteady lanes for density C=0.2 for t = t1 for 50 x 10 99

Fig.3. 30 Unsteady lanes for density C=0.2 for t=t2>t1 for 50 x 10 99

Fig.3. 31 Steady lanes for density C=0.2 for t = t3> t2 for 50 x 10 99

Fig.3. 32 Traffic deadlock at exit.....100

Fig.3. 33 Layout of a typical building and its topological network 103

Fig.3. 34 Schematic evacuation network of a tunnel.....104

Fig.3. 35 Topological tunnel network adopted in scenario I 106

Fig.3. 36 Comparison of evacuations of different cases.....108

Fig.3. 37 Real-time output for IDCP=60.....109

Fig.3. 38 Real-time output for IDCP=90.....109

Fig.3. 39 Real-time output for IDCP=220.....110

Fig.3. 40 Topological evacuation network adopted in scenario II.....110

Fig.3. 41 Comparison of evacuations of different cases in scenario II 112

Fig.3. 42 Comparison of evacuations in different scenarios 113

Fig.3. 43 Comparison of evacuations in different scenarios 113

Fig.3. 44 Real-time output for IDCP=60 in scenario II.....114

Fig.3. 45 Real-time output for IDCP=90 in scenario II.....114

Fig.3. 46 Real-time output for IDCP=220 in scenario II.....114

Fig.4. 1 Movement of cars along a road.....118

Fig.4. 2 Simple intersection.....120

Fig.4. 3. Influence of static capacity.....124

Fig.4. 4 the simulation flowchart for one step.....128

Fig.4. 5 Structure of simulation-based traffic assignment.....132

Fig.4. 6 Three types of integration of models with GIS.....137

Fig.4. 7 Flow-chart of iterative GIS-based evacuation model.....139

Fig.4. 8 Schematic of the urban freeway studied site.....140

Fig.4. 9 Comparison of results of model with observed data.....141

Fig.4. 10 Comparison of model results with observed data for different intervals
.....143

Fig.4. 11 Hypothetical network (extracted from Han (1990)).....145

Fig.4. 12 Evacuation process of the whole network.....145

Fig.4. 13 Number of running and loading cars.....146

Fig.4. 14 the comparison of evacuation process of two assignments.....147

Fig.4. 15 The convergence of iterations 147

Fig.4. 16 Evacuation process after 35% of increase in population 149

Fig.4. 17 Evacuation process after 90% of increase in population 149

Fig.4. 18 Difference in TET after different iterations.....151

Fig.4. 19 Cars loaded and evacuated.....152

Fig.4. 20 Cars loaded and evacuated.....153

Fig.4. 21 Comparison of results between two types of assignment 153

Fig.4. 22 Presence of background traffic.....154

Fig.5. 1 General form of evacuation problem in a static network. 161

Fig.5. 2 A simple multi-source problem 165

Fig.5. 3 Transformation of multi-source to single source 166

Fig.5. 4 Transformation of multi-sink to single sink.....167

Fig.5. 5 An expanded intersection 169

Fig.5. 6 A schematic illustration of the procedure for updating the network ...172

Fig.5. 7 The network (from Chapter 4) 177

Fig.5. 8 Evacuation process at different section capacities (10 seconds per step) 179

Fig.5. 9 Performance of TET: reverse lane strategies in use 180

Fig.5. 10 Comparison of TET under dry and flood conditions 181

Fig.5. 11 Comparison of TET obtained by using 182

Fig.5. 12 Comparison of TET by car and on foot.....182

Fig.5. 13 Comparison of TET by car and on foot.....183

Fig.5. 14. The network of building 101 (extracted from Chalmet(1982)]) 185

Fig.5. 15 The flow rate of four links.....186

Fig.5. 16 Flow rate of two links 187

Fig.5. 17 Flow rate of two links 189

Fig.5. 18 Flow rate of link 58-61 for two groups 190

Fig.5. 19 Flow rate of link 59-60 for two groups 191

Fig.5. 20 Comparison of results at link 59-60 in two algorithms 191

Fig.5. 21 Comparison of results at link 58-61 in two algorithms 192

Fig.6. 1 Simple location-allocation problem with capacity constraints 196

Fig.6. 2 GIS attribute data for evacuation planning 199

Fig.6. 3 GIS map of a City (network, population and shelters distribution) 201

Fig.6. 4 Evacuation process without capacity constraints 203

Fig.6. 5 Evacuation process for each shelter without capacity constraints 203

Fig.6. 6 Optimal load schedule for unconstrained evacuation problem 204

Fig.6. 7 Optimal evacuation routes 206

Fig.6. 8 Cumulative traffic load for each link 207

Fig.6. 9 Three actual load schedules 208

Fig.6. 10 Optimal load schedule for LT=900 and LT=2700 210

Fig.6. 11 Evacuation process with different load processes 211

Fig.6. 12 Evacuation process for capacity evacuation problem 213

Fig.6. 13 Cumulative number of cars arriving at each shelter 214

Fig.6. 14 Constrained and unconstrained evacuation problems compared. 214

Fig.6. 15 Optimal load schedule for capacity evacuation problem (LT=0) 215

Fig.6. 16 Optimal schedule for load time (LT) =900 seconds 215

Fig.6. 17 Optimal schedule for load time (LT) =1800 seconds 216

Fig.6. 18 Optimal schedule for load time (LT) =2700 seconds 217

Fig.6. 19 Comparisons of the optimal schedule for different LT 218

Fig.6. 20 Comparisons of the evacuation process for different LT 218

Fig.6. 21 Traffic loads with capacity constraints of shelters 219

Fig.6. 22 Evacuation route for the constrained evacuation scenario.....220

Fig.6. 23 Comparison of traffic load at each link for constrained problem and unconstrained problem 221

Fig.6. 24 Schematic structure of hybrid evacuation model.....223

Fig.6. 25 Evacuation process in an iterative assignment simulation.....224

Fig.6. 26 Cumulative number of cars loaded and running at each step.....224

Fig.6. 27 Comparison of evacuation process for unconstrained evacuation 225

Fig.6. 28 Comparison of evacuation processes for constrained evacuation.....226

List of Tables

Table 2. 1 Summary of the evacuation models available 49

Table 3. 1 Train car details..... 105

Table 3. 2 Six cases..... 107

Table 3. 3 Results for six cases..... 109

Table 3. 4 Six cases for scenario II..... 111

Table 4. 1 Characteristic of the studied roadway network 141

Table 4. 2 Simulation results 147

Table 4. 3 Comparison of TET using different load times 151

Table 5. 1 Performance of TET at different section capacities..... 179

Table 5. 2 Performance of TET at different mean velocities..... 179

Table 6. 1 Total number of cars in each shelter 204

Table 6. 2 The capacity of shelters 212

Nomenclature

Symbol	Meanings
v	the velocity of a people or a car
ρ	the density of flow
$c\,(\rho)$	kinematics waves
$p(t)$	the cumulative percentage of trips generated at time t
F(t)	the percentage of the population mobilized at time
a	the response of the public to the disaster
H	the time when half of the vehicles in the system have been loaded onto the highway network
$p_{t,x}, p_{t,y}, p_{t,-y}$	transition possibilities in three directions namely, forward, upward, downward
D	drift point which represents the randomness of people during movement
ϑ	the likelihood of movement of a person at each step
P	the summation of the transition possibility of the three persons moving to a free cell
CLS	a competitive level coefficient
N_{ij}	the number of vehicles wanting to move from outgoing link i to incoming link j
C_i	section capacity for a link
C_k	the approach capacity at intersection k
NN_j	the requests for service to enter into link j at intersection

ΔT	the length for a simulation interval
NN	the total requests for service to pass through intersection k
mm	the number of inbound links at current intersection
G_j	the green split for j-th incoming link
T_i	the total waiting time of all vehicles at i-th link
M_{ij}	the allowance number of vehicles from the i-th link to j-th link related to dynamic capacity of link
n_j	the number of lanes in the j-th incoming link
CA_i	the through capacity assigned to enter into link j
$N_{\max,j}$	the number of cars a road j can accommodate
$NV_j(t-1)$	the available free space in link j at simulation step t
$NS_{ij}(t)$	the allowance numbers of vehicles from link i to link j at t step related to static storage capacity
$MNS_{ij}(t)$	the allowance number of vehicles from i-th link to j-th link
G (V, E)	a graph composed by nodes and arcs, be represented where V and E stand for the set of nodes and the sets of arc respectively
a_{ij}	the cost coefficient of arc (i, j)
b_{ij} , c_{ij}	the lower bound and upper bound of arc (i, j) respectively
s_i	the supply of node i
x_{ij}	the flow on arc $(i, j) \in E$

G (V, E, U, C, T)	a directed graph with the vertex set V, arc set E, link capacity constrains set U, node capacity constraints set C, and the time space T
$u_{ij}(t)$	a nonnegative time-varying maximum capacity for a link where t denotes the departure time
$\lambda_{ij}(t)$	a positive travel time (or cost)
$C_i(t)$	the dynamic node capacity of vertex i at t
$x_{ij}(t)$	the flow on arc $(i, j) \in E$ that leaves node i at time t and will arrives at node j at time $t + \lambda_{ij}(t)$
$y_i(t)$	the flow waiting at vertex i during period [t, t+1]
$f(h,T)$	the total value under a schedule h, which specifies when and how to send flows from the source to the sink within the time limit T.
$G'(V,E',U',C',T$	the dynamic residual network
$\lambda'_{ij}(t)$	the negative transit time of artificial link (i, j) at step t
$u'_{ij}(t)$	the negative capacity of artificial link (i, j) at step t
$d'_i(t)$	the negative storage within which the flow can be stored or wait from t to t-1

Chapter 1

Introduction

1.1 Background

Humanity has been beset by disasters for centuries. Natural disasters (e.g., earthquakes, flooding, storms, hurricanes, etc.) and industrial accidents (e.g., nuclear power plant accidents, hazardous gas spills) are becoming more frequent and more severe. In the past decades, the rapid growth of urban populations has worsened the effects caused by such disasters.

When preparing for major international events, such as the Olympic Games or World Expo, which can attract more than 500,000 people, a proper crowd movement strategy is essential. Under normal conditions, large population gatherings pose no serious problems. However, a combination of inadequate facilities and deficient crowd management may cause chaos or catastrophe. For example, in 1990, 1426 people were killed in a crowd crush during the annual pilgrimage in Mecca, Saudi Arabia; in 2004, the most notorious tsunami in history caused more than 200,000 casualties in South Asia due to a lack of evacuation planning on the coast.

In fact, most major crowd disasters can be prevented by implementing proper crowd management strategies, such as the avoidance of critical crowd densities and effective and efficient evacuation of populations in danger.

Transportation planning is the usual way of improving the traffic flow in road networks in terms of both efficiency and effectiveness. However,

traditional transportation planning focuses only on routine traffic analysis, such as the A.M. peak or the P.M. peak periods during weekdays. In some special circumstances, the demand for traffic may increase rapidly, scenarios defined by the National Highway Institute of the U.S.A.(Corbin 2003) as special traffic events, which include range of events from football matches to marathons and parades. Such events require a distinct way of circulating the population safely and efficiently.

Note that the designation ‘special event traffic’ ignores one of the most important circumstances, emergency traffic during disasters which, after recent incidents, seem increasingly likely to occur. Although the possibility of these events occurring is very remote, it is prudent to be prepared and have emergency plans which provide a flexible response to incidents and reduce their effects.

1.2 Emergency Planning and Emergency Traffic

Emergency planning plays a vital role in ensuring the safety and security of people in danger during disasters. Its effectiveness depends on understanding the scope and magnitude of potential incidents and the extent of their disruption to the mobility of people and goods in the transportation system. Comprehensive emergency preparedness planning includes detecting, forecasting, identifying, planning, analyzing, and responding to, any unanticipated events that may result in injury, or loss of human life and damage to or destruction of critical infrastructure elements.

The provision of emergency planning is quite a challenge for emergency managers because it concerns the interaction between humans and their

environment under in a wide range of disasters.

Meyer(1995) defines evacuation planning as a process in which the evacuation procedures and the local infrastructure of an area are evaluated in order to assess their sufficiency for safely and effectively evacuating a potential impact area in the event of a hazardous incident. Even though the processes that generate the disasters might be fundamentally different, techniques for assessing risk, evaluating preparedness, and assisting responses appear to have much in common and can be applied in many different scenarios. To develop an effective evacuation plan, the following main procedures should be followed:

- Determination of legal or other authority to evacuate
- Establishment of a management structure and clear definition of roles and responsibilities
- Development of effective warning and information system
- Assessments of Vulnerability Analysis and Probability Impact
- Development of appropriate and flexible evacuation plans

The first step deals with problems arising from the legal responsibilities of each government department during an unexpected event. The second step establishes the manner in which the public is to be informed of an evacuation. The community risk assessment examines the source of risks, implications of their impact and possible mitigating action. The last step determines the feasibility of evacuation routes and identifies bottlenecks that would constrain the flow of traffic, assesses the effectiveness of alternative traffic control strategies and estimates clearance times for the network or portions of the network.

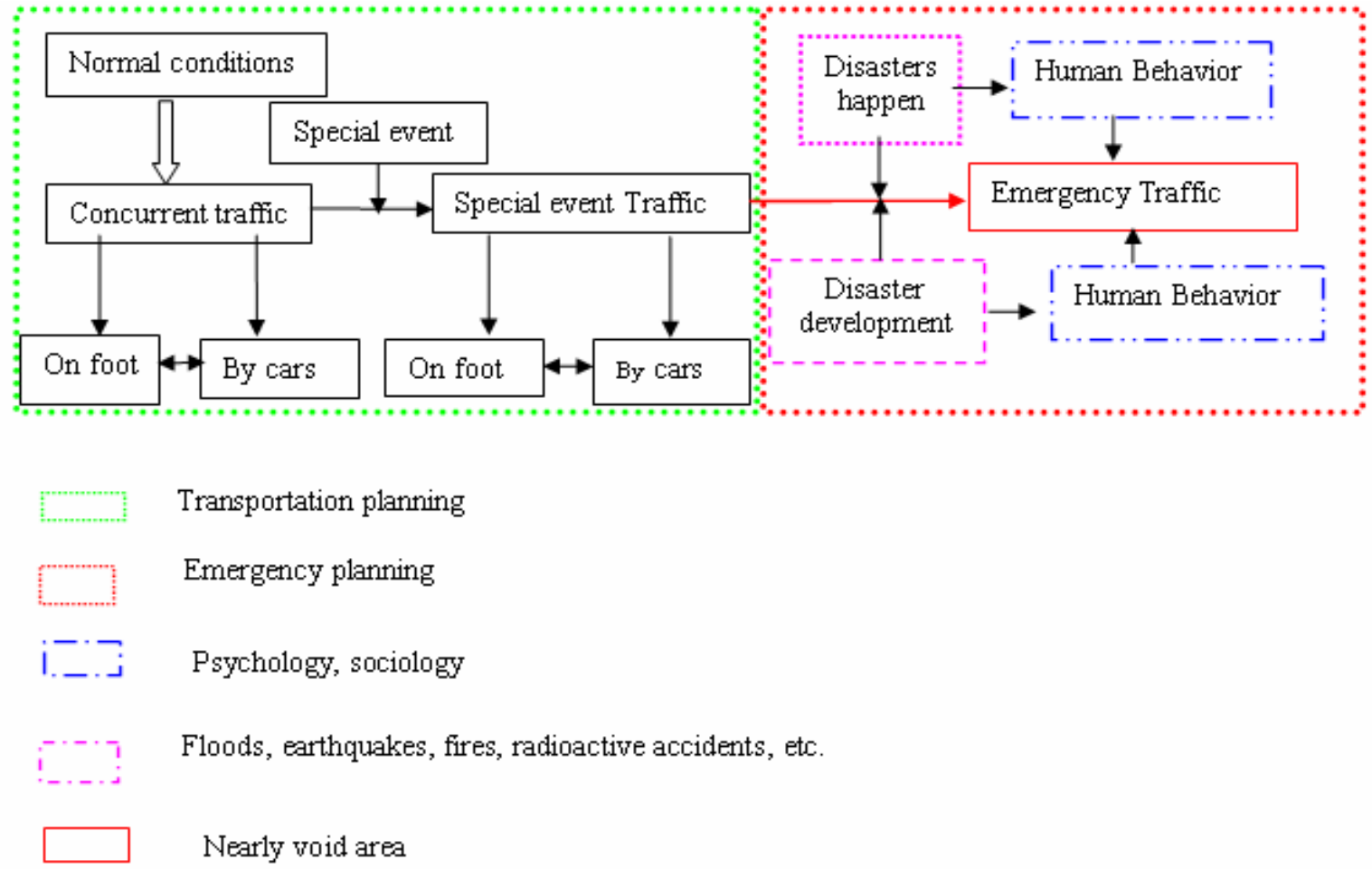


Fig.1. 1 Schematic overview of research areas

Clearly, the provision of a comprehensive evacuation plan is a quite challenging task as this process covers a variety research areas, including transport engineering, physiology, sociology, computer technology and operation management, *inter alia*. Fig.1.1 gives a schematic overview of research areas involved in transportation and emergency planning.

Note that the link between transportation planning and emergency planning is emergency traffic planning, which is an area of importance but has been underestimated for years. Emergency traffic is different from traditional traffic in three ways:

(i) The rapid increase in traffic demand

(ii) The unexpected reduction of road capacity

(iii) The time factor

In emergency traffic situations, traffic congestion is pronounced all over the network so quickly evacuating people in danger is very important for preventing loss of life. Emergency traffic is an area of study which encompasses a number of disciplines, including transportation engineering, sociology, economy, information and computer technology, psychology and operations management. In Fig.1.1, two factors are shown, human behavior and nature of disaster, but these actually interact and interconnect with each other, as will be demonstrated in the next chapter.

Urban evacuation planning plays an important role in responding to natural disasters and other catastrophic incidents. To efficiently and quickly evacuate a population threatened during an emergency, appropriate traffic control must be implemented to guide the evacuees to pre-planned routes. Evacuation simulation models are ideal solutions for traffic engineering analysis and design as they can

model many kinds of scenarios individually, or combine two or more scenarios, and then test the feasibility of current evacuation plans or propose an alternative so as to facilitate the circulation of evacuees.

1.3 Aims and Objectives

The principal aim of the current study was to propose a spatial decision support system which integrates simulation models, visualization tools, GIS, and optimization algorithms for managing large-scale evacuations of densely populated regions prone to disasters. The decision tool can be used to improve the design of transportation network, devise efficient evacuation plans and establish effective evacuation management strategies at place-in-use stage.

The study had the following specific objectives:

- To establish a mathematical optimization model of large-scale evacuation. The solution of the model should include the optimal evacuation schedules, routing assignment plans and shelter schemes. The optimization model is based on dynamic network flow and it can be a useful tool for helping emergency managers to evacuate the population in danger as quickly as possible.
- To develop a simulation model, which includes two sub-models, one is a microscopic model for pedestrian evacuation, and the other is a mescoscopic model for traffic evacuation. The first represents the most common means of evacuation, e.g., in building evacuation. The latter is more common in larger scale evacuations, i.e., regional evacuation, which involve greater distances and more people.

- To develop a hybrid model to integrate the optimization and simulation model. Optimization model is used to develop the optimal evacuation plans and simulation model is used to model the evacuation process according to the optimized plans.
- To set up a spatial analysis tool to facilitate data pre-processing and present the results in a vivid and interactive way.

1.4 Methodologies

To accomplish the objectives listed in the last section, the following process shown in Fig.1.2 was adopted.

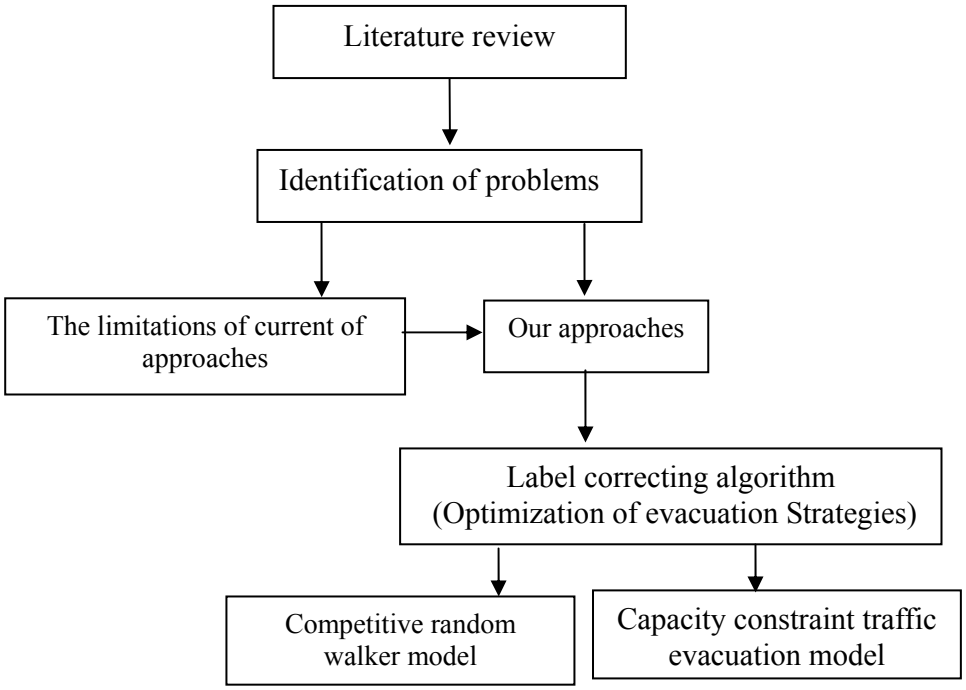


Fig.1. 2 Methodology of the study

Firstly, a brief review of research on the movement of people was presented. Then, an extensive range of review of current evacuation models was given. A

total of 56 evacuation models, covering both building and regional evacuation, were examined and their strong points and shortcomings are summarized. Then, our solution, a hybrid approach, was proposed to deal with the evacuation problem. The hybrid model includes one optimization model and two simulation models.

- A label correcting algorithm based on dynamic flow network was adopted to optimize the evacuation strategies which include the evacuation routes, evacuation schedule and evacuation destinations. Dynamic network flow is based on their corresponding static networks by expanding network over a time horizon.
- A competitive random walker model was developed for modeling the evacuation of evacuees on foot.
- A mesoscopic simulation model (capacity constrained evacuation model) for modeling the evacuation of evacuees by automobiles. This model was built up based on queue simulation models.

1.5 Contributions

The contribution of this dissertation was twofold. The first one was to develop a hybrid evacuation model, which integrated optimization model and simulation model and the second one was identifying the importance of shelter capacity on evacuation analysis by using our models.

1.5.1 Establishing a hybrid evacuation model

The structure of the hybrid model is shown as Fig.1.3. The optimization model was adopted to provide the optimal evacuation strategies, and simulation

models were used for a detailed analysis. so, three models are developed.

First, a time-varying quickest flow problem (TVQFP), based on dynamic network flow, had been developed to optimize the evacuation plan.

Secondly, a competitive random walker model had been built up to simulate the pedestrian evacuation.

Thirdly, a capacity constrained evacuation model, based on the queue model, had been established on a GIS platform to model a regional traffic evacuation.

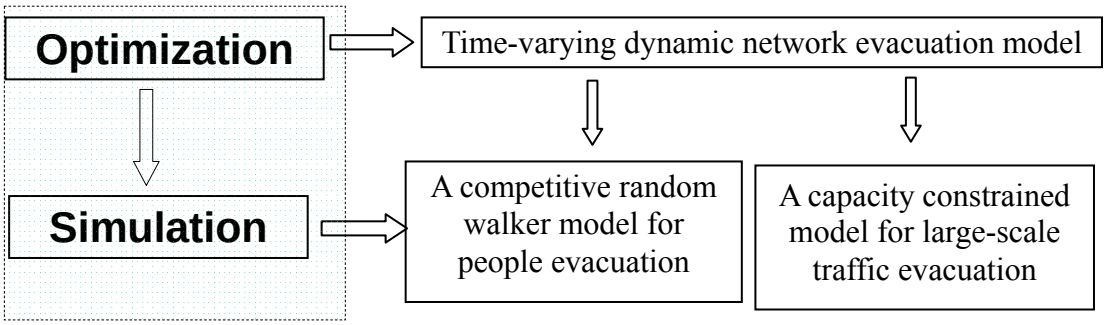


Fig.1. 3 Structure of the hybrid evacuation model

A detailed description of these models was summarized as follow:

- A time-varying quickest flow problem (TVQFP), based on dynamic network flow, had been developed to optimize the evacuation plan. This algorithm can be adopted to optimize the evacuation shelters, evacuation routes and evacuation schedule simultaneously. It can effectively simulate the effect of unconstrained (unlimited capacity) and constrained (limited capacity) shelters – temporary safe places. The influence of load time (LT) on the total evacuation time was analyzed in detail under these two conditions, i.e., the constrainted condition and the unconstrainted condition. Our studies found that under the unconstrainted condition, LT plays an importance role on the total evacuation time (TET) and the TET increases with prolong of LT. But for constrainted condition, LT has

little effect on the TET within a time interval. Furthermore, TVQFP is particularly suitable for evacuation planning as through capacity of roads or intersections may decrease or totally be blocked due to the effects of adverse environments such as fires, floods, or lethal gas. Dynamic network can reflect theses time-varying features and optimize the whole evacuation process to a system optimum.

- Phased evacuation is an arrangement for the evacuation of an area in the event of disaster. Whereby the occupants pose to direct danger will be evacuated immediately. Then, the remaining occupants of the area to be evacuated subsequently as necessary. A lexicographically quickest flow was presented in this dissertation and it can minimize the number of occupants located at the most dangerous place, at the same time optimize the total evacuation time in the system optimization. It can be used to arrange the schedules and routes during a phased evacuation in multi-compartment buildings or cities.
- A microscopic simulation evacuation, an improved random walker model, was developed and it can model the detailed behavior of each evacuee during evacuation process, such as the route and destination selection. As random walker model ignores the lane change behavior, a modified cellular automaton was presented to simulate the bi-direction pedestrian flow. It can model the lane formation and deadlock phenomena of crowd movement. As the computational demand for the model is reasonable, it was further developed for evacuation analysis. The model had been adopted to simulate the evacuation of a subway and

an interesting and counter-intuitive phenomenon, known as the Braess's Paradox, had been observed in the people's moving network.

- A mesoscopic level evacuation model, based on the queue model has been established on a GIS (geographical information system) platform to model a regional traffic evacuation. It consisted of two link scanning processes, which check the dynamic capacity and static capacity respectively at each step. This model simplified the lane change behavior of drivers on roads and focused on the behavior of drivers at intersections. It provides a cost-effective way to evaluate the evacuation planning in real time application. Despite its simplicity, it can model the congestion and spillback process during an emergency evacuation. Two types of assignment were implemented in the meso-simulation model, the all-or-nothing assignment and the simulation-based iterative assignment. The former allocates the evacuees to their shortest routes and the later distributes the evacuees to the quasi-optimal routes. The performance in term of total evacuation time of two approaches were compared and results illustrated that the iterative assignment decreased the total evacuation time (TET) greatly, particular for the congestion condition. Iterative assignment can help making full use of the whole evacuation network thus facilitating the movement of evacuation. However, the performance of iterative assignment is closely related to the length of load time. This regional evacuation was integrated with Netengine, a GIS component, which can provide all kinds of network algorithms. The GIS-based meso-evacuation model can provide us a cost-effective way to simulate and evaluate the safety of population in an

area in terms of TET, and can also be used to guide and control the evacuee's traffic during a real-time evacuation subject to any kinds of disasters.

- A hybrid evacuation model, integrating the dynamic network flow optimization approach and simulation, had been established in this study. The optimization model was used to optimize the evacuation routes, schedules, and shelters. The simulation model took the optimized strategies and provided a description about the evacuation behavior under emergency situations. The hybrid model made full use of the advantages of both simulation-based model and dynamic network flow based optimization model.

1.5.2 Identifying the importance of shelter capacity on evacuation analysis

The second contribution was to identify the importance of shelter capacity on evacuation analysis. My study first revealed that the capacity of shelters may have a paramount impact on the evacuation process particular for large-scale evacuation.

Two important types of evacuation problems, constrained and unconstrained, had been addressed. The former takes into account the capacity constraint of shelters while the latter does not. Our studies revealed that shelter capacity has an impact on the total clearance time: generally speaking, an evacuation happens much more quickly under unconstrained conditions. The influence of load time on the total evacuation time was analyzed under these two conditions and it was found that, under unconstrained conditions, the TET increases with the duration of LT. However, under constrained conditions, LT

has little effect on the TET within a time interval.

1.6 Outline of the Dissertation

A schematic view of this dissertation is given in Fig.1.4

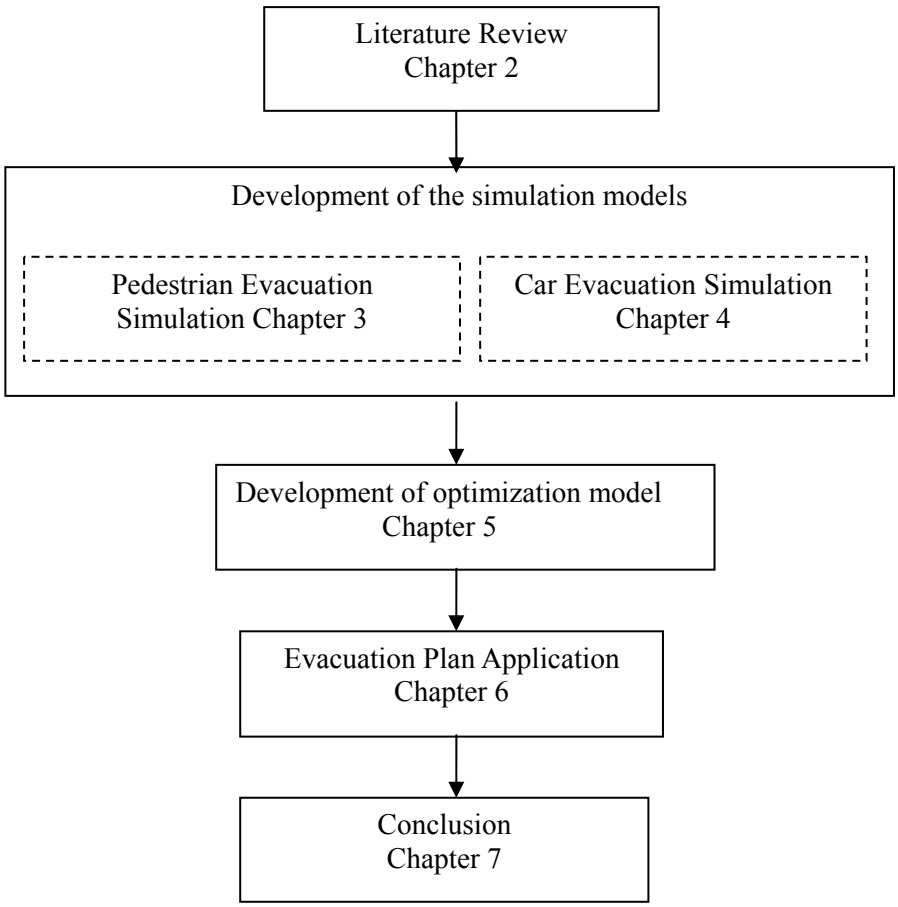


Fig.1. 4 Structure of the Dissertation

Chapter 2

Literature Review

In this chapter, a brief review of research on the movement of people was presented. Then, an extensive range of review of current evacuation models was given. A total of 56 evacuation models, covering both building and regional evacuation, were examined and their strong points and shortcomings are summarized.

2.1 Introduction

Research on the movement of human beings, either on foot or by vehicle, is an area of importance for long-range transportation planning and concurrent traffic congestion analysis, for example in the matter of home-to-work journeys in the morning or work-to-home journeys in the evenings on weekdays, and for the evaluation and operation of transportation facilities in terms of efficiency and effectiveness. The scientific study of traffic flow had its beginnings in the 1930s with the application of probability theory to descriptions of road traffic by traffic volume and speed. After World War II, with a tremendous increase in the use of automobiles and the expansion of the highway system, there was a dramatic increase in the number of studies on traffic characteristics and traffic-flow theories began to be developed.

From the view point of physicists, pedestrian or vehicular movement is a kind of self-driven many-particle system (Helbing 2001), in which the driving force is not external but comes from within each particle, which has the ability

to supply and save energy. This system is characterized by not being closed, i.e., by having an exchange of energy, particles and/or information with the environment.

The general concepts adopted when modeling pedestrian flow and automobile traffic are similar, often exhibiting complex behavior such as pattern formation (Helbing 1997) and jamming transition (Nagatani 1993; Muramatsu, et al, 1999; Muramatsu and Nagatani 2000). A significant phenomenon found in both traffic flow and pedestrian flow is so-called phase transition behavior, in which a system transforms from a state of free movement to a state of total jam or blockage at a critical density. Modern developments and research may help prevent some accidents due to overcrowding, e.g., understanding the transition density of exits is of importance for the design of evacuation network because throughput decreases dramatically near the transition point.

However, the two forms of movement (pedestrian or vehicular) are quite different in that they have different degrees of freedom. Moving on foot is freer than moving by vehicle as pedestrians can move around in a more flexible way, changing their route and direction freely. Pedestrian flow has attracted the attention of physicists and sociologists in recent years and many interesting phenomena have been studied, for example panic escapes (Kelley et al. 1965; Helbing et al. 2000), counter-channel flow (Muramatsu et al. 1999), bottleneck flow (Tajima et al. 201) and lane formation (Helbing 1997).

Models for human motion range in scope from macroscopic through mesoscopic to microscopic. Macroscopic models describe the traffic at a high level of aggregation as flow; microscopic models describe the behavior of the entities making up the traffic stream (vehicles, pedestrians), and their

interactions in detail; mesoscopic models are at an intermediate level of detail, for instance describing the individual vehicles, but not their interactions.

2.2 Macroscopic Model

2.2.1 Lighthill-Whitham Model

The best-known macroscopic traffic model is the Lighthill-Whitham model (Lighthill and Whitham 1955.). It describes the evolution of traffic over time and space using a set of differential equations and treats movement of cars like flow of liquid characterized by velocity v density ρ. The following continuity equation is satisfied:

$$\frac{\partial}{\partial t}\rho + \frac{\partial}{\partial x}\rho v = 0 \tag{2.1}$$

The kinematic equation can be derived as following by taking into account a velocity density relationship $v = v(\rho)$.

$$\frac{\partial}{\partial t}\rho + c(\rho)\frac{\partial}{\partial x}\rho = 0 \tag{2.2}$$

Where the velocity of the kinematics waves c (ρ) is governed by

$$c(\rho) = \frac{d}{d\rho}\rho v(\rho) \tag{2.3}$$

These partial differential equations can be solved at discrete space. Macroscopic models run much faster and are easier to apply and calibrate. Therefore they are most suitable for modeling large networks and for long time period application. However, due to the high-level aggregate representation of traffic flow and road geometry, the individual behavior of drivers cannot be modeled.

2.2.2 Hughes Pedestrian Flow Model

Hughes (2002; 2003) proposed a continuum model for pedestrian flow, in which only one type of pedestrian is involved.

Density (ρ) of the flow, which is the expected number of individuals located within a unit area of floor space at a given time t;

Velocity (u, v) of the flow, which is the expected velocity of individuals at a given time t.

Thus, the conservation equation for pedestrian can be derived as:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) = 0 \tag{2.4}$$

This equation is rigorously derived in the context of the continuity equation in fluid mechanics.

Hughes (2003) studied the annual Muslim Hajj using this continuum equation and surprisingly found that placement of barriers in appropriate places increases the rate of flow greatly. However, this model is only suitable for a dense population moving in one direction and no individual behavior is considered.

2.3 Microscopic Simulation Model

As the macroscopic models generate only aggregated outputs, a new generation of models is needed to model the process of traffic interaction in detail. These are microscopic models, in which detailed behaviors such as acceleration, deceleration and lane changes, are captured in detail.

With respect to the representation of space in a microscopic model, there are two basic approaches, discrete and continuous. The former refers to the

modeled space being represented in a discrete manner, as a regular lattice, and the entity modeled moves forward one grid or more each time. The later, in contrast, treats the space as continuous.

2.3.1 Continuous Models

2.3.1.1 Social Force Model

Helbing (Helbing 1992; Helbing and Molnar 1995; Helbing 1997; Helbing, et al. 2000; Helbing et al. 2000) proposed this model for pedestrian modeling. In the model, people are assumed to be subjected to social forces that motivate pedestrians to move forward and prevent them from colliding with others and with obstacles. The summation of forces drives the acceleration or deceleration of movement. According to Newton's second-law, the movement of persons can be derived as:

$$m_i \frac{dv_i(t)}{dt} = m_i \frac{v_0 e_i - v_i(t) + \xi_i(t)}{\tau} + \sum_{j(\neq i)} (f_{ij}(x_i(t), x_j(t)) + f_b(x_i(t))) \qquad (2.5)$$

Where

$x_i(t)$:the location of pedestrian i at time t,

$v_i(t)$: the velocity of pedestrian

m_i : the mass of pedestrian

τ : the reaction time of pedestrian per step

v_0 : the desired velocity in scale format

e_i :the desire direction movement of pedestrian

$\xi_i(t)$:the fluctuation of individual velocity

f_{ij} :the repulsive interaction force with others

f_b :the repulsive force with obstacles or walls

Many interesting phenomena are observed using this model, such as lane formation, oscillation at bottleneck, and clogging. However, there are two criticisms of it. First, the behavior of humans is over-simplified and many parameters involved in the model have never been validated by real-world data. Second, the model is a computational demand. If there are N persons in the space, there will be $N \times (N\text{-}1)$ interaction forces for each person. For complicated structures (like shopping centers) or large populations, this is a major challenge.

2.3.1.2 Magnetic Force Model

The underlying theory of the magnetic force model (Okazaki 1979; Okazaki and Matsushita 1993) was adopted from magnetic theory. It assumes that each entity simulated, whether person or obstacle, has a positive pole, while the target location has a negative pole. People move to their goals and avoid collisions with each other and obstacles. Each person is acted on by two forces, one is a magnetic force formulated by Coulomb's law, which describes the force between two charged particles, and the other one is a force to avoid the collision of persons with others or obstacles.

The model has been used in Okazaki's(1979) evacuation but few applications have been reported. Furthermore, some parameters, such as the value of the magnetic intensity, are difficult to validate in real world observation.

2.3.1.3 Car-Following Model

The car-following models were derived from several principles from everyday experience which govern the action-reaction behavior of a driver (Gazis et al. 1961; Ludmann et al. 1996) .

N cars are traveling on a single-lane road where they are numbered sequentially 0,1,…i ,i+1,…N. (car i ±1 is in front of car i.). The reactions of the drivers are delayed by their reaction time Δt . The following delayed differential equation can be derived:

$$\frac{dv_i}{dt} = f(v_i, v_{i+1}, \Delta x_i)|_{t-\Delta t} \tag{2.6}$$

Where $\Delta x_i = x_{i+1} - x_i$, and v_i represents the velocity of car i .

2.3.2 Discrete Models

2.3.2.1 Cellular Automaton Models

Cellular automata were invented by mathematicians Neuman and Ulam (1986). The most famous cellular automaton is the "Game of Life" invented by mathematician John Conway in the 1960's. Despite the simplicity of the rules governing the changes of states as the automaton moves each step, the evolution of such a system is quite complex.

Cellular automata divide the space into discrete cells, and each cell is allowed to be in one of the states, either 0 or 1. At each simulation step, the state of cell changes according to the states of its neighbors, and simple rules are adopted to determine what state it should change to. This basic step is repeated over the whole array, again and again.

The cellular automaton was first applied in traffic simulation by Nagel and

Schreckenberg (Nagel and Schreckenberg 1992; Nagel et al. 1998). The street is discretized in cells of length $\Delta x = 7.5\,\mathrm{m}$, as shown in Fig.2.3, and the velocity is discretized in units of $\Delta x = \Delta t$. Parallel update, which means that all cars move synchronously, is adopted at each step. The update rules (parallel update) for $t \rightarrow t+\Delta t$ are:

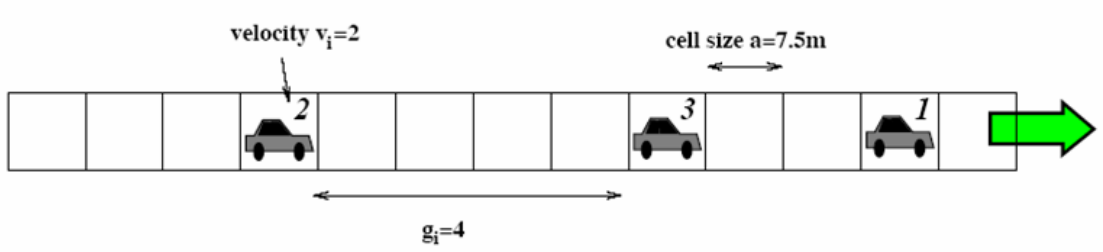


Fig.2. 1 Definitions and notation in the Nagel-Schreckenberg model

Note: The numbers in the cells give the current velocity. g_i denotes the gap between car i and its predecessor. The cell size in the standard model is 7.5m which leads to Δt =1s to a maximum velocity of 135km/h and an acceleration of 7.5 m/s^2.

(i) Accelerate: $v_i^t \rightarrow \min(v_{\max}, v_i^t + 1)$

(ii) Mind the gap: $v_i^t \rightarrow \min(v_i^t, g_i^t)$

(iii) Decelerate: $v_i^t \rightarrow \max(0,\ v_i^t - 1)$ with probability $p_{decrease} \in [0,1]$

(iv) Move: $x_i^{t+1} = x_i^t + v_i^t$

This model has the shortcoming that if a different desired velocity is set for each car, the result is the formation of platoons in which slow vehicles are followed by faster ones, and the average velocity is reduced to the free‐flow velocity of the slowest vehicle (Rickert et al. 2004). So the single lane model is not capable of modeling real traffic. Recently, a two-lane model has been proposed to model a realistic scenario (Nagel et al. 1998).

Burstedde et al. (2001) proposed a two-dimensional cellular automaton model to simulate pedestrian traffic by taking into consideration long-range interactions among pedestrians mediated by a so-called static and dynamic fields. The basic prototype for the movement of pedestrians is shown in Figure 2.2. Kirchner and Schadschneider (2002) presented simulations of evacuation processes using a cellular automaton model by applying a bionics approach to describing the interaction between pedestrians using ideas from chemo-taxis. Some interesting human movements, such as the evacuation of people from a large room with reduced visibility (e.g. due to failure of lights or smokes), bi-directional flow, unidirectional flow, four-direction flow, and cross flow, were all modeled and it revealed many phenomena of interest, such as lane formation, lane oscillation, and jamming transition.

The cellular automaton model is very simple to develop and fast to run. However, to what extent the discrete rules comply with the real behavior of pedestrians needs further study.

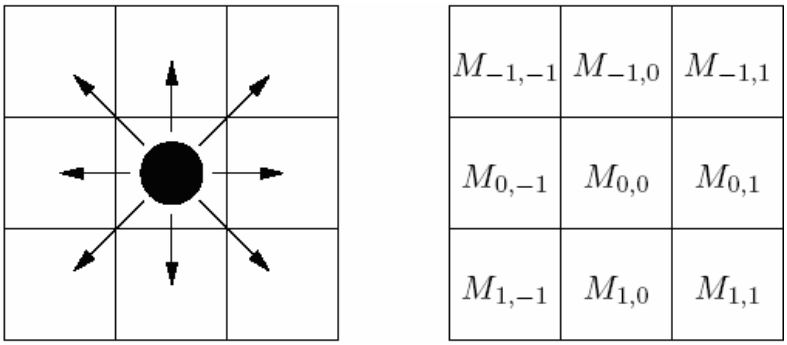


Fig.2. 2 Cellular automaton model for pedestrian movement

Note: The preferred walking direction can be presented via a 3×3 matrix and each element denotes the probability of next step. The summation of elements equals to 1.

2.3.2.2 Random Walker Model

Tajima et al. (Tajima et al. 201; Nagatani 1993; Muramatsu et al. 1999; Muramatsu and Nagatani 2000; Muramatsu and Nagatani 2000; Tajima and Nagatani 2001) presented a driven random walk model for pedestrian motion. The pedestrians move one cell per time step on a square lattice in three directions forward, upward, download, with different transition probabilities $p_{t,x}, p_{t,y}, p_{t,-y}$, and $p_{t,x} + p_{t,y} + p_{t,-y} = 1$.

Each grid has a set to illustrate its state; 0 indicates the cell is void, and 1 shows that it is occupied by one person. Pedestrians move in the preferred direction defined by rules shown in Figure 3.1, with no back steps. The exclude-volume effect is taken into account, so one cell can accommodate no more than one person at each step and walkers are inhibited from overlapping on the cell. Takimoto (2002) adopted this model to study the escape-time distribution of crowds in the evacuation process through an exit from a hall and the spatio-temporal distribution of escape time was derived.

In this model, the summation of transition possibility always equals 1, which means each person will move one grid at each step, and so it does not consider the detailed behavior of each pedestrian.

2.3.2.3 Agent-based Model

Batty et al.(2003) proposed an agent-based model to simulate the movement of pedestrians during specific events, and event space was explored by agents armed with information about space. The agents move according to their internal rules. Many types of example have been illustrated in this approach, such as congestion and flocking at a local street, semi-organized

street festivals, and so on. PEDFLOW (Kerridge and McNair 1999) is another example of the adoption of an autonomous agent approach to modeling pedestrians in urban environments. Each pedestrian is represented as an agent capable of making its own decisions based upon a part of the observable scene. Pedestrian behavior is controlled by a set of rules, which can be considered as functions whose input variables (observation of the virtual environment) combine with parameters that are specific to him. This cycle is repeated continuously.

The PEDFLOW model is useful for helping urban planners to evaluate the influence of changes in infrastructure on the movement of pedestrians in the urban environment.

2.4 Mesoscopic Models

Microscopic simulation models provide a detailed representation of the traffic process, in which traffic is described at the level of individual vehicles and their interaction with each other and the road infrastructure. However, microscopic models have proven to be difficult and time consuming to calibrate and difficult to apply because of the richness in their parameters and their dependency on large sets of fine-grained, accurate input data (Burghout 2004).

Mesoscopic models attempt to utilize the best features both macroscopic and microscopic models by describing their behaviors and interactions at a lower level of detail. In mesoscopic models, vehicles are grouped into packets or platoons, or cells (Ben-Akiva et al. 1998). The group of vehicles acts as one entity and its speed on each road (link) is derived from a speed-density function. The lane changes and acceleration/deceleration of vehicles are not modeled.

FASTLANE (Gawron 1998) adopts a very simple queuing mode to simulate traffic movement. The basic idea of this model is that the travel time on a link is the sum of the time needed to travel along the length of the link and the time spent waiting in a queue, and that the characteristics of a link can be described by its length, its capacity and by the number of cars. This simplified queuing model was adopted by the TRANSMIS project, in which millions of trips on a 20000 links network were successfully performed on a single CPU workstation (Simon and Nagel 1999.).

Queuing models have been used to describe pedestrian evacuation behavior from buildings. Lovas (1994;1995;1998) used a Markov-chain model to described how pedestrians move from one node (mostly a room) to another in the network. Random waiting occurs in the links due to the build-up of queues when pedestrian traffic demand is larger than the exit capacity. Smith et al. (Talebi and Smith 1985; Talebi and Smith. 1985; Smith 1991; Kerbache and Smith 2000) and Cruz (2005) propose a state- dependent queuing network model which incorporates the mean value analysis algorithm into Powell's derivative free unconstrained optimization algorithm to study the effect of varying circulation widths on throughput.

2.5 Emergency Traffic

Traffic simulation is an important tool for modeling the operations of dynamic traffic systems and it helps analyze the causes of and potential solutions to traffic problems such as congestion and traffic safety. When transportation systems are studied, researches usually assume that all elements, or at least most parts of them, function well. But is a transportation system still

effective in extreme circumstances? One of the important applications which have received little attention thus far is emergency traffic, which is characterized by three distinct features: an abnormal increase in traffic, an unpredictable reduction in the throughputs of road networks and the unpredictable behavior of humans.

Generally, models developed for the movement of people under normal conditions can be used in emergency conditions as well, but using different parameters to characterize human behavior under a particularly abnormal environment, as described in Chapter 1 of this Dissertation. Gwynne et al. (2002) investigated the behavioral aspects required for evacuation modeling and found four major factors that influence evacuation performance and should be represented in an evacuation model. The four factors are: configuration of enclosure, environmental factors inside the structure, procedures implemented within the enclosure, and, most important of all, behavior of the occupants.

There are many studies of human behavior during times of disaster, e.g., fire (Wood 1990; Sime 1992; Sime 1994), earthquake (Murosaki and Yamada 1980; Aoki et al. 1992; Murosaki and koizumi 1993; Petruccelli 2003), debris flood or flood (Takahashi et al. 1989; TAKAHASHI and NAKAGAWA 1990; Imamura and Katada 1999) ,tsunami (Kawata and Koike 1995), hurricanes (Whiteheada 2000; Whiteheada et al. 2000), chemical explosion incidents (Quarantelli et al. 1983; Quarantelli 1984) and ship accidents (Lee et al. 2004).

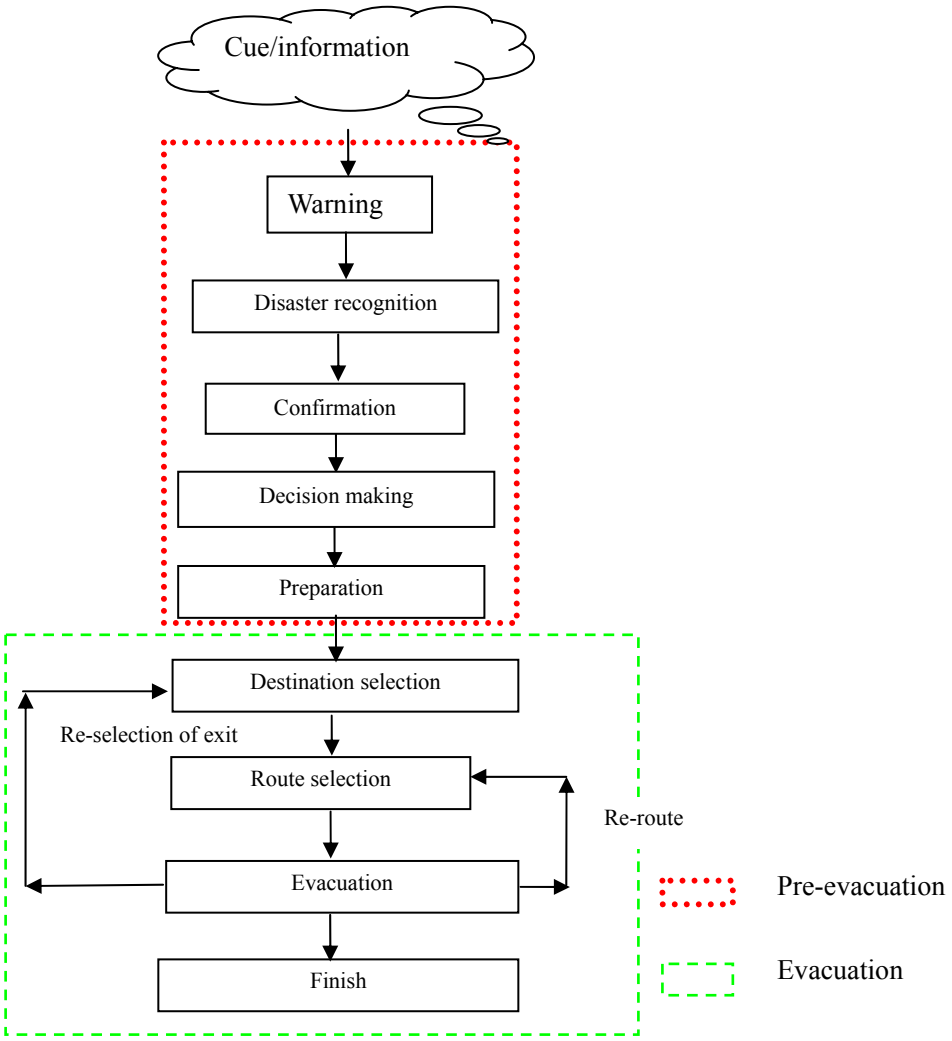


Fig.2. 3 General behavior of people in emergencies

Early research was conducted using qualitative analysis in order to study behavioral responses and decision making in an emergency (Breaux et al. 1976; Proulx 1993). In recent decades, with the development of computer models, simulation-based methods have been widely adopted. A number of modeling and simulation tools for emergency-response related applications are currently available and more are under development. Lo (1996) found that the reaction of individuals in a fire situation is complicated and a series of decision-making steps, involving recognition, validation, definition, and evaluation, will be undertaken. In fact, the behavior of people is quite different in different disasters.

Here, we adopt a more general model of reaction to disaster, as shown in Figure 2.3 (warning, disaster recognition and confirmation, preparation, destination selection and route selection). Note that these processes do not take place in a fixed sequence but in an iterative process as lacking of sufficient dynamic information.

2.5.1 Pre-Movement Time

People's pre-movement time is influenced by the following parameters: their belief in the evacuation warning, their status, perceived level of risk, existence of an evacuation plan or not, *inter alia*. It consists of the following parts: the time occupants take to perceive any cues (alarms or warnings), time taken to interpret the situation by searching for more information before making a decision to evacuate, and the time occupants use to engage in other actions, such as getting dressed or notifying others, before starting to evacuate.

The pre-prepare time of evacuees has a strong influence on the total evacuation time. For example, if all evacuees are mobilized instantly and loaded into the road network, then, most of time, there will be over-congestion of the network, which will significantly prolong the total evacuation time. In contrast, if the evacuees' preparation is delayed too long, then the preparation time will take much portion of the total evacuation time than that of the on-journey time.

Appropriate approaches must be adopted to determine an optimal evacuation departure time, and these generally take one of two forms, generating behavioral response curves from past evacuation surveys or developing mathematical models based on data from previous surveys. Radwan and Hobeika (1985) used a logistic curve to model the loading time of trips onto

the highway network during an evacuation from natural disaster in their MASSVAC(Hobeika,1985) model:

$$p(t) = \frac{1}{1 + \exp[-a(t - H)]} \tag{2.7}$$

Where $p(t)$ is the cumulative percentage of trips generated at time t, and a represents the response of the public to the disaster and it alters the slope of the cumulative traffic loading curve. H is the time when half of the vehicles in the system have been loaded onto the highway network. It defines the midpoint of the loading curve and can be varied by the user according to disaster characteristics.

Tweedie et al. (1986) proposed a similar loading curve that can be approximated by the Rayleigh probability distribution function given by:

$$F(t) = 1 - \exp(-t^2 / 1800) \tag{2.8}$$

Where F(t) is the percentage of the population mobilized at time t, and t is the mobilization time in minutes.

2.5.2 Destination Selection

Destination selection is the process by which evacuees decide where to go. Kimura and Sime (1989) studied building fires and found that people prefer to leave through familiar exits. Benthorn and Frantzich (1996) found that people prefer the closest exit during a fire emergency. Sekizawa et al. (1999) examined the behavior of occupants in high-rise apartment building fires in Hiroshima City and found that the occupants were likely to choose the route they usually used (44%) or a safer route (29%) rather than a closer route. Southworth (1991) reviewed evacuation destination selection studies and proposed the following as

the available exit selection choices:

- The closest destination/exit: evacuees will exit to closest destination (in terms of distance and or expected travel time)
- The optimal destination/exit: evacuees exit on the basis of traffic conditions in the network at the time
- Random selection of destination/exit
- Exit pre-defined by planners.

In fact, most of the evacuation models are embedded with a sub-model which functions as exit selection of evacuees. The BuidingEXODUS model (Gwynne et al. 1999) allocates occupants to their nearest or the most familiar exits. Simulex (Thompson and Marchant 1995), Exit89 (Fahy 1991; Fahy 1996), GridFlow (Bensilum and Purser 2002), Crisp (Boyce et al. 1998; Fraser-Mitchell 2001), and ASERI (Schneider 2001; Schneider and Konnecke 2001) allow evacuees to exit through the nearest or user-defined exits. EVACNET4 (Kisko and Francis 1985), working on the assumption that occupants view the building from a global perspective, allocate evacuees to travel through the network in the shortest time. The crowd flows are balanced on all routes in order to minimize the total time (optimization or equilibrium assignment). Yamada (1996) adopted a combined destination selection and route selection model by using the minimum-cost flow problem to assign minimal cost paths for residents from their locations to shelters, taking into consideration a shelter's capacity. Sherali et al.(1991) developed a location-allocation model to determine the most viable shelter. Once this is done, evacuees are allocated to shelters through user optimization.

2.5.3 Route Selection

Route Selection is a process by which evacuees decide how to get to their target destinations. For small-scale evacuations, such as of buildings or ships, the route and exit selection are generally combined together since there is no constraint on a destination's capacity. For a larger scale evacuation, however, the two processes must be studied separately as there are resource and space constraints. These problems are generally referred to as the 'unconstrained' evacuation problem and the 'constrained' evacuation problem respectively.

In traffic engineering, route selection is performed by traffic assignment. Hobeika et al. (1985;1985) adopted the static traffic assignment in the MASSVAC model to simulate urban traffic evacuation during disasters. IDYNEV (KLD and Associates 1984) adopted static traffic assignment using a modified TRAFFIC algorithm. However, the static traffic assignment fails to describe congestion accurately, particularly for large evacuation problems. With the advent of the Intelligent Transportation System (ITS), dynamic traffic assignment (DTA) has gradually become one of the major foci of interest for emergency mangers. Since a DTA model overcomes those problems involved in static assignment by introducing time-dependent models and can predict the dynamic nature of traffic flows, such as time-dependent link flows and link travel time, the model has the potential to be useful in real-time traffic management. Considering an evacuation process, which is dynamic by nature, the DTA model could become a viable alternative for developing dynamic evacuation plans. A comprehensive overview of dynamic network models can be found in Ran and Boyce (1996) The newly developed MASSVAC4.0 (Hobeika and Kim 1998) incorporated the dynamic user equilibrium (UE)

assignment algorithm. Shin and colleagues (Shin et al. 1998) and Sattayhatewa and Ran (2000) discussed fundamental requirements for implementing the DTA models for evacuation management and proposed an analytical DTA model.

Besides the adoption of traffic assignment, the optimum algorithm is implemented to find out the optimal evacuation routes at a certain criterion, e.g., the quickest time, shortest distance, least cost, etc. Many evacuation models, such as Simulex (Thompson and Marchant 1995), Exit89 (Fahy 1991; Fahy 1996), GridFlow (Bensilum and Purser 2002) ,Crisp (Boyce et al. 1998; Fraser-Mitchell 2001), and ASERI (Schneider 2001; Schneider and Konnecke 2001) use algorithms for optimizing the evacuation routes so as to minimize the total evacuation time. The evacuation network is a simple topological network composed of links and nodes with constraints.

However most of the time, during emergency evacuations, traffic will exceed the capacity of the links. There is no feasible flow in the static network. A time-expanded network, or dynamic network, can be used to deal with this kind of problem. Dynamic networks are based on static networks but expand them over a longer time period. They can be either time-dependent or time-independent. Time-independent dynamic networks assume that network characteristics such as link travel and capacity are constant and do not vary with time. Time-dependent dynamic networks, on the other hand, assume that all parameters are time-dependent and vary with time. Chalmet et al. (1982) developed an algorithm based on a time-independent dynamic network to optimize building evacuation. This algorithm was later implemented in EVACNET4 (Kisko and Francis 1985). Choi et al. (Choi 1984; Kimura and Sime 1989; Choi et al. 1988) proposed a minimal cost flow problem with side

constraints for building evacuation in time-independent dynamic networks. Other work on time-independent networks include Hamacher and Tufekci (1987), who presented a lexicographic minimal cost flow problem to solve the multi-objective problem concerning building evacuation in a time-expanded network. Mamada et al.(2003; 2004) proposed an algorithm for evacuation guidance and transportation network design to optimally locate facilities, and Hoppe and Tardos (1994) discussed some evacuation problems and proposed a polynomial-time approximation scheme.

The time-dependent dynamic networks are quite complex due to their computational demands. However, time-dependent dynamic networks can reflect time-varying features, which makes them particularly suitable for evacuation analysis as the capacity of exits or paths may decrease or be reduced to nothing due to the effects of adverse conditions such as fire or smoke during an evacuation. Hamacher and Tjandra (2002) proposed an earliest arrival flow model with a time-dependent capacity for solving evacuation problems. Hooks and Patterson (2004) adopted a pseudo- polynomial time algorithm for solving the integral time-dependent quickest flow problem (TDQFP) and its multiple source and sink counterparts.

Evacuation is quite a stochastic process because every element, such as human behavior, is unpredictable. Smith (1985;1991) classified topological networks as deterministic networks, (which are assumed to have fixed topology and link length), and stochastic networks (in which link delays change from time to time but remain constant between these infrequent changes). Fig.2.4 gives a schematic view of the methodology adopted in the optimization of the evacuation route.

2.5.4 Development of Hazards

The development of hazards affects the behavior of people and their evacuation planning. Evacuation is a process of constant decision-making, involving destination and route selection. People will select what they consider to be the safest or most reliable evacuation route according to the prevailing circumstances. If the environment deteriorates due to the development of the disaster, people will adjust their evacuation planning accordingly. Hazards obviously affect the movement of people as well as their psychological reactions (e.g., toxicity may reduce their speed and the smoke may decrease their visibility).

To consider the influence of hazards on the evacuation, a sub-model (responsible for providing evacuation models with hazard related information in time-space), which includes propagation direction, velocity, and intensity should be imbedded into evacuation models. EXODUS (Galea and Markatos 1991; Galea and Galparsoro 1994; Carroll et al. 2003) incorporates a sub-model in order to determine the physiological impact of the environment (toxicity, temperature, thermal radiation, HCN, CO, CO2 etc.) upon the occupants during a fire emergency. The sub-model assumes that the effects of certain fire hazards are related to the dose received. Other building evacuation models, such as EgressPro, Exit89, CRISP, ASERI, EXITT, VEgAS, EvaSim and so on also contain fire data to achieve this purpose.

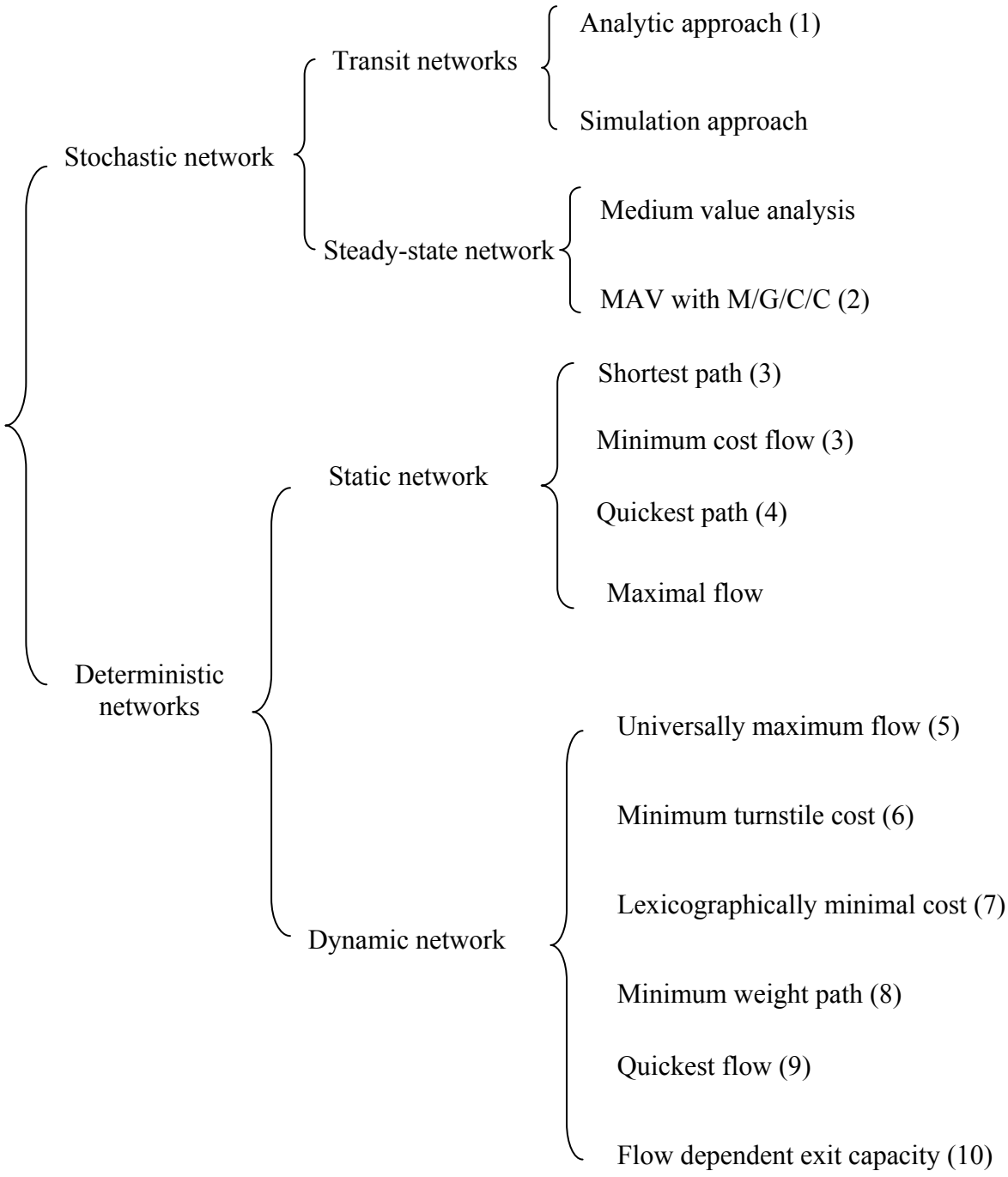


Fig.2. 4 Methodology adopted in evacuation route optimization

(1) Kisko and Francis 1985; Hall 1986; Orda et al. 1993
(2) Talebi and Smith 1985; Smith 1991; Kerbache and Smith 2000
(3) Yamada 1996
(4) Minieka. 1973; Chen and Chin 1990; Yamada 1996
(5) Minieka. 1973; Hoppe and Tardos 1994
(6) Chalmet et al. 1982; Kisko and Francis 1985
(7) Hamacher and Tufekci 1987
(8) Kostreva and Wiecek 1993
(9) Burkard, Dlaska et al. 1993
(10) Choi et al.1984; Choi et al. 1988

Ferrante et al. (2000) proposed a least-flood-risk path-finding algorithm to optimize the evacuation route in a flood-prone area and took into account flood propagation. Takahashi and Nakagawa(1990) presented a method that simultaneously simulates the overland flood flow or mud flow caused by river bank breaching and the evacuation of groups of residents bring threatened.

Note that, although many models do consider the impact of disasters on evacuation, and some have adopted optimization algorithms for static networks to establish optimal evacuation planning, none of these models have been able to optimize evacuation planning in whole time-space because time-varying features of hazards cannot be characterized accurately in a static network.

2.6 Existing Evacuation Models

The use of simulation models has enabled a much more detailed understanding of the underlying processes involved in emergency evacuations. It has also provided designers, engineers and managers with versatile and cost-effective ways of thoroughly validating and testing their planning. Furthermore, simulation-based models can reproduce various hazardous situations and so help us to assess the most vulnerable elements as well as produce recommendations for evacuation procedures which have to change due to an alteration of the environment, such as a change of building layout. In preparing this dissertation, the following 56 evacuation models were reviewed:

VEgAS (Still 2000), EVACSIM (Poon and Beck 1994), SGEM (LO and Fang 2000), EVACNET4 (Kisko and Francis 1985),BuildingEXODUS (Galea and Markatos 1991; Galea and Galparsoro 1994), ELVAC (Klote 1993), Sekizawa model (Sekizawa et al. 2003), PEDGO & AENEAS (Klupfel and

Meyer-Konig 2003), EGRESS (Ketchell et al. 1993), GridFlow (Bensilum and Purser 2002), ASERI (Schneider 2001; Schneider and Konnecke 2001),STEPS (Rhodes and Hoffman 1997), E-Scape (Reisser-Weston 1996), EXITT (Fahy 1991), EXIT89 (Fahy 1991; Fahy 1996), SIMULEX (Thompson and Marchant 1993; Thompson and Marchant 1995), EvacuatioNZ (Ko 2003), BGRAF (Ozel 1985), WAYOUT (Shestopal and Grubits 1994), PathFinder (Cappuccio 2000), Takahashi's model (Takahashi et al. 1988), HELBING MODEL (Helbing and Molnar 1995; Helbing et al. 2000), CRISP II (Boyce et al. 1998; Fraser-Mitchell 2001), Kostreva model (Kostreva et al. 1991) , FiRECAM, PEER, Evi (Vassalos et al. 2001), EvacuShip (Carroll et al. 2003), DRV (Di Gangi et al. 2003), EVAC (Drager et al. 1992; Drager et al. 2001), ODIGO (Pradillon 2003), Pedroute &PAXPORT (Buckmann and Leather 1994), Lovas model (Drager et al. 1992; Lovas 1994; Lovas 1995; Lovas 1998), MASSVAC (Hobeika and Jamei 1985; Radwan et al. 1985; Hobeika and Kim 1998), DYNEV and I-DYNEV (KLD Associates 1984), TEVACS (Han 1990), NESSY-IV (TOSHISUKE 1983) CORSIM (Blue and Adler 1998), NETSIM (Gipps and Marksjo 1985), CEMPS (Pidd et al. 1996; Pidd et al. 1997), OREMS (May 1990), Yamada (Yamada 1996) model, PBS&J model (Post 2000), Smith model (Smith 1991; Kerbache and Smith 2000), Farahmand model (Farahmand 1997), Mamada model(Mamada et al. 2003; Mamada, et al. 2004), Takahashi model (Takahashi et al. 1989; TAKAHASHI and NAKAGAWA 1990) Huang model (Huang, Wei et al. 1998) SHERALI model (SHERALI et al. 1991), Cova model (Cova and Church 1997; Church and Cova 2000; Cova and Johnson 2003), Stern model (Stern and Sinuany-Stern 1989; Sinuany Stern and Stern 1993), HURREVAC, NETVAC1 (Sheffi, Mahmassani et al. 1982),

CLEAR(Moeller et al. 1981).

The categorization has been developed to identify the important characteristics of certain evacuation models. This serves as a checklist which will help model users to choose the appropriate model for the design purpose. It is helpful to understand the differences in the characteristics of various models before making a decision. Different criteria were adopted for classifying the evacuation models. Examples of categories used are: macroscopic, mesoscopic or microscopic, discrete or continuous, stochastic or deterministic, and quantitative or qualitative. Gwynne et al. (1999) summarized three approaches to evacuation analysis; optimization, simulation and risk assessment. Optimization models ignore non-evacuation activities and assume the occupants evacuate in an efficient manner. Simulation models endeavor to embody the behavior and movement exhibited during evacuations to predict decision-making and escape routes. Risk assessment models produce a probability distribution of values by running simulation models repeatedly and thus provide a statistical distribution of evacuation times.

According to the scale of evacuation, either in terms of the traveling distance or the population involved, evacuation models can be classified as small-scale, meso-scale and large-scale. Small scale evacuation refers to circumstance in which a limited population travels a limited distance, e.g., in building evacuations. In contrast, large-scale evacuations involve a large number of people traveling a long distance, e.g., city evacuations. Meso-scale evacuations refer to circumstances in which both the population and the travel distance are between those of small-scale evacuation and large-scale evacuation. A classification of evacuations is given in Fig. 2.5.

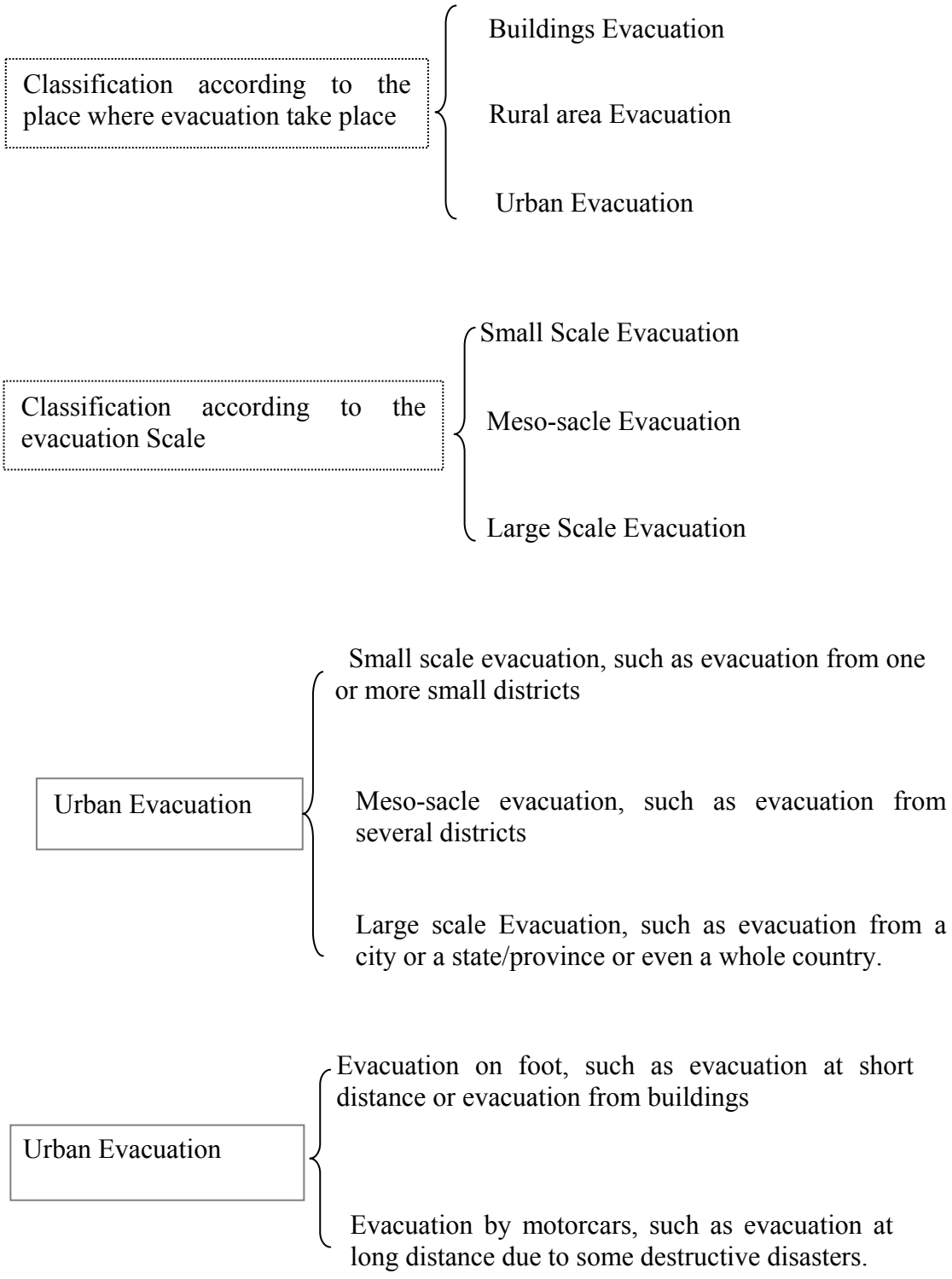


Fig.2. 5 Classification of evacuation models

In accordance with the means of evacuation, these models can be classified as pedestrian evacuation models, in which only evacuation on foot is involved, and traffic evacuation models, in which only evacuation by automobiles is involved.

Performance-based design makes building designers use computer-based models as an alterative method for assessing the safety of buildings which violate proscriptive fire codes or building regulations. The current research reviewed the 33 building evacuation models available at present and found that all of them were developed using the assumption that evacuation on foot was the only available means. Many of them have been widely validated and applied to many engineering problems. Some are still under development, so users should be careful when selecting models for a specific project. The exiting building evacuation models are:

Available Building Evacuation Models

VEgAS (Still 2000), EVACSIM (Poon and Beck 1994), SGEM (LO and Fang 2000), EVACNET4 (Kisko and Francis 1985), BilidingEXODUS (Galea and Markatos 1991; Galea and Galparsoro 1994), ELVAC (Klote 1993), Sekizawa model (Sekizawa et al. 2003), PEDGO & AENEAS (Klupfel and Meyer-Konig 2003), EGRESS (Ketchell et al. 1993), GridFlow(Bensilum and Purser 2002), ASERI (Schneider 2001; Schneider and Konnecke 2001), EGRESSPRO, STEPS (Rhodes and Hoffman 1997), Smith model(Smith 1991; Kerbache and Smith 2000), E-Scape (Reisser-Weston 1996), EXITT (Fahy 1991), EXIT89 (Fahy 1991; Fahy 1996), SIMULEX (Thompson and Marchant 1993; Thompson and Marchant 1995; Thompson and Marchant 1995), EvacuatioNZ (Ko 2003), BGRAF (Ozel 1985), WAYOUT (Shestopal and Grubits 1994), PathFinder (Cappuccio 2000), Takahashi's model (Takahashi, Tanaka et al. 1988), HELBING MODEL (Helbing and Molnar 1995; Helbing, Farkas et al. 2000), CRISP II (Boyce et al. 1998; Fraser-Mitchell 2001), Kostreva model (Kostreva et al. 1991), Evi (Vassalos, Kim et al. 2001), EvacuShip (Carroll et al. 2003), DRV (Di Gangi, Russo et al. 2003) , EVAC (Drage et al. 1992; Drager et al. 2001), ODIGO (Pradillon 2003), Pedroute &PAXPORT (Buckmann and Leather 1994), Lovas model (Drager, Lovas et al. 1992; Lovas 1994; Lovas 1995; Lovas 1998).

Some models were designed for special buildings, such as PEER, Evi (Vassalos et al. 2001), EvacuShip (Carroll et al. 2003), DRV (Di et al. 2003), EVAC (Drager et al. 1992; Drager et al. 2001) and ODIGO (Pradillon 2003) were designed for boat/ships evacuations, and Pedroute &PAXPORT (Buckmann and Leather 1994) were originally designed for bus or other public transportation evacuation. Some models consider a special way of evacuation, such as by elevator ELVAC (Klote 1993), Sekizawa model (Sekizawa et al. 2003), or deal with groups of people with special needs (handicapped, elderly,

those with medical needs, and infants), such as EXIT89 (Fahy 1991; Fahy 1996).

There are other pedestrian evacuation models intended for regional evacuation, such as Yamada's (1996), in which pedestrian evacuation was studied on a city-wide scale, and Takahashi's (Takahashi et al. 1989), in which groups of residents living in a rural area subject to floods are evacuated on foot.

Twenty-one models developed especially for regional evacuation, both of urban districts and whole cities, were reviewed, and most were found to cover only vehicular evacuation. Many models designed for transportation planning and analysis could be modified to model the evacuation process. The current regional evacuation models are:

Available Regional Evacuation Models

MASSVAC (Hobeika and Jamei 1985; Radwan et al. 1985; Hobeika and Kim 1998), DYNEV and I-DYNEV(KLD Associates 1984), TEVACS (Han 1990), NESSY-IV (TOSHISUKE 1983) CORSIM (Blue and Adler 1998), NETSIM (Gipps and Marksjo 1985), CEMPS (Pidd et al. 1996; Pidd et al. 1997) OREMS(May 1990), PBS&J model (Post 2000), Farahmand model (Farahmand 1997), Mamada model (Mamada et al. 2003; Mamada, et al. 2004), Huang model (Huang et al. 1998), SHERALI model (SHERALI et al. 1991), Cova model (Cova and Church 1997; Church and Cova 2000; Cova and Johnson 2003) Stern model (Stern and Sinuany-Stern 1989; Sinuany Stern and Stern 1993), HURREVAC, NETVAC1 (Sheffi et al. 1982) and CLEAR (Moeller et al. 1981) .

Among them, CORSIM (Blue and Adler 1998) and NETSIM (Gipps and Marksjo 1985) were not designed in specifically for evacuations but rather for

ordinary transportation planning. Some models were designed for a specific type of disaster, such as Takahashi's model(1989;1990), the Sherali model (1991) and the Huang model (1998), which are specific to flood evacuation in rural areas, and NETVAC1 (Sheffi et al. 1982) and CLEAR (Moeller et al. 1981), which are specific to nuclear disaster evacuations. NESSY-IV (Toshisuke 1983) was designed for earthquake evacuations. The Mamada model (Mamada et al. 2003; Mamada et al. 2004) and the Sherali model(1991) were designed mainly for optimizing the location of emergency shelters.

In the same way as ordinary transportation models, evacuation models are classified as macroscopic, mesoscopic and microscopic as showed in Fig.2.6 with respect to resolution, i.e., the level of detail regarding the representation of space.

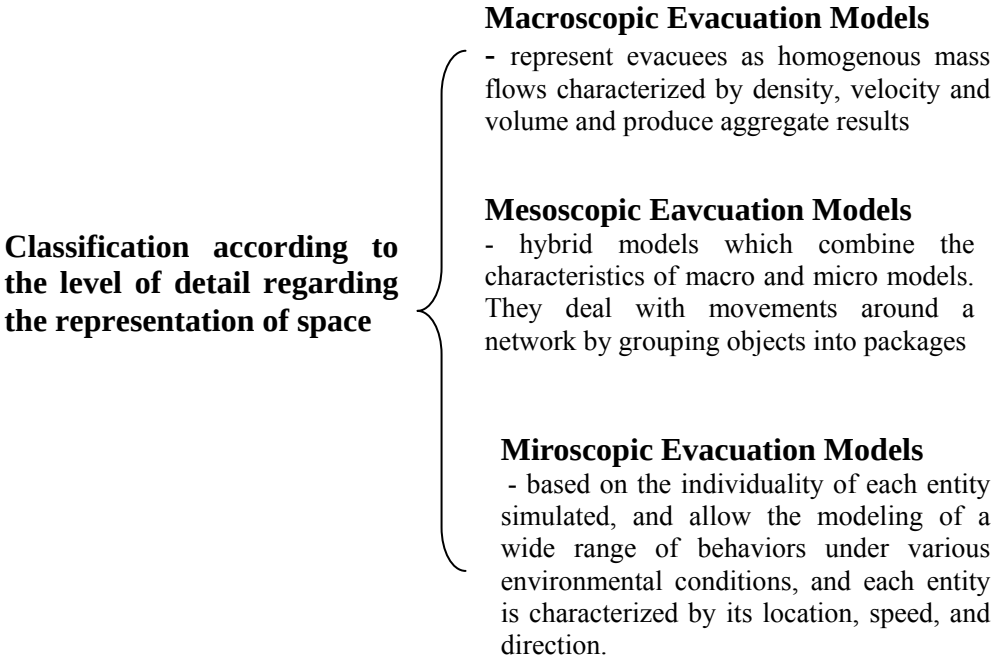


Fig.2. 6 the classification according to the level of detail

The macroscopic models represent evacuees as homogenous mass flows characterized by density, velocity and volume and produce aggregate results.

The existing macroscopic models are:

The Existing Macroscopic Evacuation models

MASSVAC (Hobeika and Jamei 1985; Radwan et al. 1985; Hobeika and Kim 1998), DYNEV and I-DYNEV(KLD Associates 1984), TEVACS (Han 1990), NESSY-IV (TOSHISUKE 1983) CORSIM (Blue and Adler 1998), NETSIM(Gipps and Marksjo 1985), CEMPS (Pidd et al. 1996; Pidd et al. 1997) OREMS(May 1990), PBS&J model(Post 2000), Farahmand model (Farahmand 1997), Mamada model (Mamada et al. 2003; Mamada et al. 2004), Huang model (Huang et al. 1998), SHERALI model (SHERALI, et al. 1991), Cova model (Cova and Church 1997; Church and Cova 2000; Cova and Johnson 2003) Stern model (Stern and Sinuany-Stern 1989; Sinuany Stern and Stern 1993), HURREVAC, NETVAC1 (Sheffi et al. 1982) , CLEAR (Moeller II et al. 1981) .

The Advantages

The advantage of these approaches is their computational efficiency, which makes them quite suitable for real-time applications.

The Weaknesses

The major weakness is that all network effects and human behavior are ignored. That is, such factors as congestion delay by network overloading, and the propagation of delays throughout the network and the interaction of individuals are not taken into account.

Twelve of these models are based on optimization network flows: Yamada (Yamada 1996), Cova (Cova and Church 1997; Church and Cova 2000; Cova and Johnson 2003), Sherali (SHERALI et al. 1991), Farahmand (Farahmand

1997), Smith (Smith 1991; Kerbache and Smith 2000), Lovas (Drager et al. 1992; Lovas 1994; Lovas 1995; Lovas 1998), Ferrante (Ferrante et al. 2000), Mamada et al.(2003; 2004), Takahashi et al(1989; 1990) , Huang (Huang et al. 1998), Kostreva (Kostreva et al. 1991) and EVACNET4 (Kisko and Francis 1985). Some models are based primarily upon establishing the likelihood of events occurring and the final results produced, and these are also called risk assessment models: FiRECAM (Tanaboriboon et al. 1986), CRISP II (Boyce et al. 1998; Fraser-Mitchell 2001), PEER, and EvacuatioNZ (Ko 2003). Lovas (Drager et al. 1992; Lovas 1994; Lovas 1995; Lovas 1998) presented a model for evaluating the performance of evacuation systems for a large and complex building in a probability distribution based on queuing network theory. Cova (Cova and Church 1997; Church and Cova 2000) developed a so-called critical cluster model to identify network and demographic characteristics of real transportation networks and produced vulnerability evacuation maps for a city by integrating with a GIS system, which can be used to identify and evaluate the difficulties of evacuation for a region.

In contrast to macroscopic models, microscopic models are based on the individuality of each entity simulated, and allow the modeling of a wide range of behaviors under various environmental conditions, and each entity is characterized by its location, speed, and direction. The existing microscopic models are:

The Existing Microscopic Evacuation models

SIMULEX (Thompson and Marchant 1993; Thompson and Marchant 1995; Thompson and Marchant 1995), E-Scape (Reisser-Weston 1996), STEPS (Rhodes and Hoffman 1997), EXODUS (Galea and Markatos 1991; Galea and Galparsoro 1994), SGEM (LO and Fang 2000), EVACSIM (Poon and Beck 1994), VEgAS(Still 2000), ASERI (Schneider 2001; Schneider and Konnecke 2001), GridFlow (Bensilum and Purser 2002), EGRESS (Ketchell, Cole et al. 1993), PEDGO & AENEAS (Klupfel and Meyer-Konig 2003), EvacuShip (Carroll, Koss et al. 2003), Evi (Vassalos, Kim et al. 2001), HELBING (Helbing and Molnar 1995; Helbing, Farkas et al. 2000), ODIGO (Pradillon 2003) , PathFinder (Cappuccio 2000), BGRAF (Ozel 1985), Stern model (Stern and Sinuany-Stern 1989; Sinuany Stern and Stern 1993), TEVACS (Han 1990), CORSIM (Blue and Adler 1998), NETSIM (Gipps and Marksjo 1985), CEMPS (Pidd, De Silva et al. 1996; Pidd, Eglese et al. 1997)

The Advantages

The advantages of these approaches are that allow they can model a wide range of behaviors under various environmental conditions.

The Weaknesses

The main shortcoming of microscopic models is that considerable computation time is needed for the preparation of input data, Again, current computer technology has its limitations when a large population or a large scale network is studied.

The Existing Mesoscopic Evacuation models

DYNEV and I-DYNEV (KLD Associates 1984).

The Advantages

The advantage of mescosopic models is that they require less computational power while retaining, in theory at least, the ability to deal with quite detailed stochastic events. They can therefore be used to simulate and evaluate the evacuation planning of a larger scale network with a large population, and can be used for guiding and planning evacuation routes in real-time applications.

The Weaknesses

Obviously, the weaknesses are that they are less computational efficiency than macroscopic models and can only model the detailed behavior of evacuee at a medial level.

Table 2.1 lists all the available evacuation models and classifies them according to the following properties:

- **Application area**:

Indicates the purpose of the model. B indicates that the model was developed for building evacuations, C for city evacuations and O for other areas such as special facilities, buses or ships.

- **Nature of model application:**

Indicates the methodology adopted for modeling the process of evacuation; an optimization model, simulation model or risk assessment model.

- **Population representation**:

Represents how the model views the evacuation network and evacuees.

There are three ways that a model can view the evacuees; macroscopic, microscopic or mesoscopic, as discussed above.

- **Behavior involved**:

This is presented according to Gwynne's classification of, building evacuation modes. According to this classification, the following kinds of behavior occur: non-behavior (Non), which denotes that none of behavior is modeled during simulation; implicit behavior, which denotes that behavior is implicitly modeled by assigning certain response delays or occupant characteristics; rule-based behavior, which denotes that individual actions or groups of occupants are affected by the structural or environmental conditions of the evacuation (as an "if, then" behavioral method); functional analogy behavior, which represents that equations are taken from another field of study, such as Physics, to represent occupant movement; and AI-based behavior, which indicates that Artificial Intelligence resembles the models that attempt to simulate human intelligence throughout the evacuation.

Table 2. 1 Summary of the evacuation models available

NAME OF MODEL	APPLICATION AREA	NATURE OF MODEL APPLICATION	POPULATION PRESENTATION	BEHAVIOR INVOLVED
SIMULEX	Building	Simulation	micro	Implicit
The algorithms for the movement of individuals adopted in this model are based on real-life data collected using computer-based techniques for the analysis of human movement observed in real life. They have produced realistic parameters of motion for people moving through different types and geometries of door exits. Simulex accurately models the physical shape and motion of each individual person, including side-stepping, overtaking patterns, speed fluctuations, queuing behavior, body-twisting, and a choice of different exits using the automatic route-assessment functions.				
EXIT89	Building	Simulation	macro	Implicit
EXIT89 is designed to simulate the evacuation of large, high occupancy buildings, such as high-rises. The model can handle some of the most relevant components of evacuation scenarios in the evaluation of engineered building designs from a fire safety standpoint. These include: Accounting for occupants with a range of motilities, including disabled occupants and young children. Delay times, both those that can serve as surrogates for specific pre-movement activities that are set by the user at each location, and random additional delays that can account for the variability in start times among building occupants. A choice of routing options: the use of model-calculated shortest routes that can accommodate the simulation of an evacuation with a well-trained and/or				

<table>
<tr><td colspan="5">staff-assisted occupant population, or the use of user-specified directed routes that can accommodate the simulation of an evacuation where occupants are more likely to follow familiar exits or ignore available emergency exits.
Contra-flows which will occur during an evacuation when obstructions develop along the travel paths.
Travel both up and down stairways, which allows the extension of this model to buildings with occupied floors below grade level, as well as buildings where the path of some occupants will be up rather than down stairs. Occupants are more likely to follow familiar exits or ignore available emergency exits.</td></tr>
<tr><td>EXITT</td><td>Building</td><td>Simulation</td><td>macro</td><td>Rule-based</td></tr>
<tr><td colspan="5">EXITT is a sub-program in HAZARD and incorporates some behavioral aspects in its model. It simulates the occupants based on a global perspective in a deterministic way and produces optimal escape routes in a shortest path algorithm. In addition, the model will recalculate the escape routes if a location is blocked by smoke. However, it does not have queuing effects; therefore it is limited to large buildings or high population density premises. A unique feature is the behavioral rules that were developed from interviews with survivors of fires recounting their actions.</td></tr>
<tr><td>E-Scape</td><td>Building</td><td>Simulation</td><td>macro</td><td>Rule-based</td></tr>
<tr><td colspan="5">The model considers two factors as fundamental: the time taken for occupants to initiate egress, and the egress route adopted.</td></tr>
</table>

STEPS	Building	Simulation	micro	Rule-based
STEPS adopts advanced visualization techniques to produce realistic, detailed real-time 3D simulations that are easily interpreted by designers and emergency service personnel, helping identify bottlenecks and preferred exits as well as testing evacuation routes and times for different emergency scenarios. It can model any environment, incorporating blockages or restrictions such as doorways, seating or kiosks and simulating lift and escalator speed and capacity plus arriving/departing trains and buses. STEPS can assign people with specific individual characteristics to account for factors such as age, gender, patience, fitness levels, size of baggage carried and familiarity with exit routes. It can also specify how individuals will react to their particular surroundings and one another. Another unique feature is its ability to change conditions during evacuation, as in real life.				
EXODUS	Ship & Building	Simulation	Micro	Ruled based
EXODUS is agent-based software which attempts to take into consideration people-people, people-fire and people-structure interactions. The model tracks the trajectory of each individual as they make their way out of the enclosure, or are overcome by fire hazards such as heat, smoke and toxic gases. The model comprises five core interacting sub-models, the Occupant, Movement, Behavior, Toxicity and Hazard sub-models. The Behavior Sub-model functions on two levels. These are known as GLOBAL and LOCAL behavior. GLOBAL behavior involves implementing an escape strategy that may lead occupants to exit via their nearest serviceable				

<table>
<tr><td colspan="5">exit or most familiar exit. The occupants' familiarity with a particular building may be determined by the user prior to commencing the simulation. It is also possible to assign individuals an itinerary of tasks that must be completed prior to evacuation, such as visiting a pre-defined location.
The spatial dimensions within buildingEXODUS are spanned by a two-dimensional spatial grid and the progressive motion and behavior of each individual are determined by a set of heuristics or rules. The building layout can be specified using either a DXF file produced by a CAD package, or the interactive tools provided, and may then be stored in a geometry library for later use.</td></tr>
<tr><td>EVACNET4</td><td>Building</td><td>Optimization</td><td>macro</td><td>Non</td></tr>
<tr><td colspan="5">EVACNET4 employs a flow-based approach in which the densities of nodes are in continuous flow. It enables users to construct a simulated physical environment as a network of nodes. The nodes represent physical structures such as rooms, stairs, lobbies, and hallways that are all connected and comprise a single structure from which an evacuation is executed. EVACNET4 determines an optimal plan for evacuating the building in a minimum amount of time using an advanced capacitated network flow transshipment algorithm, a specialized algorithm used in solving linear programming problems with network structures.</td></tr>
<tr><td>SGEM</td><td>Building</td><td>Simulation</td><td>micro</td><td>Game theory</td></tr>
<tr><td colspan="5">The model resolves the setting of a building into a network with nodes representing enclosed spaces (zones) with at least one opening that serves as the arc of the network. The possible escape direction of each zone can be</td></tr>
</table>

<table>
<tr><td colspan="5">found by analyzing the function of each zone (the usage of the room) and the geometrical location and way-finding tendency of the evacuees. The movement of evacuees is solved by a series of difference equations within a finite grid of cells that is generated within a zone. The trajectory of each individual is recorded and the evacuation pattern can be visualized within the AutoCAD environment. SGEM simulator and VR presentation (output module). The AutoCAD recognition processor facilitates the process of transforming computer-drawn architectural plans into the evacuation network outline. The SGEM simulator performs the calculations to determine the relative positions of each evacuee at any point of time, and the VR presentation provides visualization of the whole evacuation process.</td></tr>
<tr><td>EVACSIM</td><td>Building</td><td>Simulation</td><td>micro</td><td>Rule based</td></tr>
<tr><td colspan="5">This model uses the QNAP2 network analysis tool to represent the behavior of occupants in relation to congestion and route-finding and is built around four aspects of the simulation process: the Network Model, the Simulation Process, Animation and the Presentation of Results.</td></tr>
<tr><td>VEgAS</td><td>Building</td><td>Simulation</td><td>micro</td><td>AI based</td></tr>
<tr><td colspan="5">This model uses simulated annealing and cellular based approaches and considers the interaction of four parameters: Objective, Motility, Constraint and Assimilation. The model can simulate how people read and react to their environment in a variety of conditions, which allows the user to study a wide range of crowd dynamics in different geometries and highlights the interaction of the crowd with its environment.</td></tr>
</table>

EGRESSPRO	Building	Simulation	Macro	Non
Based on ideas from the SFPE Handbook of Fire Protection Engineering, the model calculates the response of sprinklers/heat or smoke detectors and evaluates the response behavior of people from the time of an alarm to the end of the egress from rooms, floors or buildings on fire. The program predicts the flow of groups of persons in emergencies based on the relationship between speed of movement and the population density.				
ASERI	Building	Simulation	micro	Rule based
An individual-based model of egress movement in complex geometries, including behavioral response to smoke and fire spread and evacuee's movement governed by certain behavioral aspects that are triggered by external stimuli.				
GridFlow	Building	simulation	micro	unknown
This model takes into consideration the pre-movement activities of humans, defined by a mean and standard deviation obtained from experimental evacuations.				
EGRESS	Building	Simulation	micro	AI Based
The model is based on artificial intelligence techniques and represents the decision-making process during the evacuation and how individuals react to a specific event type through the use of equations, which define responses. EGRESS is able to represent and predict a number of evacuation phenomena including the formation of high density crowds and the time needed to clear specific locations.				

PEDGO & AENEAS	Building	Simulation	micro	multi-agent
The model simulates the behavior of each individual using several parameters: maximum walking speed, patience before individual selects a new route, a factor determining visual perception of the surrounding conditions, a delay time determining the amount of time that the individual will wait before attempting to evacuate, a dawdle probability determining time when an individual will delay en route in order to wayfind or recuperate, and a factor that represents the inertia of the person's movement.				
Sekizawa model	Elevator	Simulation	Macro	Non
This model mimics the behavior of an elevator, such as its speed and/or capacity, as well as the priority of floors, and can examine quantitatively both the performance and the applicable strategy of elevator in evacuation.				
ELVAC	Elevator	Simulation	macro	Non
An interactive computer program which estimates the time required to evacuate people from a building with the use of elevators and stairs. It includes detailed analysis of elevator car travel, including constant acceleration, transitional acceleration, constant velocity, transitional deceleration, constant deceleration, and leveling.				
FiRECAM	Building	Risk Assessment	macro	Non
It assesses the expected risk to the life of an occupant in a building in all probable fire scenarios over the design life of the building, and the fire				

protection costs (capital and maintenance) and expected fire losses.				
Kostreva	Building	Optimization	macro	Non
This is a network based model and adopts a dynamic programming equation. A multi-attribute analysis is proposed to evaluate a building design with respect to evacuation paths.				
CRISP II	Building	Risk Assessment	macro	non
An object oriented software developed for the deterministic simulation of fire hazards. The model covers random aspects by using Monte Carlo to estimate fire risk in a given building.				
Pedroute & PAXPORT	Public Transport	simulation	macro	Implicit
This is the extension of Fruin's Level of Service and it relies on logistical statements to model human interaction. It is a computer simulation system which was originally developed to model crowd parameters in underground networks.				
EVAC	Ship	Simulation	micro	Rule-based
EVAC is derived from EVACSIM, and the actual evacuation is modeled as a statistical stochastic process known as a stationary Markov process.				
DRV	Ship	Simulation	Macro	unknown
Groups of passengers are treated as packets and move along the network in groups. Within each packet, all passengers are assumed to experience the same traffic conditions.				
EvacuShip	Ship	Simulation	micro	unknown

The model is able to represent the impact of heave, sway, pitch, yaw and roll upon the mobility of the passengers.				
Evi	ship	Simulation	micro	Rule-based
Evi treats agents within the model as moving in a "command" and "decision" structure. This is modeled by attributing "genes" to individual agents, so that the activity of the gene influences the behavior of, for example, family members trying to regroup, children following parents, parents searching for their children at the onset of a fire scenario, as well as simulating behaviors such as passengers returning to their cabins or getting lost, or even exhibiting panic.				
HELBING	Building	Simulation	micro	Panic
A microscopic evacuation model in which the movement of people is based on the concept of gas-kinetics.				
ODIGO	Ship	Simulation	micro	AI
It is possible to specify various events and scenarios in this model, such as fire, list, blocked escape routes etc. but the impact is specific. It produces quantitative results, with relevant evacuation times, and is able to identify bottlenecks and areas of congestion, as well as assess the egress routes adopted and the suitability of location of obstacles.				
PEER	ship	assessment	macro	Non
It is designed specifically for the analysis of offshore installations and uses the Monte Carlo simulation technique to model some of the events which occur during the course of a simulation stochastically.				
PathFinder	Building	Simulation	micro	Non

This model incorporates speed reductions based on the density of the space and the capacity of the doors and stairways. The primary areas of analysis focus on movement in open spaces, on stairways, and through doorways.				
WAYOUT	Building	Simulation	macro	non
The movement of the occupants is based on density vs. speed data collected by Predtechenskii and Milinskii and the model considers flows throughout the route from door to door of each compartment.				
Huang model	flood	Optimization	macro	Non
A location-allocation model, based on the minimal cost flow and GIS technique, for dispatching flood victims to their best emergency shelters.				
Takahashi	Flood	Simulation	macro	Non
The model was developed to evacuate rural areas prone to flood disasters. It simulates the evacuating action of groups of residents linked with a simulation of an overland flood due to river bank breach.				
Mamada	Urban	optimization	macro	Non
An efficient algorithm for evacuation guidance and transportation network design to optimally locate safety facilities.				
Ferrante model	Flood	optimization	macro	Non
This model incorporates both flood propagation and evacuation planning. The reduced efficiency of transportation due to the flood is evaluated based on a least-flood-risk path-finding algorithm.				
Lovas	Urban	optimization	macro	Non
This model presents a methodology for modeling evacuation systems and shows how queuing network theory and simulation methods can be used to				

calculate the performance of a large, complex building with many occupants.				
BGRAF	Building	Simulation	micro	unknown
This model takes into consideration individual characteristics such as walking speed, occupant mobility status, alertness, smoke tolerance, and the occupant's initial location in the building.				
EvacuatioNZ	Building	risk assessment	macro	non
Human behavioral aspects such as the pre-movement time and the choice of exit are modeled in detail.				
Smith	Building	Optimization	macro	non
This model enhances the class of queuing network models by adding state-dependent queuing models to capture the nonlinear effects of increased occupant traffic flow along emergency evacuation routes. It can be used to optimize the topological structure of buildings during the design stage.				
Farahmand	Flood evacuation	Optimization	macro	non
This model was developed to predict with a certain degree of probability the optimal escape routes from the coastal areas and it can provide information on where traffic bottlenecks may be expected. It can be used to assist the authorities in designating official evacuation routes away from a storm.				
SHERALI	Urban	Optimization	Macro	Non
A location-allocation model for determining a set of viable shelter locations from among a given set of admissible alternatives and then assigning the traffic on the network in a user's optimization method.				
Cova	Urban	Optimization	Macro	Non

This model adopts a network flow model for identifying optimal lane-based evacuation routing plans in a complex road network. The model is an integer extension of the minimum cost flow problem. It can be used to generate routing plans that trade total vehicle travel-distance against merging, while preventing traffic crossing-conflicts at intersections. A mixed-integer programming solver is used to derive optimal routing plans.				
STERN	URBAN	SIMULATION	MICRO	RULE-BASED
A behavioral-based simulation model for spontaneous urban evacuation is used to examine the sensitivity of network clearance times using several traffic factors (e.g. interaction with pedestrians, intersection traversing time, and car ownership) and route choice mechanisms (shortest path and myopic behavior). This is a micro traffic simulation model based on stochastic simulation of series of events in a radiological emergency situation. Evacuation time comes closer to reality when interaction with pedestrians and a uniform distribution of intersection traversing time are assumed. More realistic results are also found whenever routes are selected according to the maximal distance from the last car. The sensitivity of clearance time to population growth and car ownership indicates that the model can be easily applied to cities of various sizes.				
HURREVAC	hurricane	Simulation	Macro	non
The program tracks hurricanes and helps users make evacuation decisions for their communities.				
NETVAC1	Nuclear accidents	Simulation	Macro	non

<table>
<tr><td colspan="5">This model is comprised of two modules, the link pass and node passes. The link pass moves vehicles along each link, determining the number of vehicles which reach the link exit queue during the particular simulation interval, and the node pass determines the turning movement. It is specifically designed to model evacuation traffic patterns including queue formation processes, dynamic route selection, and a wide variety of options designed to simulate alternative evacuation scenarios (in terms of weather, intersection controls, lane management strategies, and so forth).</td></tr>
<tr><td>CLEAR</td><td>Nuclear accidents</td><td>Simulation</td><td>Macro</td><td>non</td></tr>
<tr><td colspan="5">CLEAR (Calculating Logistic Evacuation and Response) is a macroscopic model developed to estimate the time required for a population of a specified density and distribution to evacuate from an area using a specified transportation network. It calculates the velocity of traveling on the road as a function of vehicles' density. In accounting for the delay of vehicles in traffic queues, the model also considers the distribution of times required by the individuals to prepare for an evacuation.</td></tr>
<tr><td>MASSVAC</td><td>urban</td><td>Simulation</td><td>Macro</td><td>non</td></tr>
<tr><td colspan="5">MASSVAC is a macroscopic computer simulation model developed for the analysis and evaluation of evacuation plans for urban areas threatened by natural disasters. The model takes the network geometry, the natural disaster type and severity and the socio-economic parameters of the threatened as input parameters, and produces outputs such as network clearance times, best evacuation routes by zone, optimum shelter locations, and sites of possible traffic bottlenecks, and develops proper traffic management strategies to</td></tr>
</table>

alleviate them. MASSVAC 3.0 utilizes all-or-nothing traffic assignment or Dial's algorithm to simulate the traffic movements during evacuation and loads evacuating vehicles onto the highway network according to loading rate curves.

MASSVAC 4.0, which incorporates new modeling features such as the user equilibrium (UE) assignment algorithm, can represent the dynamic characteristics of traffic flow onto the network. Vehicles from each origin are loaded onto the network through an assignment-simulation process. This can be adopted to investigate the features of the UE algorithm in evacuation modeling and compare the differences between the UE deterministic method and Dial's stochastic method.

DYNEV and I-DYNEV	Urban	Simulation	Meso	non

DYNEV (Dynamic Network Evacuation) model was developed by KLD Associates, Inc. It is a macroscopic model for simulating evacuation from sites around a nuclear power plant, and employs the principles of flow continuity and flow dynamics. I-DYNEV is an evacuation modeling system derived from DYNEV but with improved operational characteristics in certain areas. I-DYNEV system consists of three distinctive models:

A macroscopic, deterministic traffic simulation model;

An equilibrium traffic assignment model;

An intersection approach traffic capacity model.

The models are applicable to a general system of roads including freeways with access control, rural roads, and urban arterials. The types of traffic control used in the model include traffic signals, stop and yield signals, and no control. It estimates evacuation travel time, moving time, delay time, mean

speed, and so on. The IDYNEV model differs from DYNEV in the way it computes the number of vehicles leaving a roadway segment. The improved computational efficiency serves to substantially reduce the computing time and storage.				
TEVACS	Urban	Simulation	Micro	non
It was developed to help an emergency managers make decisions about evacuation planning. The model consider two factors specific to Taiwan: the need for public transportation as a means of evacuation and the characteristics of mixed traffic.				
NESSY-IV	Earthquake	Simulation	Macro	non
The network in this model consists of two kinds of flows, mass flow and information flow. It is sensitive to the operating characteristics of the transportation network and the behavioral characteristics of the evacuated population. It can identify the potential bottlenecks within the network and their location and delay.				
CORSIM	Transportation planning	Simulation	Micro	non
This is a combination of two other micro-simulators, the urban micro-simulator NETSIM and the freeway micro-simulator FRESIM, and has the ability to predict congestion development and dissipation with acceptable accuracy.				
NETSIM	Transportation planning	simulation	Micro	non

This is a microscopic, stochastic highway traffic simulation model and keeps track of every individual vehicle in the system, including an array of characteristics relating to the vehicle type and the behavior of its driver in various traffic situations. It can be used to simulate traffic performance using different control strategies and for heavy traffic.				
CEMPS	Urban	Simulation	Micro	non
CEMPS (Configurable Evacuation Management and Planning Simulator) is a prototype SDSS that has been developed through the integration of a simulation model with GIS to benefit evacuation plans. It attempts to track the detailed movement of individual entities (such as vehicles or persons), and can simulate the real-life factors such as the route choices of evacuees during evacuations, spill-back arising from traffic congestion, and breakdowns of vehicle. It comprises four major components: traffic simulation model, GIS, an integrating link module, and a user interface. The traffic simulator simulates the behavior of individual entities on the road network on their journey to the shelter while GIS provides the dynamic mapping output of the simulation as it progresses.				
OREMS	Urban	Simulation	Micro	non
REMS (Regional Evacuation Modeling System) is a decision support system capable of testing different emergency scenarios which arise from hurricanes, chemical accidents or nuclear accidents. The underlying models are optimization models based on a regional transportation network. One of the most significant aspects of the model is its ability to handle a problem's time dimension explicitly, and it is this aspect of REMS that makes incorporation of road blockages due to the presence of extremely hazardous substances, or				

<table>
<tr><td colspan="5">inundation of roads due to accidents or flooding, possible in evacuation scenario test. The analytical core of OREMS is ESIM (Evacuation SIMulation), which combines a trip distribution and traffic assignment sub-model with a detailed traffic flow simulation sub-model. The combined trip distribution and traffic assignment sub-model was developed by the researchers at ORNL, and the traffic simulation model was derived primarily from the TRAF simulation system developed by FHWA and therefore has many similarities with that system.</td></tr>
<tr><td>Yamada</td><td>Urban</td><td>Optimization</td><td>Macro</td><td>non</td></tr>
<tr><td colspan="5">This model adopts a minimum-cost flow problem to assign and allocate evacuees to their optimal shelters at the city level.</td></tr>
</table>

2.7 Summary of Literature

Handling of natural and man-made disasters places great demands on emergency managers. Some of these disasters are small and can be effectively handled by local authorities and resources, while other disasters may be larger or spread over a large geographical area and therefore require coordination of authorities and resources in many localities, as well as authorities at a higher level, as in the case of large earthquakes and terrorist activities. Emergency managers are under great pressure to make decisions which will handle these complicated situations within minutes. Recent developments in operations research methods and technology (mathematical optimization, simulation), artificial intelligence (knowledge-based systems, pattern recognition), and information management (network based, platform independent, GIS) enable decision support and process management systems to handle major disasters in

ways that would not have been possible a few years ago.

Detailed discussion of the elements involved in emergency management is beyond the scope of this thesis. We focus our attention instead on one of the core modules of emergency management, emergency traffic, and 56 models have been summarized in this chapter. Of these, 20 models were designed for regional evacuation and 35 for building evacuations, 12 of which adopt an optimization approach, 40 adopt a simulation-based approach and 4 adopt a risk assessment approach. Their application areas, methodology and distinct characteristics were illustrated and compared. It was noted that each model has its advantages and disadvantages, so it is the responsibility of users themselves to choose the most suitable one to perform simulation and analysis according to their specific objectives and the resources at hand. As computer technology advances, more and more individual-based models are being developed which can incorporate many complicated individual parameters, such as the mean speed, the route selection action and physical fitness. Generally speaking, computer-models can be used as a testing ground for designers or managers for analysis and evaluation. However, these complicated parameters do not necessarily guarantee a more reliable result, or may even worsen it, and current models have some limitations and disadvantages:

(i) The models divide emergency traffic into pedestrian traffic and vehicular traffic. None of them has considered the two kinds of activities together and so they can only be used for a specific objective. In fact, it is inevitable that both kinds of evacuations coexist and interact with each other in large-scale evacuations, and in densely populated areas it is pointless to merely consider vehicular evacuation.

(ii) The methodology adopted by these models is either simulation-based or an optimization approach. The former focuses on the macroscopic behavior of mass flows while the latter pays attention to individuals' characteristics. No model takes both features into consideration. In fact, optimization-based approaches provide us with the most optimal results and can be used as benchmarks in the planning stage. The simulation-based approach can provide more variable scenarios and enrich our understanding of the inter-processes involved. So a combination approach (integrating the simulation approach and optimization approach) would be helpful to emergency managers and would aid planning and action.

(iii) Most regional evacuations are either micro-based models or macro-based models. Only one meso-based evacuation model has been developed. Since the hybrid of micro and macro model is beneficial both in describing the individual behavior at a middle level and in terms of computational efficiency, it can provide us with reasonable results closer to real scenarios. Furthermore, because of its simplicity and efficiency it can be adopted for real-time applications. So more meso-based models are needed for the analysis of large-scale evacuations, such as of cities or states.

(iv) The current optimization algorithms adopted in evacuation models are mostly based on static networks. During an emergency, the throughput capacity of roads or exits is a time-dependent variable and may decrease or be cut off because of adverse environments such as fires, floods or lethal gas. Comprehensive evacuation planning should take into account

these time-varying parameters and present an optimal or sub-optimal evacuation plan. So dynamic networks should be used to characterize dynamic features of networks during an emergency evacuation. Currently, only one evacuation model has been developed based on a dynamic network, Evanet, but it is time-independent. An evacuation model based on time-dependent dynamic network flow is urgently needed.

Chapter 3

A Pedestrian Evacuation Model

In this chapter, an improved random walk model for pedestrian evacuations was proposed. Many interesting phenomena related to pedestrian movement, such as panic evacuation, lane formation of bi-direction pedestrian flow, were studied. This evacuation model was applied in a subway evacuation analysis and an interesting and counter-intuitive phenomenon, known as Braess's Paradox (Pas and Principio 1997), was observed.

3.1 Introduction

The safety of occupants depends very much on the design and operation of the escape system of buildings they are in. In order to ensure that buildings are constructed adequately in terms of safety, building codes and fire codes in various countries provide guidelines for building designers in the design stage and judgment criteria for government managers in the evaluation process. However, it is hard to say to what extent these codes can provide a satisfactory level of safety, even if the escape system of buildings complies with prescriptive building codes. As an alterative, the United Kingdom, New Zealand, Australia, Sweden, Hong Kong and many other developed countries/cities are moving away from prescriptive building/fire codes and towards a performance based approach (Lo et al. 2004).

Simulation models can provide a versatile and cost-effective way for designers, fire engineers and managers to implement performance-based fire

assessment by reproducing various hazardous situations, helping identifying the most vulnerable elements, and generating recommendations for evacuation procedures. Many researchers have developed computer-based evacuation models, which can be used to simulate the movement of evacuees subject to a fire disaster and can provide valuable information to help building designers to design the circulation paths and exits of a building in an optimal or sub-optimal way. As mentioned in Chapter 2, more than 35 evacuation models have been developed specifically for building evacuation and they provide valuable information for fire specialists who perform fire safety engineering analysis. The best known models are: EXODUS (Galea and Markatos 1991; Galea and Galparsoro 1994; Gwynne et al. 1999), SIMULEX (Thompson and Marchant 1995; Thompson and Marchant 1995), EGRESS (Ketchell et al. 1993), VEGAS (Still 2000), SGEM (LO and Fang 2000; Zhi et al. 2003; Lo et al. 2004), EXIT89 (Fahy 1991; Fahy 1996), EXITT (Levin 1998), EVACNET (Kisko and Francis 1985).

3.2 Random Walk Model

Nagatani et al. (Tajima et al. 201; Nagatani 1993; Muramatsu et al. 1999; Muramatsu and Nagatani 2000; Tajima and Nagatani 2001; Takimoto and Nagatani 2003) developed a driven random walk model for pedestrian motion. The pedestrians move on a square lattice. The size of the cell is the average size of an adult, 40cm×40cm. pedestrians are allowed to move one cell per time step in three directions namely, forward, upward, downward, with different transition possibilities $p_{t,x}$, $p_{t,y}$, $p_{t,-y}$.

Each grid has a set to illustrate its state, 0 indicates the cell is void, and 1

indicated that it is occupied by one person. Pedestrians move in a particular direction according to rules shown in Figure 3 with no back step. The exclude-volume effect is taken into account, so one cell can accommodate no more than one person at each step and walkers are inhibited from overlapping on the cell. Equations (a-h) list all the possible configurations of a walker and their transition possibilities. A parameter was introduced by Nagatani(1993) called drift point D ranging from 0~1, indicating the randomness during movement. The smaller D is, the larger the randomness during movement. Certainly, D=0 denotes a total random walker without direction, while D=1 represents a walker moving strictly in the target direction without randomness.

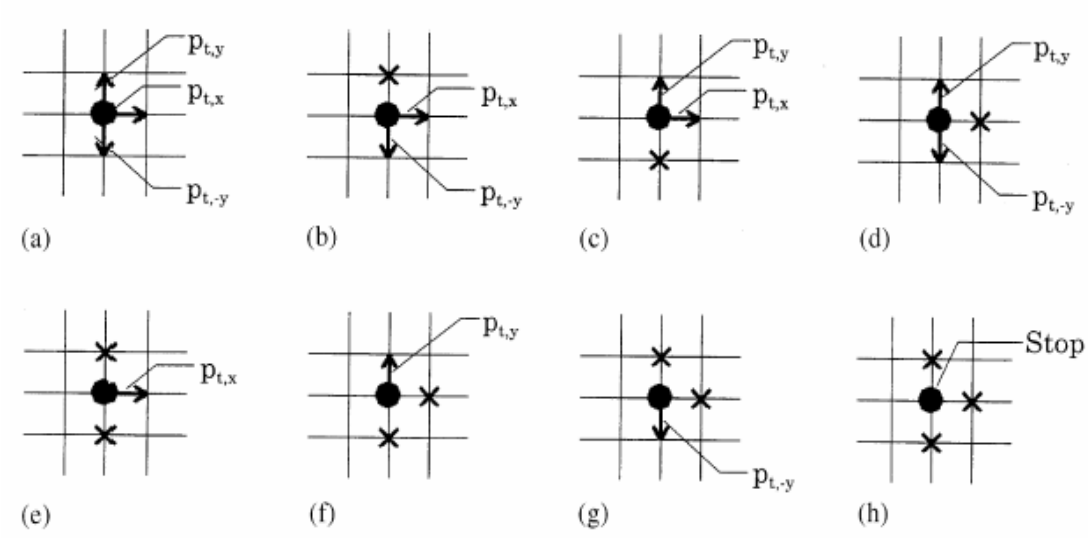


Fig.3. 1 Possible configurations of a walker on the square lattice

Note: The walker is indicated by the solid circle. The cross point indicates the site occupied by others. Each walker can hop only to the unoccupied nearest neighbors. D *is Drift point.*

$$p_{t,x}=\mathrm{D}+(1-\mathrm{D})/3,\ p_{t,y}=(1-\mathrm{D})/3,\ p_{t,-y}=(1-\mathrm{D})/3 \tag{3.1}$$

for configuration (a)

$$p_{t,x}=\mathrm{D}+(1-\mathrm{D})/2,\ p_{t,y}=0,\ p_{t,-y}=(1-\mathrm{D})/2, \tag{3.2}$$

for configuration (b)

$$p_{t,x}=\text{D}+(1-\text{D})/2,\ p_{t,y}=(1-\text{D})/2,\ p_{t,-y}=0, \tag{3.3}$$

for configuration (c)

$$p_{t,x}=0,\ p_{t,y}=0.5,\ p_{t,-y}=0.5, \tag{3.4}$$

for configuration (d)

$$p_{t,x}=1,\ p_{t,y}=0,\ p_{t,-y}=0 \tag{3.5}$$

for configuration (e)

$$p_{t,x}=0,\ p_{t,y}=0,\ p_{t,-y}=1 \tag{3.6}$$

for configuration (f)

$$p_{t,x}=0,\ p_{t,y}=1,\ p_{t,-y}=0 \tag{3.7}$$

for configuration (g)

$$p_{t,x}=0,\ p_{t,y}=0,\ p_{t,-y}=0 \tag{3.8}$$

for configuration (h)

3.3 A competitive Random Walk Model

Note that for Takashi's model, for all the configurations (a-g), the summation possibility of movement $p_{t,x}+p_{t,y}+p_{t,-y}$ always equals 1 except for configuration h, which indicates that the possibility of movement in Nagatani 's model is always 100% if any one of three cells around is void, i.e., with the state of 0.

In reality, each person has his inclination of movement at each step. For example, the elderly are less inclined to move than adults are, and men are more inclined to move than women. So it is not necessary for pedestrians to move around at each step even if free space is available around them. The person may

stop for a short rest or for information gathering so as to adjust his movement.

Another parameter $\vartheta \in [0,1]$, which represents the likelihood of movement of a person at each step, was introduced. ϑ for man is larger than for woman, and for the adult is greater than for the old. With this definition, the possibility of movement at each step is scaled down ϑ times. For example for the configuration (a) in Figure 3.1, the transition possibility is changed as following:

$$p_{t,x} = \vartheta \times (D + (1-D)/3) \tag{3. 9}$$

$$p_{t,y} = \vartheta \times (1-D)/3 \tag{3.10}$$

$$p_{t,-y} = \vartheta \times (1-D)/3 . \tag{3.11}$$

and then $p_{t,x} + p_{t,y} + p_{t,-y} = \vartheta$. The transition possibilities for all configurations (a-h) are adjusted in the similar way.

If more than one person select a cell at the same time, as in Figure 3.2, cell [i][j] is void (cell[i][j]=0), and his three neighbors, i.e., cell[i][j-1], cell[i][j+1](=1), and cell[i-1][j](=1), are occupied, each with a possibility to cell[i][j] $p_{t,y}(i, j-1)$, $p_{t,-y}(i, j+1)$, $p_{t,x}(i-1, j)$ respectively. The summation of the transition possibility of the three persons moving to cell [i][j] is:

$$\text{P}= p_{t,x}(i-1, j) + p_{t,y}(i, j-1) + p_{t,-y}(i, j+1) \tag{3.12}$$

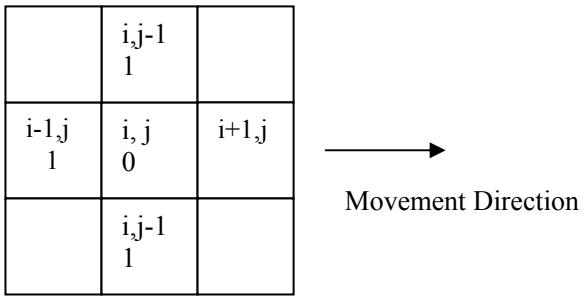


Fig.3. 2 More than one person choose one cell

Then the actual possibility of a person at cell [i-1] [j] to cell [i] [j] adjusts accordingly: $p_{t,y}(i, j-1) = \frac{p_{t,x}(i-1, j)}{P}$ [1-Cell[i][j]], and similar adjustments are applied for $p_{t,-y}(i, j+1)$ and $p_{t,x}(i-1, j)$.

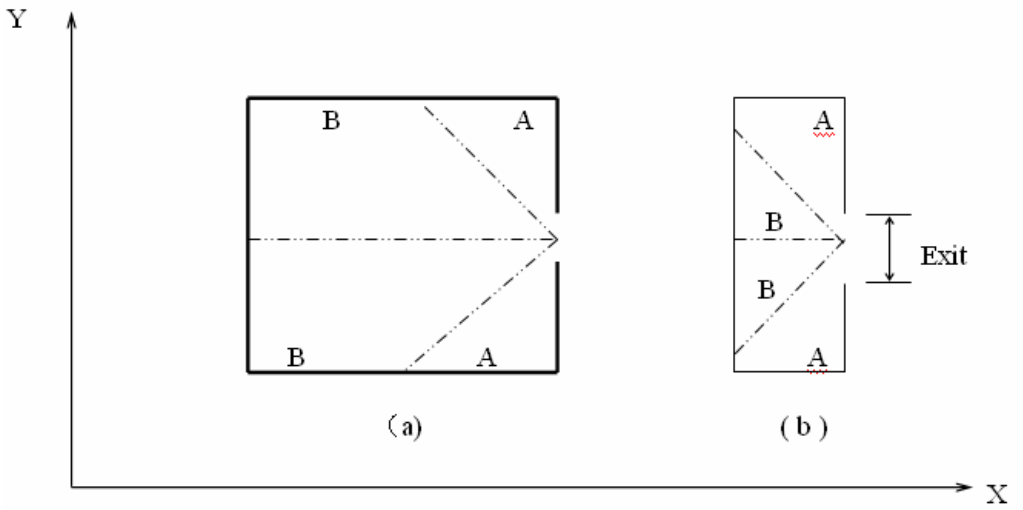


Fig.3. 3 Schematic picture of room divided by many districts

From rules (a-h), we find that when a person moves ahead, the transition possibility in x direction always takes priority, except for a total random walker (D=0). If D>0, the transition possibility $p_{t,x}$ for configuration a-c is always larger than the other two, i.e., $p_{t,y}$ and $p_{t,-y}$. This model ignores the behavior of a person adjusting his direction continuously during moving according to his current position and target location. As shown in Figure 3.3, a person in a room located at position (x, y) selects the exit (x_0, y_0) as his target. If $\frac{|x-x_0|}{|y-y_0|}$>=1, which means that he is located at area B, he will move ahead by taking x as his

priority direction. If $\frac{|x-x_0|}{|y-y_0|}<1$, which means that he is located at area A, he will select y as his priority direction. Only after the determination of the priority direction can he judge his transition possibility according to the states of his neighbors. Then he will move either upward, right, or left according to his transition possibility. The transition possibility is defined in a similar way as $p_{t,y}$, $p_{t,x}$, $p_{t,-x}$ respectively, which represents the possibility of moving upward (downward) or turning left (right).

$$p_{t,y}=\text{D}+(1\text{-D})/3,\ p_{t,x}=(1\text{-D})/3,\ p_{t,-x}=(1\text{-D})/3 \tag{3.13}$$

for configuration (a)

$$p_{t,y}=\text{D}+(1\text{-D})/2,\ p_{t,x}=0,\ p_{t,-x}=(1\text{-D})/2 \tag{3.14}$$

for configuration (b),

$$p_{t,y}=\text{D}+(1\text{-D})/2,\ p_{t,x}=(1\text{-D})/2,\ p_{t,-x}=0, \tag{3.15}$$

for configuration (c)

$$p_{t,y}=0,\ p_{t,x}=\text{D}/2,\ p_{t,-x}=\text{D}/2 \tag{3.16}$$

for configuration (d)

$$p_{t,y}=\text{D},\ p_{t,x}=0,\ p_{t,-x}=0 \tag{3.17}$$

for configuration (e)

$$p_{t,y}=0,\ p_{t,x}=0,\ p_{t,-x}=\text{D} \tag{3.18}$$

for configuration (f)

$$p_{t,y}=0,\ p_{t,x}=\text{D},\ p_{t,-x}=0 \tag{3.19}$$

for configuration (g)

$$p_{t,y}=0,\ p_{t,x}=0,\ p_{t,-x}=0 \tag{3.20}$$

for configuration (h)

3.4 Uncooperative Behavior of Crowds

Under emergency evacuation conditions, most evacuees are selfish individuals. People in crowds crush each other and selfish behavior results in the effect of "the faster, the slower" (Helbing, Farkas et al. 2000). We extended our model by taking into account un-cooperative behavior of evacuees. For a void cell (i,j), the neighboring grids are occupied by three people, so each has a transition possibility of movement to cell [i][j], as shown in Figure 3.4. Then the summation possibility of this cell is:

$$\mathrm{P}= p_{t,x}(i-1,\, j) + p_{t,y}(i,\, j-1) + p_{t,-y}(i,\, j+1) \tag{3.21}$$

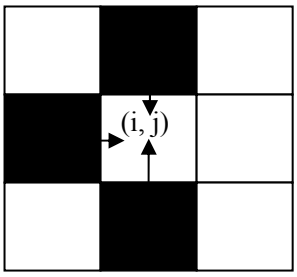


Fig.3. 4 Competitive movement of persons

It can be seen that the larger P is, the more competitive the three people are. Since the possibility of cell (i,j) being occupied by any of the three people is always less than or equal to 1, we introduced a competitive level coefficient (CLC) as follows:

CLS=1 if P< =1

CLS=1/P if P>1

Then the summation possibility of cell [i][j] being occupied is scaled down CLS times and the possibility of each person moving to cell [i][j] will adjust accordingly. For example, if a person is at cell [i-1][j], his possibility moving to cell [i][j] will be:

$$p_{t,y}(i, j-1)=\text{CLS}\times \frac{p_{t,x}(i-1, j)}{P}\text{[1-Cell[i][j]]} \tag{3.22}$$

With this definition, we can see that if all people (three at most) select cell [i][j] with possibility of 1, and the summation possibility P=3. Then CLS=1/3, and the possibility for each person moving to cell [i] [j] is 1/9. Note that the probability of each person moving to cell [i] [j] is 1/3 without consideration of competitive behavior.

To study the competitive effect on the throughput of exits, we simulated the movement of people out of a hall with width of 200 m and length of 100 m as shown in Figure 3.5. The width of the exit varies from 0.5m to 5m. The initial population in the hall was 4000 and they are randomly distributed in the hall at each run. The open boundary condition was adopted in our simulation. The flow rate per second was calculated by the average of 50 steps, and two scenarios (competitive evacuation and orderly evacuation) were modeled.

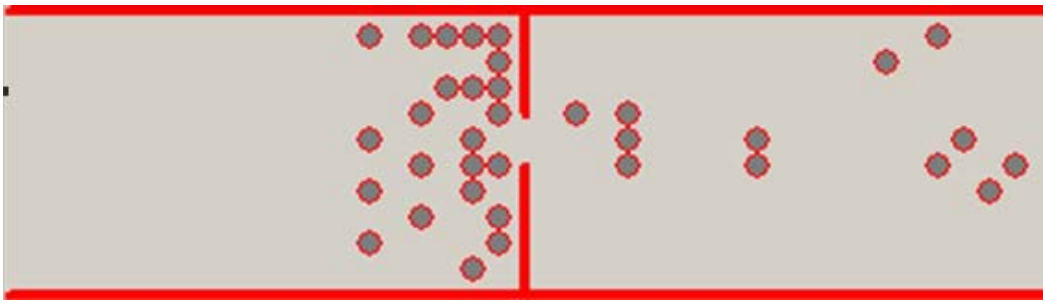


Fig.3. 5 Movement of pedestrians through an exit

For an orderly evacuation, the flow rate per step was recorded as shown in Figure 3.6. It is closely followed a power law as shown in Figure 3.7 and can be represented in the following equation:

$$p = 2.5869d^{0.6183} \tag{3.23}$$

where d denotes the width of the exit in meters, and p represents the flow rate per second. The orderly evacuation shows perfect scale behavior.

For a competitive evacuation, the flow rate follows a power law. But for the width d=0.5m, there is a large deviation. In fact, the narrower the exit, the more competitive behavior will arise. The flow rate can be expressed in the following equation:

$$p = 2.467d^{0.5729} \tag{3.24}$$

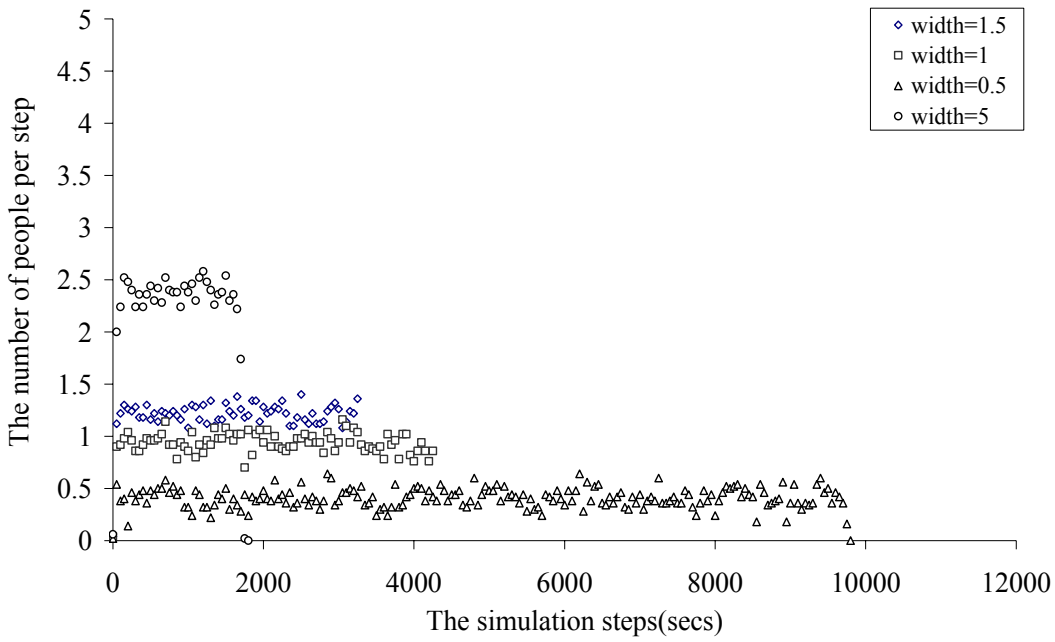


Fig.3. 6 Flow rate per step for an orderly evacuation

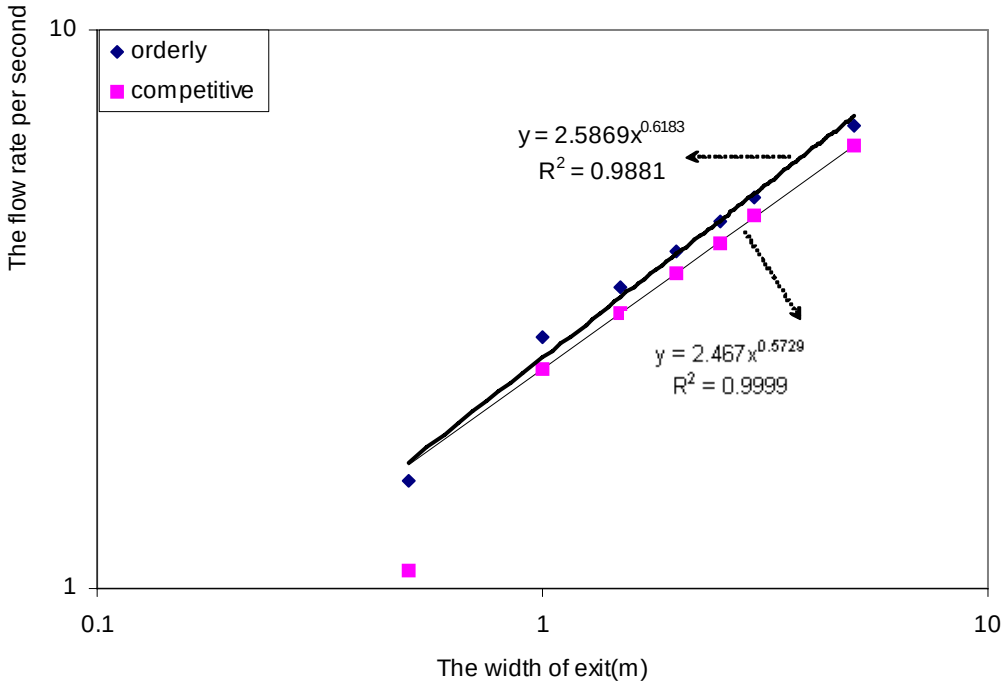


Fig.3. 7 Flow rate of orderly evacuation and competitive evacuation

3.5 Fundamental Diagram of the Model

To test and validate our model as well as our programmed codes, we studied the movement of crowds through a corridor with 100×20 cells under the periodic boundary condition, as shown in Figure 3.8. The periodic boundary condition means that no people can move out of this corridor. If one person arrives at the exit of this corridor, he will be removed and added to the ingress of this corridor. Initially, the people are randomly distributed along the corridor for a given density and the mean velocity is computed for an average of 3000 runs for all walkers. Then, the statistical velocity–density relationship can be established.

To simulate the movement of walkers, we assumed that a grid is 0.4m×0.4m, which is the average size of an adult. For every simulation step, a walker is supposed to move to an adjacent cell and that the velocity of the

walker is 0.4m/step. Accordingly, if we take free movement velocity of people as 1.4m/s, then we can deduce that a simulation step is 0.4/1.4=0.286 second. Similarly, if the size of grid is 0.5m×0.5m and the free speed is 1.0m/s, then a simulation step equals 0.5 second.

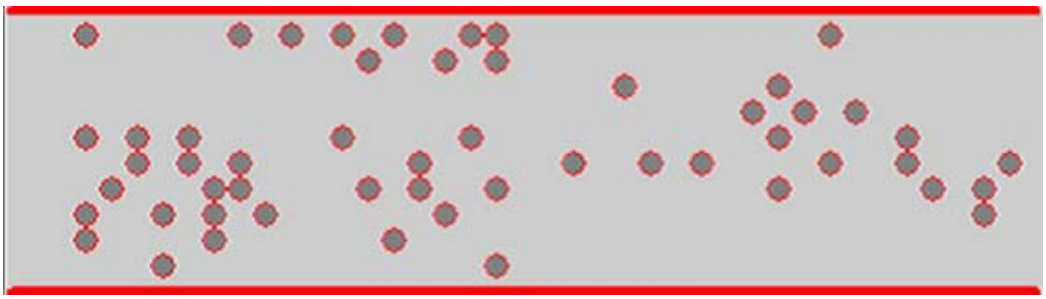


Fig.3. 8 Movement of pedestrians through a corridor under periodic conditions

By using the above model, a relationship between the crowd flow density and crowd flow velocity is generated (average of 3000 runs). Figure 3.9 compares the findings of various researchers and their simulated results. It shows that the simulation results agree well with the ‘‘Guide to Safety at Sports Ground’’ (the ‘‘Green Guide’’) and Togawa’s report. Then the following equation expressing the mean values of velocity as a function of density can be derived as:

$$u = \begin{cases} 1.4 & \rho \le 0.75 \\ 0.0412\rho^2 - 0.59\rho + 1.867 & 0.75 < \rho \le 4.2 \end{cases} \tag{3.25}$$

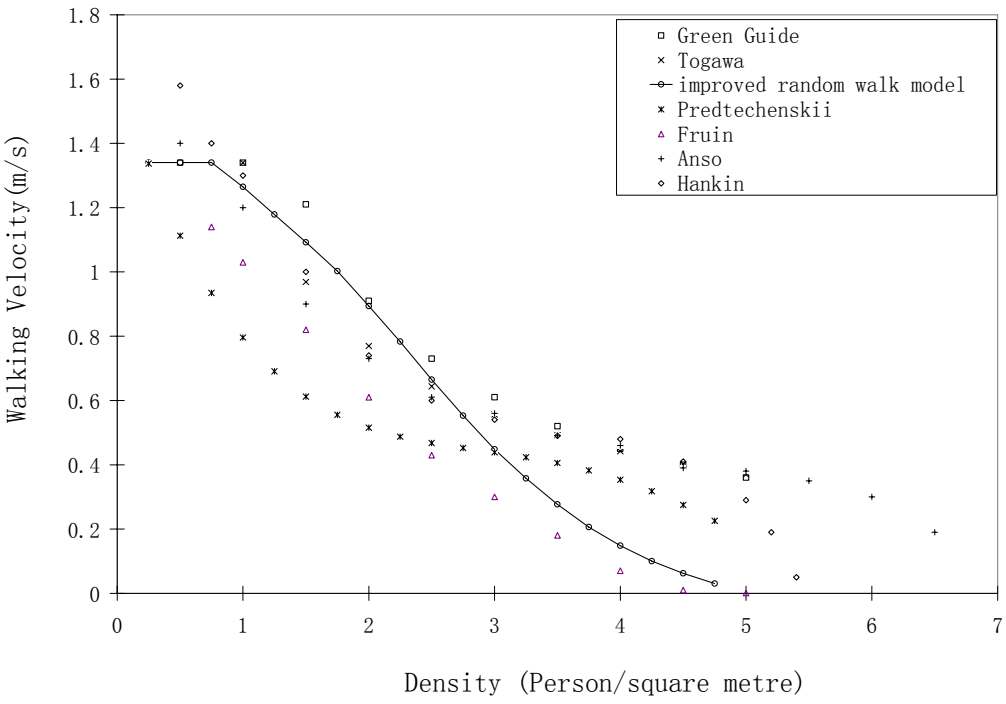
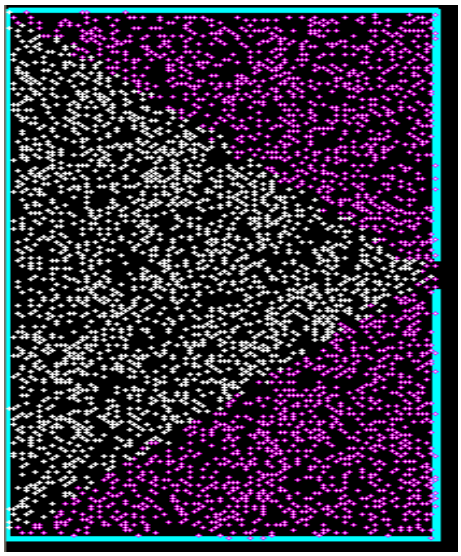


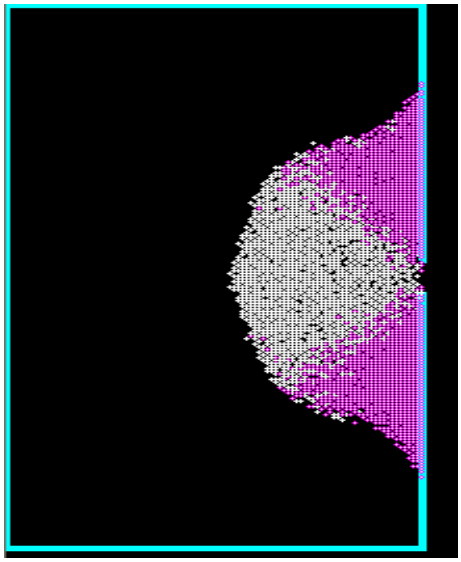
Fig.3. 9 Relationship between pedestrian density and walking velocity

3.6 Spatio-temporal Distribution of Escapes

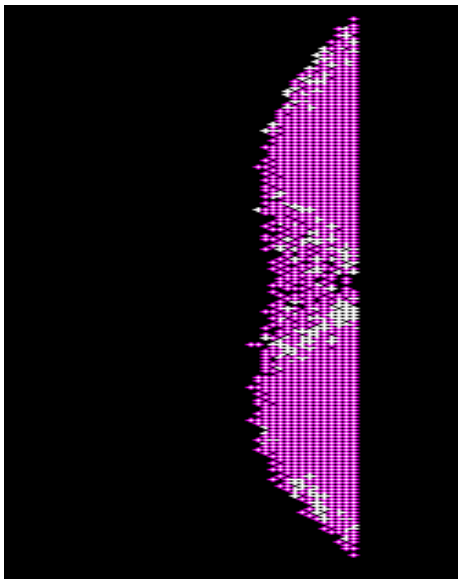
To illustrate the difference between our model and the original random walk model, we studied the flow pattern of pedestrians out of a room using both models. Takimoto and Nagatani (2003) studied the spatio-temporal distribution of escape time using Takashi's model and concluded that the escape time of a person depends on the position he is in inside the hall at the time of the incident.



(a) t=0



(b) t=2000

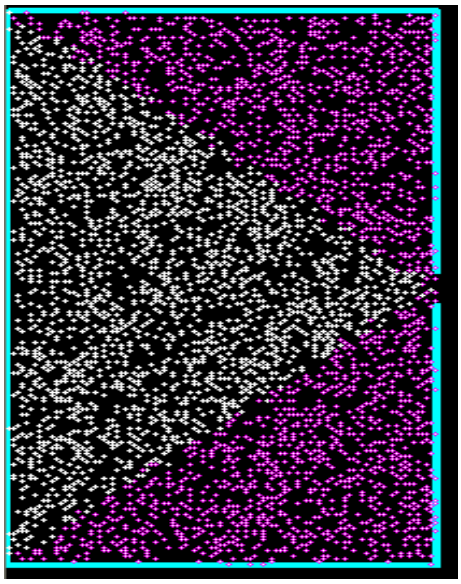


(c) t=3000

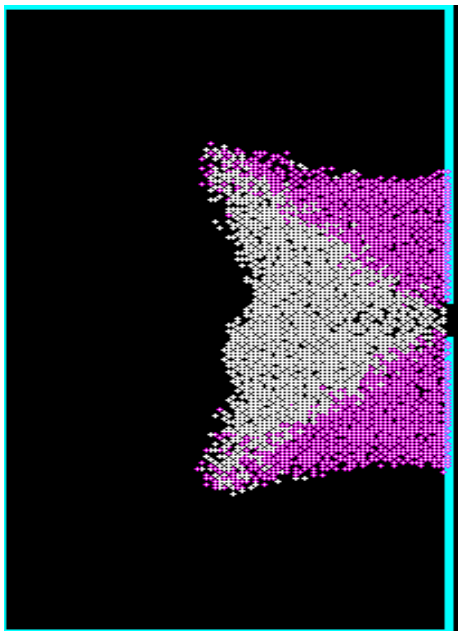
Fig.3.10 Flow pattern of people out of a hall simulated by Nagatani's model at different simulation times

Note: t=0 represents the initial distribution of people

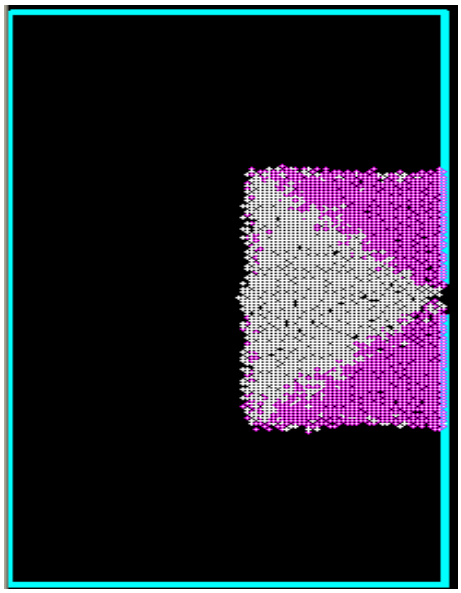
We studied the escape-time distribution of a population of 4000 people in different positions in the hall with the width of 100 meter and with length of 200 meter(100×200) and with a width of exit as 3. Initially people were randomly distributed through the whole hall, as shown in Figure 3.10. (a). People in different areas are distinguished by different colors. The number of people per unit time coming out from the exit was recorded for each area. Drift D = 0.7.



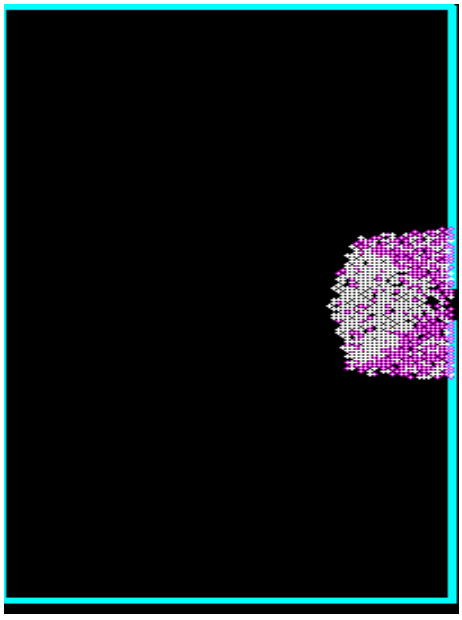
(a) t=0



(b) t=1000



(c) t=2000



(d) t=3000

Fig.3. 11 Flow pattern of people out of a hall by our improved random walk model

The flow pattern using Takashi's model is shown in Figure 3.10 (b-c). After about 2000 steps, the flow pattern is shown in Figure 3.10 (b). It was found that

people initially located at area B exited much more smoothly and quickly than those located in area A. The whole flow pattern is shaped like a cap. After about 3000 steps, most of the people who remain are those who were initially located in area A. People from different areas show quite distinctive escape behavior.

The flow pattern was further studied by our improved model, as shown in Figure 3.11. The results are quite different and a small difference in the spatio-temporal evacuation process for people located in different areas was observed. People located in both areas A and area B moved out of the exit at almost the same flow rate. After about 2000 steps, the whole picture is shaped like a rectangle.

The flow rate per step is illustrated for further analysis. Figure 3.12 gives the results of using Takashi's model and shows that for the first 1800 steps, the flow rate from area B is much greater than that of from area A, and as time goes by, most of people located in B go out and then the flow rate from area B increases rapidly. Figure 3.13 gives the cumulative outputs from each area. The flow rate derived using our improved model (Fig.3.14) shows that there is little difference in the flow rates from different areas as people will adjust their priority direction according to their relative position. So people located in area A will choose the Y direction as their preferred direction; in this way, their movement behavior is similar to that of persons located at B. Figure 3.15. gives the cumulative outputs from each area using our improved model.

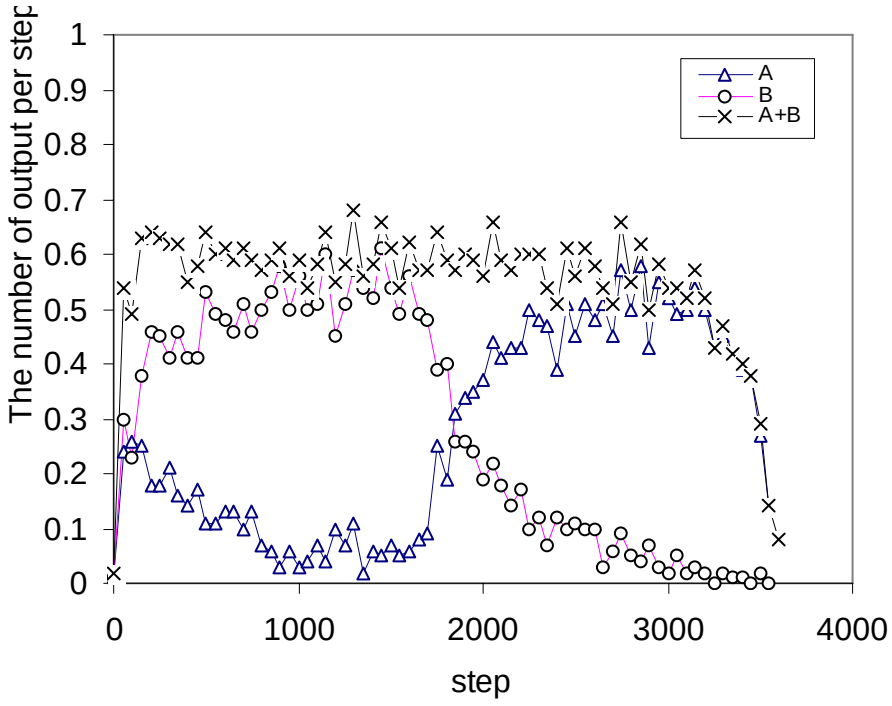


Fig.3. 12 Flow rate of area A and B

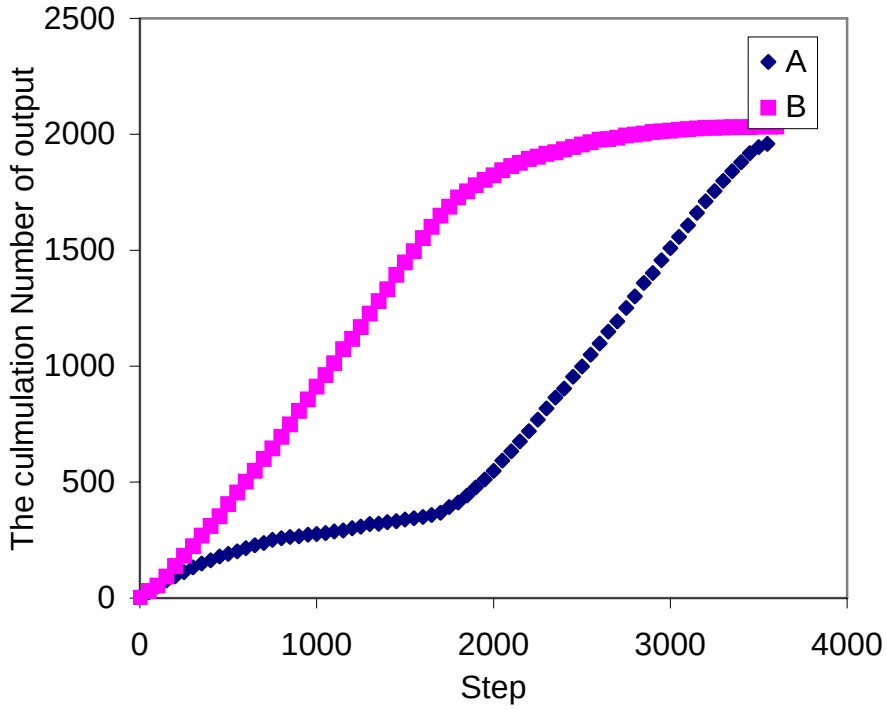


Fig.3. 13 Cumulative output of persons at area A and B

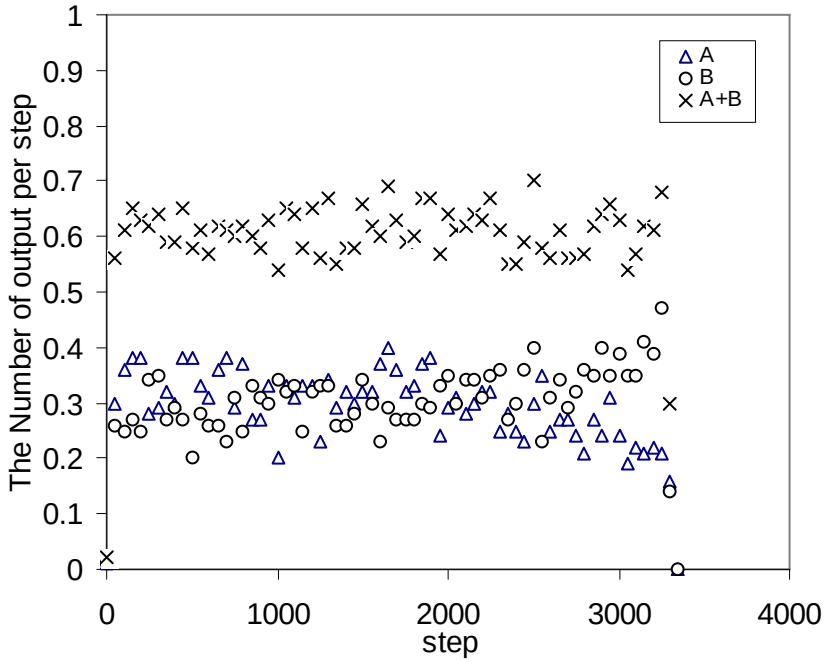


Fig.3. 14 Flow rate of area A and B

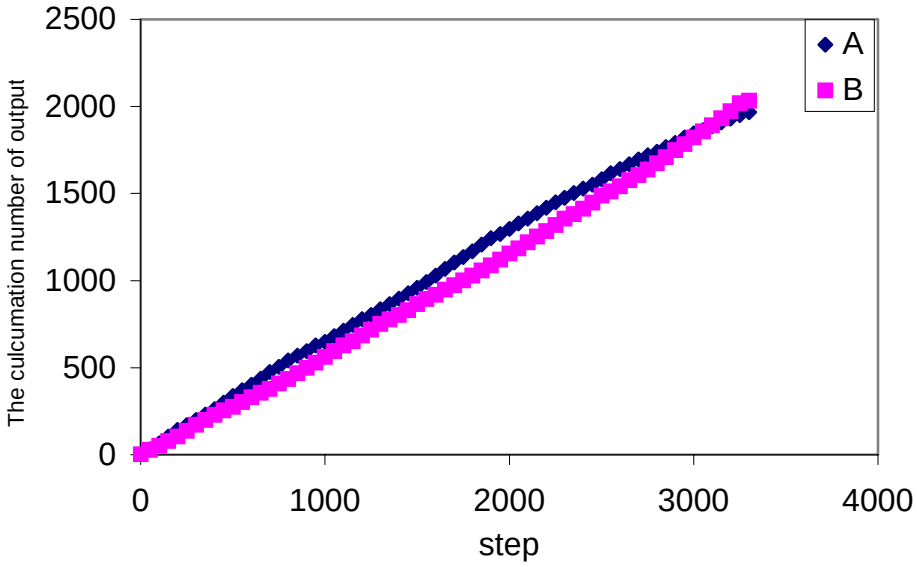


Fig.3. 15 Cumulative output of persons

3.7 An improved Model for Bi-direction Pedestrian Flow

Previous evacuation models have focused almost exclusively on the egress of occupants from a building but it is also critically important to consider the potential problems that could arise from the ingress flow during an emergency evacuation.

To understand a variety of behaviors of bi-direction flow, an improved cellular automaton was first proposed. We described the extended cellular automation of the crowd movement in a channel with the size of W×L, where W is the width of channel and L is the length of channel. Two kinds of walkers are included in our model, those moving to the right and those moving to the left.

Fig.3.15 is a schematic illustration of the counter flow of the crowd within a channel. Walkers moving towards the right are indicated by fully filled circles and those moving towards the left are indicated by non-filled circles. Let the density of the crowd in the channel be *C*, the density of walkers moving to the left be C_L , and the density of walkers going to right be C_R and let $C_L = C_R = C/2$.

Each cell has its states set (Fleischer 2001); -1 indicates that the cell is occupied by a walker moving to the right (right walker), 0 indicates that the cell is void, and 1 that it is occupied by a walker moving to left (left walker).

Each walker moves forward in the preferred direction and no back steps are allowed. The right walker moves towards the right, up (the walker's left-hand side) or down (the walker's right-hand side) with transition possibilities of $p_{t,x}$, $p_{t,y}$, $p_{t,-y}$ respectively; similarly, the left walker moves with transition possibilities $p_{t,-x}$, $p_{t,y}$, $p_{t,-y}$. Each site contains only a single walker at any time

and walkers are inhibited from overlapping on the site, which is called the exclude-volume effect.

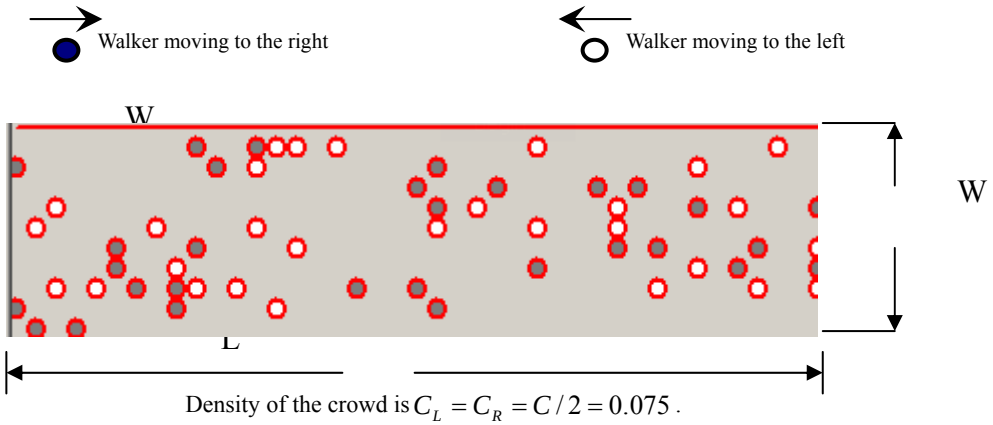


Fig.3. 16 Schematic illustration of the bi-directional flow in a channel

In order to effectively model bi-directional crowd flow, another effect observed in our daily life was considered, an effect which prevents head-on collisions with reverse walkers. In Figure 3.17, a right walker is considered to be at site [i][j]. The adjacent sites, [i+1][j], [i][j+1] and [i][j-1] are empty. Site [i+2][j] is occupied by a left walker. In the subsequent time step, if the right walker moves ahead, he may collide with the left walker at site [i+2][j]. Accordingly, it is reasonable to assume that both of them make no attempt to move ahead at the next step. Similarly, the right walker will not attempt to move up (colliding with the left walker at site [i+1][j+1]) or down (colliding with the left walker at site [i+1][j-1]). However, left walkers at site [i+1][j+1] or site [i+1][j-1] can move ahead without considering the influence of the right walker on site [i][j]. As the preferred movement is to move forward (right or left), forward movement has a higher priority than upward or downward movement. If a walker wants to change his route (up or down in next step), he needs to

ensure that no head-on collision will happen, and cooperation other than competition between walkers dominates the whole process.

0	-1	
1	0	-1
0	-1	

Remarks: the right walker will stay still in the next step (1 denotes right walker, -1 represents left walker and 0 indicates unoccupied sites).

Fig.3. 17 Avoidance of collision with left walkers

The conditions for right walkers are shown in Fig.3.18:

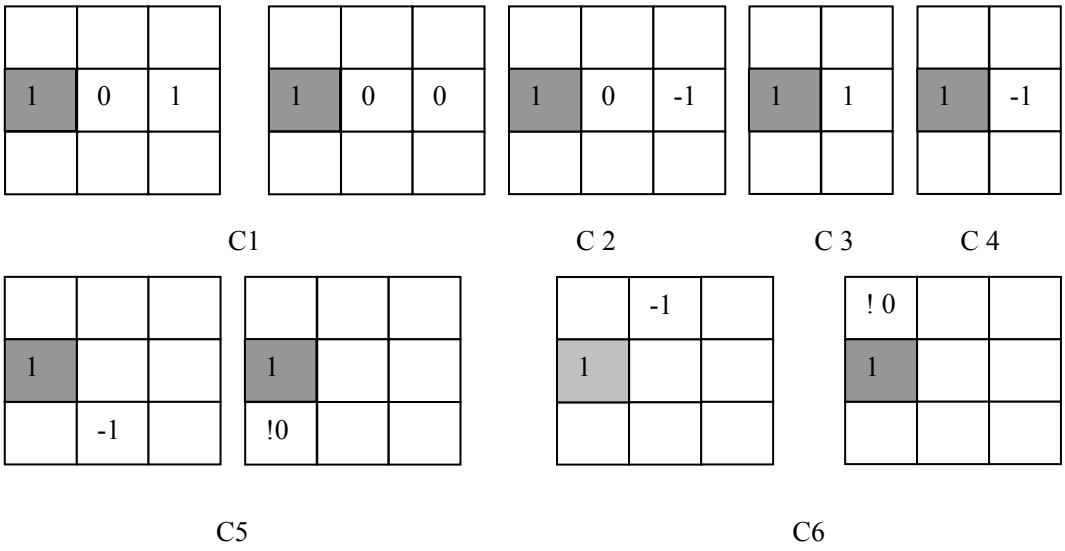


Fig.3. 18 Adjacent site conditions of right walkers

Note: Six kinds of conditions are described. Filled grid 1 *represents a right walker,* -1 *denotes a left walker,* !0 *denotes a right walker or a left walker and 0 represents unoccupied.*

C1 - A right walker is at site [i][j]; the nearest site [i+1][j] to his right is empty and the next nearest site [i+2][j] to his right is empty or occupied by another right walker.

C2 - A right walker is at site [i][j]; the nearest site [i+1][j] to his right is empty and the next neatest site [i+2][j] to his right is occupied by a left walker.

C3 - A right walker is at site [i][j] and the nearest site [i+1][j] to his right is occupied by another right walker.

C4 - A right walker is at site [i][j], and the nearest site [i+1][j] to his right is occupied by a left walker.

C5 - A right walker is at site [i][j] and the nearest site below [i][j-1] is occupied by a walker (a right walker or a left walker) or the nearest downward right site [i+1][j-1] is occupied by a left walker.

C6 - A right walker is at site [i][j] and the nearest upward site [i][j+1] is occupied by a walker (right or left) or the nearest upward right site [i+1][j+1] is occupied by a left walker.

C1, C2, C3 and C4 consider the 'ahead' conditions, whereas C5 and C6 consider the side conditions for a right walker. Similar conditions can be obtained for a left walker. Then, the updating rules are as follows:

Rule 1 if C1 is satisfied, then $p_{t,x}$=1, $p_{t,y}$=0, $p_{t,-y}$=0;

Rule 2 if C2 is satisfied:

Rule 2.1 if both C5 and C6 are satisfied, then $p_{t,x}$=D, $p_{t,y}$=0, $p_{t,-y}$=0;

Rule 2.2 if C5 is satisfied but C6 is not satisfied, then $p_{t,x}$=1-D, $p_{t,y}$=D, $p_{t,-y}$=0;

Rule 2.3 if C6 is satisfied but C5 is not satisfied, then $p_{t,x}$=1-D, $p_{t,y}$=0, $p_{t,-y}$=D;

Rule 2.4 if neither C5 nor C6 are satisfied, then $p_{t,x}$= (1-D), $p_{t,y}$=D/2, $p_{t,-y}$=D/2;

Rule 3 if C3 is satisfied:

Rule 3.1 if both C5 and C6 are satisfied, then $p_{t,x}$=0, $p_{t,y}$=0, $p_{t,-y}$=0;

Rule 3.2 if C5 is satisfied but C6 is not satisfied, then $p_{t,x}=0$, $p_{t,y}=0.5$, $p_{t,-y}=0$;

Rule 3.3 if C6 is satisfied but C5 is not satisfied, then $p_{t,x}=0$, $p_{t,y}=0$, $p_{t,-y}=0.5$;

Rule 3.4 if neither C5 nor C6 are satisfied, then $p_{t,x}=0$, $p_{t,y}=0.5$, $p_{t,-y}=0.5$;

Rule 4 if C4 is satisfied:

Rule 4.1 if both C5 and C6 are satisfied, then $p_{t,x}=0$, $p_{t,y}=0$, $p_{t,-y}=0$;

Rule 4.2 if C5 is satisfied but C6 is not satisfied, then $p_{t,x}=0$, $p_{t,y}=1$, $p_{t,-y}=0$;

Rule 4.3 if C6 is satisfied but C5 is not satisfied, then $p_{t,x}=0$, $p_{t,y}=0$, $p_{t,-y}=1$;

Rule 4.4 if neither C5 nor C6 are satisfied, then $p_{t,x}=0$, $p_{t,y}=0.5$, $p_{t,-y}=0.5$.

3.8 Lane Formation and Oscillation in Bi-directional Flow

Computer simulations were performed in accordance with the above rules. Initially, the walkers were randomly distributed along the corridor with crowd density *C*.

We have presented the simulation results and now focus our attention on the pattern formation of the crowd flow. For different drift (D) ranges from 0 to 1, similar lane patterns were observed. Figure 3.19 shows the patterns formed

by walkers where the initial crowd density C is 0.15 and D=0.9 and the corridor length (L) is 40 and width (W) is 10. After some runs, a steady pattern formed and 7 lanes were observed, 3 lanes for right walkers and 4 lanes for left walkers. Fig.3.20 shows the lane formation at an initial density of 0.3, where 5 lanes were formed, 2 for right walkers and 3 for left walkers. Fig.3.21 shows the lane formation at an initial density of 0.35 where 4 lanes were formed, 2 lanes for right walkers and 2 for left walkers. At higher densities, fewer lanes were observed. An interesting situation was observed when the crowd density was higher than 0.35 in that jamming occurred after several runs (Figure 3.22 refers).

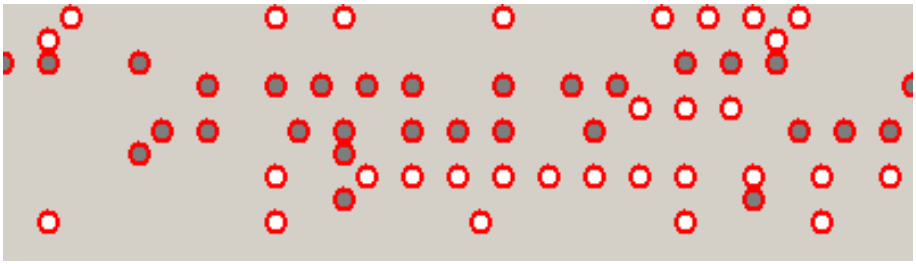


Fig.3. 19 Lane formation for crowd density of 0.15

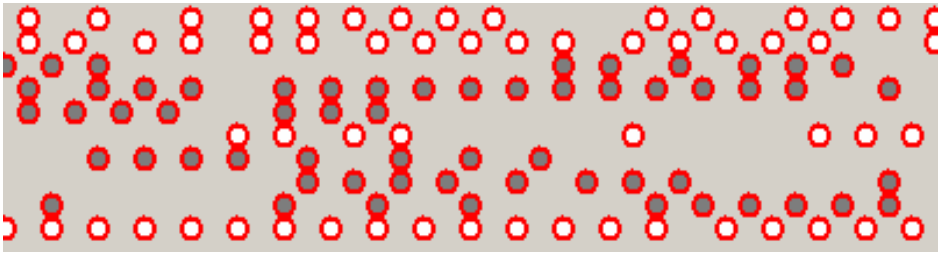


Fig.3. 20 Lane formation at crowd density 0.3

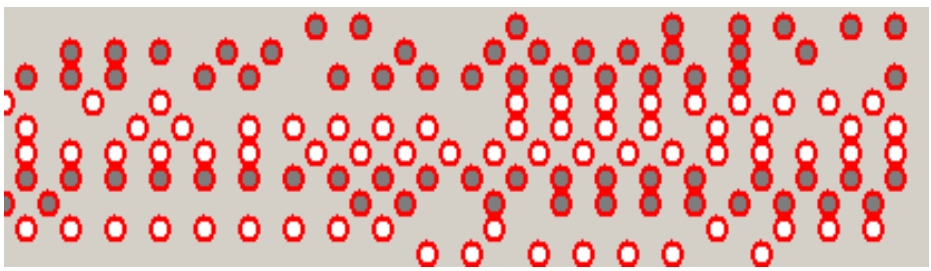


Fig.3. 21 Lane formation at crowd density 0.35

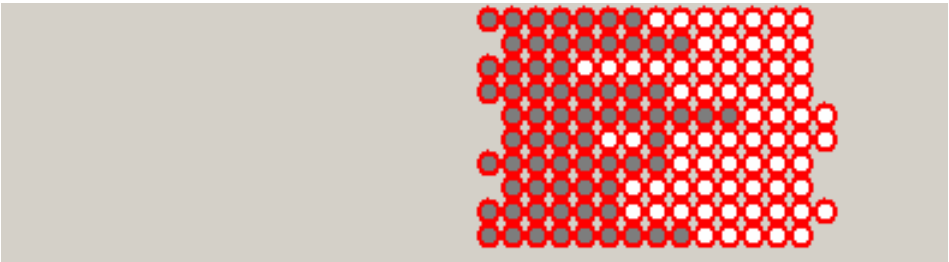


Fig.3. 22 Occurrence of jamming at $C \geq 0.35$

Although 7 lanes were formed at low crowd densities (as shown in Fig.3.22), some lanes were unsteady due to the influence of side lanes. Such a situation is congruent with our daily experience. A walker moving ahead along a lane will feel uncomfortable and most likely will change lanes if either side has reverse walkers. A parameter called noise, which can resemble this friction, was introduced to model the effect of reverse walkers.

-1	-1	
1	0	1
-1	-1	

-1	-1	
1	0	0
-1	-1	

Fig.3. 23 Influence of reverse walkers on each side

We define noise as follows:

For a right walker at site [i][j], if either his adjacent sites [i][j+1], [i][j-1], [i+1][j+1], [i+1][j-1] is occupied by left walkers, then we can say that there is noise, also know as the 'friction' of walkers. If there are no reverse walkers at these sites, then we say that noise = 0.

Accordingly, Rule 1 mentioned above was changed as follows:

Rule 1 if C1 is satisfied, then $p_{t,x} = 1$ - noise, $p_{t,y} = 0$, $p_{t,-y} = 0$

The other rules were unchanged and simulations performed. The crowd flow patterns given by the simulations are shown in Figure 3.24. Where the initial density of the crowd $C = 0.2$ and noise = 0.3, two lanes were formed, one lane for right walkers and the other for left walkers (for initial positions of walkers A_1). For the same density but assuming different initial positions for the walkers (A_2, A_3, A_4), three other kinds of steady pattern were observed, as shown in Figures 3.25, 3.26 and 3.27. For different noise levels, similar flow patterns were observed.

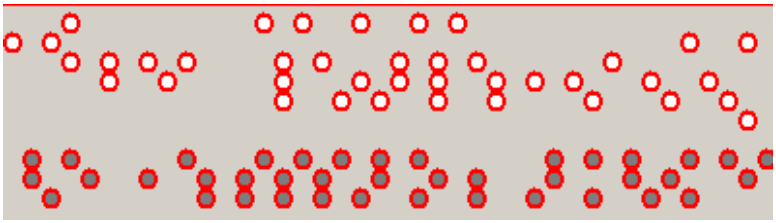


Fig.3. 24 Lane formation for density 0.2 with initial walkers' positions A1

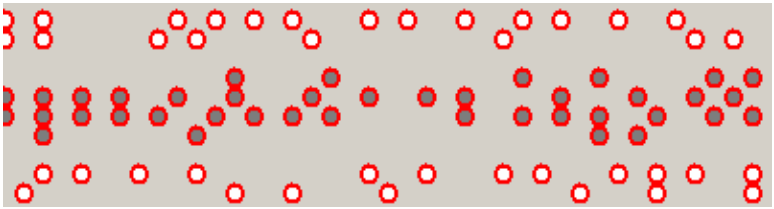


Fig.3. 25 lane formation for density 0.2 with initial walkers' positions A2

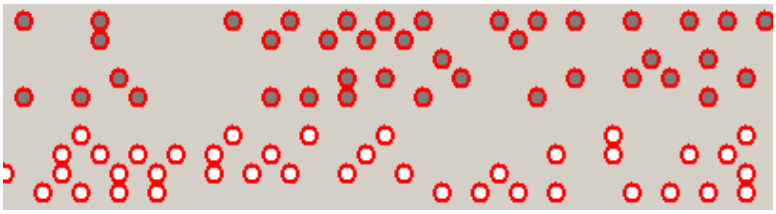


Fig.3. 26 Lane formation for density 0.2 with initial walkers' positions A3

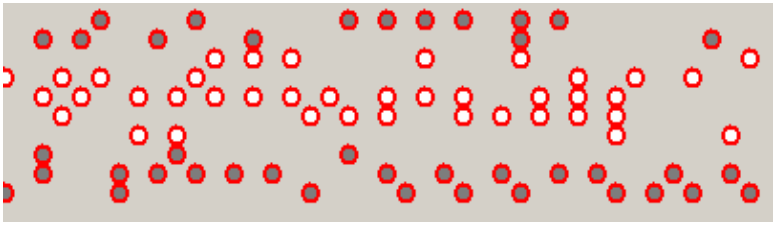


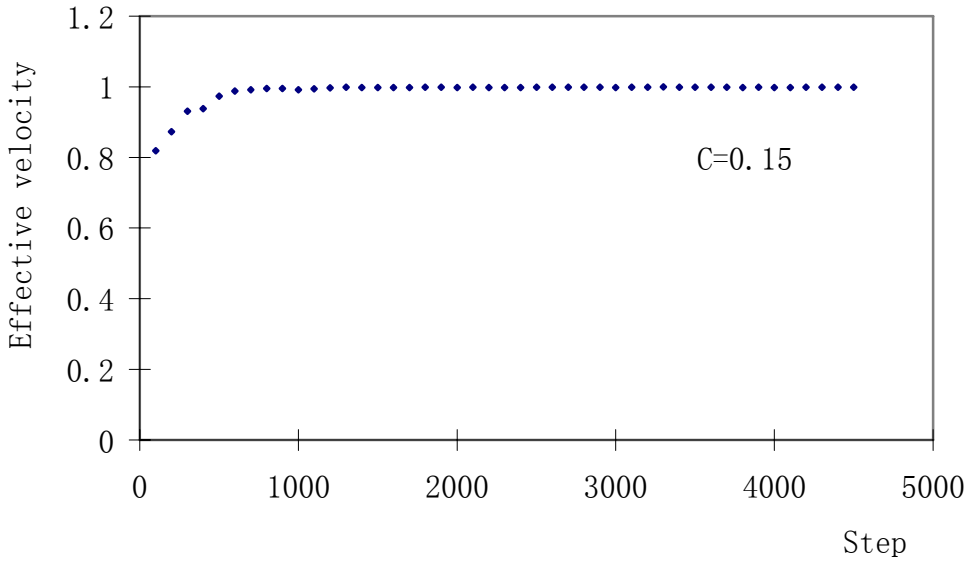
Fig.3. 27 Lane formation for density 0.2 with initial walkers' positions A4

To further investigate the evolving process of bi-directional flow, we defined an effective velocity, which only includes the velocity of moving ahead. For example, for a right walker, only movement towards the right is regarded as effective. When we computed the average effective velocity of every 100 steps, the velocity quickly reached its maximum value and flow patterns were quite steady for density = 0.15 (see Fig.3.28). However, for higher densities (i.e. density = 0.2 or above), lane formation was much more time consuming.

We also noticed an interesting phenomenon in that the lane oscillates during the simulation. During the evolution from the unsteady to the steady state, many unsteady flow patterns were observed in the transition states (Figure 3.29). The lanes formed at the transition states were unsteady and were only maintained for a few runs. This process continued until the whole system reached a steady state (i.e. steady lanes were formed; see Fig.3.30, Fig.3.31).

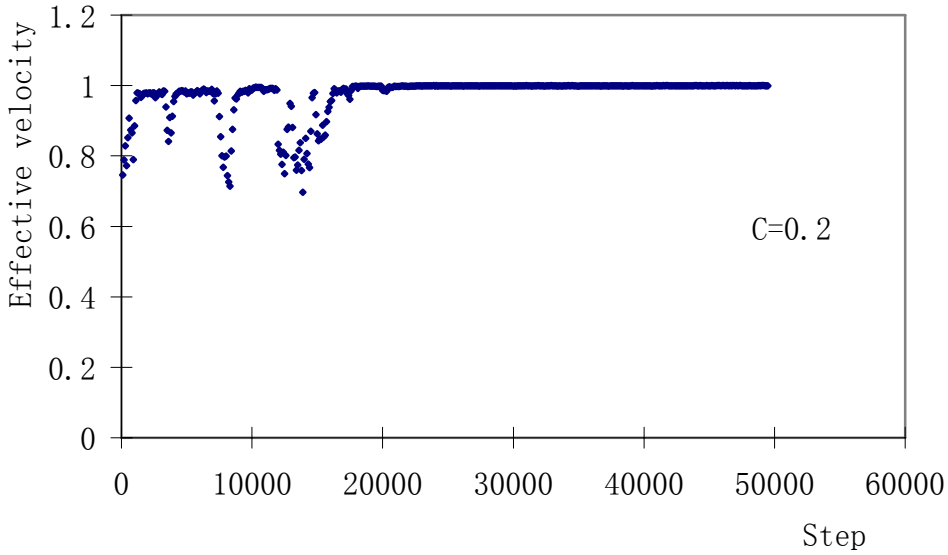
The introduction of noise will lead to the oscillation of lanes in transition states. However, steady lanes can still be formed. This process is different from other physical systems in that the noise (i.e. friction) will lead to loss of energy and an unsteady state. This may be a distinct characteristic of self-driven particles which resembles human behavior in that walkers endeavor to optimize

their own success (Helbing et al. 2000) and reduce the effect of friction (noise). This phenomenon will make the system more successful and the oscillation of lanes reveals the system's development from a low to a high success level.



(a)

(a)For initial density =0.15



(b) For initial density=0.2

Fig.3. 28 Evolution of effective velocity with simulation steps for different densities

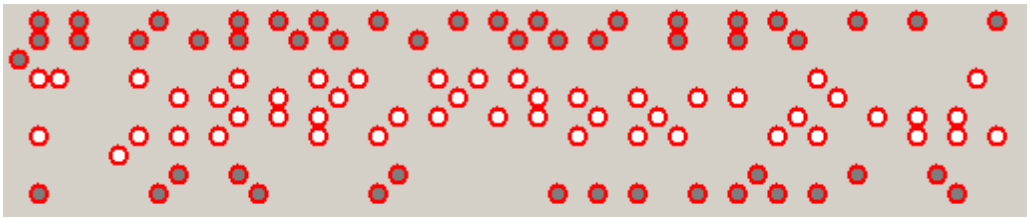


Fig.3. 29 Unsteady lanes for density C=0.2 for t = t1 for 50 x 10

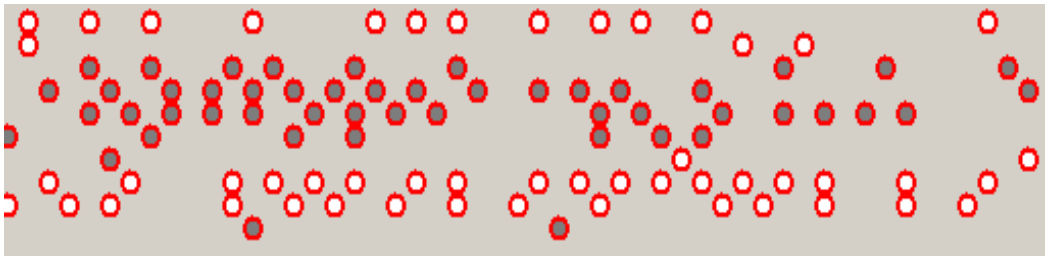


Fig.3. 30 Unsteady lanes for density C=0.2 for t=t2>t1 for 50 x 10

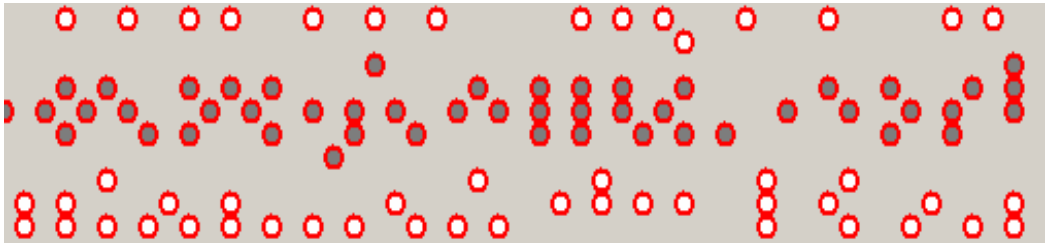


Fig.3. 31 Steady lanes for density C=0.2 for t = t3> t2 for 50 x 10

The movement of bi-directional pedestrian flow had been studied and the traffic transition was found when the density of occupation greater than a critical density and the occurrence of blocked flows results in deadlock (Figure 3.32). This situation is similar to what happened in panic evacuations. However, under normal conditions, pedestrians are cooperative, and to mimic this cooperative behavior, and avoid deadlock during the simulation, we introduced an exchange rate defined as follows:

If a right walker is blocked by a left walker, and all their surrounding grids are occupied by others, then the two pedestrians exchange their position with a certain rate varied from 0 to 1.

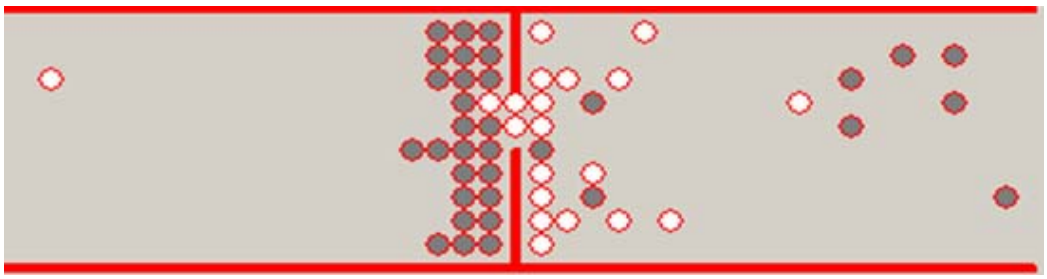


Fig.3. 32 Traffic deadlock at exit

3.9 Other Aspects Considered in Evacuation Model

The approach mentioned above is a sub-model that can be used to analyze the flow pattern for a specific part region. However, evacuation simulation is not only based on the dynamics of crowd movement, it also has to take into account other aspects of human behavior in emergencies, such as response times and route selection. When considering real evacuation scenarios, the number of influences and parameters increases.

3.9.1 Evacuation Way-finding

Another important aspect involved in the evacuation process is the way-finding process algorithm. Way-finding is a popular research area in Robotics and Artificial Intelligence (AI) and in these disciplines the route-selection behavior of each entity is modeled in detail. One of the most popular algorithms is the A* algorithm (or A* pathing algorithm), a heuristic for finding single source shortest paths. The idea behind A* is to look for the shortest possible

route to the destination, not through exploring exhaustively all the possible combinations but by utilizing all the possible directions at any given time. Lovas (Lovas 1998) gives a compressive description of the wayfinding behavior of evacuees during an emergency evacuation. For the present research, we adopted a very simple algorithm, Dijkstra's algorithm but a more complicated optimization algorithm will be introduced in Chapter 5.

3.9.2 Total Evacuation Time (TET) (Klüpfel 2003)

Total Evacuation Time, the time needed to complete an evacuation, serves as one of the most important indications of the risk to occupants. It consists of three main time components:

(i) The time needed for evacuees to recognize a fire, which is influenced by the reliability of the alarm system and the familiarity of evacuees with emergency signals.

(ii) The time needed for evacuees to decide what kind of action to take, which is mainly influenced by the behavior of evacuees as they face an emergency situation.

(iii) The time needed for evacuees to move towards the safety area, which is influenced by the availability of emergency exit signs, well planned evacuation procedures, construction-related factors (effective width of walkway, slope of stairs), and human behavior during panic situations.

Since the behavioral and organizational factors are the main contributors to the first two time components, it is hard to predict their duration. Therefore, we focused on calculating egress time as total evacuation time (TET) and treated

the result as the lower bound of real evacuation time.

3.9.3 Representation of the Evacuation Network

The basic theory of our model has now been introduced and applied to simple buildings. In this section, we extend our model to simulation in more complex buildings, as shown in Figure 3.33.

It is time-consuming to prepare data, so, in order to facilitate the pre-processing of our model, our group developed an automatic process for transforming computer-drawn architectural plans into a form which could be used by our simulator] (Zhi, Lo et al. 2003; Lo, Fang et al. 2004). An Automatic Region Generator (ARG), which uses a region-based approach (Zhi, Lo et al. 2003), was developed to capture architectural information originally produced by architects/building designers in CAD plans. It rebuilds the regions and their topological relationships, and identifies the evacuation direction at every portal. The rooms, halls, lobbies, corridors etc. are treated as regions on the basis of Graph Theory. The corresponding geometrical information is captured from the CAD plan by means of a series of graph algorithms.

The model transforms the building layout into a network layout with nodes representing exit (door) and links representing rooms or corridors. At least one node serves as the link of the network, each link (room) is uniformly divided into cells according to its size, and each cell has a value of 1 or 0 or1, which indicates whether the cell is occupied by a person or is an obstacle. A topology the network of a building can be built up in this way, as shown in Figure 3.33.

The possible escape direction of a person at each link can be determined by the shortest route algorithm and the way-finding tendency of the evacuees. The

movement of evacuees in each room is simulated according to the random walk model in each link according to rules per step. The trajectory of each individual is recorded and the evacuation pattern can be visualized within the AutoCAD environment or in our real time simulation. Our model was developed in C++ using an object-oriented method, and several classes - Link, Node and Evacuee - were implemented.

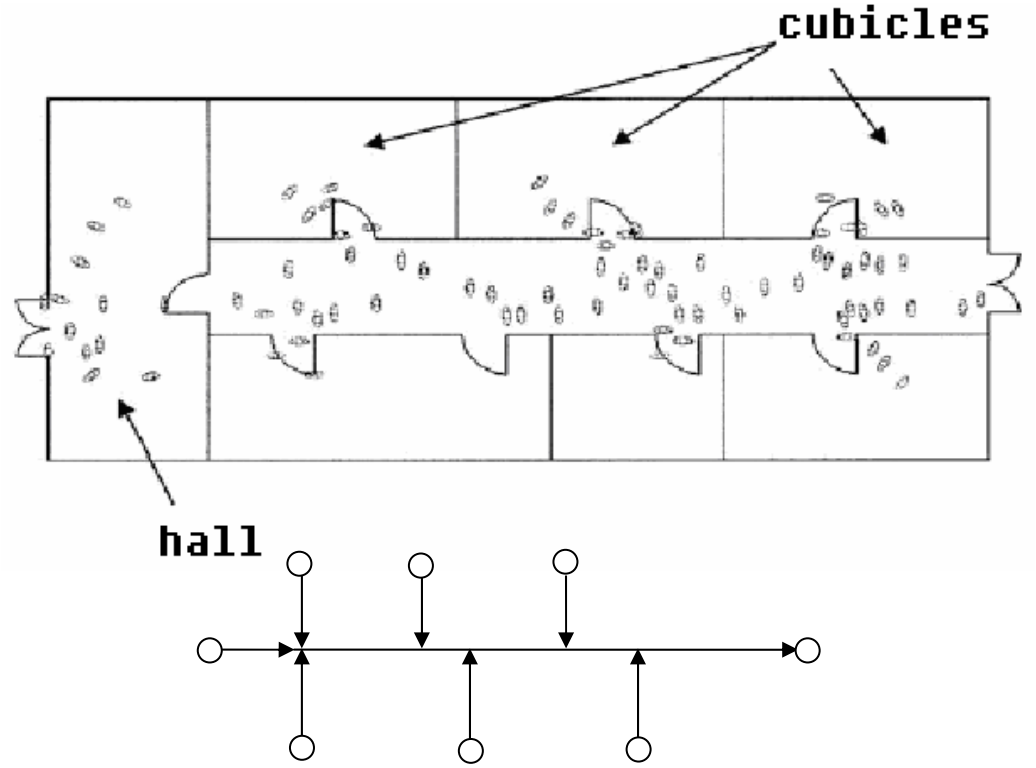


Fig.3. 33 Layout of a typical building and its topological network

3.10 Application to Tunnel Evacuation

In the case of an evacuation from a train in a tunnel, passengers will be required to alight from the train through the nearest exit and walk along an

evacuation walkway, then pass through a cross passage and finally get to a twin safety tunnel. Our improved random walker model was used to evaluate the evacuation system of a tunnel during a fire emergency.

3.10.1 Layout of the Tunnel Evacuation

A schematic evacuation network of a tunnel is shown in Figure 3.25. We have assumed that the train has 8 carriages, is disabled due to fire and can only be evacuated where it stopped. All the doors on one side of the train, but not the front and end doors, will open as evacuation procedures are activated. The passengers are considered safe if they enter a cross-passage, as shown in Figure 3.34.

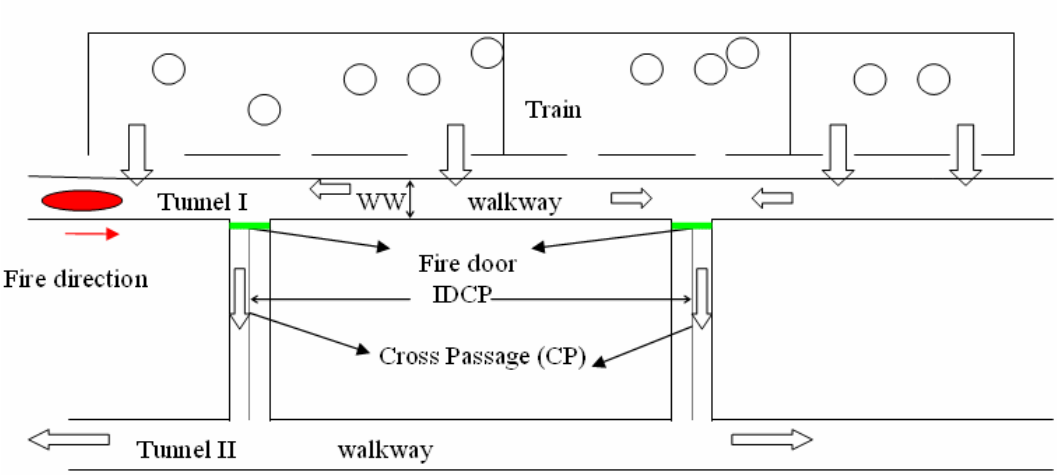


Fig.3. 34 Schematic evacuation network of a tunnel

Note: WW denotes the width of evacuation walkway (WW), and IDCP represents the interval distance of the cross-passage (IDCP).

Detailed information is given in Table 3.1.

Table 3. 1 Train car details

Train Dimensions	3m×25m per car (8 cars in total)
Train Exit Doors	1500mm width (5 exit per car on each side)
Intercar Gangway	1600mm width
Built in train seats	2600mm×600mm (12 seats per car, located on both sides)
Train capacity	2500 people

The train is assumed to have 8 carriages, each with a length of 25+1.6m and width of 3m. Seats in the cars were viewed as grids occupied by obstacles. We divided the train into cells with a unit size of 0.5×0.5m. As many of the parameters of the tunnel network were yet to be determined, including the width of the walkway (WW) and the interval distance of the cross-passage (IDCP), we varied the two parameters to study the sensitivity of TET on them. The evacuation walkway is a link 300m long and with a width which varies from 0.5~1.0m. The cross passage interval distance varies between 60m and 220m with a width of 1.5m. Each link was divided into grids with a unit size of 0.5×0.5. The width of 0.85m for the walkway assumes that it can accommodate one person at most at each step, and the width of 1.1m that it can accommodate a maximum of two persons side by side at the same time. A 1.5m wide cross-passage can accommodate three persons side by side at the same time.

3.10.2 Evacuation Scenario I

According to the general conception, we assume that passengers are safe if they enter the cross passage. So in our first simulation, the movement of

passengers in tunnel II was not considered and we assumed that passengers would not block the second tunnel. A simplified topological network of the train and tunnel network are given in Figure 3.35.

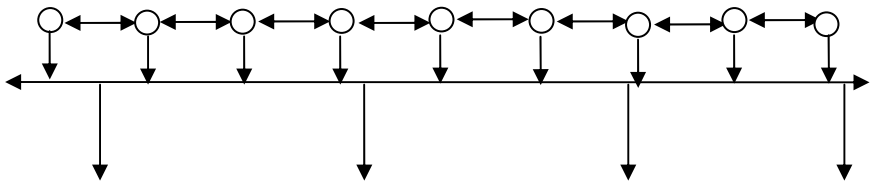


Fig.3. 35 Topological tunnel network adopted in scenario I

Different types of passengers are characterized by different variables ϑ which represent different movement inclinations. Generally, adult passengers make up 75% of all passengers according to SimuleX default values (Thompson and Marchant 1995). To get more conservative simulation results, the percentage of the elderly and children was artificially increased, so that slower walkers dominated the evacuation. We assumed that 40% of passengers were children or elderly, with a mean walking speed of 0.5m/s, and that the other 60% of passengers were adults, with a mean speed of 1.0 m/s.

The ϑ value was as follows:

ϑ=0.5 for child or elderly

ϑ=1 for adults

Table 3. 2 Six cases

	Interval distance cross passage (IDCP)(m)	Width of walkway (WW)(m)
Case 1	60	0.85
Case 2		1.1
Case 3	90	0.85
Case 4		1.1
Case 5	220	0.85
Case 6		1.1

As stated before, the drift value D represents the randomness of pedestrians when moving ahead, and two values D=0.8 and D=0.5 were adopted in our simulation. The drift of 0.8 represents a smaller degree of passenger randomness. Six cases were studied and the combinations are listed in Table 3.2.

Initially, passengers with different values of ϑ were randomly distributed throughout the train. As the evacuation was activated, passengers evacuated through their closest exits. Once people passed through the cross passage, they were removed from the simulation and when the last person had left tunnel I, the simulation stopped. Real-time outputs for different IDCP are shown in Fig.2.37-39. The simulation results are shown in Fig.3.36 and Table 3.2.

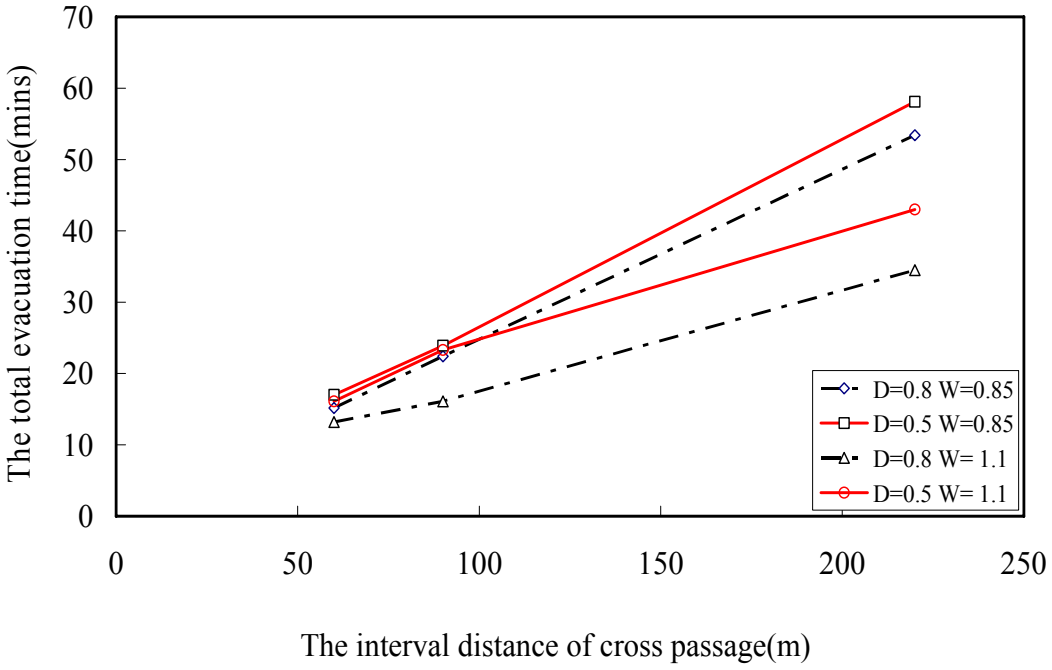


Fig.3. 36 Comparison of evacuations of different cases

The following conclusions can be drawn from the results. When the interval distance of the cross-passage (IDCP) and width of walkway (WW) are fixed, the total evacuation time (TET) increases with the decrease in drift value D. As shown in Figure 2.27, the solid line represents the case for D=0.5, and the dashed-line denotes the case for D=0.8. The decrease in randomness during movement significantly benefits the total clearance time.

When the drift value D and the WW are fixed, the increase of IDCP increase TET greatly. This is quite reasonable as passengers have to travel a longer distance if IDCP increases.

When the drift value D and the IDCP are fixed, the increase in the WW will decrease the TET overall. But for a smaller value of IDCP, e.g., for IDCP=60, there is little difference in the TET.

Table 3. 3 Results for six cases

	Interval of IDCP(m)	Width of walkway(m)	Clearance time (Mins) D=0.8	Clearance time (Mins) D=0.5
Case 1	60	0.85	15.15	17
Case 2		1.4	13.2	16.1
Case 3	90	0.85	22.4	23. 9
Case 4		1.4	19.3	23.3
Case 5	220	0.85	53.4	58.1
Case 6		1.4	34.5	43

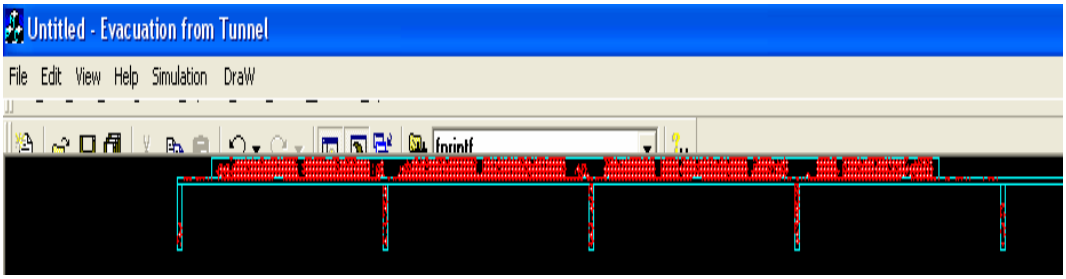


Fig.3. 37 Real-time output for IDCP=60

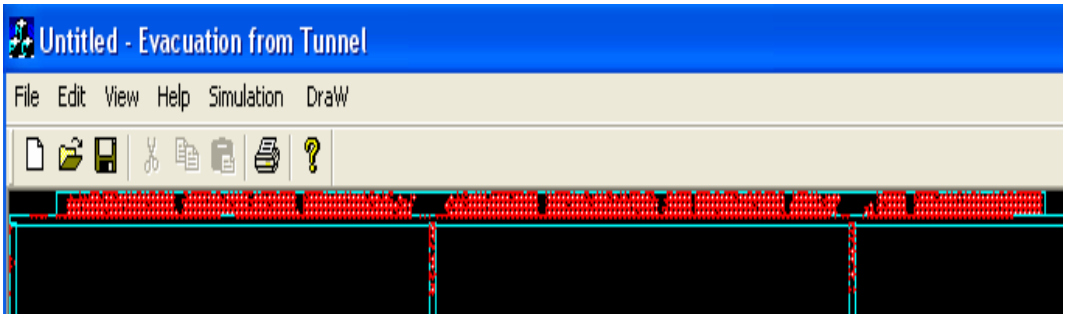


Fig.3. 38 Real-time output for IDCP=90

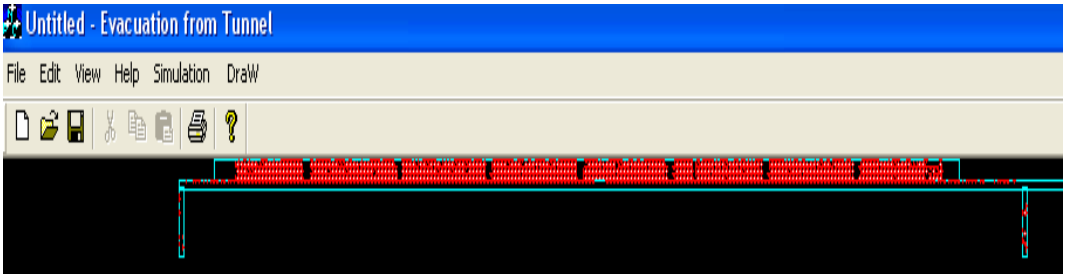


Fig.3. 39 Real-time output for IDCP=220

3.10.3 Evacuation Scenario II

As noted, in scenario I, the movement of passengers in the second tunnel was not considered. To study tunnel evacuation more comprehensively, the whole network, including the second tunnel, was studied in the second scenario. The topological network is shown in Figure 3.40.

Generally, it is assumed that when passengers get out of the cross passage and enter the second tunnel, they jump down onto the track, directed by emergency guides. However, it is difficult to decide how many passengers will jump down. For simplicity, we assumed that 50% of passengers would do so for a conservative purpose and that others would stay in tunnel II and evacuate along the second tunnel until they reached the safety exits.

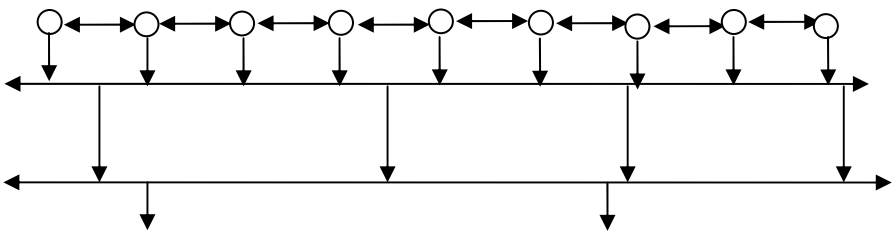


Fig.3. 40 Topological evacuation network adopted in scenario II

It was demonstrated in scenario I that a smaller value for drift D gave a more conservative evacuation time, so we only studied D=0.5 in this scenario while other parameters remained the same as the first scenario. The simulation results are shown in Table 3.4.

A comparison of evacuation times in different cases in shown in Figure 3.41. The relationships between TET and IDCP and between TET and WW were similar to those observed in scenario I except for WW=0.85. As pointed out in scenario I, if the drift value D and the WW are fixed, the TET increases with the increase in IDCP. However, in scenario II for WW=0.85, the increase of IDCP from 60 to 90, resulted in a reduction of TET from 35 minutes to 30 minutes. This is a quite interesting and counter-intuitive phenomenon. It is clear that the increase in IDCP is equivalent to the addition of evacuation routes.

Table 3. 4 Six cases for scenario II

	The interval of IDCP (m)	The width of walkway (m)	The clearance time (Mins) D=0.5
Case 1	60	0.85	35.2
Case 2		1.4	16.5
Case 3	90	0.85	30.8
Case 4		1.4	23.4
Case 5	220	0.85	64.8
Case 6		1.4	43.3

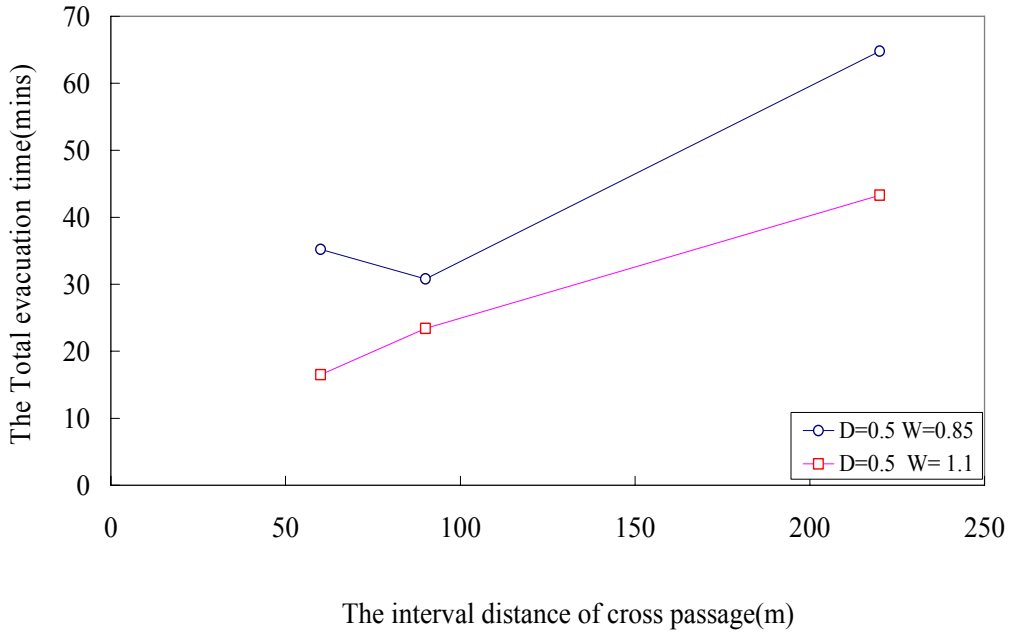


Fig.3. 41 Comparison of evacuations of different cases in scenario II

In fact, this phenomenon is the well-known Braess's Paradox (Pas and Principio 1997). It is an important consideration for the analysis of network systems that has alternative routes and it can explain why the addition of links results in deterioration in the throughput of whole network and why a road network may suffer worse congestion after improvements have been made to it. Braess' Paradox is well understood in transport planning, but little attention had been paid to it in studying pedestrian networks, and none in pedestrian evacuations.

A further comparison of the TET in scenario I and in scenario II is shown in Figure 3.42. This clearly shows that, for width of walkway W=0.85, and after taking into account tunnel II, the TET range increases significantly from 11.5% to 107%. Passengers walked along tunnel II, blocking the exits and thus dramatically increasing the total clearance time. For a wider walkway (1.4m

width), no block happens, so there was no discernable difference between the TETs, as shown in Figure 3.43. Real-time outputs for different interval distances of cross-passages are shown in Figures 2.44-46.

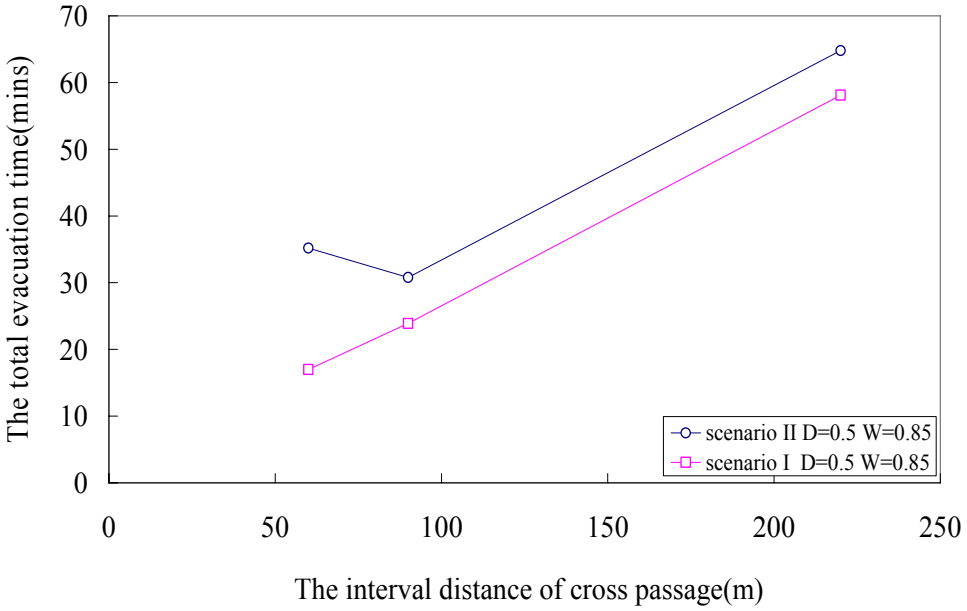


Fig.3. 42Comparison of evacuations in different scenarios

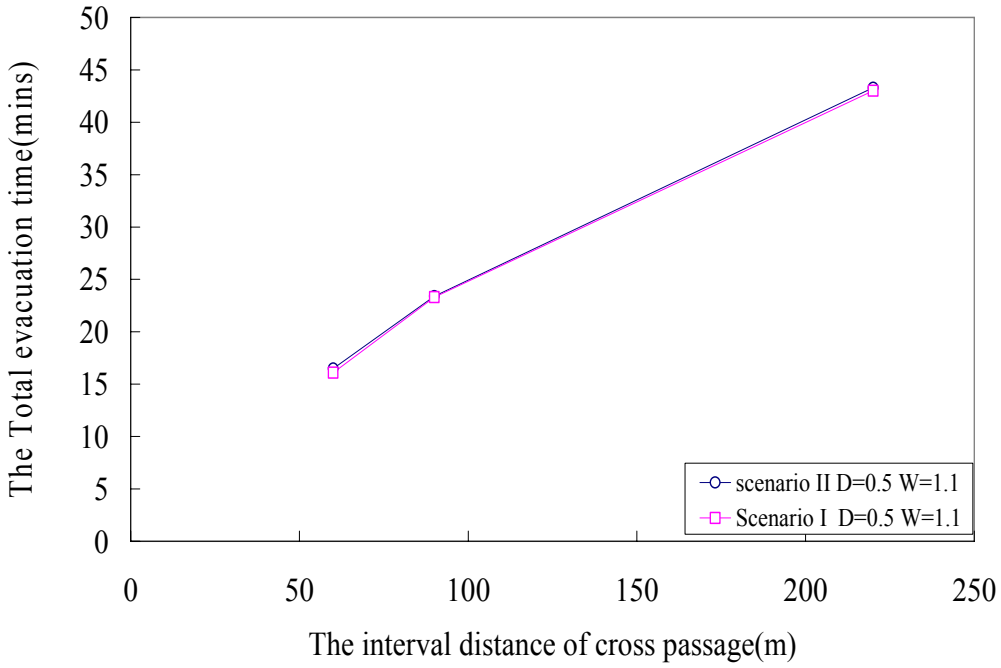


Fig.3. 43 Comparison of evacuations in different scenarios

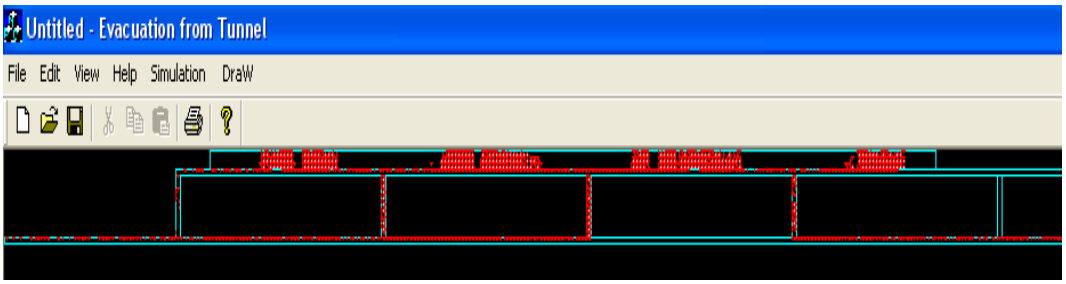


Fig.3. 44 Real-time output for IDCP=60 in scenario II

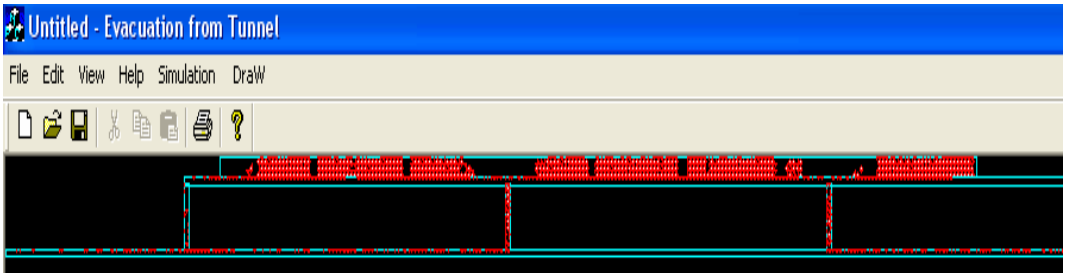


Fig.3. 45 Real-time output for IDCP=90 in scenario II

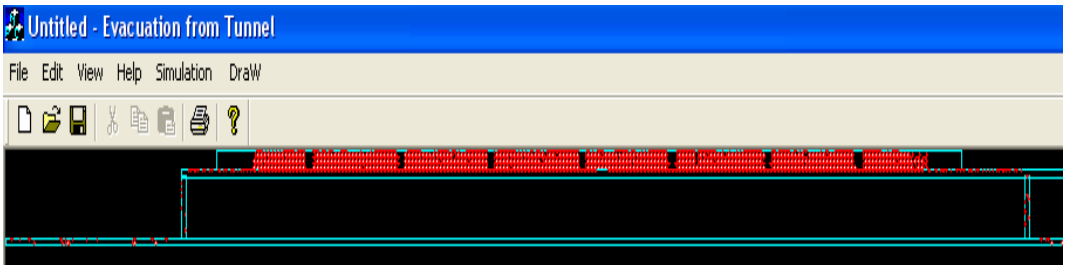


Fig.3. 46 Real-time output for IDCP=220 in scenario II

3.11 Summary

This chapter has investigated one of the most important and common types of evacuation, pedestrian evacuation.

A microscopic simulation evacuation model, based on a newly improved random walk model, was designed. The evacuation model incorporated many

distinctive features of human behavior, such as competitiveness and cooperation. The former results in a reduction in throughput while the latter leads to lane formation and improves efficiency of circulation. Generally, the bi-direction movement occurs only under some particular circumstances, such as the fire-fighters and rescuers who will move against the evacuees.

In order to facilitate the pre-processing of our model, an automatic process for transforming computer-drawn architectural plans into input data was embedded the micro-simulator model.

The evacuation model was applied in a tunnel evacuation analysis. Different scenarios were analyzed and an interesting and counter-intuitive phenomenon, known as the Braess' Paradox, was found to apply to the design of tunnel networks. The study also showed that the selection of the appropriate evacuation network is vital for ensuring that a model mimics a scenario accurately.

Chapter 4

A Capacity Constrained Model for Regional Evacuation

In this chapter, traffic congestion and spill-back during an emergency evacuation were modeled using a mesoscopic, simulation-based queue model. We described a simulation-based iteration assignment for distributing traffic load to the network in quasi-optimal routes so as to alleviate traffic congestion and decrease total evacuation time.

4.1 Introduction

The urban transportation system plays an important role in responding to natural disasters and other catastrophic incidents. To efficiently and quickly evacuate population threatened during an emergency, appropriate traffic controls must be implemented to guide those evacuating using pre-planned routes. However, it is hard to test the feasibility of the prepared plans for coping with real accidents. Even drills can only provide a limited number of scenarios. Evacuation Simulation models are therefore an ideal solution to this problem as they can model many kinds of scenarios individually or combine two or more scenarios together to test the performance of an evacuation plan, or propose a suitable plan for facilitating the circulation of evacuees. Evacuation models can be categorized as macroscopic, mesoscopic, and microscopic models according to the level of detail chosen to describe the behavior of individual entities.

Macroscopic models, e.g., NETVAC1 (Sheffi et al. 1982), CLEAR (Moeller et al. 1981), MASSVAC (Hobeika and Jamei 1985; Radwan et al. 1985; Hobeika et al, 1994; Hobeika and Kim 1998) , and REMS (Tufekci and Kisko 1991), consider traffic behaviors to be homogenous flows controlled by fluid dynamic equations. Three main variables, speed, flow and density, are used to depict the flow state as it evolves with each time step. The advantage of macroscopic simulation models is computational efficiency, which makes them practical for real time applications. Microscopic simulation models, e.g. CEMPS (Pidd et al, 1996; Pidd et al, 1997; De Silva and Eglese 2000), not only attempt to track the detailed movement of individual entities, but also consider the interactions between them. They can simulate real-life evacuation factors such as the route choices of evacuees, spill-backs, breakdowns and so on. Certainly, microscopic simulation models are computationally demanding as well as much more complicated to program. Mesoscopic models, such as DYNEV (KLD Associates 1984) draw on the best features of micro-models and macro-models by simulating platoons or groups of vehicles as they move through the network. A comprehensive review of these models can be found in Chapter 2 of this dissertation.

As noted, most regional evacuations are either micro-based or macro-based models and only one meso-based model has been developed. Since meso-simulations are more computationally efficient and model quite detailed evacuation processes, they are a simple and efficient means for modeling real-time applications. For this study, an efficient meso-based evacuation model which can handle large-scale evacuations, such as of a whole city, was developed.

4.2 Meso-Simulation Queue Model

4.2.1 The Link Model

In the present study, we have adopted the simplified meso-simulation model first proposed by Gawron (1998) and recently used in the Matsim project by Nagel (Cetin et al. 2001; Nagel 2001; Nagel 2003). The queue model ignores lane changing behavior and simplifies a driver's behavior in a single lane. Roads are seen as service providers with the service rate equal to their section capacity. Users waiting in line are allowed to leave the road by the simple FIFO (First-in First-out) rule. If the rate of request for service exceeds the service rate, a queue builds up.

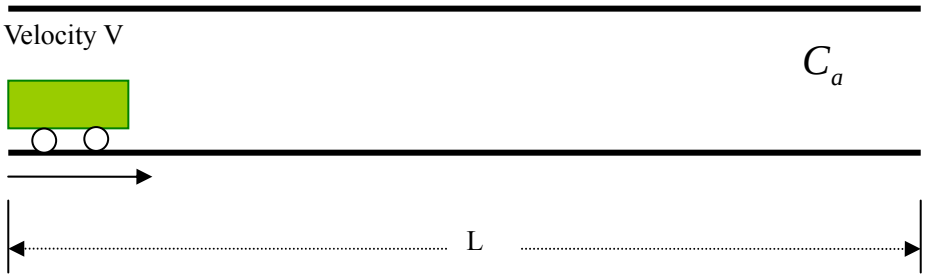


Fig.4. 1 Movement of cars along a road

As shown in Figure 4.1, a car, entering the road at time t_0, moves forward at the speed of v, and will arrive at the end of road at $t = t_0 + L/v$, where L is the road length, v is the free speed. However, the number of vehicles leaving this road in a simulation step is constrained both by the section capacity C_a and static capacity C_s. The former defines how many cars can travel along this road in a step and can be determined by Highway Capacity Manual (HCM). The

latter defines the number of cars that the road can hold. Generally, a road can hold a maximum number of vehicles $N_{\max} = L \times N_{lane} / 7.5$, where N_{lane} is the number of lanes and 7.5m is a standard space occupied by a vehicle under congestion conditions, as suggested by Nagel (2003).

The simulation-based queue model can be described as follows: at each time step, a certain number of vehicles which have arrived at the end of a link may leave the link; the number leaving is constrained by the capacity of the link and by the number of cars which can fit on the destination links; if its destination is full, no vehicle can leave the current link. Simon and Nagel (1999) described the procedure as follows:

```
For all links Do
 {
   While (vehicles can still leave in this step according to section capacity)
    {
   Get the first vehicle in the queue;
      If (vehicle has arrived at the end of link)
          {
          If (the vehicle's destination link has space)
           Adding the vehicle to the destination link;
          Else break;
          }
   else break;
   }//end of while
 }
```

This meso-simulaiton model considers the delay due to constraints in the section capacity in a quite simple way, but its limitation is that the links are always selected in the same sequence, which gives some links a higher priority than others under congestion conditions. A simple method for remedying this

shortcoming is to randomize the link sequence. Cetin et al.(2001) proposed selecting the sequence of links according to their through capacity; the higher the through capacity, the earlier the sequence being selected. However, earlier selection cannot ensure earlier movement.

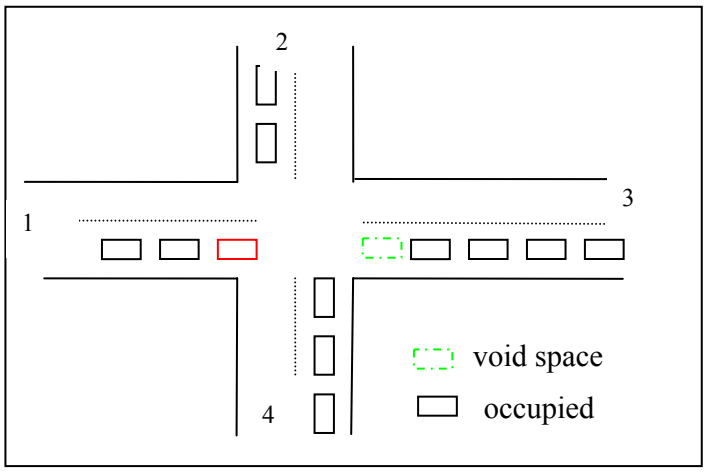


Fig.4. 2 Simple intersection

As illustrated in Figure 4.2, links are recoded sequentially 1-2-3-4, and we assume that vehicles on links 1,2,4 select link 3 as their next destination link, which can accommodate 5 vehicles at the same time. At a simulation step, 4 vehicles are waiting on link 3 and only one free space is available. Link 1 is selected first and one vehicle on it can enter link 3; link 2 is selected second, but there is no free space for vehicles on link 2 to enter; link 3 is selected third, and vehicles on this road move to the next destination and some free space is available; link 4 is selected last, as link 3 is processed early and is free, so vehicles on link 4 can enter in link 3. So the earlier selected link does not necessary have a greater chance of movement. In this example, link 2 is selected earlier than link 4, but link 4 has a greater chance of movement. If link 3 is occupied at any step, the last selected link 4 has the greatest chance of

movement.

4.2.2 The Node Model

The Link model determines how many cars pass through links in a step. However, in traffic congestion in a complicated network, most traffic congestion and delays arise at intersections (Cova and Johnson 2003), so a node model should be adopted.

DYNAMIT (Ben-Akiva et al 1998) utilized the concept of virtual links with a finite capacity to deal with node pass processes, a method also adopted by Cetin et al.(2001). The virtual link procedure can be described as follows: when a vehicle moves to a new segment, it is assumed that all vehicles on this link are temporarily stored on the virtual link. Once their destinations are processed, vehicles can move, but there are always cases when vehicles added to virtual links can't move because the destination links are full, or due to constraints in the approach capacity.

NETVAC1 (Sheffi et al. 1982) modeled an intersection by introducing a node pass which calculates how many vehicles can be removed from each of the links entering a particular inbound link constrained by approach capacity, which limits the number of cars that can actually pass the intersection.

To model the intersection process, two link scanning processes were adopted in our model. The first process calculates the requirements of cars passing through for all intersections. This scanning process is as follows: in a simulation interval ΔT, the number of vehicles wanting to move from outgoing link i to incoming link j N_{ij} is calculated. The intersection of link i and link j is represented as k. N_{ij} are constrained by the section capacity C_i. Let n be the

number of incoming links connected with i, the number of cars leaving from i at a step satisfies the constraint, as follows:

$$\sum_{j}^{n} N_{ij} \le C_i \times \Delta T \tag{4.1}$$

On the other side, let *m* be the number of outgoing links connected with j, then the number of vehicles entering into link j must satisfy the constraint

$$\sum_{i}^{m} N_{ij} \le C_k \times \Delta T \tag{4.2}$$

where C_k represents the approach capacity at intersection k. $NN_j = \sum_{i}^{m} N_{ij}$ is equivalent to the requests for service to enter into link j at intersection.

Urban road networks have many intersections. To realistically simulate throughputs at these crossings, it is important to consider complex priority rules and to treat traffic lights in a realistic manner. Each edge in the network has a driving-direction-dependent leave flag at its end, by which vehicles may be prevented from advancing any further. Two ways-of-traffic-controls are considered: signalized intersections and unsignalized intersections (include primary priority). Signalized intersections are modeled by fixed phases in which one phase is assigned to each incoming link and direction-specific phasing information is averaged over all directions weighted by the number of lanes into the respective direction.

For unsignalized intersections, an equivalent green split is assigned for all primary links (for primary priority, only primary priority inbound links are considered while secondary priority links are ignored). For j-th incoming link, the green split G_j is given by:

$$G_j = \frac{NN_j \times n_j}{\sum_{mm} NN_i \times n_i} \tag{4.3}$$

where *mm* is the number of inbound links at current intersection k. $\sum_{mm} NN_i$ represents the total number of vehicles want to move through node k to enter their destination links, and n_j represents the number of lanes in the j-th incoming link. Thus, the through capacity assigned to enter into link j is calculated as:

$$CA_j = G_j C_j \tag{4.4}$$

So, in an interval step, the total number of vehicles entering into a link must satisfy the constraint

$$\sum_{i}^{mm} NN_i \le C_k \times \Delta T \tag{4.5}$$

where C_k represents the approach capacity at intersection k. $NN = \sum_{i}^{m} NN_i$ represents total requests for service to pass through intersection k.

The allowance number of vehicles from the i-th link to j-th link can be represented as M_{ij}

$$M_{ij} = N_{ij} \frac{CA_j}{NN_j} \tag{4.6}$$

The above formula assigns the green phase according to the length of the waiting queue only (the number of vehicles wanting to move). However, this can result in gridlock because some links have too low a priority. So the waiting time of cars at links should also be considered. Then M_{ij} can be obtained as follows:

$$M_{ij} = N_{ij} \frac{CA_j \times T_i}{\sum_i^m N_{ij} \times T_i} \tag{4.7}$$

where T_i is the total waiting time of all vehicles at i-th link.

Up to now, we have focused on the dynamic capacity of intersections and ignored an important element, the static capacity of target links, which also has a considerable influence on the intersection, as illustrated in Figure 4.3:

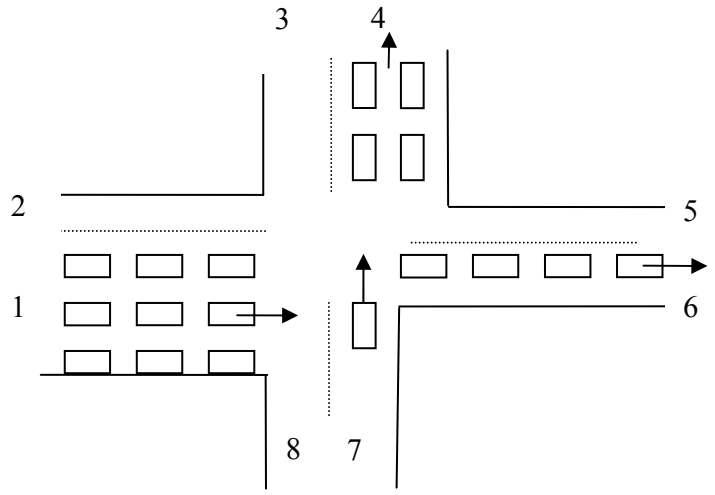


Fig.4. 3. Influence of static capacity

Nine cars have arrived at the end of road 1 and are waiting to move to road 4. Only one car arrives at this intersection from road 7. Surely, link 1 has much longer green time than link 7 according to the green split. However, the destination link of link 4 is fully occupied and no free space is available. So no car is allowed to move from 1 to 4 at this step. The green time assigned to link 1 is wasted. The second link scanning process focuses on the static capacity of each destination link. As pointed out earlier, a road j can accommodate $N_{\max,j} = Length_j \times N_j / 7.5$ vehicles at most at the same time. So the available

free space at step t in an inbound link j is constrained by the number of vehicles at step $t-1$ denoted by $NV_j(t-1)$ and the available free space $NS_j(t)$ in link j at simulation step t is obtained as

$$NS_j(t) = N_{\max,j} - NV_j(t-1) \tag{4.8}$$

The allowance number of vehicles from link i to link j at t step is further restricted by

$$NS_{ij}(t) = N_{ij}T_i \frac{NS_j(t)}{\sum_i N_{ij} \times T_i} \tag{4.9}$$

The allowance number of vehicles is constrained by both NS_{ij} and M_{ij}. Then the allowance number of vehicles from i-th link to j-th link $MNS_{ij}(t)$ will be finally restricted by

$$MNS_{ij}(t) = N_{ij}T_i \frac{\min(CA_j, NS_j(t))}{\sum_i N_{ij} \times T_i} \tag{4.10}$$

The precise condition for the algorithm of the two link scanning processes is "*can still leave in this time step according to capacity*", which can be programmed as:

While (if((N_{pass} <int(C_{link}))OR(((N_{pass} ==int(C_{link}))&&(rand( )/RAND_MAX>(C_{link} -int(C_{link}))).

Approach capacity C_k of intersection k is a function of the proportion of traffic intending to move in each direction (right turn, left turn or straight), number of lanes, and proportion of turning movements on the opposing and conflicting approaches. The detailed description can be found in HCM. The

section capacity C_i of a link i is closely related to the current density.

When the density of vehicles on a link exceeds the critical density, the section capacity may greatly decrease due to congestion.

A schematic flowchart illustrating the structure of this algorithm is shown in Figure 4.4.

The algorithm of the two scanning processes is as follows:

T=T+1:

Step 1: initialing of all parameters

For i all links Do

The update of approach capacities

Initializing N_{ij} =0

End

Step 2: The first link scanning process. This process calculates the traffic demand at each intersection by accumulating the number of cars at the intersection.

For i all primary links Do

While (vehicles can still leave in this step according to section capacity)

{

Get the first vehicle in the queue;

If (vehicle has arrived at the end of link j)

{

If (the vehicle's destination j link has space)

{

If (The number of vehicles waiting to enter into link j, $\sum_i N_{ij}$ ++);

If (The number of vehicles waiting to move from link i to link j, N_{ij} ++);

}

else break;

}

else break;

}

End do

Step 3: the second link scanning process. This process decides how many cars can leave their current links and be loaded into their target links at each intersection.

For all links Do

While (vehicles can still leave in this step according to section capacity);

{

Get the first vehicle in the queue;

if (vehicle has arrived at the end of link)

{

if (the vehicle's destination link has space)

$\{ MNS_{ij}(t) = N_{ij} \times T_i (\frac{\min(CA_j, N_{\max,j} - NV_j(t-1))}{\sum_i N_{ij} \times T_i})$

if($N_{pass} > MNS_{ij}(t)$)break;

if((N_{pass} ==int($MNS_{ij}(t)$))&&(rand( )/RAND_MAX>($MNS_{ij}(t)$ - int($MNS_{ij}(t)$)))break;

{ Adding the vehicle to the destination link;

N_{pass} ++;

}

else break;

}

else break;

}

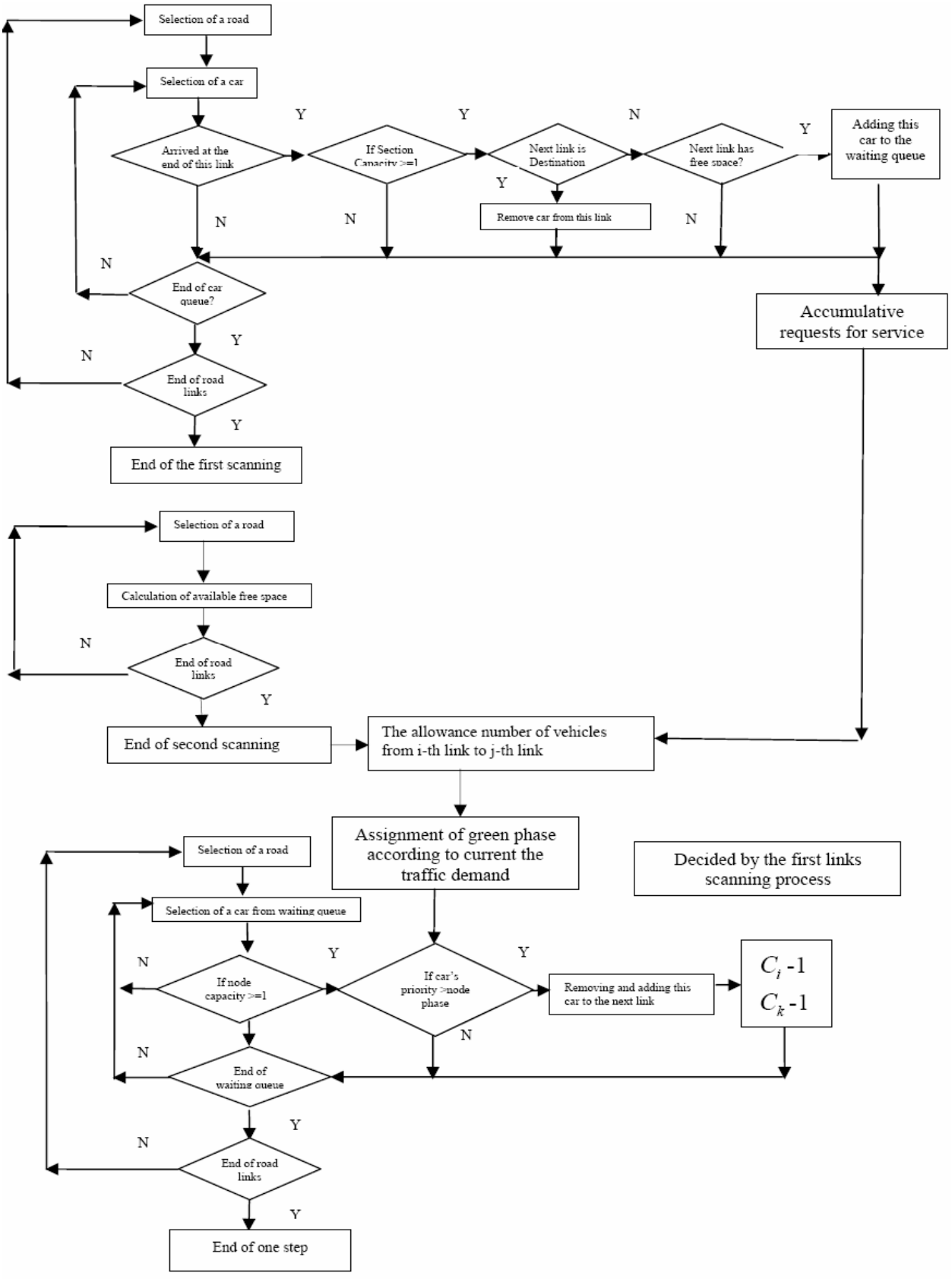


Fig.4. 4 the simulation flowchart for one step

4.3 Simulation-based Iterative Traffic Assignments

The model presented in the previous section assumes that vehicles move ahead according to pre-defined routes. However, how to define the detailed routes for each driver, particularly during an emergency, is quite a difficult problem. The problem can be further divided into two sub-problems, the destination selection problem and route selection problem.

4.3.1 Destination Selection

Destination selection deals with the problem of where to go and is generally referred to as a trip distribution problem in transportation engineering. Generally, destinations are chosen according to the following principles: the distance from the district to emergency shelters, according to a pre-defined shelter, or based on the traffic conditions in the network. Emergency personnel are responsible for distributing the evacuees to emergency shelters with limited resources.

4.3.2 Route Selection Problem

The route selection problem relates to how to get to the selected destination and is referred to as traffic assignment in transportation engineering. Southworth(1991) summarized the following way-finding processes for evacuation modeling:

(1) Myopic route selection behavior, dictated by traffic conditions at each interaction

(2) System optimal or user optimal route selection behavior

(3) Combined myopic and user route preference.

4.3.3 Expansion of Evacuation Network

These two processes can be integrated in an expanded network by introducing super-destination nodes and adding a set of pseudo-links, which connect the super-destination nodes to the original destination nodes. Each super-destination node is connected to a subset of destination nodes. These subsets of destination nodes are designed in such a way that the flow needs to be assigned from any origin to a single super-destination node. The flows on the expanded network are converted into flows on the original network by deleting the super-destination and pseudo-links.

4.3.4 Simulation-based Iterative Dynamic Traffic Assignment

Route selection in an evacuation can be performed in the expanded network by traffic assignment, either system optimal or user optimal. IDYNEV (KLD and Associates 1984) adopted a static traffic assignment. MASSVAC (Hobeika and Jamei 1985) was developed based on an all-or-nothing traffic assignment. During the evacuation hours, demand often exceeds the capacity of a road network, which leads to the buildup of traffic jams all over the network. Static traffic assignment fails to describe congestion accurately, particularly for large networks. Dynamic traffic assignment overcomes these problems by introducing time dependent models, a time-dependent origin-destination matrix (ODM). Thus, the travel time depends on the history of the system, i.e. the current lengths of the traffic jams. Advanced Traveler Information Systems (ATIS) and Advanced Traffic Management Systems (ATMS) are being developed to address traffic congestion problems. Dynamic Traffic Assignment (DTA), a component of ATIS and ATMS, uses historical and real-time data to estimate and predict

traffic conditions. A comprehensive overview of dynamic network models can be found in Ran and Boyce (1996). The newly developed MASSVAC4.0 (Hobeika and Kim 1998) incorporated the dynamic user equilibrium (UE) assignment algorithm. Shin and Ran (1998) and Sattayhatewa and Ran (2000) discussed the fundamental requirements for implementing DTA models for evacuation management and proposed an analytical dynamic traffic assignment (DTA) model for evacuation management. Here, we adopt simulation-based iterative dynamic traffic assignment, as proposed by Growan (1998) and Rickert (1997) in their PhD dissertation. The time-dependent user equilibrium iterative assignment is described in more detail below and is shown in Figure 4.5.

Step 0: setting the iterative time Iteration=N

Step 1: Iteration=0, Disaggregating the time-dependent ODM into a set of drivers with predefined departure times.

Step 2: Initializing the shortest route for each driver. In our model, NetEngine computed the shortest route for each evacuee.

Step 3: Running the evacuation simulation by our queue model and calculating the mean travel time at each link.

Step 4: if (Iteration>=N), go to step 5

Else

Updating the time dependent costs of the links, and recalculating the optimal routes for a certain portion p of the drivers.

Go to step 3.

Step 5: end of iteration

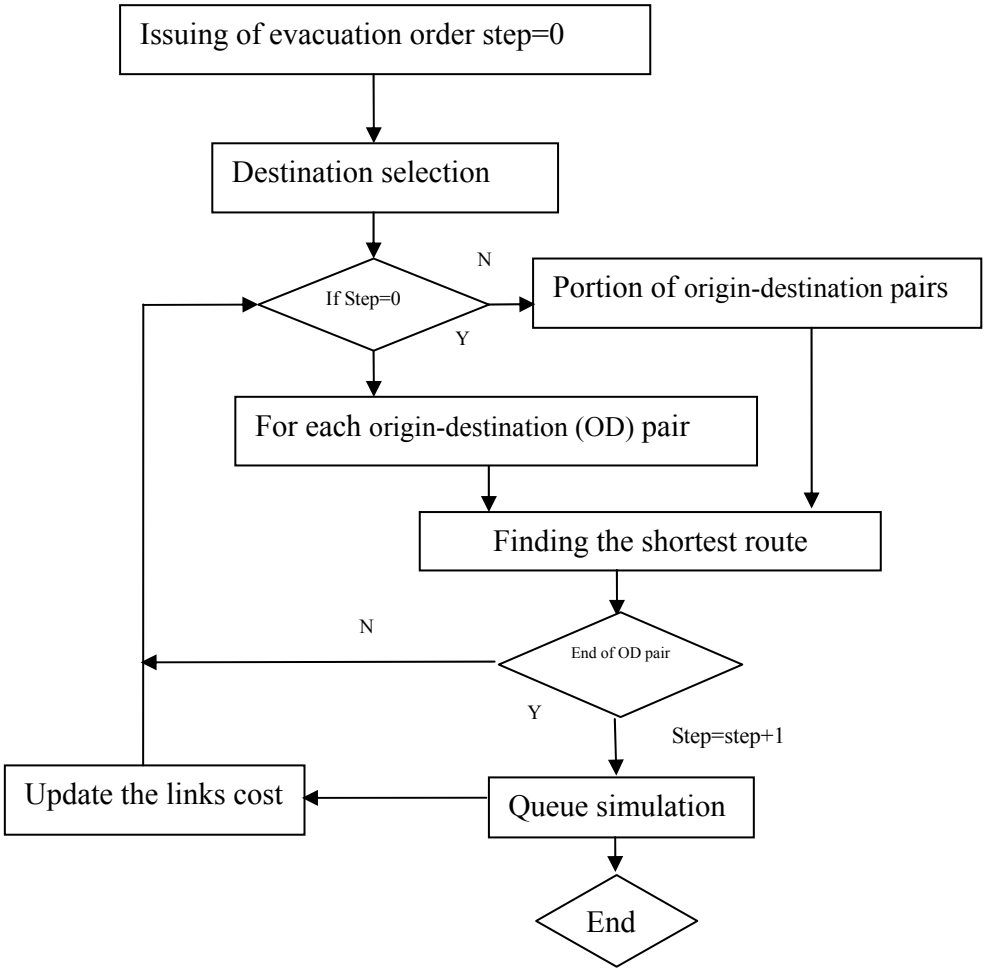


Fig.4. 5 Structure of simulation-based traffic assignment

Note that, if the iteration time N=0, it means that all users will be allocated to the shortest route. This is an all-or-nothing assignment. The main advantage of selecting a dynamic model over a static model is that the former employs a more realistic representation of traffic flow. As a result, dynamic models offer greater potential for capturing reality, and in particular, queuing and congestion during an emergency evacuation. By modeling the delays and queuing due to traffic conflicts, dynamic models provide the transportation engineer with feedback on how traffic volumes and capacity can change according to different

design options.

4.4 Evacuation Model Implementation

The first step in addressing an evacuation simulation is to define the evacuation zone (EZ) and the evacuation exit shelter on the EZ boundary.

The size and shape of an EZ vary considerably depending on the size, strength and rate of growth of the emergency source. For micro-scale evacuation simulations, the evacuation scale is limited by the computer technology and the coded network. For example, scenarios involving evacuation can be modeled to test the use of diversion alternatives for facilitating the evacuation process. It is also feasible for simulating the evacuation of a major facility and testing the ability of the local transportation network to handle evacuation needs.

4.4.1 Topological Network Representation

Having defined an evacuation zone, we much represent the topological network of the streets within the zone. A road network is composed of nodes and links. Links represent the roads and nodes represent the intersections of links. To avoid misunderstandings, an edge is defined as a directed edge, and one road usually consists of two (oppositely directed) edges.

By adopting an object oriented program (OOP) C++, two classes were defined, namely class CLink and class CNode respectively.

The class CNode typically contains:

(1) A unique identity (ID) number for each node, and

(2) Geographical coordinates.

(3) Intersection Capacity

(4) Means of traffic control (traffic light)

The class CLink contains:

(1) A unique ID number for each link

(2) The ID number of the node where the link starts

(3) The ID number of the node where the link ends,

(4) Length of the link

(5) Number of lanes

(6) Capacity

It is noticeable that Netengine represents a network in a different way; three elements, junctions, edges and turns, are used to represent the intersections, edges, and the accessibility between intersection and edge. This is particularly true for edge definition, in which one edge can represent the arc being traversed in the from–to direction as well as in the to–from direction. Another attribute called 'layer' is used to discriminate the direction of edge. The turns element in Netengine enables us to model movement from one edge to another via a junction, which has an interesting advantage for modeling traffic operation during evacuation. For example, a negative turn value prohibits movement from one edge to its adjacent edge.

To make full use of the algorithms of Netengine, a relationship between the two data structures was built up.

Netengine provides us with the following advanced and efficient algorithms:

• The shortest path between two or more points

- The solution to the traveling salesman problem (TSP)
- The identification of the closest facility
- The computation of origin–destination distance matrices
- The allocation of service areas to a location
- The capability of using hierarchical networks.

4.4.2 Vehicle Types

Each vehicle is characterized by type, maximum speed, and capacity. Three kinds of vehicles are considered, i.e., public vehicles, personal cars and emergency cars. Emergency cars have higher priority at intersections irrespective of traffic signals.

4.4.3 Mode Choice

Mode choice refers to the choice of evacuation means, either by car or on foot. Evacuation on foot was discussed in the previous chapter. In this chapter, we focus on evacuation by car.

4.4.4 Traffic Demand Forecasting

The evacuation demand depends on the size of the evacuation area as well as the level and scale of the disaster. To forecast the evacuation demand, it is essential to have information about the makeup of the population, including household size, age, and income level and so on. The demand also depends on the time of day and location of the evacuation area.

Usually, methods of forecasting traffic demand simplify variables. For example, vehicles trips per household from the Traffic Analysis Zone (TAZ) in

the evacuation area are often used to represent the trip generation rate, which is a practical way of forecasting evacuation demand. An in-depth study of traffic demand forecasting can be found in the PhD dissertation of Fu (Fu 2004), who discusses how to develop dynamic travel models for hurricane evacuation.

4.4.5 Evacuation Departure Time

In the case of emergencies that affect the transportation system, the response time is a critical factor in minimizing adverse impacts, including fatalities and loss of property. A good evacuation model should be able to load the evacuation trips onto the highway network in the order in which they are generated rather than load all the trips onto the network at the same time, as has been done in many previous evacuation models. A detailed discussion of evacuation departure time is presented in Chapter 5 of this dissertation. Here, we assume a very simple linear relationship within a time interval to model the evacuation load process.

4.4.6 Integration of Evacuation Model with GIS

The advantages of a geographical information system(GIS)-based system are that information can be quickly and easily updated from a variety of sources, which include available evacuation routes, the distribution of population, cars per family, the position of special facilities, such as fire stations, police stations and emergency shields. GIS can be adopted for evaluating, displaying, sending and receiving information to emergency management personnel.

Generally, there are three approaches to integrating models with GIS, as shown in Figure 4.6. In Type I, the GIS is embedded into the evacuation model;

in Type 2, the evacuation model is connected loosely with GIS; and in Type 3, the evacuation model is embedded within GIS. Type 1 and Type 3 represent an inclusive relationship between transportation and GIS models. It is generally believed to be difficult to build customized programs for GIS due to the complicated mechanisms of GIS data. CEMPS (Pidd et al. 1996; Pidd et al. 1997) is an integrated Type 2 evacuation system.

One possible solution is to use current object-oriented GIs function libraries and ActiveX controls, i.e. MapObjects, NetEngine, and MapX. Object libraries and controls allow users to perform spatial and attribute-based queries, communicate with external applications and build custom application interfaces in conjunction with object-oriented development environments such as Visual Basic, Visual C++.

Type 1 is the most efficient module of the three and thus was adopted in this study. By using ActiveX controls provided by GIS vendors, it is easy to build a bridge over the GIS and evacuation model.

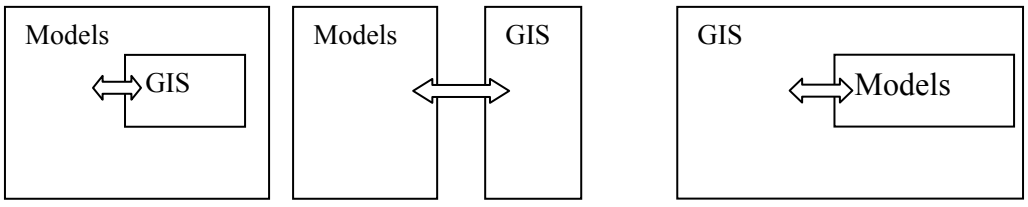


Fig.4. 6 Three types of integration of models with GIS

4.5 Structure of the GIS-based Evacuation Model

The structure of the capacity constrained evacuation model (CCEM) is illustrated in Figure 4.7. It is suitable for the analysis of all types of evacuations.

Firstly, the GIS data of an area of interest, including both geological and attribute data, was collected. The geological data was used to build up the topology of the road network and the location of emergency shelters and districts. The attributes data, including household size, age, income level and car ownership, was used to generate traffic demand in a time-dependent matrix.

Secondly, the topological network was expanded by introducing two super nodes and virtual links, as described in section 4.4.3.

Thirdly, the evacuation simulation was run iteratively, and at each step the attribute data of network was updated. Details are shown in section 4.4.4.

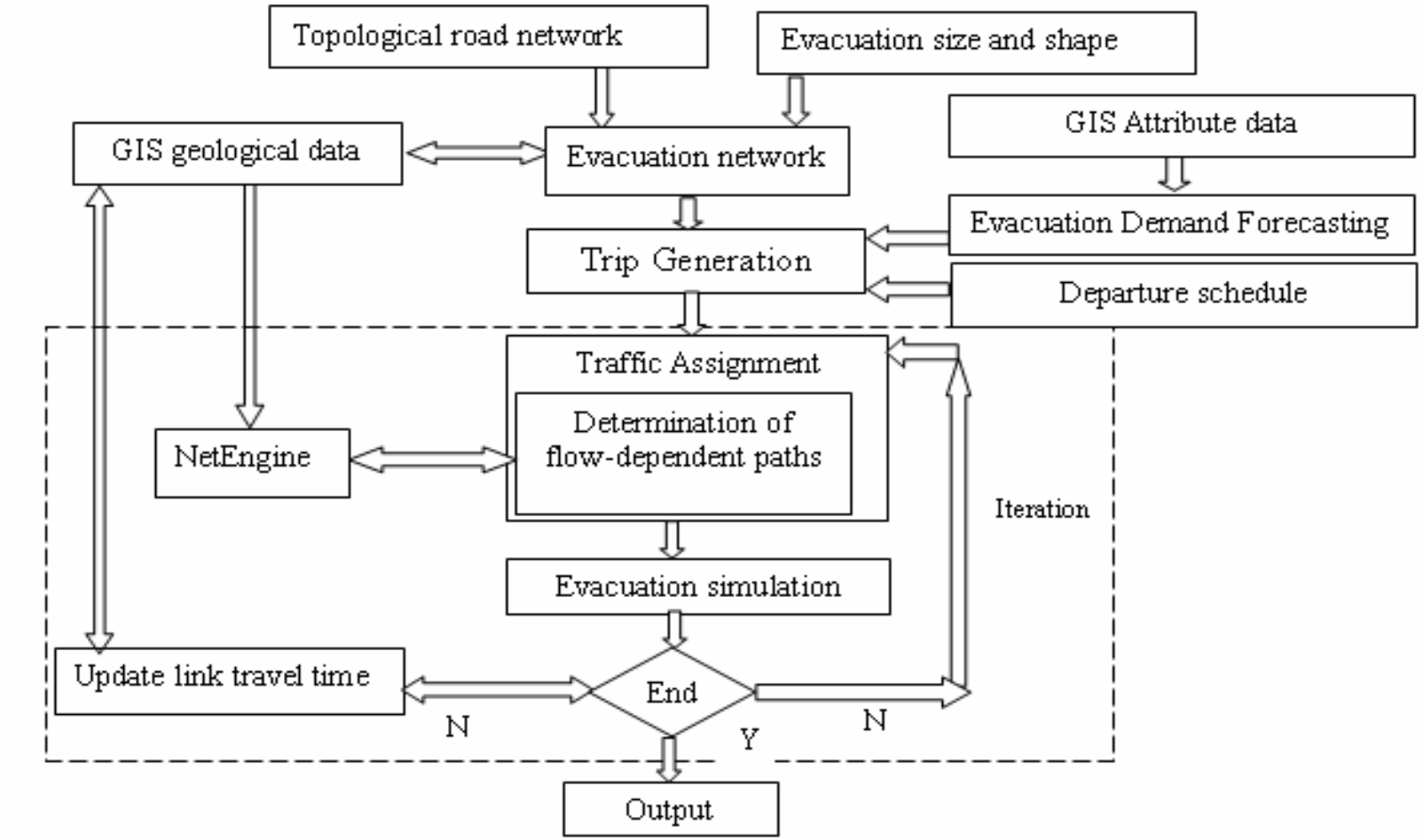


Fig.4. 7 Flow-chart of iterative GIS-based evacuation model

4.6 Comparison with Field Measurement

Some traffic evacuation data are available. However, the evacuation times calculated by the evacuation model can be compared with observed conditions similar to evacuation, such as commuter traffic, athletic events at stadiums and large construction projects (Urbanik II et al. 1988).

A comparison was made between the simulation results of the capacity constrained evacuation model (CCEM) and data from Urbanik II et al.(1988) relating to a congested urban freeway. Urbanik et al.(1998) had compared his data with simulation results of I-DYNEV. The studied site is represented schematically in Figure 4.8.

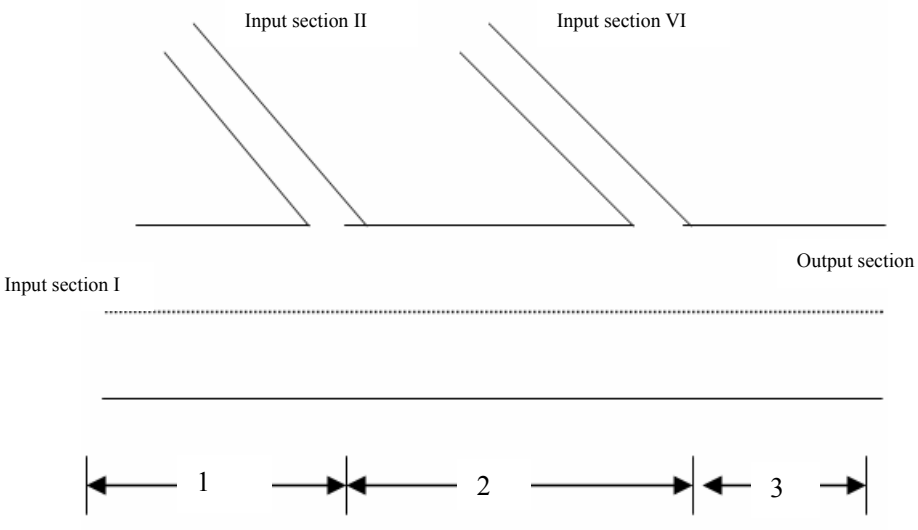


Fig.4. 8 Schematic of the urban freeway studied site

Data was collected on a 2.9-mile section of interstates 35 in Travis country, north of Austin, Texas. The site is a four-lane freeway (two lanes in each direction) in rolling terrain with 12-ft lanes, a 3-ft paved left shoulder, and a 10-

ft paved right shoulder. The section capacity is 2040, which is equivalent to a discharge headway of 3600/2040=1.76 second.

Table 4. 1 Characteristic of the studied roadway network

Roadway segment	Length(ft)	Speed	Number of Lanes
1	2000	60	2
2	9620	60	2
3	3710	60	2
4	500	45	1
5	500	45	1

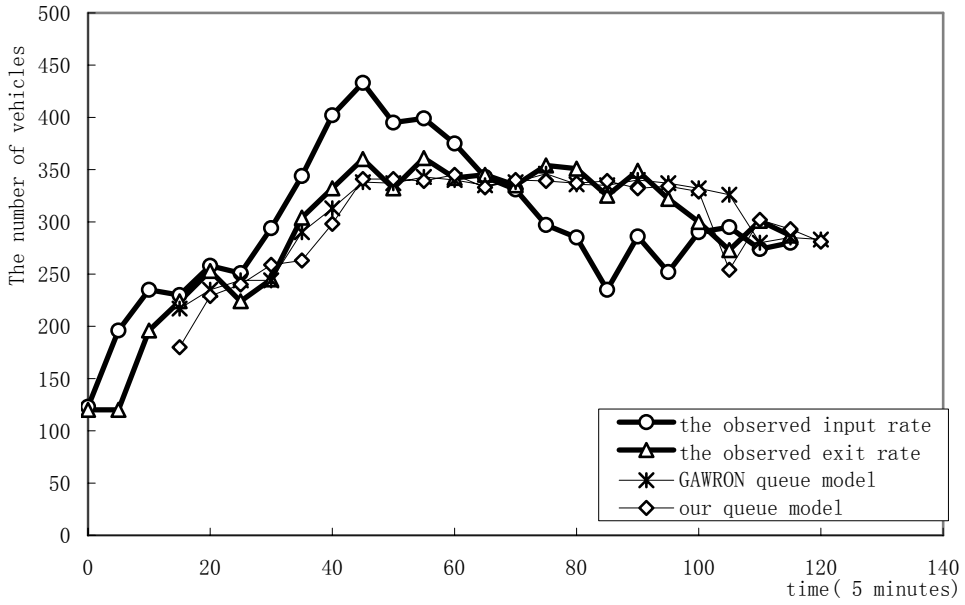


Fig.4. 9 Comparison of results of model with observed data

Traffic volumes were observed at the starting point, endpoint and at each ramp along the transportation network at 5-min intervals, and were available for 25 time periods (from 0 to 120).The rate of vehicle input to the network and the

rate of exiting are shown in Figure 4.9. The highest input rate happened between 40-60 intervals. It is worth mentioning that there is no congestion-induced capacity reduction. The only stop-and-go phenomenon was observed from the 40th step and a traffic queue was formed on the main roads and on-ramp roads.

The rate of vehicles exiting the transportation network as a function of time is a critical parameter for describing traffic conditions during an evacuation. The traffic volumes on the network at initial time were set to zero, and then increased according to their rate of input as observed. The rate of vehicles leaving the network was computed using both Gawron's queue model and our evacuation model and then compared, as shown in Figure 4.6. Both models produced quite satisfactory agreement compared with observed data.

From the comparison, we can conclude that the queue simulation model was appropriate for modeling dynamic aspects of rush hour traffic without congestion-induced capacity reductions. However, whether it is suitable for simulating congestion-induced capacity reductions in traffic should be studied case by case. Further field data and more complicated traffic networks are used for a complete comparison in next section.

Another issue is the simulation interval DT. The sensitivity of the model to the time interval was tested by two simulation intervals, 1 second and 100 seconds. The simulation interval is restricted by the static capacity of links, as pointed out by Sheffi et al.(1982). For example, if a link can only accommodate 100 vehicles at most at the same time, then the maximum number of vehicles leaving the link in a step cannot exceed 100. Similarly, the maximum number of vehicles that can join j-th cannot exceed its static capacity. Finally, the simulation interval cannot be greater than the free flow travel time $T_0 = L / V_0$.

The maximum simulation interval is determined as:

$$dt \le \min\left(\frac{N_{sites}}{C_{link}}, \frac{N_{sites}}{C_j}, L/V_o\right) \tag{4-11}$$

The maximum simulation interval in this network was 13 seconds ($500 \times 0.3048/12.5$). Certainly this is only a theoretical value; as illustrated in Figure 4.10, the interval of 100 seconds still produced results which are fairly congruent with observed data.

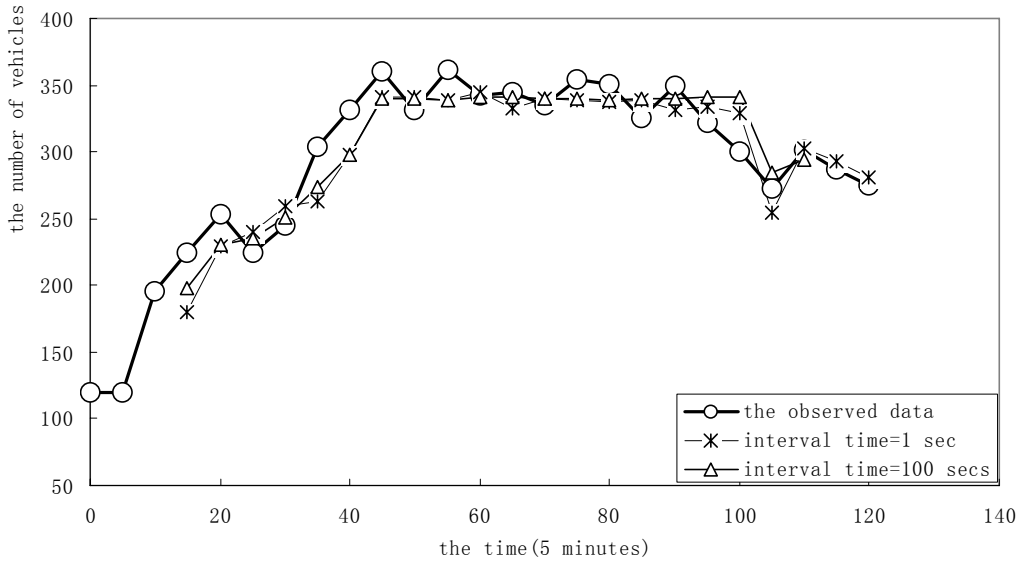


Fig.4. 10 Comparison of model results with observed data, for different intervals

4.7 Comparison with TEVACS Model

A hypothetical network (Figure 4.11) was selected for a further comparison of CCEM with Han (1990). The number of links is 56 and the number of nodes is 20, the number of public emergency shelters is 4, the total number of vehicles

to be evacuated is 7000 and the number of resident districts is 9. All links in the network are 500m long and have 3 lanes. The section capacity is 1500(passenger car units) pcu/lane, the free speed is 50km/h, and the jam density is 200pcu/km.

Many possible evacuation scenarios can be developed, depending upon the area to be evacuated, the time of day, the presence of background traffic and emergency vehicles, and so on. The scenario of interest is one of the worst-case scenarios: the full evacuation of the entire population living in this area. This scenario would typically occur at night (everyone at home) or after an emergency has been declared for some time (i.e. non-resident traffic has been banned from entering the area, residents have been allowed to return prior to evacuating) (Han 1990).

Since the initial distribution of residents is not clearly stated, we uniformly distributed the population to the 9 resident districts. All people were to be evacuated by car.

To regulate the traffic flow and avoid over-congestion at all nodes, pre-timed or unsignalized signals were adopted at intersections. The cycle length of a pre-timed signal was fixed, regardless of current volumes, allowing equal usage of the intersection by all connected streets. However, the operation of unsignalized controllers varied according to the observed volume. Unsignalized controllers distribute the signal phases according to the traffic demand and adjust signal timing accordingly. Both unsignalized intersection control and pre-timed traffic control were adopted to allow a comparison to be made.

Furthermore, we define the following:

The total evacuation time (TET): the time when 95% of evacuees have arrived

at their destinations.

The load time (LT): the length of time needed to prepare for an evacuation and all people are mobilized and loaded into network within load time.

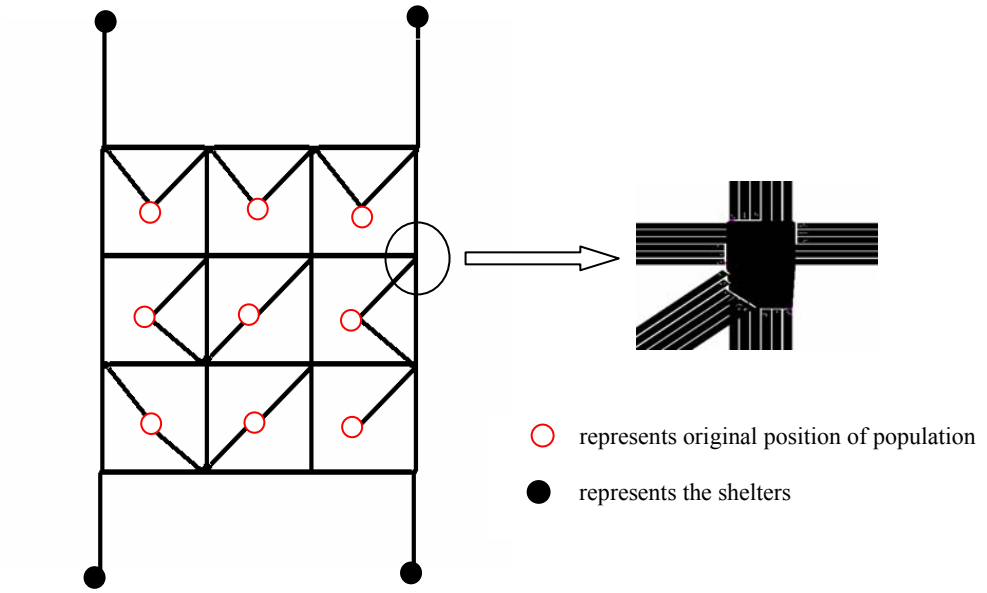


Fig.4. 11 Hypothetical network (extracted from Han (1990))

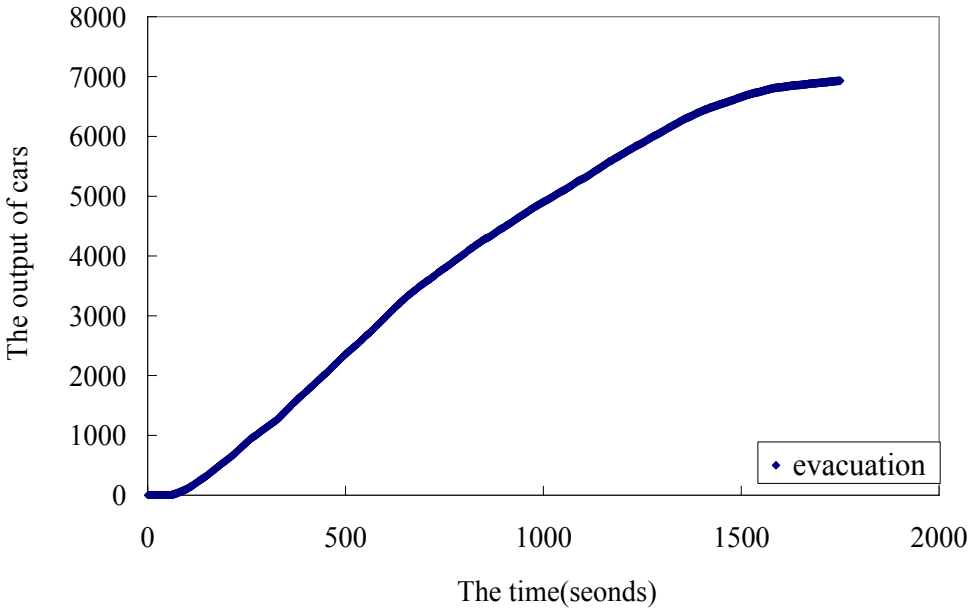


Fig.4. 12 Evacuation process of the whole network

The LT was set at 600 seconds, and two ways of traffic assignment, all-or-nothing assignment and iterative traffic assignment were conducted. The results are shown in Figures 4.12-15. For the all-or-nothing assignment, the total evacuation time (TET) was about 1809 seconds; the evacuation process is shown in Figure 4.12. Figure 4.13 gives the number of running and loading cars per step.

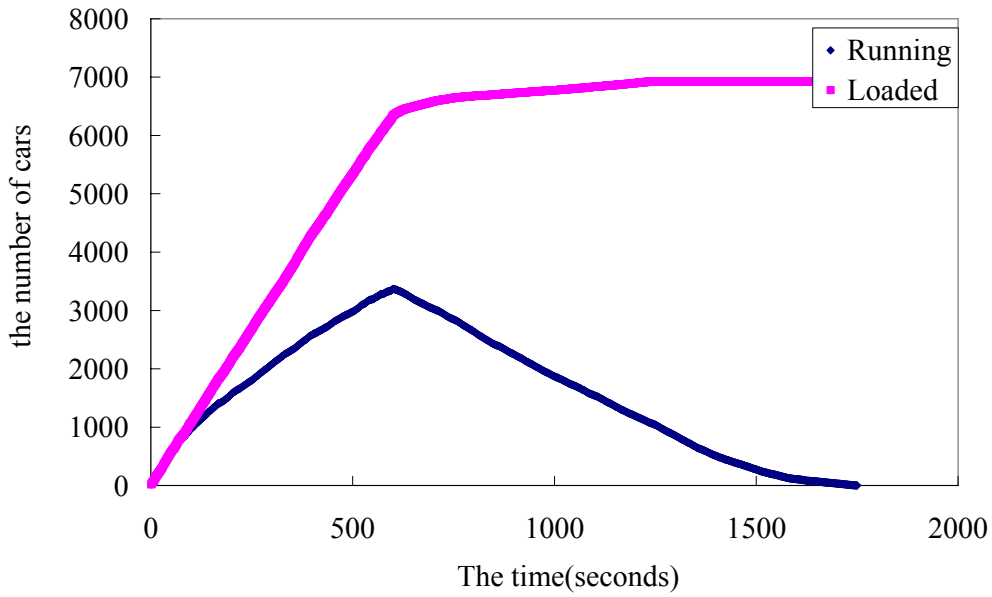


Fig.4. 13 Number of running and loading cars

For the simulation-based iterative assignment, the iteration time was set as 10. The simulation results are illustrated in Figure 4.14. TET decreases to 1657 seconds, a reduction of about 8.5% compared with the all-or-nothing assignment. The convergence of the iterative process is shown in Figure 4.15. The iteration reaches a relative balance convergence very quickly, after 3-5 times. After that, the iteration process shows certain degree of variation.

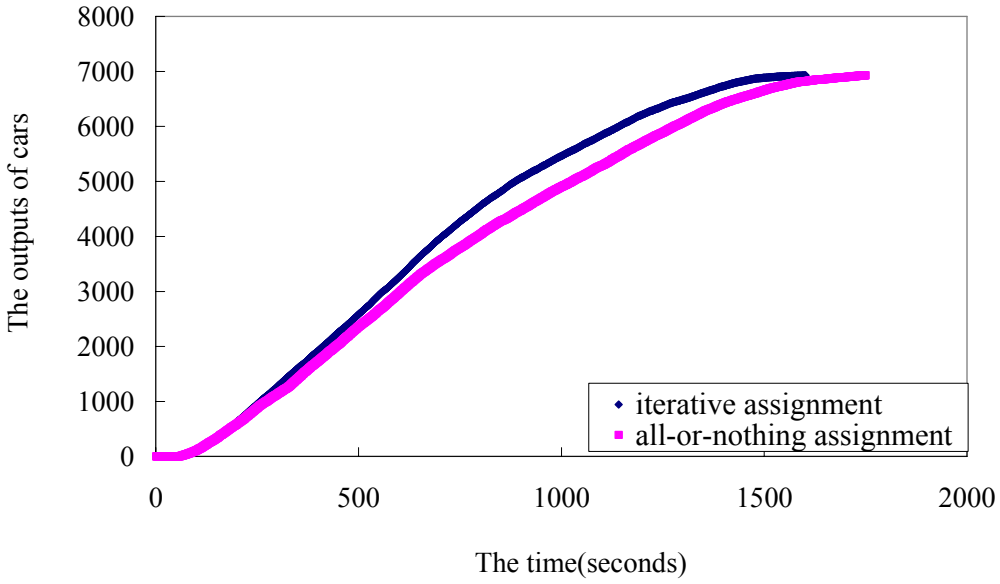


Fig.4. 14 the comparison of evacuation process of two assignments

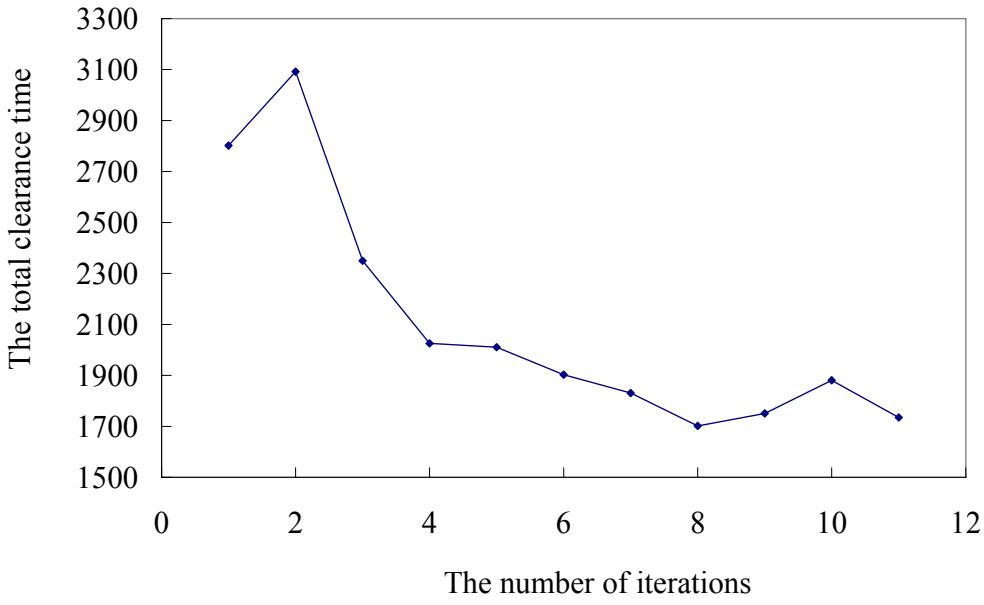


Fig.4. 15 The convergence of iterations

Table 4. 2 Simulation results

Simulation interval	**Capacity Constrained evacuation model(CCEM)**	Gawron's queue model	TEVACS
1 sec	**27.6 mins**	25.7mins	unavailable
100 secs	**29.7 mins**	26.6 mins	32 mins

Table 4.2 presents a summary of the TET performance of three models, Gawron's, TEVACS and capacity constrained evacuation model (CCEM), with simulation intervals of different lengths. It seems that the three models produced quite similar results. However, as Gawron's model ignores the constraint of approach capacity at intersections, our model generates more conservative results.

Another type of signal control, pre-time signal control, was also adopted and the TET is about 4300 seconds. As expected, the pre-timed signals performed much worse than the unsignalized intersection control.

4.8 Sensitivity Analysis

The principal goal of evacuation time estimate studies should be to evaluate the sensitivity of the ETE in a specific area to variation in controllable and uncontrollable variables such as traffic routing, signalization, population, weather and traffic accidents. Once protective action analysts understand the sensitivity of evacuation times to each of these variables, they can estimate the evacuation time for any set of conditions not specifically analyzed in the study. Sensitivity analysis was further conducted focusing on the following parameters: population size, load time, closure of a shelter and the presence of background traffic.

4.8.1 Sensitivity to Population Size

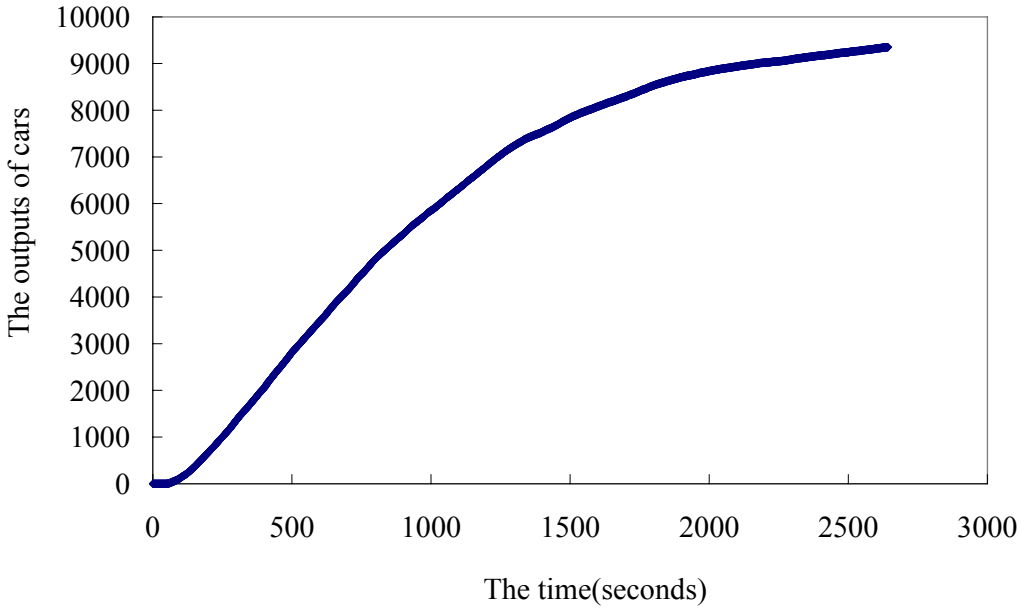


Fig.4. 5 Evacuation process after 35% of increase in population

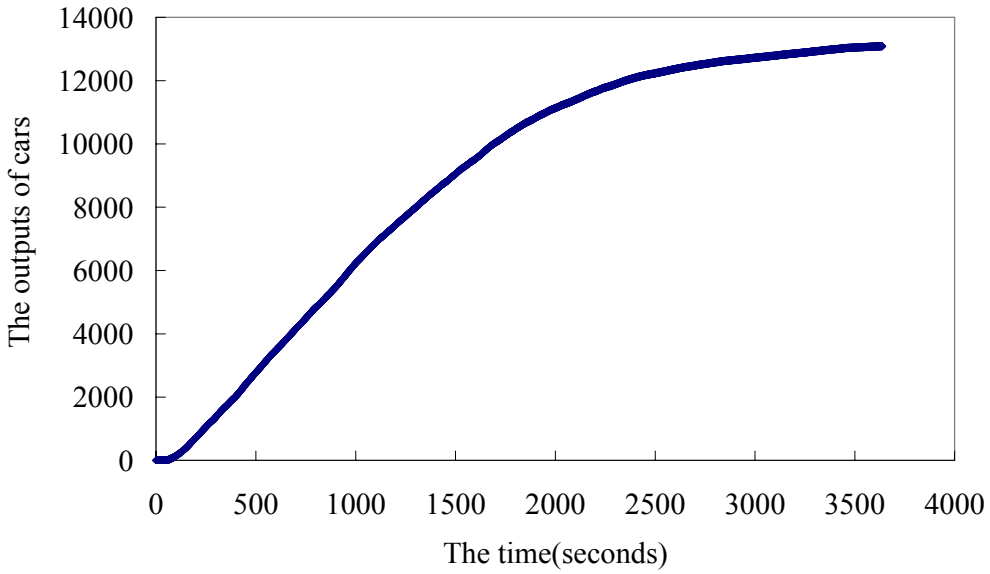


Fig.4. 17 Evacuation process after 90% of increase in population

If the population of the city increases by 35%, the TET will be increased to 2526 seconds, as shown in Figure 4.16, an increase of about 52% in total

evacuation time. If the population size increases by 90%, the TET will be increased to 3642 seconds, as shown in Figure 4.17, increase of about 120%. So an increase in population has a significant effect on the TET.

4.8.2 Sensitivity to the Evacuation Load Time

To test the influence of load time on the total evacuation time, we simplified the load process and assumed a linear load process within a time length LT (load time) =0, 600, 1200 and 1800 seconds respectively. LT=0 means that the population is mobilized instantly as soon an evacuation order is issues. LT=1800 seconds denotes that a population will be uniformly loaded into the network within 1800 seconds.

The results are shown in Figure 4.18 and Table 4.3. If the load time is zero, the evacuation time is about 2100 seconds by the all-or-nothing assignment and 1578 seconds by iterative assignment, a 25% reduction in the evacuation time. This implies that the iterative assignment can effectively improve the efficiency of an evacuation. At longer loading times, the TET difference between the two approaches decreases. For example, for LT=1800, there is no discernable difference between them, as shown in Figure 4.18. This is quite understandable because as the preparation time increases, the traffic congestion is alleviated, thus each evacuee can be allocated to his shortest route. So the performance of iterative assignment is related to the length of the load time.

Table 4. 3 Comparison of TET using different load times

	The Total Evacuation Time			
The load time(LT)(seconds)	0	600	1200	1800
all or nothing assignment(seconds)	2100	1809	1820	2090
Iterative assignment(seconds)	1578	1629	1723	2034
Percent difference %	-25%	-10%	-5%	-2.6%

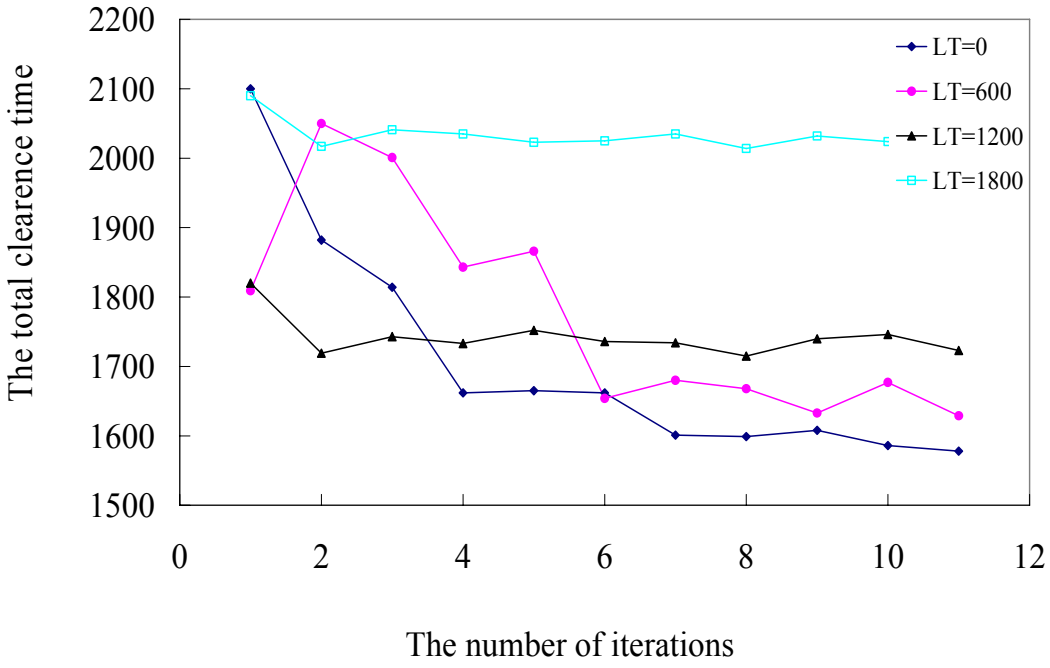


Fig.4. 18 Difference in TET after different iterations

In this example, we can see that the TET increases with the increase in loading time. When the loading time is 1800 seconds, the TET is about 2034 seconds, an increase of approximately 29% compared with LT=0. However, this is not always true for a more complicated network or when more people are involved. The influence of load time on the TET is discussed in detail in Chapter 6.

4.8.3 Sensitivity to the Closure of One Shelter

If one of the emergency shelters is closed and only the remaining three shelters are used to accommodate evacuees, the total clearance time is 2802 seconds using all-or-nothing assignment (Figure 4.19), and 1780 seconds using iterative assignment (Figure 4.21), a 36% improvement. Though one of the shelters is abandoned, the total evacuation is not affected much if the appropriate traffic assignment method is adopted.

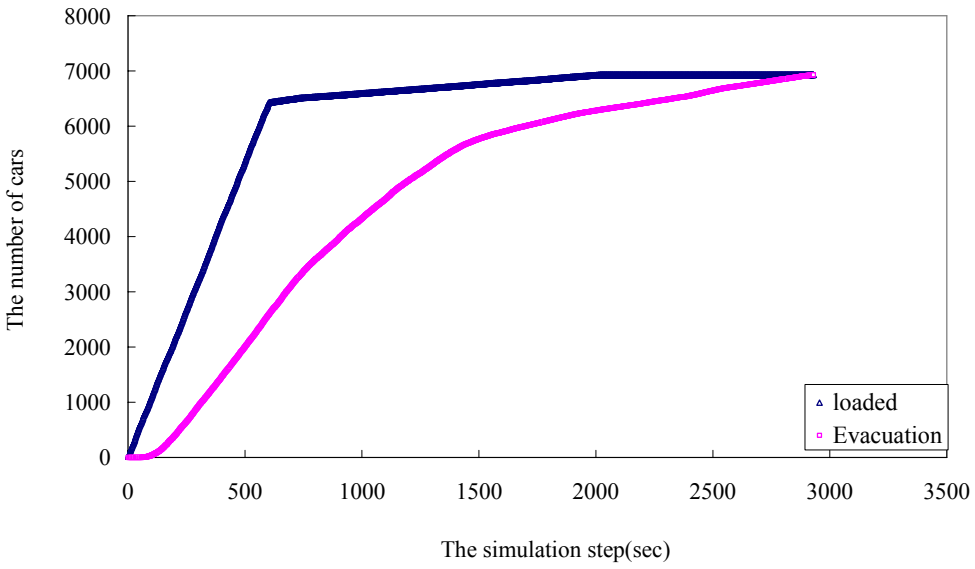


Fig.4. 19 Cars loaded and evacuated

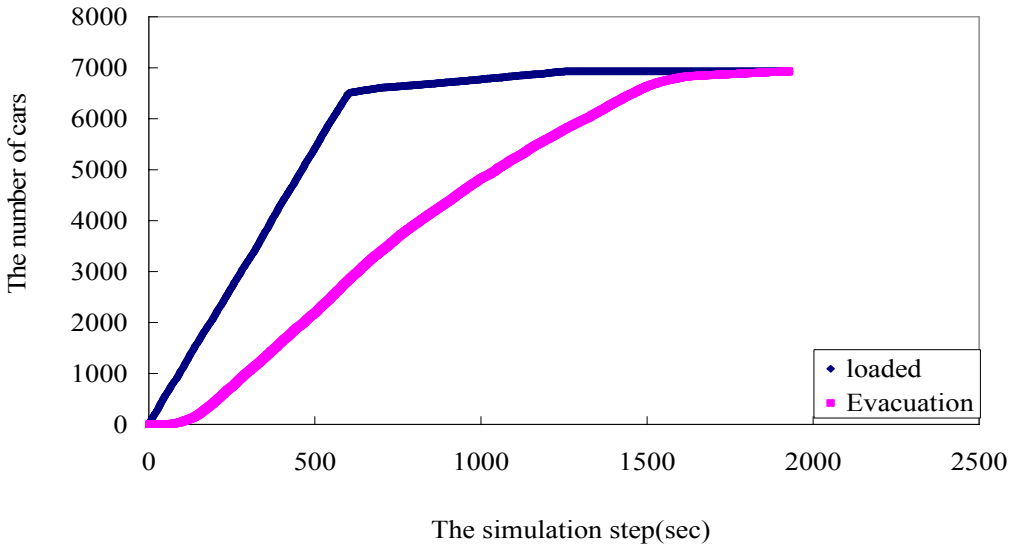


Fig.4. 20 Cars loaded and evacuated

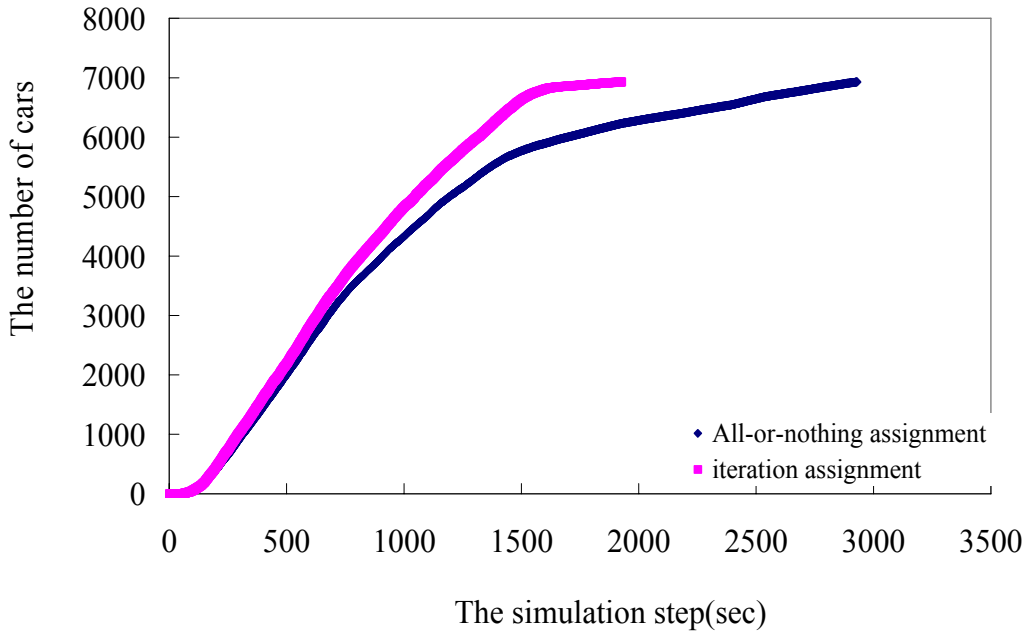


Fig.4. 21 Comparison of results between two types of assignment

4.8.4 Influence of Background Traffic

The scenarios discussed above did not consider the presence of background traffic and assumed that the people remain in their districts during the initial

stage of an emergency and are then evacuate according to predefined routes.

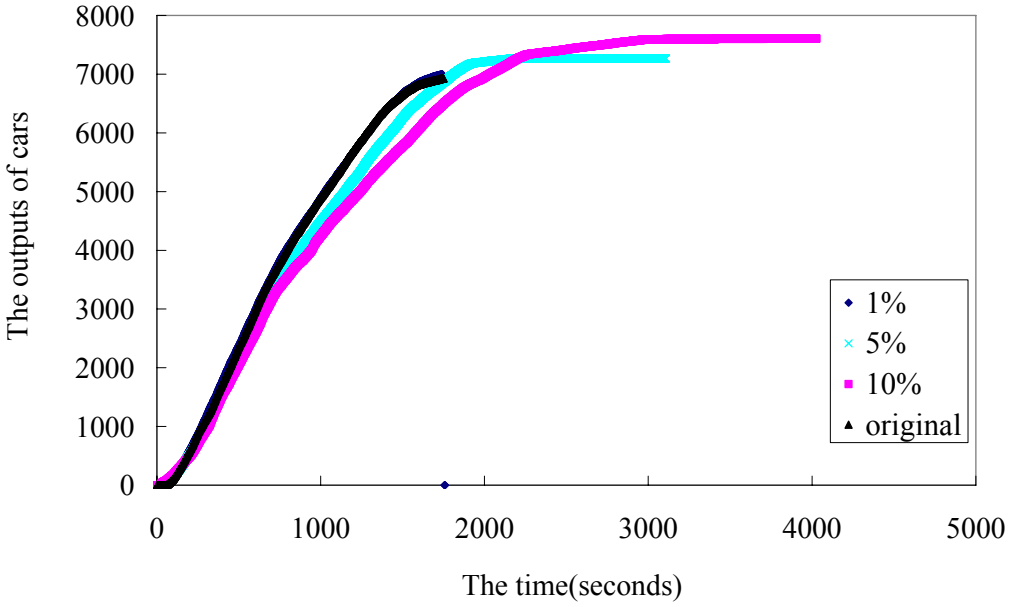


Fig.4. 22 Presence of background traffic

We studied the influence on the TET of background traffic, which moves randomly through the network until it reaches the destination shelters. Background traffic volume was varied from 1%, 5% to 10%. The results are shown in Figure 4.22. It was found that the addition of 1% background traffic has little effect on the TET. However, the addition of 5% and 10% has a considerable influence on the TET, increasing it by about 77% and 130 % respectively. However, if we define the evacuation time at 95% of the evacuation level, which means that 95% of the population has been evacuated, then evacuation times are 2041 and 2180 seconds respectively, increases of about 5% and 24%.

4.9 Summary

The threat to the urban population is increasing due to an increase in the

number of disasters. As our cities become more densely populated, the need for evacuation planning is becoming more urgent.

A capacity constrained evacuation model(CCEM) was established based on the queue model. It consisted of two link scanning processes, which check the dynamic capacity and static capacity respectively at each step. This model simplified the lane change behavior of drivers on roads and focused on the behavior of drivers at intersections. Despite its simplicity, it was able to model the congestion and spillback process during an emergency evacuation. This mesoscopic model attempted to combine the best features of both macroscopic models and microscopic models by filling the gap between the aggregate level approach of macroscopic models and the individual interactions of the microscopic ones. They normally describe the traffic entities in great detail, but behavior and interaction in less detail.

Two types of assignment were implemented in the meso-simulation model, all-or-nothing assignment and simulation-based iterative assignment. The former allocates the evacuees to their shortest routes and the latter distributes the evacuees to quasi-optimal routes. The performance of the two approaches was compared and it was found that the iterative assignment decreased the TET greatly, particularly under conditions of congestion. Iterative assignment can help making full use of the evacuation network, thus facilitating the movement of evacuees. The performance of iterative assignment is closely related to load time.

CCEM model was integrated with Netengine, a GIS component, which can provide all kinds of network algorithms. The GIS-based meso-evacuation model can provide a cost-effective way to simulate and evaluate the safety of a

population in an area in terms of TET, and can also be used to guide and control the evacuee traffic during a real-time evacuation.

Chapter 5

Evacuation Optimization in Dynamic Networks

In this chapter, a time-varying quickest flow problem (TVQFP) is first used to optimize city evacuation planning. Then a lexicographically time-varying quickest flow problem (LTVQFP) is used to determine the minimum clearance time for evacuating high priority residents. Both TVQFP and LTVQFP were adopted so as to minimize the clearance time of residents in danger.

5.1 Introduction

Network flow problems have attracted research interest in the past decades (Ford and Fulkerson 1962), but most researchers have focused on algorithms and problems in static networks. A flow circulating at a link on static network passes through this link as soon as the flow enters it. In other words, the flow travels at an unlimited velocity. This assumption is reasonable for some kinds of flow problems, such as electricity or light, but for other kinds of problems, such as traffic flow in urban networks or fluid in ducts, it may bring about many problems. For example, we want to know the minimum time needed to evacuate a city in an emergency. If we solve this problem using a static network, and ignore the transit time on roads, it is not possible to get the correct evacuation time. Furthermore, if the population evacuated is greater than the capacity of roads, there is no feasible solution at all in a static network.

Ford and Fulkerson (1962) first introduced the concept of dynamic networks, which are different from static networks in that flow traveling over a link needs time to reach its end. All classic flow problems arising in static networks also apply in dynamic networks, such as the maximal flow problem (Ford and Fulkerson 1958) and minimal cost flow problem (Klinz and Woeginger 1995). However, as the dynamic network expands the original network in time and space, it also generates many new flow problems, such as the quickest flow problem and the earliest arrival problem.

The minimum cost dynamic flow problem is how to send an amount of flow from the source to the sink within T at the minimal cost. Klinz and Woeginger (1995) proved that minimum cost problems are NP-hard. Cai et al. (2001) proposed a minimum cost flow problem on a time-varying dynamic network, in which the travel cost and transit time are time-dependent variables.

A flow that maximizes the throughput for every interval [0, t], $t \in [0,T]$, is called the earliest arrival flow. A closely related problem is the latest departure flow, which maximizes the amount of flow leaving the source for every interval [t, T], $t \in [0,T]$. A universally maximum dynamic flow is both the earliest arrival flow and the latest departure flow. Wilkinson (1971) gave algorithms for computing a universally maximum dynamic flow based on Ford and Fulkerson's shortest augmenting path algorithm. Hoppe and Tardos (1994) gave a polynomial approximation. Orda and Rom (1990) gave a construction for the earliest arrival flow in continuous time with piecewise continuous network parameters. Aronson (1989) is a comprehensive review of dynamic network flow problems.

There are many applications of dynamic networks in studies of evacuation

problems. Chalmet et al. (1982) adopted a time-expanded network with constant parameters to optimize building evacuation. Choi et al. (1984;1987,;988) proposed a minimal cost flow problem with side constraints for building evacuation. Hamacher and Tufekci (1987) presented a lexicographic minimal cost flow problem for solving the multi-objective problem of building evacuation in a time-expanded network. The earliest arrival flow problem, equivalent to the quickest flow, was widely used in evacuation planning for route optimization. Hamacher and Tjandra (2002) proposed an earliest arrival flow with time-dependent capacity to solve evacuation problems. Hooks and Patterson (2004) adopted a pseudo-polynomial time algorithm for solving the integral time-dependent quickest flow problem (TDQFP) and its multiple source and sink counterparts. Hoppe and Tardos (1994) provided a polynomial algorithm for the evacuation problem with a fixed number of sources. Hamacher and Tjandra (2002) gave an excellent review of the application of dynamic networks to evacuation problems.

5.2 Static Network Flow Approach

Static flow theory (Ford and Fulkerson 1962) has been widely adopted for optimizing urban evacuation planning, in which the classic problem is the minimum cost flow problem. This is defined by a given set of arcs and nodes, where each arc has a known capacity and unit cost and each node has a fixed external flow. Evacuation optimization planning attempts to determine the minimum cost n for sending flow through the network to satisfy demand, which represents the initial number of people to be evacuated, and supply, which represents the capacity of shelters, as well as the arc constraints. We need to

produce evacuation route plans consisting of a set of origin-destination routes and scheduling of people to be evacuated via the arcs, with the objective of minimizing the total cost or travel time needed for evacuation.

We now formulate the evacuation problem in mathematical terms for a static network. Let the graph, composed by nodes and arcs, be represented as G(V, E), where V and E stand for the set of nodes and the sets of arc respectively.

$$\text{Minimize: } \sum_{(i,j)\in V} a_{ij} \cdot c_{ij} \tag{5.1}$$

Subject to:

$$\sum_{\{j/(i,j)\in V\}} x_{ij} - \sum_{\{j/(j,i)\in V\}} x_{ji} = s_i \qquad \forall i \in N \tag{5.2}$$

$$b_{ij} \le x_{ij} \le c_{ij} \qquad \forall (i,j) \in V \tag{5.3}$$

Where a_{ij} represents the cost coefficient of arc (i,j), b_{ij} and c_{ij} are the lower bound and upper bound of arc (i,j) respectively and s_i denotes the supply of node i. x_{ij} is the flow on arc $(i,j) \in E$

The constraints given in (5.2) and (5.3) are referred to as conservation of flow constraints and capacity constraints respectively. A flow vector satisfying both of these constraints is called a feasible flow.

These equations can solve a typical single-source and single-destination transportation problem. However, for an evacuation network, the number of source nodes is larger than 1, so is the number destination nodes, as shown in Figure 5.1. There are two virtual nodes, one representing the virtual source node and connecting with all actual source nodes by many virtual links; and the other node representing the virtual destination node and also connecting all actual destination nodes by virtual links. In the definition, our network can be

represented as a standard single-source and single-destination minimum cost flow problem. The cost of virtual links is zero and the upper capacity is constrained by the capacity of connected nodes. If the capacity of destination nodes is unlimited, the minimum cost flow problem can be transformed as the shortest problem.

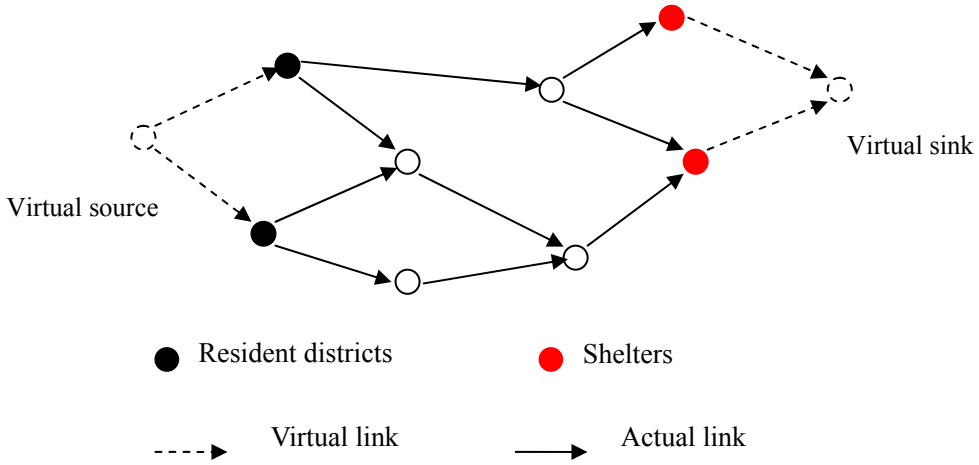


Fig.5. 1 General form of evacuation problem in a static network.

5.3 Dynamic Network Definitions

Dynamic network flow expands the time horizon of static networks. Let G (V, E, U, C, T) be a directed graph with the vertex set V, arc set E, link capacity constrains set U, node capacity constraints set C, and the time space T. Each arc $(i, j) \in E$ has a nonnegative time-varying maximum capacity $u_{ij}(t)$ and a positive travel time (or cost) $\lambda_{ij}(t)$, where t denotes the departure time. The capacity $u_{ij}(t)$ limits the amount of flow rate entering an arc at a specified time t. $C_i(t)$ represents the dynamic node capacity of vertex i at t, which is the

maximum number of vehicles passing through this intersection. Both link capacity and node capacity can be determined by HCM(Highway Capacity Manual). Each vertex is associated with a maximum hold capacity $d_i(t)$ and a maximum waiting time $w_i(t)$. The network is a standard single-source s and single-node d and $s(t)$ represents the amount of supply at source at time t.

Without any ambiguity, we let $x_{ij}(t)$ be the flow on arc $(i, j) \in E$ that leaves node i at time t and will arrives at node j at time $t + \lambda_{ij}(t)$, $y_i(t)$ be the flow waiting at vertex i during period [t, t+1] and $f(h,T)$ be the total value under a schedule h, which specifies when and how to send flows from the source to the sink within the time limit T. It can be represented as:

$$f(h,T) = \sum_{(i,d)\in E, t+\lambda_{id}(t)} x_{id}(t) \tag{5.4}$$

Then a feasible schedule for sending a given flow from source to sink within a time limit so as to minimize the total evacuation time can be derived. The set of predecessor and successor nodes to a node i are given by $\delta^-(i) = \{j/(j,i) \in E\}$ and $\delta^+(i) = \{j/(i,j) \in E\}$ respectively. A general discrete-time minimal cost flow problem can be formulated as follows.

$$\text{Min} \sum_{(i,j)\in E} \sum_{t=0}^{T} \lambda_{ij}(t) x_{ij}(t) \tag{5.5}$$

s.t.

$$\sum_{(s,j)\in E} \sum_{t=0}^{T} x_{ij}(t) = \sum_{t=0}^{T} s(t) \tag{5.6}$$

$$\sum_{j\in\delta^+(i)} x_{ij}(t) - \sum_{j\in\delta^-(i)\{t'/t'+\lambda_{ji}(t')=t\}} x_{ji}(t') = y_i(t) \quad \forall i \in V \setminus d \quad t \in \{0,...T\} \tag{5.7}$$

$$\sum_{(i,d)\in E} \sum_{t=0}^{t+\lambda_{id}(t)\le T} x_{id}(t) = \sum_{t=0}^{T} s(t) \tag{5.8}$$

$$x_{ij}(t) \le u_{ij}(t) \tag{5.9}$$

$$x_{ij}(t) \ge 0$$

$$\forall (i, j) \in A, t = 0,1,...T$$

All parameters and variables are integers.

The objective (5.5) is to find the minimal cost of sending an amount of flow from the source to the sink within a time interval [0, T]. The constraints (5.6) and (5.8) consider the balance of flow at sink and source; constraints (5.7) refer to the flow conservation at internodes; Equations (5.9) are capacity constraints.

To send all the initial flow $s(t)$ from the source s to the sink d as quickly as possible, a more general single-source-single-sink formulation of quickest flow is given by:

$$\text{Min:} \quad T \tag{5.10}$$

Subject to:

$$\sum_{(s,j)\in E} \sum_{t=0}^{T} x_{ij}(t) = \sum_{t=0}^{T} s(t) \tag{5.11}$$

$$\sum_{j\in\delta^+(i),\{t'+\lambda_{ji}=t\}} x_{ji}(t') - \sum_{j\in\delta^-(i)} x_{ij}(t) = \begin{cases} s(t) & i = s \\ y_i(t) & otherwise \end{cases} \quad \forall i \in V \setminus d \;\; t \in \{0,...T\} \tag{5.12}$$

$$\sum_{i\in\delta^+(d)} \sum_{t=0}^{t+\lambda_{id}(t)\le T} x_{id}(t) = \sum_{t=0}^{T} s(t) \tag{5.13}$$

$$x_{ij}(t) \le u_{ij}(t) \tag{5.14}$$

$$x_{ij}(t) \ge 0$$

$$\forall (i, j) \in A, t = 0,1,...T$$

5.4 Multi-source and Multi-sink Problem (MSMSP)

Sources are places where residents are when an evacuation order is first issued and sinks are emergency shelters or places far from hazards. An evacuation can be thought of as a multi-source and multi-sink problem.

In a static network, this multi-source and multi-sink problem can be easily reduced to a single-source single-sink problem by introducing a super-source and a super-sink, as described in the last section.

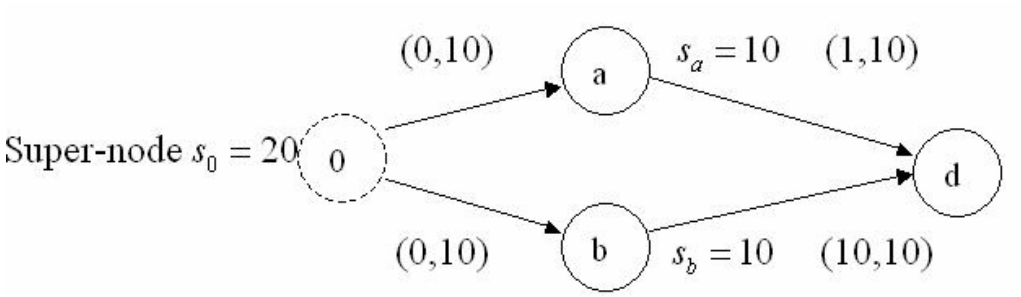
However, in a dynamic network, the oversimplified definition of supernode (sink) may result in problems. As illustrated by a simple example (Figure 5.2), a and b represent two original source nodes with occupants 10 and 10 respectively. d is the destination node and we want to know the minimal time needed to send all flow from a and b to destination d. It is quite clear that the minimal time is 10 seconds and the evacuation routes are a-d and b-d.

If we connect two original source nodes by introducing a super-node 0 with the demand requirement of 20 in a similar way to a dynamic network, and the capacity and transit time of each virtual arc are defined as:

$$u_{oa}(t) = 10 \qquad \lambda_{oa}(t) = 0 \qquad t \in [0,T] \tag{5.15}$$

$$u_{ob}(t) = 10 \qquad \lambda_{ob}(t) = 0 \qquad t \in [0,T] \tag{5.16}$$

With this definition, the solution is that all flow will go through one route o-a-d and the minimal clearance time is 2 seconds. Clearly, this is a wrong solution.



$(\lambda, u), \lambda$ represents the travel time and u represents the through capacity.

Fig.5. 2 A simple multi-source problem

Another issue which may arise from the evacuation problem is that the traffic demand at source is time-varying. In other words, not all traffic demand is mobilized and loaded at once but at a time-varying rate. This is common in real-life evacuations: people have different preparation times and only those who are prepared at each step can be loaded into the network at that time.

So the transformation of a multi-source-multi-sink problem into a single-source-single-sink problem should be treated on a case-by-case basis. For the example shown in Figure 5.2, the network can be amended by re-defining the capacity of two virtual arcs as follows:

$$u_{oa}(t) = \begin{Bmatrix} 10 & t = 0 \\ 0 & t > 0 \end{Bmatrix} \quad u_{ob}(t) = \begin{Bmatrix} 10 & t = 0 \\ 0 & t > 0 \end{Bmatrix} \tag{5.17}$$

If the supply at source is time-dependent, and production rate is $p_a(t)$, then we define the capacity of virtual link oa as:

$$u_{oa} = p_a(t) \tag{5.18}$$

Summing up, if the number of source nodes K is greater than one ($K \geq 1$), a super-source o is added to the network, and virtual arcs associated with travel time $\lambda_{ok}(t) = 0$, and capacity $u_{ok}(t)$ are added to connect each original source

node with the super-node, as shown in Figure 5.3. The capacity $u_{ok}(t)$ equals the number of occupants joining the evacuation at original source node k at time t. If we assume that all occupants mobilize as soon as the evacuation begins, then the through capacity of each virtual arc at t=0 equals the total number of occupations (TNO) at each source node.

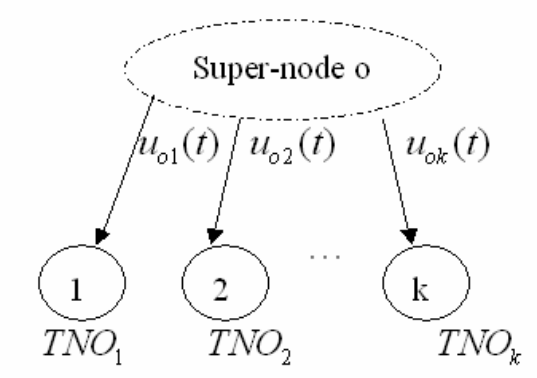


Fig.5. 3 Transformation of multi-source to single source

$$u_{ok} = \begin{Bmatrix} TNO_k & t=0 \\ 0 & t>0 \end{Bmatrix} \qquad k=\{1,2,...K\}, t=\{0,1,...T\} \tag{5.19}$$

If occupants are mobilized at a pre-defined rate P (t), then the capacity of virtual links can be treated in the following way:

$$u_{ok} = P_k(t) \qquad k=\{1,2,...K\}, t=\{0,1,...T\} \tag{5.20}$$

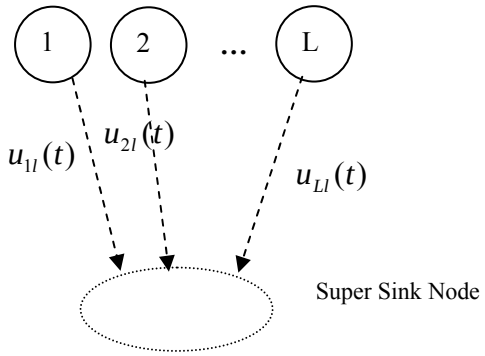


Fig.5. 4 Transformation of multi-sink to single sink

Let the number of original destinations be L ($L \geq 1$) as shown in Figure 5.4, and a super-sink l and its associated virtual arcs connecting the super-sink with original sinks be added. Each original destination provides a limited capacity C_j or has a service rate $c_j(t)$, or is of unlimited capacity. The travel time is $\lambda_{jl}(t) = 0$, $j = \{1,2,...L\}, t = \{0,1,...T\}$. The capacity of the arcs at time t $u_{jl}(t)$ can be defined as follows.

For un-constrained condition:

$$u_{jl}(t) = \infty \tag{5.21}$$

For capacity constrained condition:

$$u_{jl}(t) = \begin{cases} 0 & t < T \\ C_j & t = T \end{cases} \tag{5.22}$$

For service at rate:

$$u_{jl}(t) = c_j(t) \tag{5.23}$$

5.5 Storage at Nodes

Storage means that the flow conservation is not satisfactory at each time instance because the amount of flow arriving at a node at a given time can be

different from the amount of flow that leaves the node at that time.

Generally, in an evacuation problem, the population at source surpasses unit capacity of roads and therefore cannot be loaded into the network all at once. Only a portion of the population can be loaded at each step, so the original source nodes should be assigned an amount of storage capacity to temporarily store the remaining population until it can continue on a road. Let the number of source nodes be K, and the total number of occupations (TNO) at source k $\mathrm{TNO_k}$. We define the storage of original source nodes as

$$d_k(t) = \mathrm{TNO_k} \qquad \text{k=1,…,K.} \tag{5.24}$$

Similarly, at each original sink, people are allowed to wait until they are allocated to the super sink before entering it at the last step. Let the number of original destinations be L and the total capacity of the original destinations j C_j. We define the storage of the original sink nodes as:

$$d_j(t) = \mathrm{C_j} \qquad \text{j=1,…,L} \tag{5.25}$$

We restrict the flow waiting at inter-nodes by defining it as:

$$d_i(t) = 0 \tag{5.26}$$

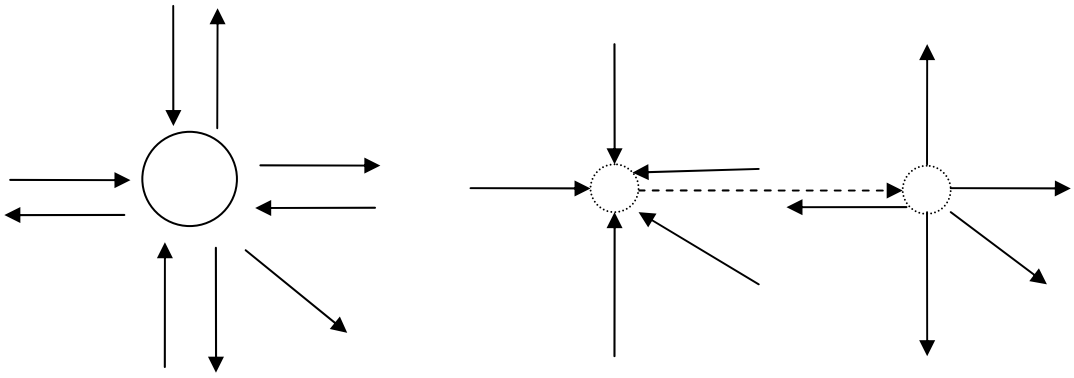
5.6 Constraints Imposed by Intersections

Most traffic delays during an evacuation occur at intersections (Southworth 1991). To better model the constraints of the intersection, an extended one can be modeled, as shown in Figure 5.5. The original intersection is separated into two nodes; one node is connected to all incoming links and the other is connected to all out-coming links. If a virtual link, with the cost of 0 and upper capacity of C, is added to connect the two nodes, the constraints imposed by

intersections can be appropriately modeled.

The expanded network will increase the computation time greatly but a simpler approach can be used. Approach capacity, which is the maximum number of vehicles going into the download intersection which can be handled by the link, is denoted as C_{ci}, and then we can implement the intersection constraints by introducing a further constraints equation:

$$\sum_{j \in \delta^+(i)} x_{ij}(t) \le C_i(t) \tag{5.27}$$



The original intersection

The expanded intersection

Fig.5. 5 An expanded intersection

Besides the capacity of intersections, there are many other factors at work in an evacuation, such as the operation of traffic lights and the interaction with pedestrians. In our current dynamic network algorithm, these intersection restrictions are relaxed. More detailed investigation of the influence of intersection constraints is outside the scope of this study and will the undertaken in future research.

5.7 Algorithms

The time-varied dynamic network flow can be implemented in a time-expanded static network in a standard minimum cost flow algorithm. However, it is an NP-hard problem and an algorithm proposed by Hamacher and Tjandra (2002) and Hooks and Patterson (2004) was adopted to solve it. The quickest flow problem is generally transferred to its equivalent, the earliest flow problem, which maximizes the flow arriving at sinks for each step over a time period (Fleischer 2001). This algorithm is based on successive shortest augmenting paths on dynamic residual networks and the capacity of each arc in the dynamic residual network is updated for each run.

Let $G'(V,E',U',C',T)$ be the dynamic residual network and $\lambda'_{ij}(t)$ be the negative transit time and $u'_{ij}(t)$ the negative capacity of artificial link (i, j) at step t. Initially, the negative transit time is set as ∞ and negative capacity is set as zero for all $(i, j) \in E', t = [0,1,...T]$.

Given a flow $x_{ji}(t')$ passing through arc (j,i) in original network G and departures vertex j at time t' and arriving at vertex i at $t' + \lambda_{ji}(t')$, then we update the capacity of original network in the following way, and as shown in Figure 5.6:

$$\lambda_{ji}(t') = \lambda_{ji}(t') \tag{5.28}$$

$$u'_{ji}(t') = u'_{ji}(t') - x_{ji}(t') \qquad t' \in \{0,1,...,T\} \tag{5.29}$$

Accordingly, the negative capacity and negative transit time in a dynamic residual network are updated in the following way, and as shown in Figure 5.6:

$$\lambda'_{ij}(t) = -\lambda_{ji}(t') \qquad t = t' + \lambda_{ji}(t') \in [0, \ T] \tag{5.30}$$

$$u'_{ij}(t) = -x_{ji}(t') \qquad t = t' + \lambda_{ji}(t') \in [0,\ T] \tag{5.31}$$

Similarly, for each vertex $i \in V$ in G', we define the $d'_i(t)$ as the negative storage within which the flow can be stored or wait from t to t-1, and initially this is set as zero. Given a flow $y_i(t)$ stores at i at time from t to t-1, then we update the storage of vertex i in the original network according to the following rules:

$$d_i(t) = d_i(t) - y_i(t) \tag{5.32}$$

The negative storage $d'_i(t)$ of vertex i in the dynamic residual network is updated as:

$$d'_i(t) = -y_i(t-1) \tag{5.33}$$

A label-correcting algorithm was adopted to find the shortest route in the dynamic residual network. In this method, an out-forward tree from the source node s is constructed and improved until no further improvements can be made. Four pieces of information are maintained for each node i in the labeling method: the earliest arrival time $a(i)$, which represents the earliest arrive time from source node s to current node i; a parent $p(i,t)$, which records the node that immediately precedes node i from node s that arrives at node i at time t in the out-tree, $d(i,t)$, which is the departure time from node i, and a node status S(i) $\in$ {un-reached, labeled, scanned}. An un-reached node is a node whose distance label has an infinite value (sufficiently large). A labeled node has a distance label that has been updated at least once, that is, its distance label is different from infinite. A node is said to be permanently labeled if its distance label represents the final and optimal quickest path from the source node. A node is considered scanned if it has undergone a scanning operation and its

distance label has not subsequently been updated.

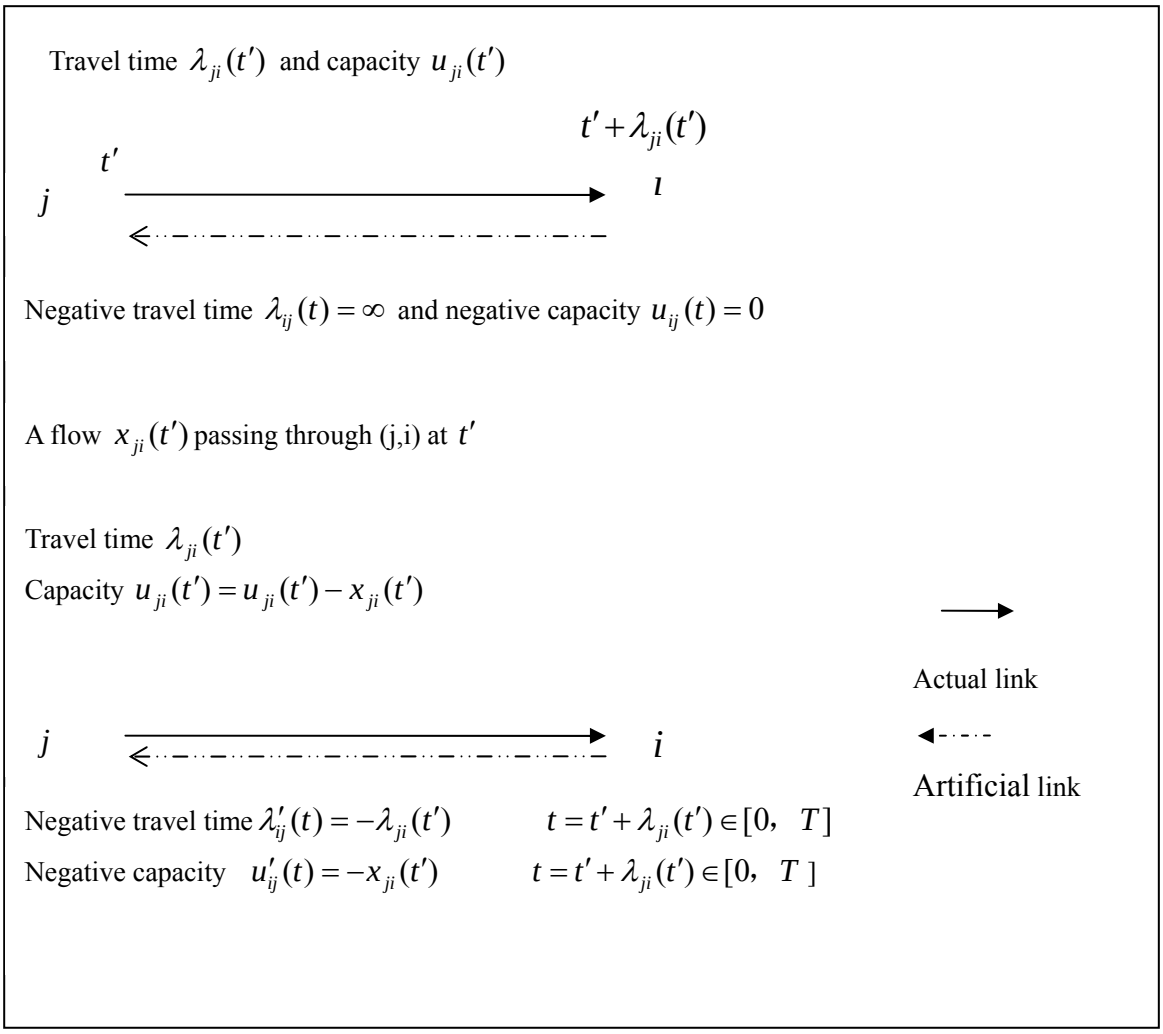


Fig.5. 6A schematic illustration of the procedure for updating the network

The Algorithm of Earliest Arrival Problem

Step 0: Initialize labels.

Insert source node s into a scan eligible list (SEL). SEL = {s},

$$a(s)=0,\ p(s,t)=\begin{cases}0 & t=0\\ s & else\end{cases}\qquad d_0(s,t)=\begin{cases}0 & t=0\\ t-1 & 0<t\le T\end{cases}$$

$$a(i)=\infty,\ p(i,t)=\infty,\ d_0(s,t)=\infty,\ \text{for } i\in V/\{s\},\ t\in\{0,...T\}$$

Step 1: Optimality test.

If the SEL is empty, terminate the algorithm. Make all labels permanent. The labels represent the shortest path costs from the origin to the corresponding nodes, and the predecessor labels can be used to trace the shortest path.

If SEL is not empty, continue with step 2.

Step 2: Find a quickest path

Pick a node from the SEL (usually just pick the first one in the list)

Make the node as current node (assume it's node i) and delete it from the SEL,

SEL = SEL − {i}.

Step 3: Correct labels.

Find out all of the out-forward links of node i

For all $j\in\delta^+(i)$

For all $t=d(i,t)\in[a(i),...,T]$

Check every node that is accessible from the current node

If ($r_{ij}(t)>0$ and t + $\lambda_{ij}(t)<a(j)$ and $p(i,t+\lambda_{ij}(t)=\infty)$) then

Update the label for node j: $a(j)=a(i)+\lambda_{ij}(t)$

Update the predecessor label: $p(j,t)=i$, $d(j,t)=t$

Insert node j into the SEL : SEL = SEL ∪ { j};

End for

End for

Go to Step 1

Step 4: Find the maximal Capacity MC along the quickest path and if MC<=0, Stop.

Step 5: Augment MC unit of flow along the quickest path and update the capacity of dynamic residual network $G(x,t)$.

The quickest flow problem asks for a flow of value d that finishes in minimal time. More precisely, it looks for the minimal T such that a flow with value d can be sent from the source to the sink in the time interval [0, T]. In the discrete setting, this is solved easily by a binary search on the time bound. Burkard et al. (Burkard, Dlaska et al. 1993) gave an efficient, strongly polynomial algorithm based on the discrete Newton method. In this section, the time-varying quickest flow problem was solved by the bi-search iteration processes and implemented as follows:

Step 0: Set the time length T large enough to ensure the solution is feasible and initial the flow variable $x = 0$, and $e(0) = TNO_k$, a conversion for transferring the evacuation problem (multi-source and multi-sink problem) to a standard single-source and single-sink one.

Step 1: Solve the earliest arrival problem and find the maximal amount flow (MAF) before T.

Step 2: If MAF$< e(0)$, increase T=T+1; else decrease T=T-1.

Go to step 1.

5.8 Lexicographically Time-varying Quickest Problem

A lexicographically maximum dynamic flow is a feasible dynamic flow that, given an ordering of the terminals S = 0 ,1,…,k, and a time bound T , maximizes the amount of flow leaving each terminal in the given order. Minieka (Minieka 1973) noted that this objective is also equivalent to simultaneously maximizing the amount of flow leaving every high priority subset.

The Quickest Problem is used to determine the minimum clearance time needed to evacuate all residents from a threatened area. During an evacuation, some special groups have a higher priority than others, such as the elderly or handicapped persons or occupants closer to the fire. These persons are more vulnerable and should be taken care of first. We divided occupants into several groups in each region, and allowed higher priority evacuees to be evacuated first, to minimize the potential loss of life.

Definition: The lexicographically quickest flow problem is used to find out the minimal clearance time needed to evacuate all residents and, at the same time, to maximize the output of higher priority occupants.

According to the definition, the lexicographically quickest flow can minimize the number of occupants threatened, and at the same time optimize the total evacuation time in the system optimization. In fact, the problem can be viewed as a stage of the quickest flow problem. First, high priority occupants are loaded and the quickest evacuation routes are solved according to the quickest flow problem, and the evacuation network is then updated according to the following rules:

$$u_{ij}^{k+1}(t) = u_{ij}^{k}(t) - x_{ij}^{k}(t) \tag{5.34}$$

where k represents the groups of occupants with priority k, the greater the value of k, the lower the priority, so a group with k=0 has the highest priority. $x_{ij}^{k}(t)$ is the flow rate of occupants with priority k at arc (i, j) at t. $u_{ij}^{k}(t)$ is the residual capacity of arc (i, j) at time t, $u_{ij}^{0}(t) = u_{ij}(t)$. The updated network is called the

stage-residual network and it is different from the traditional dynamic residual network in that the backward links are not added. After the highest priority occupants have been completely evacuated, second highest priority occupants are loaded in the same manner.

The multi-stage quickest flow problem can be solved by a series of quickest flow problems. We assume the number of occupants with the priority k in district i at t is denoted as $\varepsilon_i^k(t)$ and the number of priority is PN, and $e_i(t) = \sum_{k=1}^{PN} \varepsilon_i^k(t)$ is the total number of occupants waiting at district i at t. If we ignore the pre-evacuation process, $e_i^k = e_i^k(0)$. A brief statement of the algorithm is given below.

Step 0: Initial the k=0, $G_k = G$

Step 1:

For k=0, PN.

Loading the number of occupants with priority k

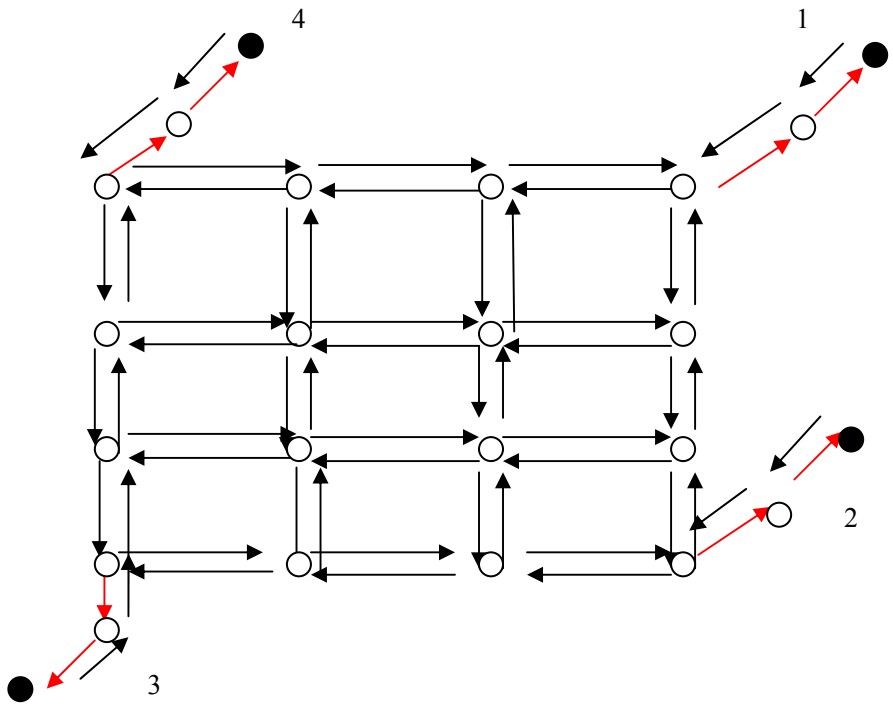
Step 1.1 Solving the time-vary quickest flow problem and find the quickest clearance time T_k for group k.

Step 1.2 Updating the stage-residual network G_k .

5.9 Case I: Urban Evacuation Optimization

An application of the dynamic network flow in the optimization of urban evacuation was adopted by using the hypothetical networks described in Chapter 4 to analyze the performance of the optimization model. The evacuation

network is composed of 56 roads and 24 nodes. Each link represents a one-way road 500m long and 3 lanes wide. Each road is provided with a 2-meter-width footpath for pedestrians. There are four emergency shelters, distributed as shown in Figure 5.7. The population is 7000.



(○ represents intersection of road and ● represents the shelters)

Fig.5. 7 The network (from Chapter 4)

The evacuation problem is multi-source and multi-sink problem which can be easily reduced to a single-source single-sink problem by introducing a supersource o, a supersink l, and artificial arcs.

The capacity $u_{ok}(t)$ equals the number of occupants joining an evacuation at original source node k at time t. The maximum holdover capacity of each original source node k, $d_k(t)$, equals it's the number of occupants. If we

assume that all occupants mobilize at the beginning of the evacuation, then the through capacity of each virtual arc at t=0 equals the total number of occupations (TNO) at each source node.

Then the capacity of virtual links connecting the virtual source with original source nodes can be defined as:

$$u_{ok}(t) = \begin{cases} TNO_k & t = 0 \\ 0 & t > 0 \end{cases} \qquad d_k(t) = TNO_k \tag{5.35}$$

$$k = \{1, 2, ..., K\}, \; t = \{0, 1, ...T\}$$

Where TNO_k represents the total number of occupations (TNO) at each original source node k. K=9.

For simplicity, we assume that the capacity of destinations is unlimited and so this is an un-constrained evacuation problem. The virtual links connecting the virtual sink with original sink nodes can be defined as:

$$u_{jl}(t) = \infty \qquad d_j(t) = 0 \tag{5.36}$$

Let the section capacity be 1500 cars per lane per hour, the free speed 50km/h and the simulation step be 10 seconds. The total evacuation time (TET) is 1560 seconds.

A sensitivity analysis was carried out to study the variation in road capacity, mean velocity, and adoption of improved strategies. Figure 5.8 and Table.5.1 show that road capacity has a great impact on the TET.

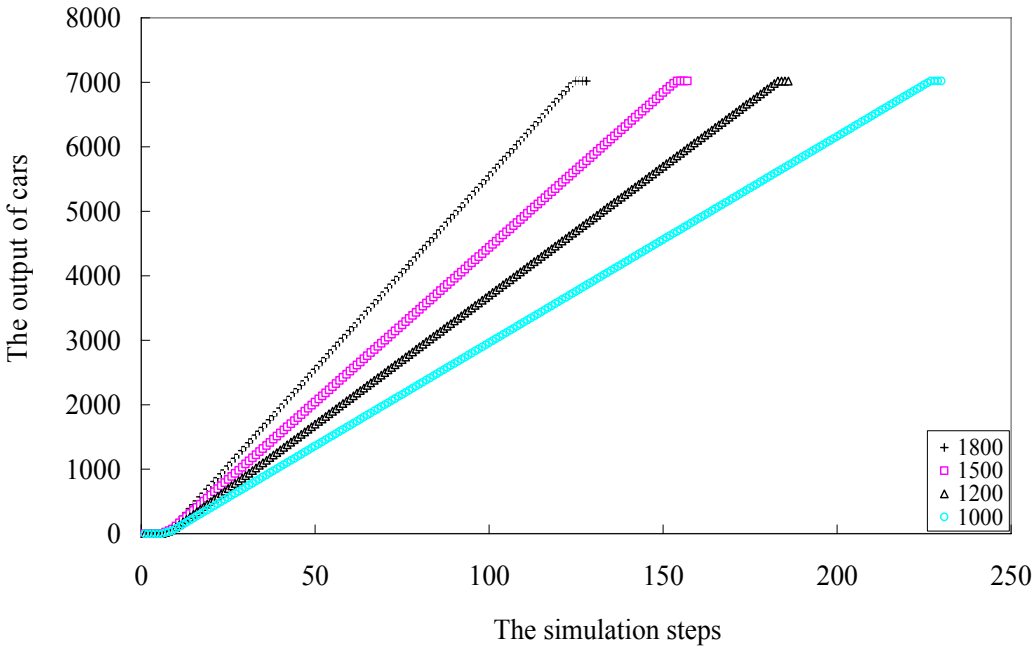


Fig.5. 8 Evacuation process at different section capacities (10 seconds per step)

Table 5. 1 Performance of TET at different section capacities

(mean velocity=60km/hour)

Section capacity(cars per hour)	1800	1500	1200	1000
TET(seconds)	1270	1560	1850	2290

Table 5. 2 Performance of TET at different mean velocities

(Section capacity=1500 cars per hour)

Mean velocity(km/hour)	60	50	40
TET(seconds)	1560	1600	1640

Results at various mean velocities are given in Table 5.2. It seems that the mean velocity of cars has little influence on the TET. By reducing the velocity

from 60km/h to 40 km/h, there is only a 5% reduction in the evacuation time.

As expected, roads connecting with emergency shelters were over-congested and appropriate alterative methods had to be used to alleviate the congestion and to improve evacuation efficiency. One such method is lane reversal. Let capacity=1500 cars per hour and simulation step=10 seconds. Figure 5.9 shows that the use of reversible lanes improves the efficiency of the evacuation greatly: the 4/2, 5/1, 6/0 distributions decrease the total evacuation time by 23%, 36% and 46% respectively.

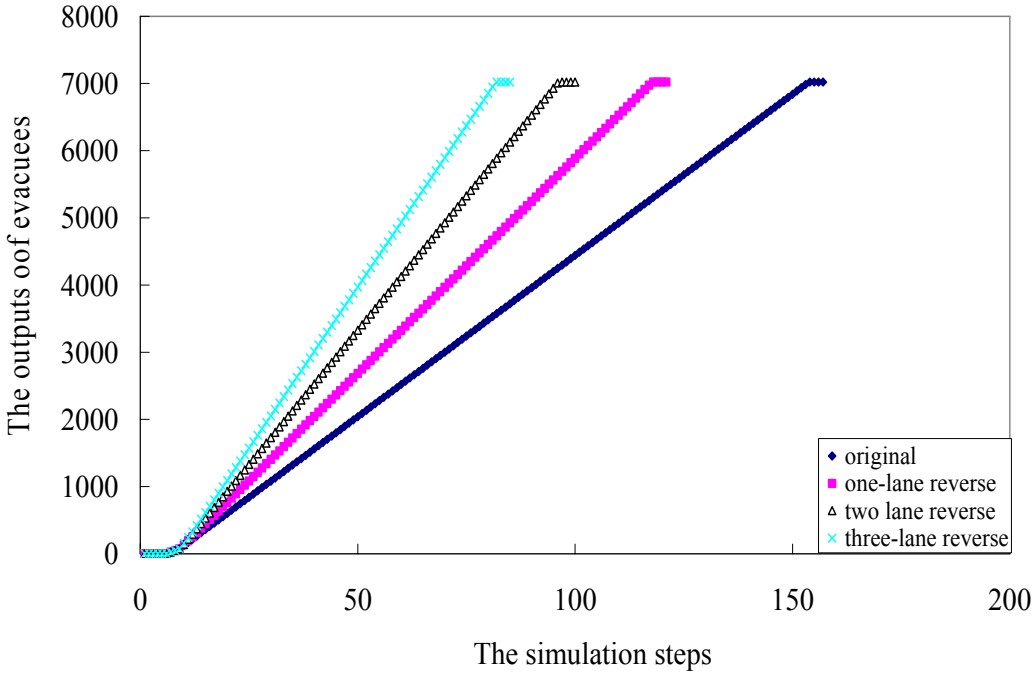


Fig.5. 9 Performance of TET: reverse lane strategies in use

Until now, all associated parameters were time-independent. If a flood disaster occurs and water inundates the roads connecting with shelter 1, within the first 100 seconds, the road capacity decreases linearly with time and the road is totally blocked after 100 seconds, then road capacity per step is 1500/3600*3*10=15.

$$u(t)=\begin{cases}15-t*15/100 & t\le 100\\ 0 & t>100\end{cases} \quad \lambda(t)=\begin{cases}3 & t\le 100\\ \infty & t>100\end{cases} \tag{5.37}$$

Figure 5.10 gives TET results in a flood disaster. Since roads connecting with one shelter are blocked, the TET increases significantly from 1560 seconds to 1970 seconds.

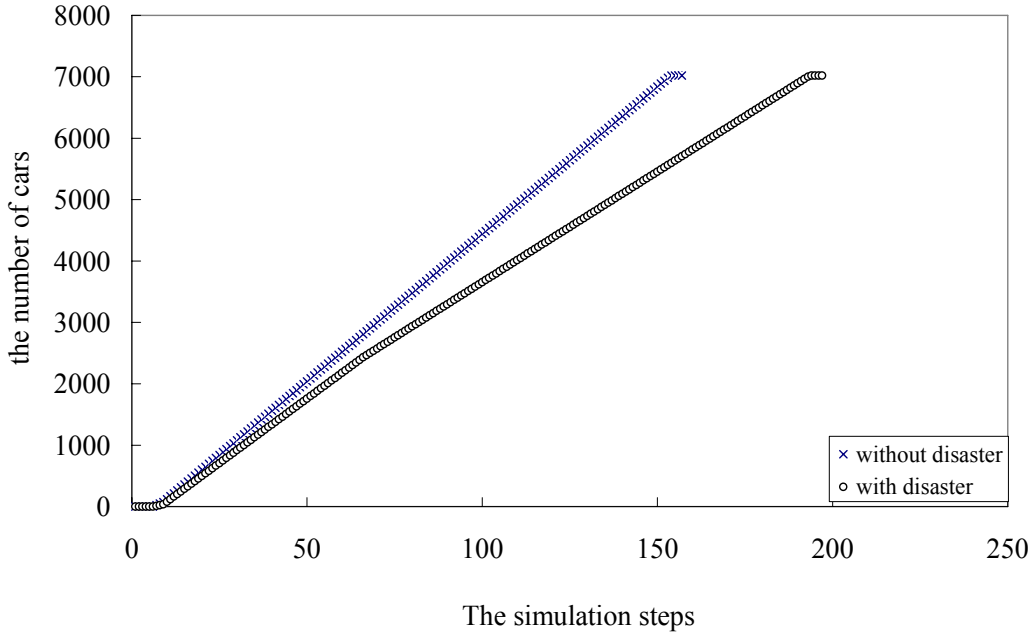


Fig.5. 10 Comparison of TET under dry and flood conditions

A comparison of the simulation results and the optimization results is given in Figure 5.11. The TET is 26 minutes for the optimization-based approach and 30 minutes for the simulation-based approach, meaning that the former is quicker.

The scenarios discussed above consider only vehicular evacuation. If we assume instead that 50% of the population will evacuate by car and 50% on foot, it is clear that pedestrians and cars will interact at intersections. This scenario can be solved using a multi-community flow problem. A simplified approach,

which ignores the intersection of cars and pedestrians, is adopted here and the two are assumed to move forward on two separate networks. The mean velocity of pedestrians is 1.5 m/s, and the unit capacity of footpaths is 1 person per meter per second.

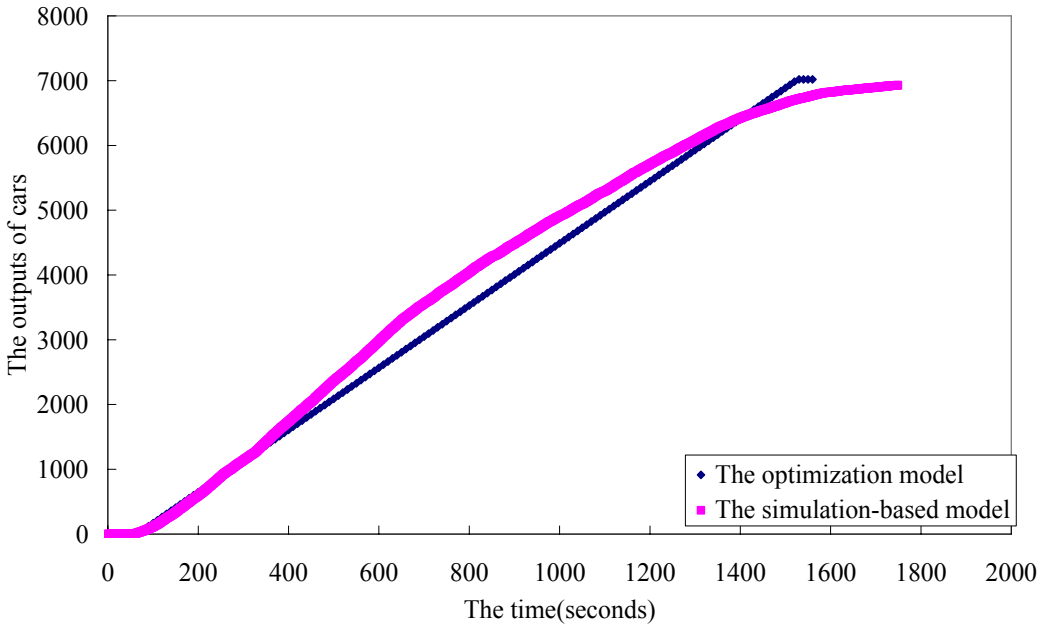


Fig.5. 11 Comparison of TET obtained by using optimization model and simulation model

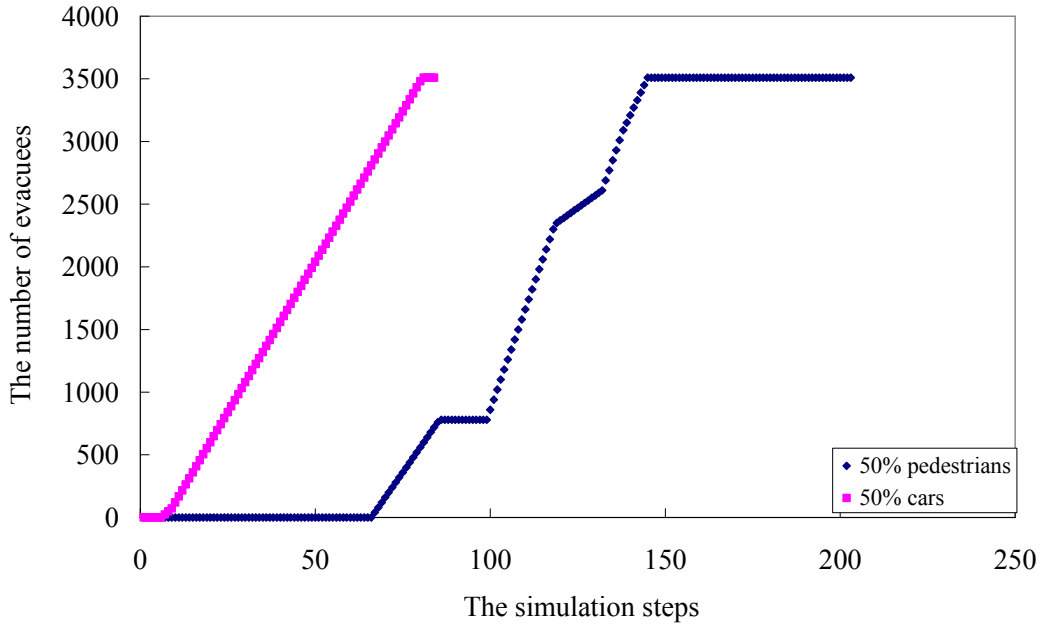


Fig.5. 12 Comparison of TET by car and on foot

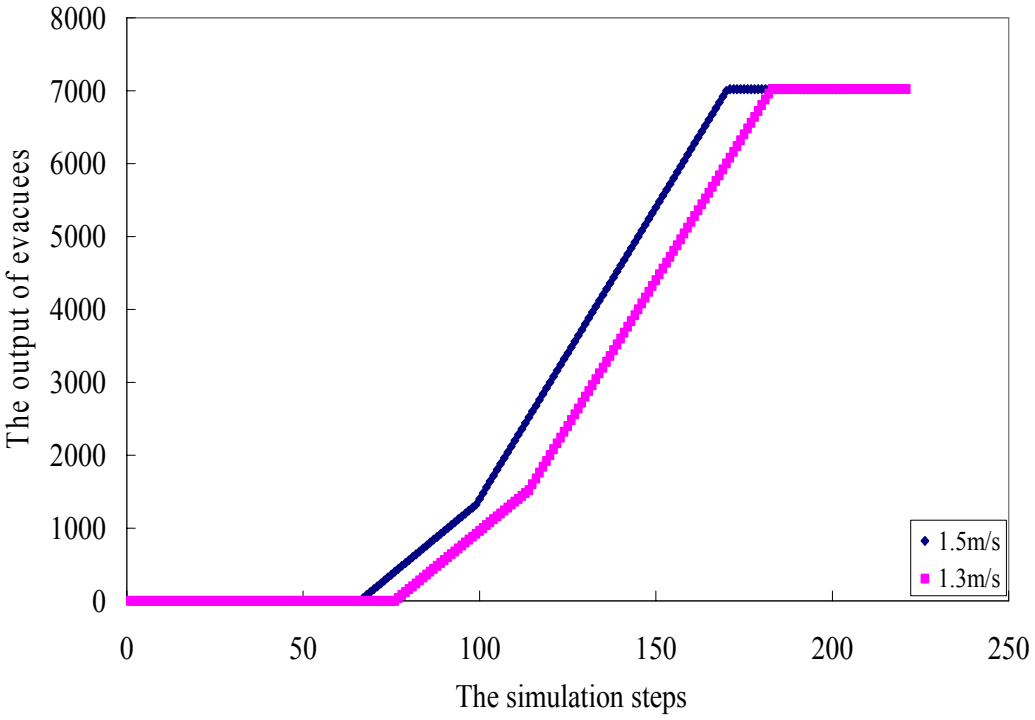


Fig.5. 13 Comparison of TET by car and on foot

Figure 5.12 shows that evacuation by car will be finished within 1060 seconds and evacuation on foot will be finished within 2030 seconds.

Clearly, pedestrian evacuation plays a dominant role on the TET. Figure 5.13 shows what happens if we adjust the mean velocity of pedestrians. For a velocity of 1.5m/s, the TET is 2030 seconds, and for a mean velocity of 1.3m/s, the TET is 2200 seconds.

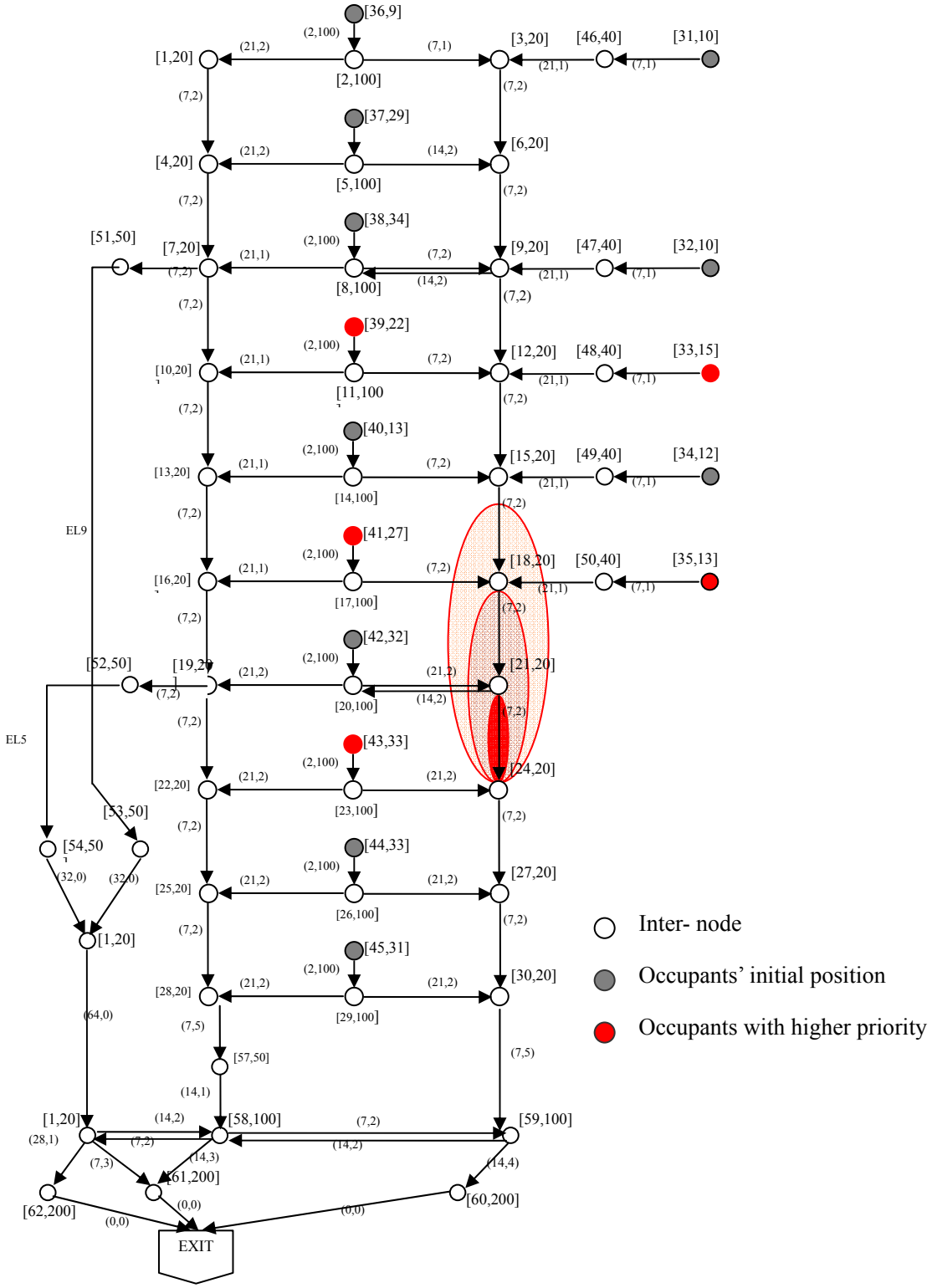
5.10 Case II: High-rising Building Evacuation

A multi-zone high-rising building is considered to be a network composed of nodes and links. Each link is associated with travel time and dynamic capacity varying with time and each node is associated with holdover capacity and dynamic capacity. The dynamic capacity is concerned with the width of

exits and the cooperation of crowds. Chalmet et al. (1982) adopted the dynamic maximum flow approach with constant parameters by a time-expanded static network to optimize evacuation from building 101, an 11-floor building located on the Gaithersburg, Maryland campus of the National Bureau of Standards, as shown in Figure 5.14. We have used the 101 building to compare the two approaches and illustrate the advantages of our approach.

The network topology, the initial occupation distribution and dynamic capacity of each link, are shown in Figure 5.14, and a more detailed description can be found in Chalmet et al. (1982). The simulation step is 10 seconds. Occupants were permitted to wait at internodes according to a node's storage capacity and all occupants were assigned the same degree of priority.

To simplify, our model was reduced to an LRP model, and the quickest evacuation was 35 steps, equivalent 350 seconds, which agreed quite well with results given in Chalmet et al. (1982). The flow rate of four links along time is shown in Figure 5.15. The flow rate of link 59-60 is zero from 0 to 80 seconds and maintains a constant rate at its maximal capacity of 80 persons per step to 31 seconds.



(a, b), a is the dynamic arc capacity ,b is the transit time
[c,d], c is the node ID number and d denote the storage hold capacity of node for inter-nodes and denote the initial number of occupants for source nodes

Fig.5. 14. The network of building 101 (extracted from Chalmet(1982)])

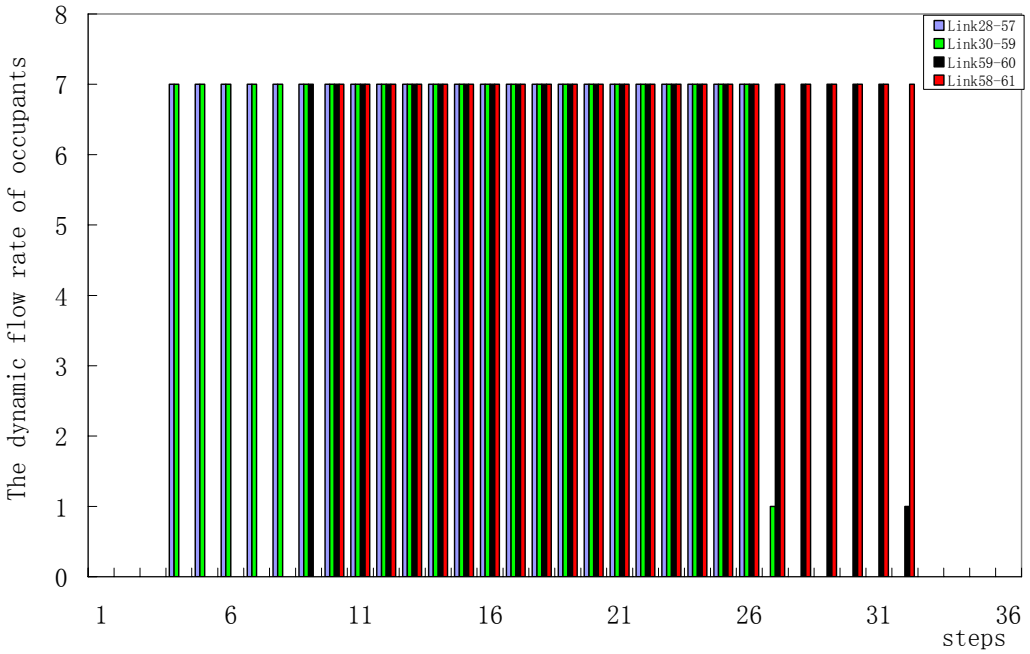


Fig.5. 15 The flow rate of four links

If elevator 9 is used during an evacuation, the quickest evacuation time will be reduced to 28 steps, and if elevator 5 is used, the evacuation time is 25 steps; if both elevators are used, the evacuation time is reduced to 19 steps, equivalent to 190 seconds. If the initial number of occupants in each room is doubled, the evacuation time increases to 58 steps or 580 seconds.

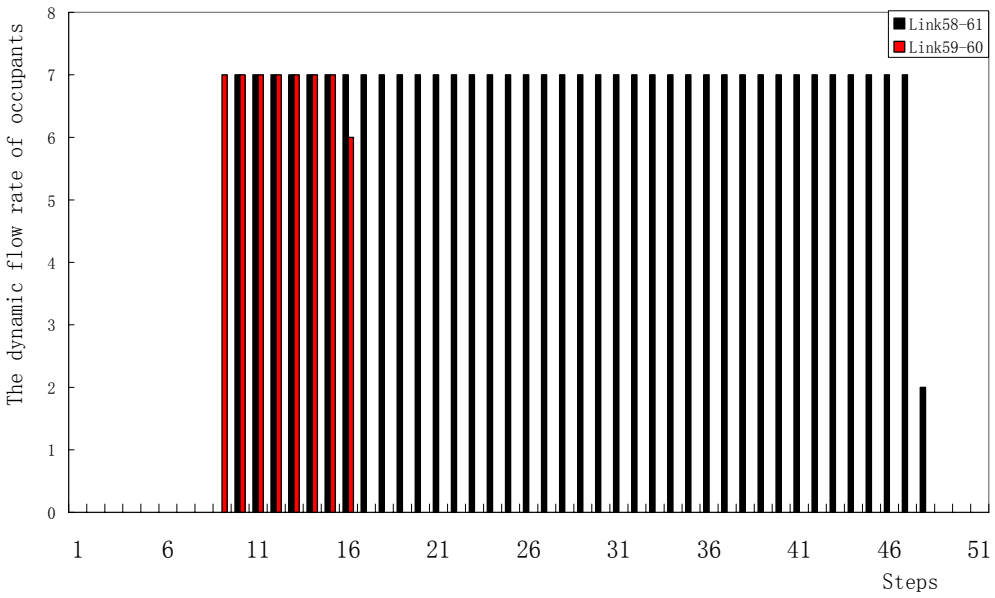


Fig.5. 16 Flow rate of two links

Imagine that a fire breaks out in a room on the fourth floor and the stairwell from floors 21 to 24 is blocked by fire and only one stair is available for use. In a time-constant network, the capacity of this link is assigned as zero. The quickest evacuation time is 50 steps under these conditions. The flow rate over time of two links, link 59-60 and link 58-61, is shown in Figure 5.16. For link 59-60, the earliest arrival time is 80 seconds and it maintains a constant rate of persons per step from 80 seconds to 160 seconds. After 170 seconds, no evacuees pass, and all evacuees should get out through link 58-61 at a constant rate of 7 persons per step from 90 seconds to 470 seconds.

5.11 A MSTVQFP Approach

We further analyzed the optimization process by considering the dynamic property of evacuation networks. We still assumed that a fire breaks out in a room on the fourth floor at t=0, but now, due to the influence of wind, it has

spread to stair 24. The following assumptions were made:

(1) Fire reaches the stairs after 20 seconds.

(2) The smoke layer moves upwards at a speed of 1 floor every 10 seconds.

(3) For each stair filled with smoke, the capacity decreases by 50% and travel time doubles. If a stairway is covered in a smoke layer for more than 20 seconds, it is assumed to be unavailable for use, in which case the capacity decreases to zero and travel time becomes unlimited.

$$u_{23->24}(t)=\begin{cases}21 & t\le 2\\ 10 & 2\le t\le 4\\ 0 & t>4\end{cases} \qquad \lambda_{23->24}(t)=\begin{cases}2 & t\le 2\\ 4 & 2\le t\le 4\\ \infty & t>4\end{cases}$$

$$u_{21->24}(t)=\begin{cases}7 & t\le 4\\ 3 & 4\le t\le 6\\ 0 & t>5\end{cases} \qquad \lambda_{21->24}(t)=\begin{cases}2 & t\le 4\\ 4 & 4\le t\le 6\\ \infty & t>5\end{cases}$$

$$u_{18->21}(t)=\begin{cases}7 & t\le 5\\ 3 & 5\le t\le 7\\ 0 & t>6\end{cases} \qquad \lambda_{18->21}(t)=\begin{cases}2 & t\le 5\\ 4 & 5\le t\le 7\\ \infty & t>6\end{cases}$$

The same priority was assigned to all occupants. The quickest evacuation time was found to be 480 seconds, and the flow rates of link 59-60 and link 58-61 are illustrated in Figure 5.17.

We assigned one of two priority levels to all occupants: those living on floor 4, floor 6 and floor 8 were assumed to be older persons and so were given higher priority and had to be evacuated first. The others were given lower priority.

Working with these assumptions, the quickest evacuation time for first priority occupants is 29 steps, that is to say, all occupants living on floors 4, 6, and 8 were evacuated within 290 seconds. The other occupants were evacuated in 50 steps, or 500 seconds. So the final quickest evacuation is 500 seconds.

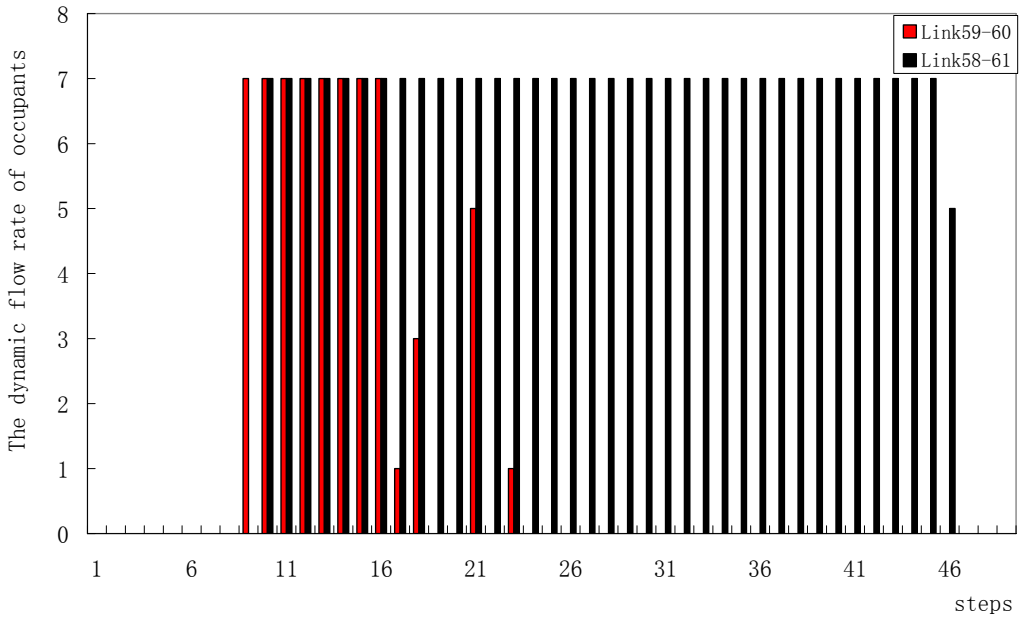


Fig.5. 17 Flow rate of two links

The dynamic flow rate over time at link 58-61 for each group is shown in Figure 5.18. It can be seen that at the initial stage, the second group arrives at 100 seconds and passes through at the rate of 7 persons per step for 40 seconds. After 40 seconds, higher priority occupants arrive, and they occupy the link until they all pass. Then the second priority occupants are able to pass through. Figure 8 shows the flow rate over time of link 59-60 for each group.

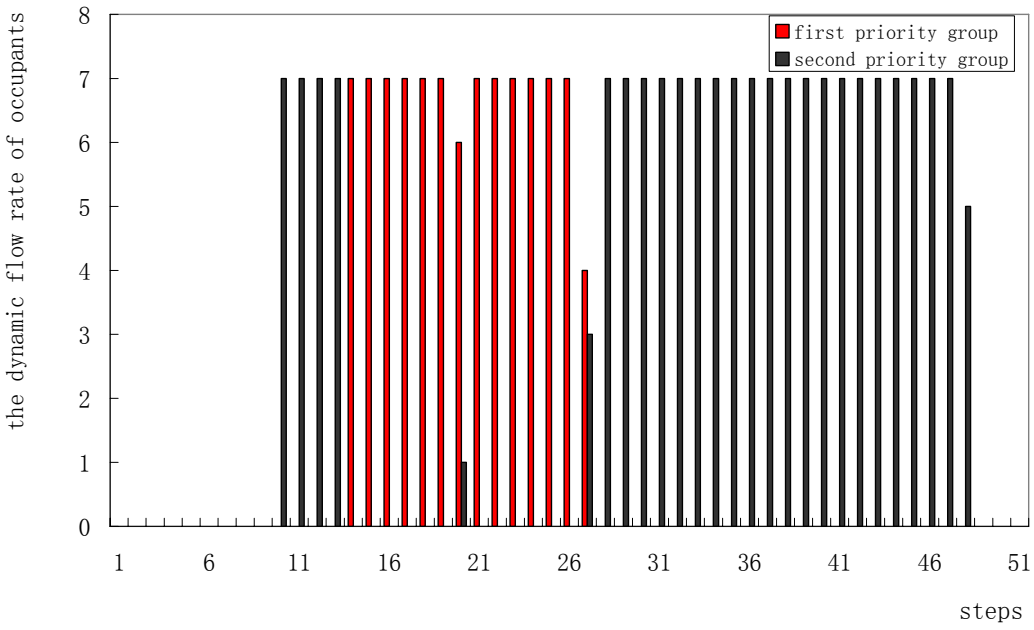


Fig.5. 18 Flow rate of link 58-61 for two groups

Finally, we compared the results of the two algorithms, as shown in Figure 5.20 and Figure 5.21. The evacuation schedules were found to be quite different. The overall evacuation time is 480 seconds for the single-stage quickest flow problem and 500 second for the two-stage quickest flow problem. This is quite reasonable as the maximization throughput of special groups will scarify the system optimization to a certain degree.

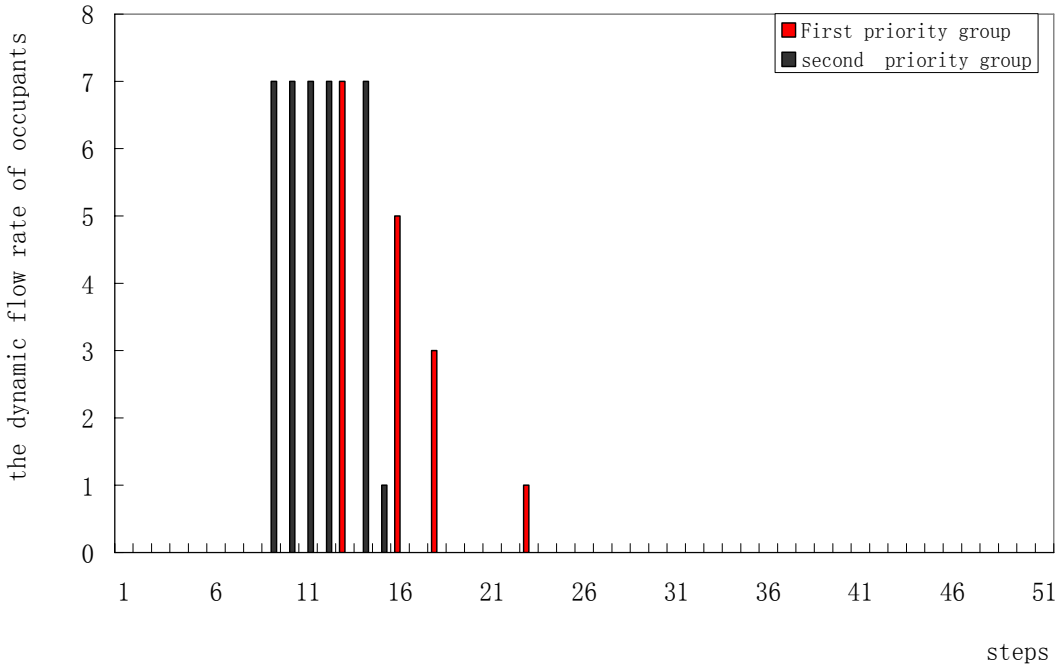


Fig.5. 19 Flow rate of link 59-60 for two groups

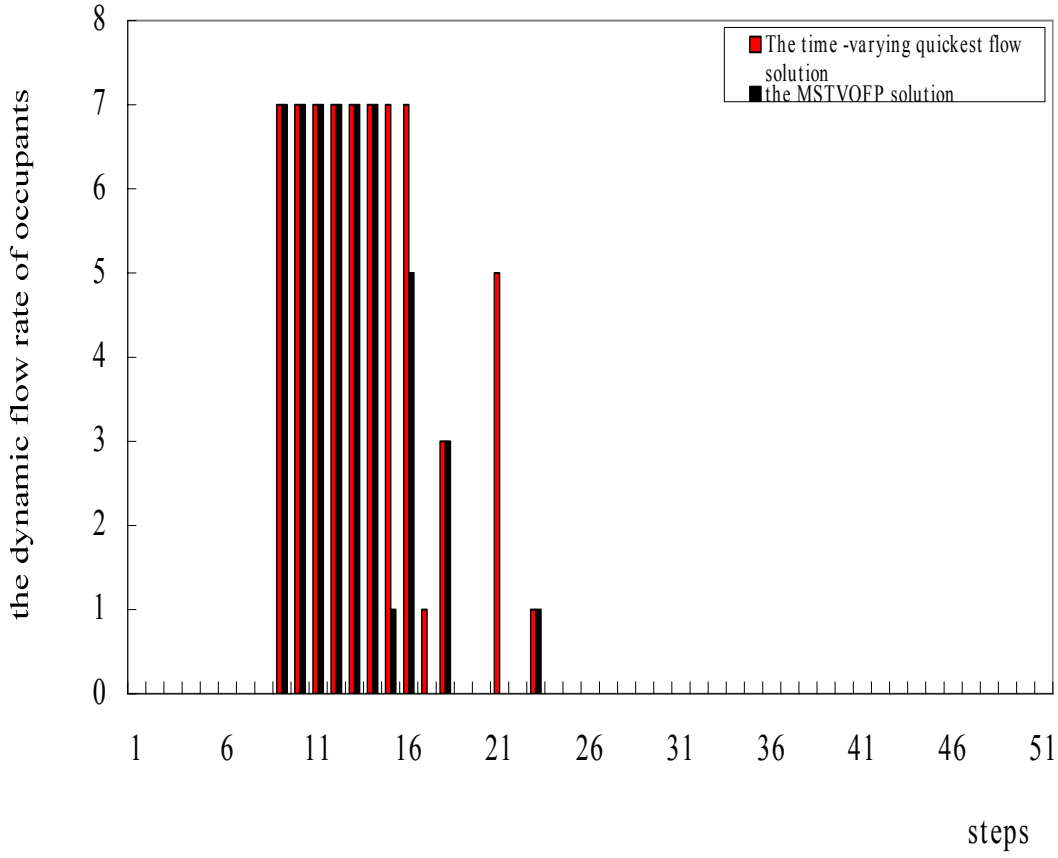


Fig.5. 20 Comparison of results at link 59-60 in two algorithms

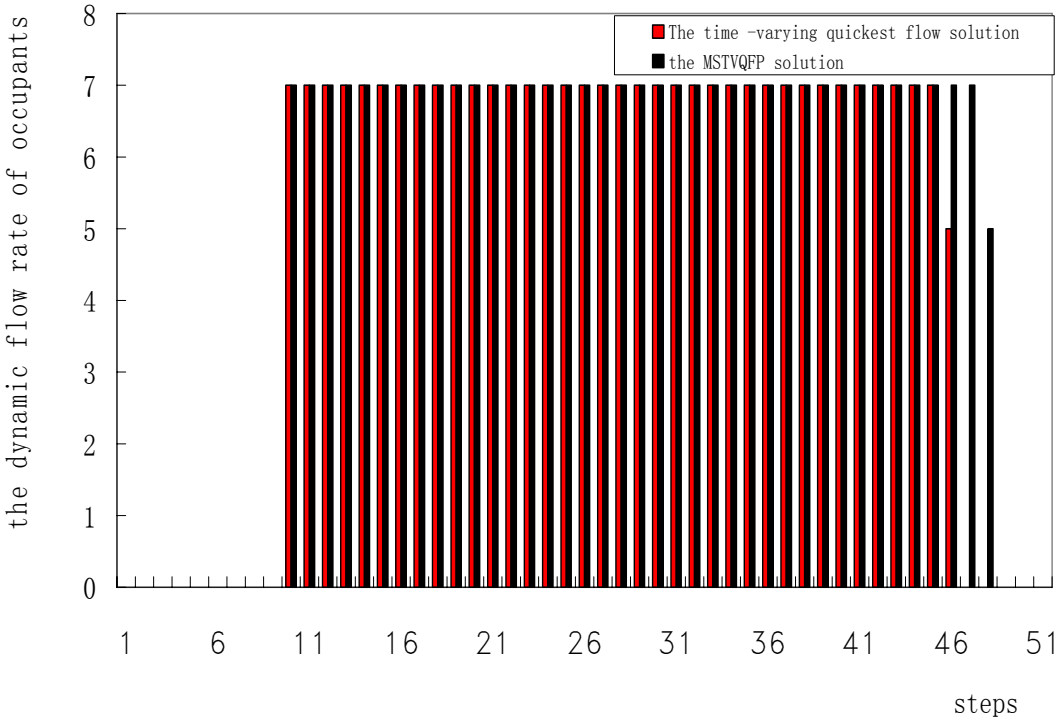


Fig.5. 21 Comparison of results at link 58-61 in two algorithms

5.12 Summary

Urban evacuation plans are needed to minimize the number casualties in disasters, but their design and programming are a great challenge for engineers and researchers due to the complexity of the problems involved. Evacuation problems may arise from different types of systems, such as buildings, cities or regions, or transportation carriers (e.g. trains, ships and airplanes). The system structures (e.g. population and the behavior of people at risk, hazard propagation speed and characteristics) influence planning in the corresponding system.

A time-varying quickest flow problem (TVQFP) was presented in this chapter to optimize evacuation planning. TVQFP is different from its prototype problem, the quickest flow problem, in that all parameters associated with a network, such as travel time, capacity etc., are time-dependent. These time-

varying features make TVQFP particularly suitable for evacuation planning as the through capacity of roads or intersections may decrease or become zero due to the effects of adverse environments such as fires, floods or lethal gas. Dynamic networks can reflect these time-varying features and optimize the evacuation process.

Phased evacuation is an arrangement for the evacuation of an area in the event of disaster whereby occupants exposed to danger directly will be evacuated immediately, followed by other residents. The lexicographically quickest flow can minimize the number of occupants located in the most dangerous place, and at the same time optimize the total evacuation time in the system optimization. It can be used to arrange schedules and routes during a phased evacuation from multi-compartment buildings or cities.

Since the current optimization model is based on a global view-point, or a system optimum, the behavior of evacuees wasn't modeled. Optimization models can be used to make comparisons with other alternatives or be used as a benchmark to test the feasibility of an evacuation plan. It is also noticeable that the evacuation plan produced by this model is only one of many possible optimal solutions.

The present algorithm adopts the assumption that flow circulating along a link does not depend on the traffic volume existing on this link. This assumption is quite controversial as it is clear that the velocity and through capacity are density-dependent. So a fully realistic model of flow-dependent transit times on arcs must take density, speed, and flow rate evolving along an arc into consideration.

Chapter 6

Evacuation Planning for a City

This chapter first discusses the application of an optimization model to solving two kinds of evacuation problems, unconstrained and constrained. Then, a hybrid evacuation model, which integrates a simulation model and an optimization model, is used to plan an urban evacuation.

6.1 Introduction

The accident at the Three Mile Island Nuclear Power Station in 1979 drew attention to the importance of evacuation planning for nuclear plants. Evacuation planning is a process in which evacuation procedures and the local infrastructure of an area are evaluated in order to assess their sufficiency for safely and effectively evacuating a potential impact area in the event of a hazardous incident (Meyer 1995). Evacuation planning analyzes possible hazard scenarios for the given facility (building, town, etc.) and develops procedures for the safe transfer of people from the affected area to safe areas.

6.2 Shelter-route-schedule Planning

As stated before, three basic elements involved in evacuation planning are shelter selection, route selection and schedule determination. The route selection and shelter selection are combined together by adding super-nodes, as described in Chapter 5.

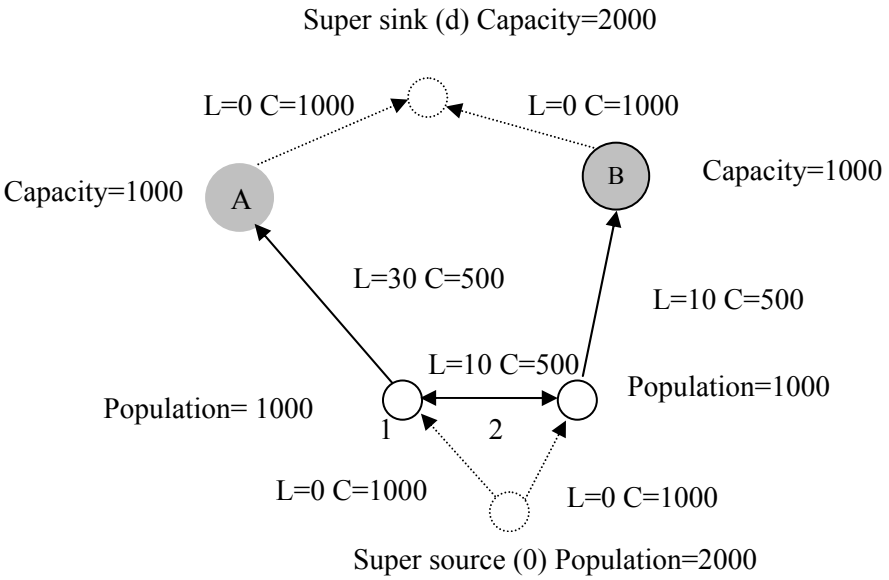
6.2.1 Constrained vs. Unconstrained Problem

Shelter selection is a transmission problem. It is used to determine the target evacuation locations and to deal with the problem of where to go. If the capacity of shelters is limited, the evacuation problem is classified as a constrained evacuation problem. However, if there is no limit on the number of evacuees who may enter a shelter, this is considered an unconstrained problem.

In fact, the unconstrained evacuation problem is the most common in, for example, building evacuations and small-scale or temporary traffic evacuations, so we pay attention only to the threatened population in affected regions.

Furthermore, in the design and planning period, the unconstrained evacuation problem can provide us with the optimal capacity of shelters. This process is quite simple: we just assume that the capacity of shelters is unlimited and all evacuees are allocated to shelters at which they can arrive in the quickest time. The optimal capacity of each shelter can be derived by adding together the capacity of each shelter.

However, for large-scale evacuations such as natural disaster, when we need to evacuate whole cities, capacity constraints must be taken into account and the destination shelters must be selected carefully in system optimization. This is then a constrained evacuation problem, which have received little attention. The importance of considering capacity constraints can be illustrated using the following example. Two resident districts, represented as 1 and 2, both have a population of 1000. Two emergency shelters, represented as A and B, both have a capacity of 1000. The topological network, capacity and length of each arc are shown in Figure 6.1.



L represents the distance, C represents the unit capacity

Fig.6. 1 Simple location-allocation problem with capacity constraints

This is quite a simple allocation problem and the optimal solution is to send all people located at 2 to shelter B and all people located at 1 to shelter A. The total travel cost is 1000*10+1000*30=35000. Then we adopt an assignment based allocation. Two super nodes, one connecting with the source nodes, and the other connecting with the destination nodes, are added and let the assignment step be 4. The initial population accumulates at the super source node at the supply of 2000, so at each step 500 will be distributed. For step=1, 500 persons will be sent along the shortest path 0-2-b-d; for step=2, 500 persons will be sent along 0-1-2-b-d; for step=3, since shelter B is full, 500 persons will be sent along 0-1-a-d; for step=4, 500 persons will be sent along 0-2-1-a-d to shelter B. In this way, the total cost will be 1000*10+1000*30+10*1000. Clearly, the iterative assignment can't obtain the optimal solution.

If we further consider the section capacity of each road, there is no feasible

solution to the static flow in network algorithm. Dynamic network flow, by considering the time-expansion of the network, is quite suitable for optimizing this kind of problem.

By redefining the capacity of virtual links as:

$$C_{s1}(t) = \begin{cases} 1000 & t = 0 \\ 0 & t > 0 \end{cases} \tag{6-1}$$

$$C_{s2}(t) = \begin{cases} 1000 & t = 0 \\ 0 & t > 0 \end{cases} \tag{6-2}$$

$$C_{Bd}(t) = \begin{cases} 0 & t < T \\ 1000 & t = T \end{cases} \tag{6-3}$$

$$C_{Ad}(t) = \begin{cases} 0 & t < T \\ 1000 & t = T \end{cases} \tag{6-4}$$

The optimal solution is, as expected, to send all people at 2 to B, and to send all people at 1 to A. The evacuation time is 20 steps.

6.2.2 Evacuation Schedule Problem

Schedule determination is designed to determine the departure time of the evacuation, which has a significant effect on the total clearance time. If all traffic is loaded simultaneously, this will result in congestion of the whole network most of the time. On the other hand, if the load time is too long, the TET will be prolonged accordingly. An appropriate load schedule is needed to facilitate the clearance time. Schedule delay is defined as the difference between actual and desired arrival or departure times. Trip departure time modeling has been a popular area of research over the last decade. Two questions which have

been asked are whether, and to what extent, urban traffic congestion can be reduced through shifting work trip departure times by implementing various transportation management strategies. Wohl (1970) argued that schedule delay should be an essential consideration in forecasting and evaluating peak-period congestion. Hendrickson and Kocur (1981) developed a simple approach for modeling schedule delay in a deterministic setting based on user equilibrium concepts and deterministic queuing theory. Hurdle (1974) considered route choice decisions based upon the sum of travel and schedule delay times. Poon et al. (2004) proposed a model and algorithm for solving the equilibrium assignment problem in a congested, dynamic and schedule-based transit network by assuming that the time varying origin – destination trip demand was given and all travelers had full predictive information about present and future network conditions. To date, much of the research on modeling trip departure times and the effects of time-varying traffic flows on congested networks had focused on the development of closed-form analytical models or simulations of small, idealized networks. A comprehensive evaluation of potential congestion mitigation strategies (e.g. timed signal control, ramp metering, flexi-time and staggered working hours) requires having dynamic models of traffic flows over time throughout a network. In this chapter, a quickest flow based on the time-varying dynamic network is adopted in order to optimize the evacuation schedule.

Shelter-route-schedule planning is crucial to move a population out to safe areas in the event of catastrophes, natural disasters, and terrorist attacks. In this chapter, we illustrate the use of dynamic network flow to optimize the evacuation schedule, shelters and routes simultaneously.

6.3 Case Study

In this scenario, a local emergency planning commission has been appointed to evaluate the impact of earthquakes on the local community. The total population of this city is 14550, distributed over 129 districts. The local government is planning to build 5 emergency shelters to accommodate the evacuees in emergencies. The recommended locations of the five shelters are determined, but the capacity of each shelter is not. Evacuation planning should address the following issues:

(1) Calculate the minimal clearance time

(2) Delineate the optimal evacuation route

(3) Determine the optimal departure time

(4) Determine the capacity of each shelter

(5) Allocate residents to their optimal shelters.

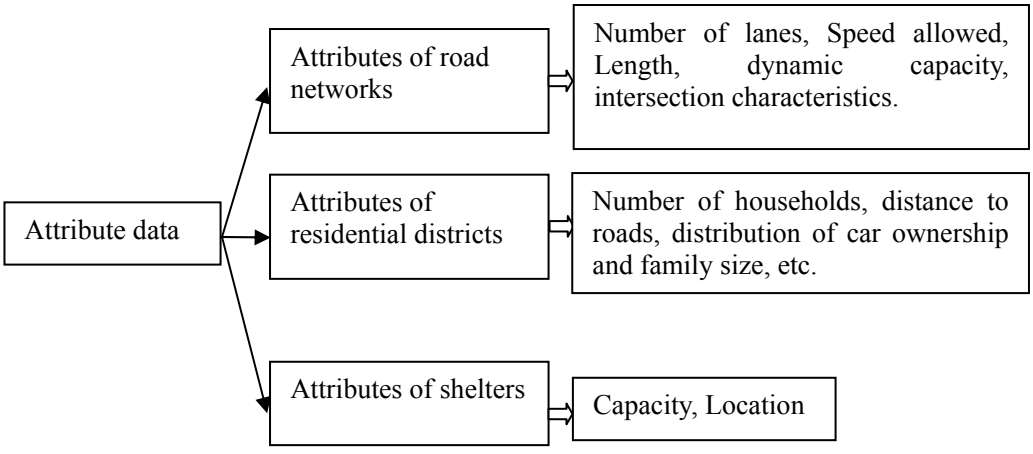


Fig.6. 2 GIS attribute data for evacuation planning

First, attribute data, which includes the attributes of the road network, residential districts, and of emergency shelters, is prepared. Census population and vehicle ownership data are obtained from the local or state census department. The description and mapping of the physical alignments and capacities of the road network is based on local transportation department information. GIS is used to store, display and coordinate these data in *.dbf files. Figure 6.2 gives the basic attribute data for the evacuation analysis.

Geographical data, which records the geological position of each entity such as intersection position, the resident's district position, emergency location, and the position of emergency facilities, is stored as *.shp in Arcview format. The road network of a city is composed of 912 intersections and 2072 roads. Each road is composed of 2 lanes. It remains an open question as to what percentage of these vehicles would actually be generated during an earthquake-generated evacuation. Many evacuation scenarios are possible depending on the time of day, the presence of background traffic, emergency vehicles, etc. One of the anticipated worst scenarios, the full evacuation of all persons living in this area at night, is considered.

Let the mean speed of cars be 60 km per hour, the road section approach capacity be 1200 cars per hour, car ownership be 100%, car usage rate be 100%, and the simulation step be 30 seconds. With these assumptions, the number of cars being evacuated equals the number of people, i.e., 14814. The road capacity per step is 1200/3600*30*2=20 cars per step, and the travel time of each road λ is L/3.6/30 m per step (L represents the length of this road).

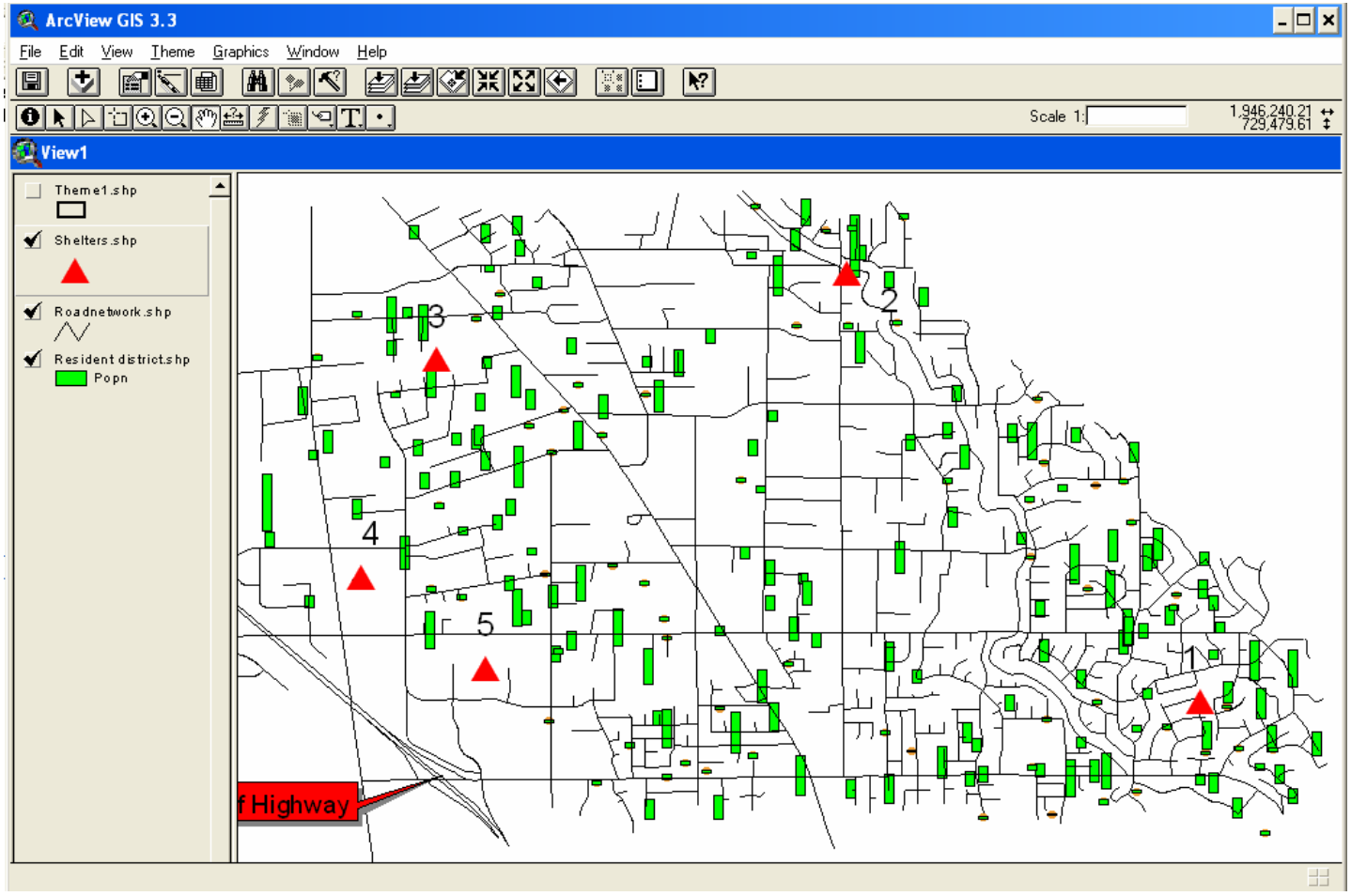


Fig.6. 3 GIS map of a City (network, population and shelters distribution)

6.4 Unconstrained Evacuation Problem

As stated before, the unconstrained evacuation problem refers to a situation in which the capacity of destination shelters is unlimited. In fact, most evacuations can be classified as this unconstrained kind. In our example, the time-varying quickest algorithm was adopted to allocate evacuees to their nearest shelter.

We assumed that people are mobilized simultaneously, that is to say, the traffic load time (LT) equals to zero. The optimization results are shown in Figure 6.4. The total evacuation time is 1770 seconds. The cumulative number of cars evacuated increases almost linearly with the simulation time and the slope coefficient is approximately 8.4 persons per second. That means the evacuation rate is 8.4 persons per second. A sub-graph embedded in Figure 6.3 also gives the evacuation rate per second.

The evacuation processes for each shelter are given in Figure 6.5. It shows that almost all evacuees arrive at their shelters simultaneously, and the arrival time is about 1770 seconds. The number of people arriving at each shelter is shown in Table 6.1, which shows that the largest number of people will be allocated to shelter No.1, and the least to shelter No.5.

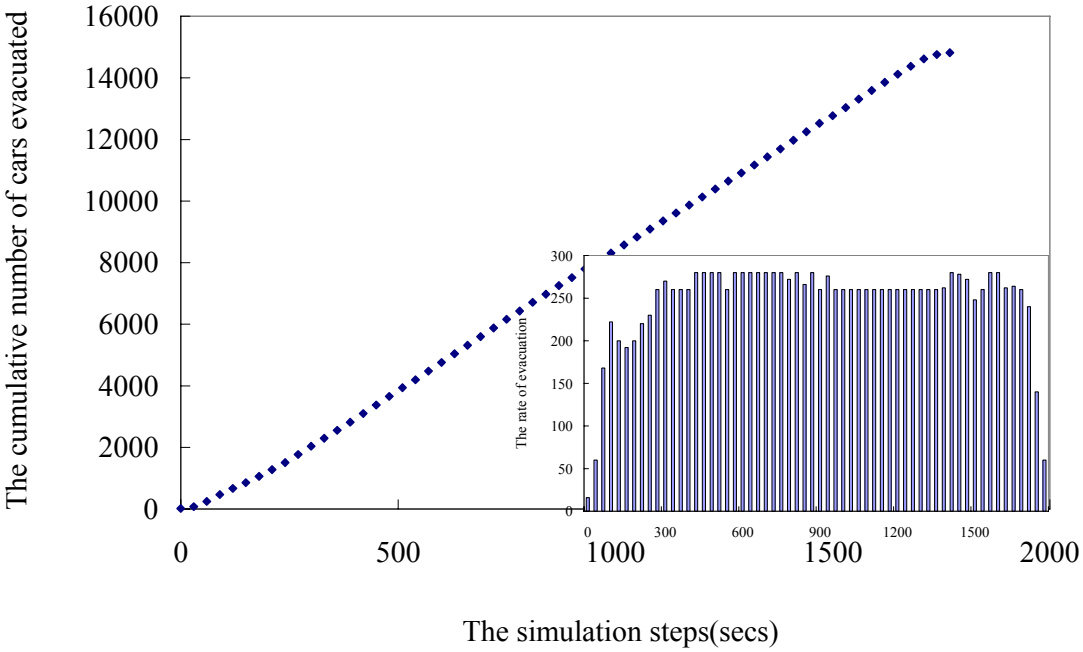


Fig.6. 4 Evacuation process without capacity constraints

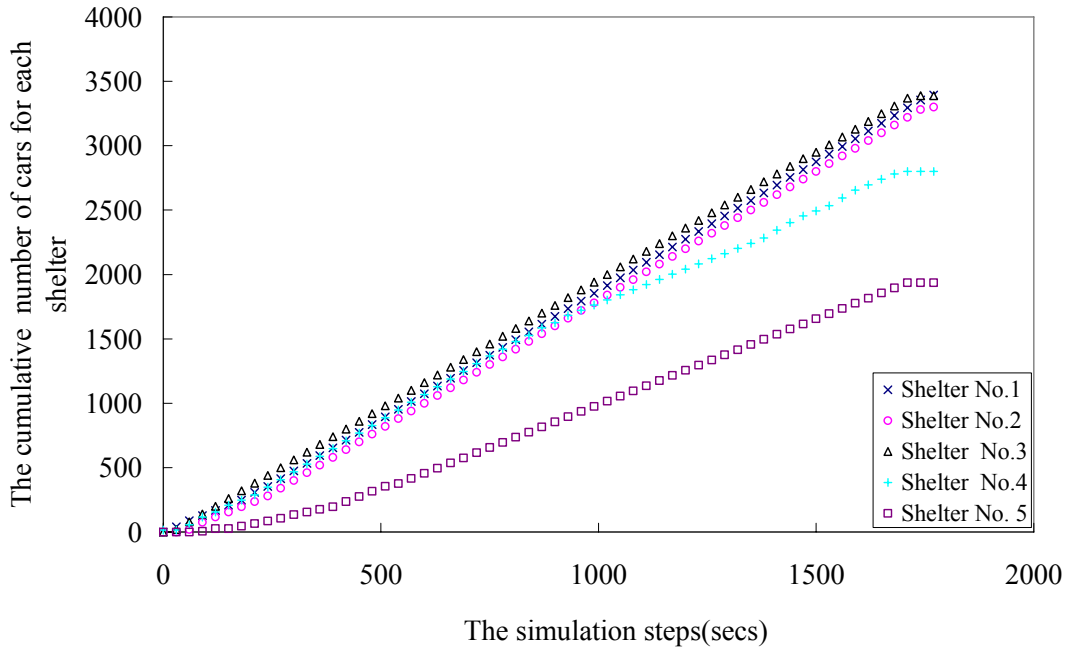


Fig.6. 5 Evacuation process for each shelter without capacity constraints

In fact, the unconstrained evacuation problem can be used to determine the optimal capacity of shelters, if this is yet to be determined during the planning stage, by summing the total number of people arriving at each shelter. The optimal capacity recommended for each shelter is illustrated in Table 6.1.

Table 6. 1 Total number of cars in each shelter

Shelter No.	1	2	3	4	5
The Number of cars	3394	3300	3388	2800	1936

By summing the total number of cars loaded on links from original source nodes to internodes at each step t, we can get the optimal load time. Let the number of initial source nodes be K, and F (t) be the optimal load schedule, then

$$F(t) = \sum_{k=1}^{K} x_{k\delta^+(k)}(t) \qquad \text{Where} \quad \delta^+(k) = \{j/(k,j) \in E\} \qquad (6\text{-}5)$$

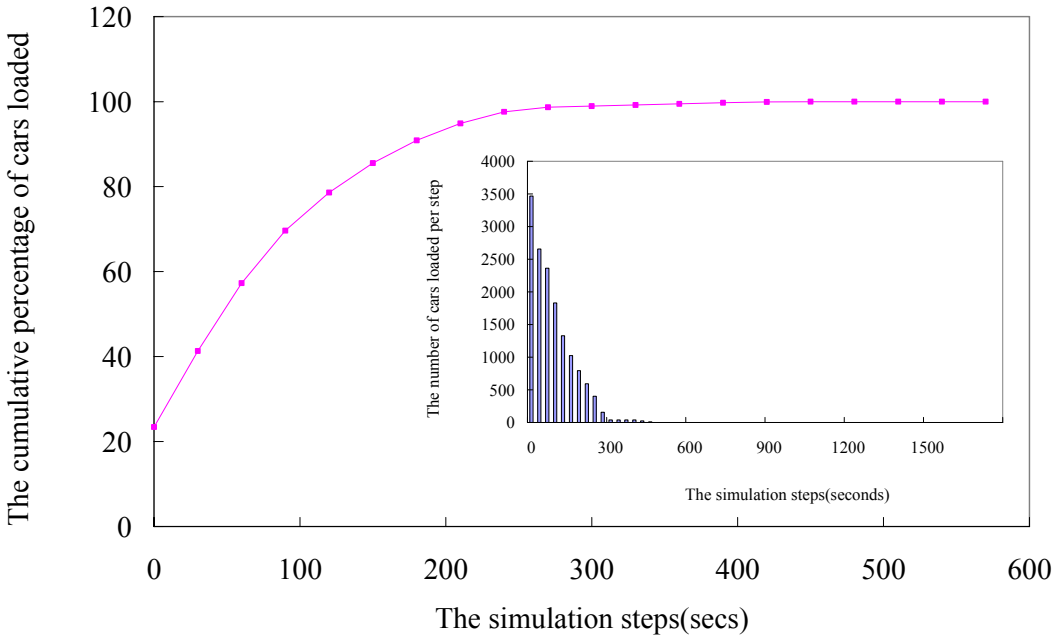


Fig.6. 6 Optimal load schedule for unconstrained evacuation problem

Figure 6.6 gives the cumulative percentage of cars loaded, with the simulation time. It shows that all traffic will be loaded within 450 seconds, 70% within 90 seconds and 95% within 210 seconds. The evacuation route can easily be drawn on the GIS map, as shown in Figure 6.6.

Throughout the simulation, the cumulative throughput for each link was updated for each step. The data output at the end of the evacuation included the total throughput of each link. Links with the highest throughput are likely to be places where evacuation improvement strategies may be implemented.

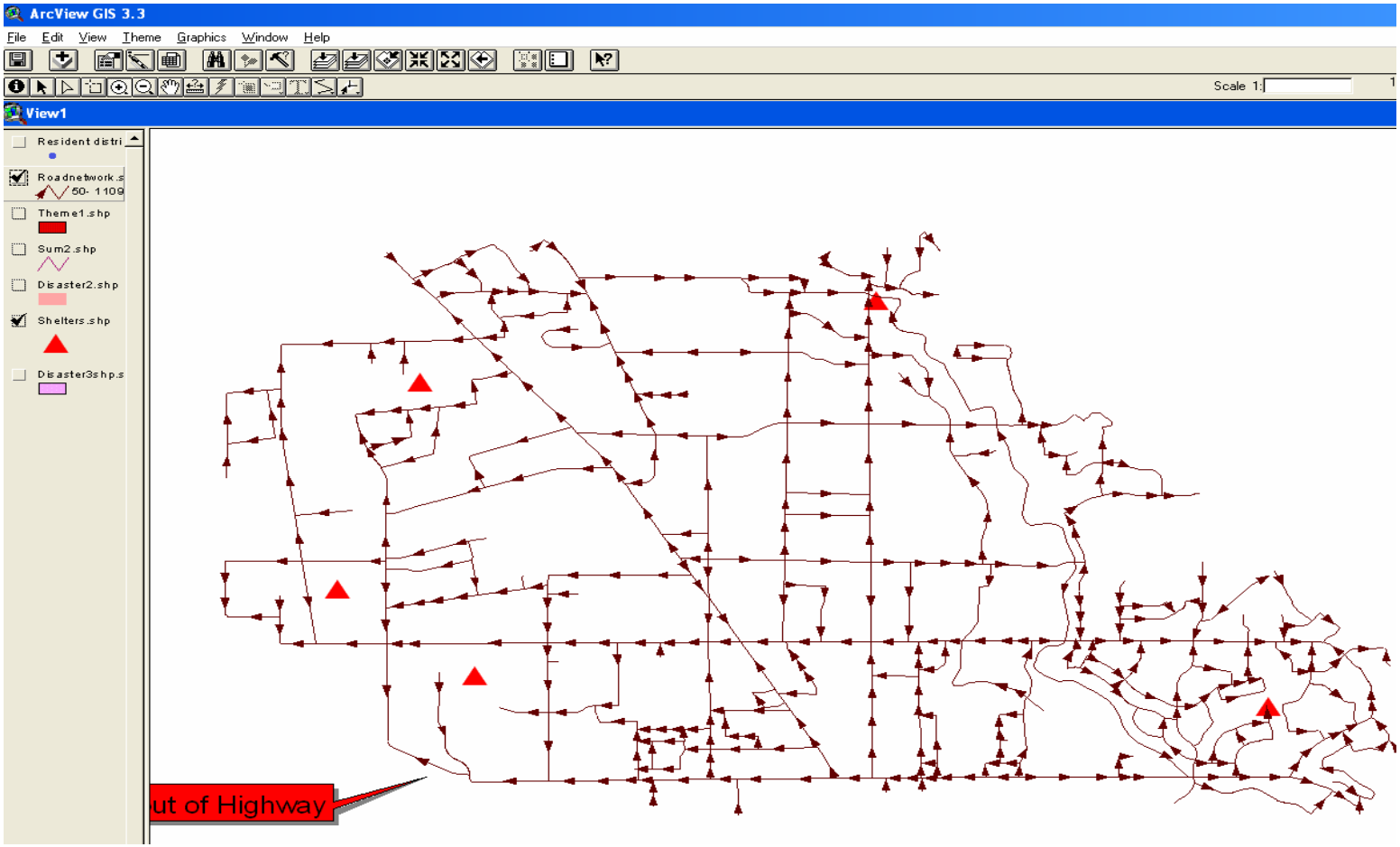


Fig.6. 7 Optimal evacuation routes

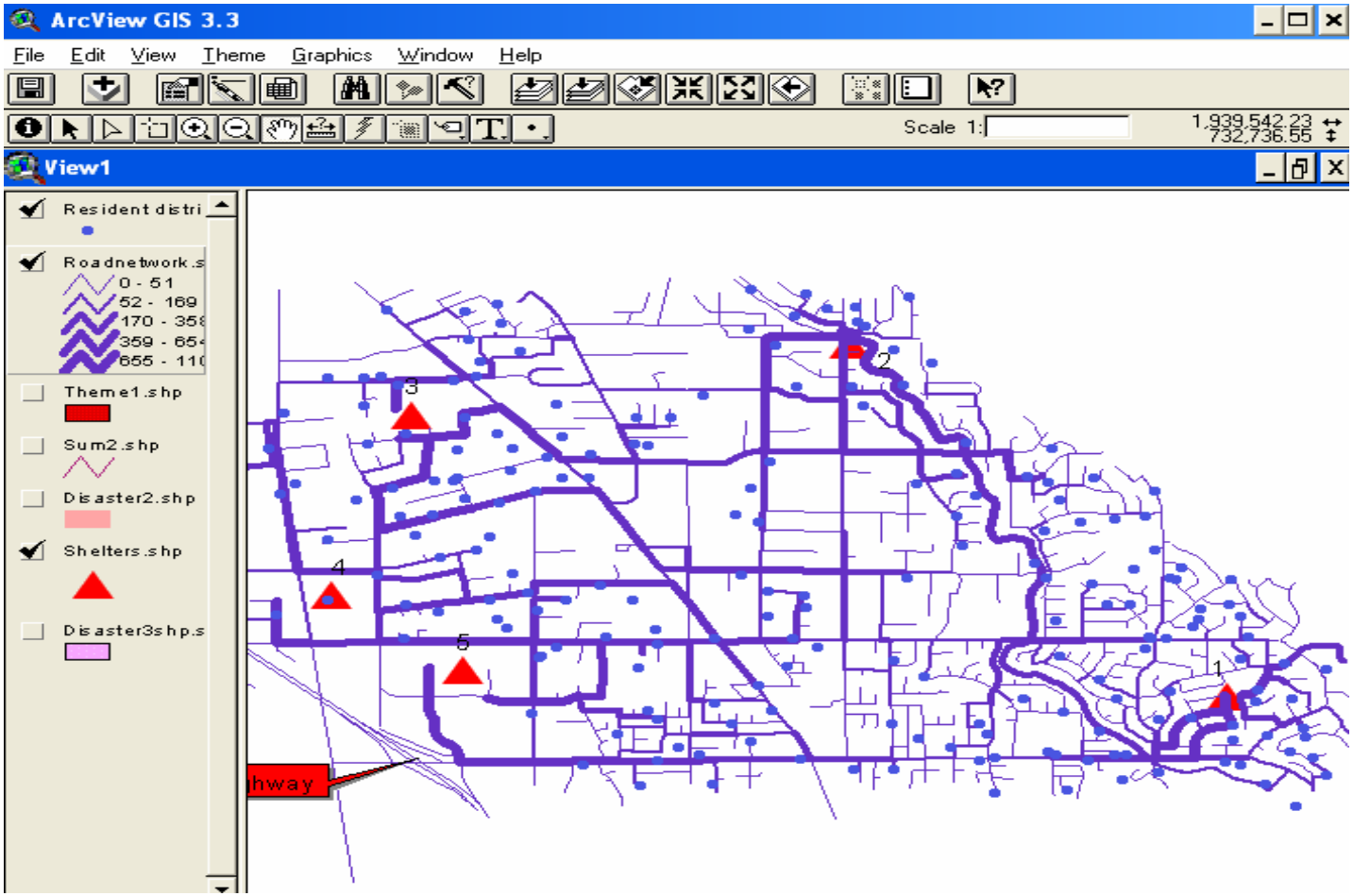


Fig.6. 8 Cumulative traffic load for each link

The cumulative traffic load at each road is shown in graduated symbol mode in Figure 6.8. The higher the traffic load, the wider the links, so the congested road can easily be identified on the GIS map.

6.5 Adoption of Different Load Times (LT)

It must be pointed out that the departure time of evacuees has a significant effect on operational traffic conditions and the severity of traffic congestion, and therefore total clearance time. If all occupants are instantly loaded into the road network, most of the time this leads to over-congestion and significantly increases the total clearance time. However, if the pre-evacuation time delay is too long, this will become the dominant factor compared with time spent on the journey.

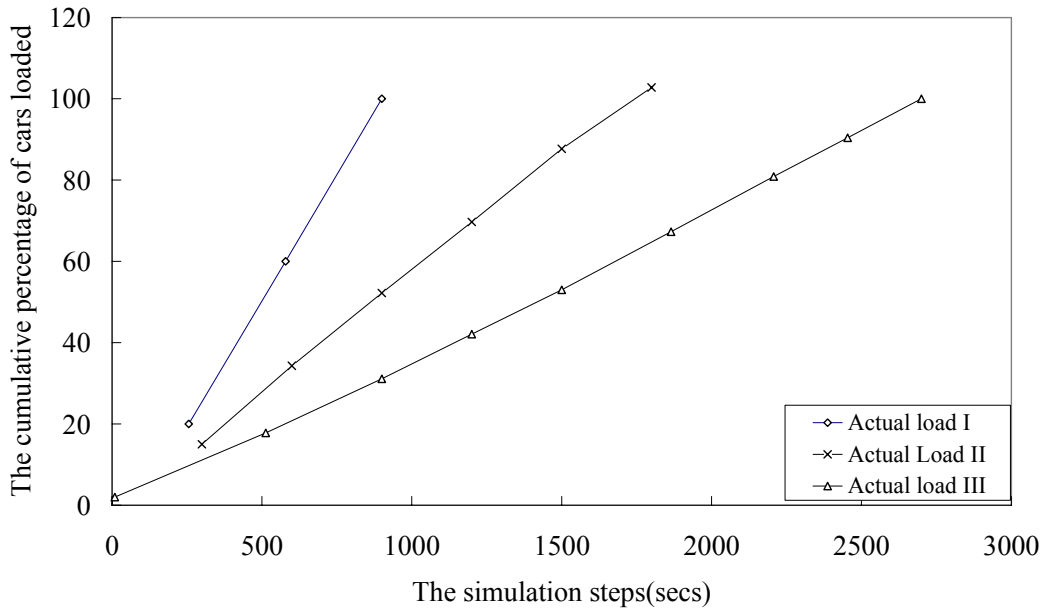


Fig.6. 9 Three actual load schedules

It is important to determine the optimal traffic load schedule since this can

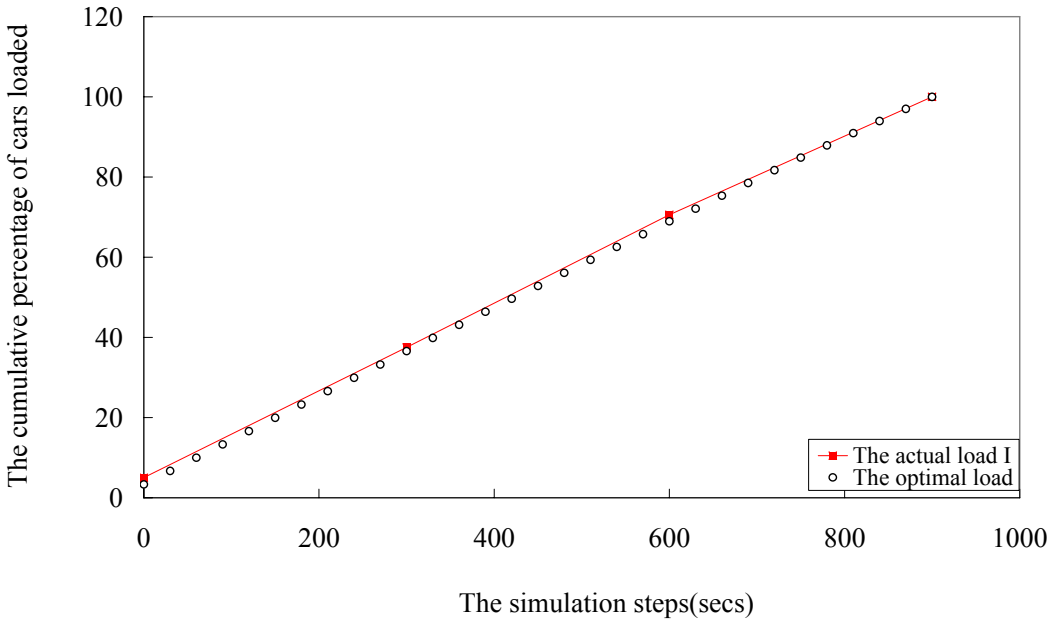
help to reduce the total evacuation time significantly and may reduce households' exposure to the hazard. Because people are informed after a certain time interval, those people loaded at a later time will spend less time on the roads, which therefore helps to reduce their exposure to the hazard. Appropriate load scheduling can help alleviate traffic jams and decreasing the probability of traffic accidents. According to survey data, to depict the preparation time we may adopt three types of load curve, as shown in Figure 6.9. Load type I (the quickest) indicates that all people will be mobilized within 900 seconds. Load type II indicates that all people will be mobilized within 1800 seconds, and load type III 2700 seconds.

Let $P_k(t)$ be the number of people generated at step t at district k, and the number of initial source nodes be K. Then the capacity of virtual links connecting between super source node o and the original source nodes k should be addressed in the following way:

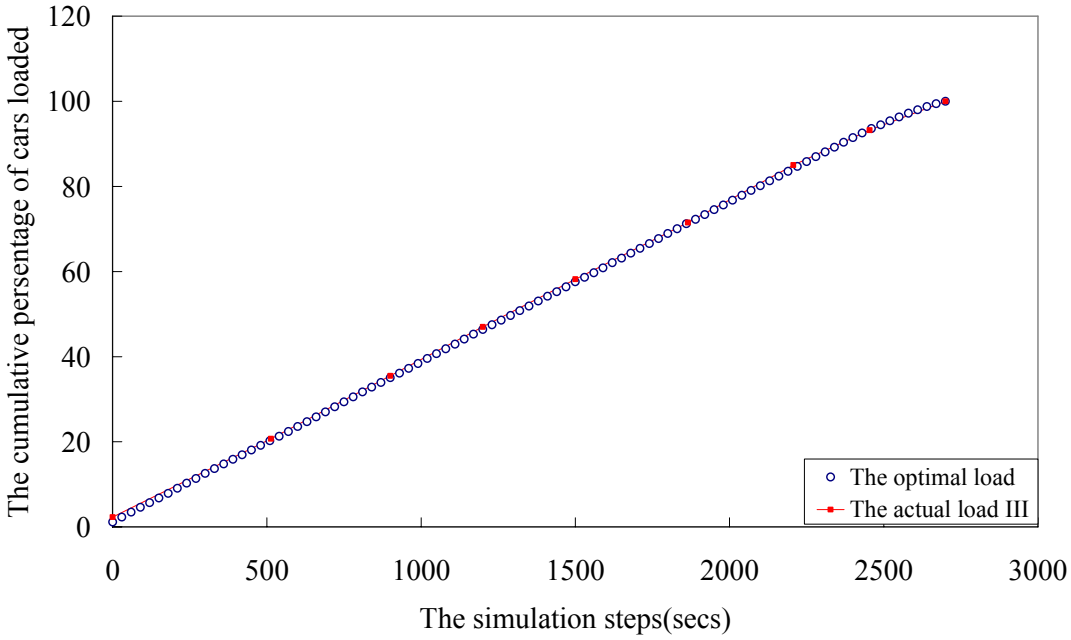
$$u_{ok} = P_k(t) \tag{6-6}$$

The maximum holdover capacity of each original source node k, $d_k(t)$, equals the number of its occupants.

$$d_k(t) = P_k(t) \tag{6-7}$$



(a)Load Time=900 seconds



(b) Load Time=2700 seconds

Fig.6. 10 Optimal load schedule for LT=900 and LT=2700

Figure 6.10 gives the optimal load schedule for two different types of

actual load processes, the quickest load process and the slowest load process. The optimal load schedules under two scenarios comply with their actual traffic load processes, which is quite sensible because for the unconstrained evacuation problem, the theoretical optimal load time is LT=450 seconds, even shorter than the quickest actual load process type I.

The evacuation processes with different load processes are shown in Figure 6.11. This shows that as load time increases, the TET increases significantly. For LT=900 seconds, the TET increases by 5%; For LT=1800; the TET increases by 27% and for LT=2700, the TET increases by 69%. So for the unconstrained evacuation problem in our case, the optimal load schedule is the actual evacuation traffic generation process. In other words, to minimize the TET, the best option is to load the evacuees as quickly as possible (but it must be within actual load time LT>=450 seconds).

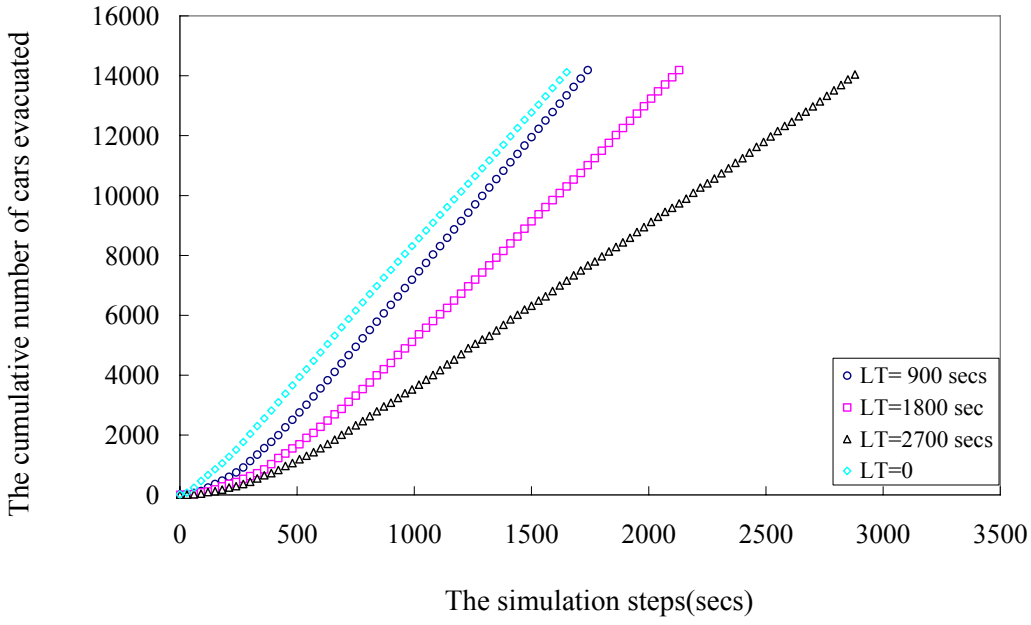


Fig.6. 11 Evacuation process with different load processes

6.6 Constrained Evacuation Problem

In this section, we assume that each shelter is has a limited capacity, as shown in Table 6.2.

Table 6. 2 The capacity of shelters

Shelter No.	**1**	**2**	**3**	**4**	**5**
Capacity C	2000	2000	4000	2000	6000

Let L be the number of shelters, and l be the super sink. The capacity of virtual links connecting original destinations and the super sink can be defined as:

$$u_{jl}(t) = \begin{cases} 0 & t < T \\ C_j & t = T \end{cases} \qquad j = \{1,2,...L\}, t = \{0,1,...T\} \tag{6-8}$$

The maximum holdover capacity of each original sink node j $d_j(t)$ equals its maximal capacity.

$$d_j(t) = C_j \qquad j = \{1,2,...L\}, t = \{0,1,...T\} \tag{6-9}$$

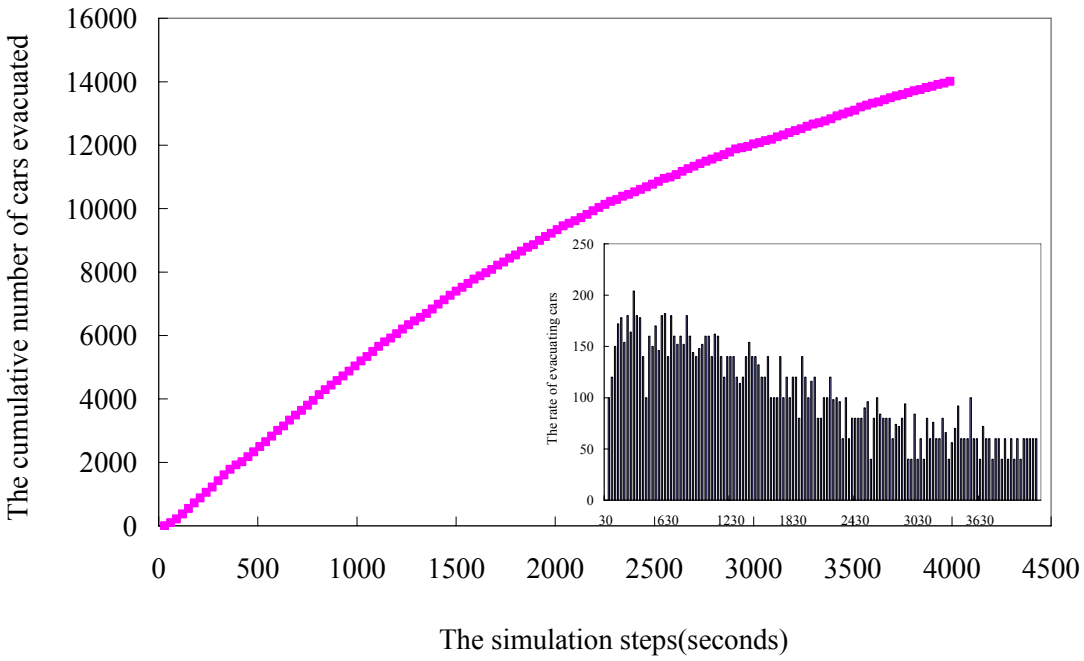


Fig.6. 12 Evacuation process for capacity evacuation problem

We first assume that all people are mobilized simultaneously, i.e., LT=0 (see Figure 6.12). The total evacuation time is 3990 seconds. The evacuation rate per step is also given in Figure 6.12. There is considerable difference in the TET between the unconstrained and constrained evacuation problems. The TET increases by more than 132% in the latter scenario. The evacuation processes for shelters are given in Figure 6.13. This shows that only 2000 persons could be allocated to shelter No.1 due to its capacity limitations and all of them will arrive within 2100 seconds; for shelter No.5, 4354 persons were allocated and they spent the longest time, 3990 seconds, to arrive. Figure 6.14 compares the unconstrained and constrained evacuation. It is clear that the capacity constraints of destination shelters have a great impact on the TET, and it is important to classify these two kinds of evacuation problem carefully and thoroughly before any evacuation analysis.

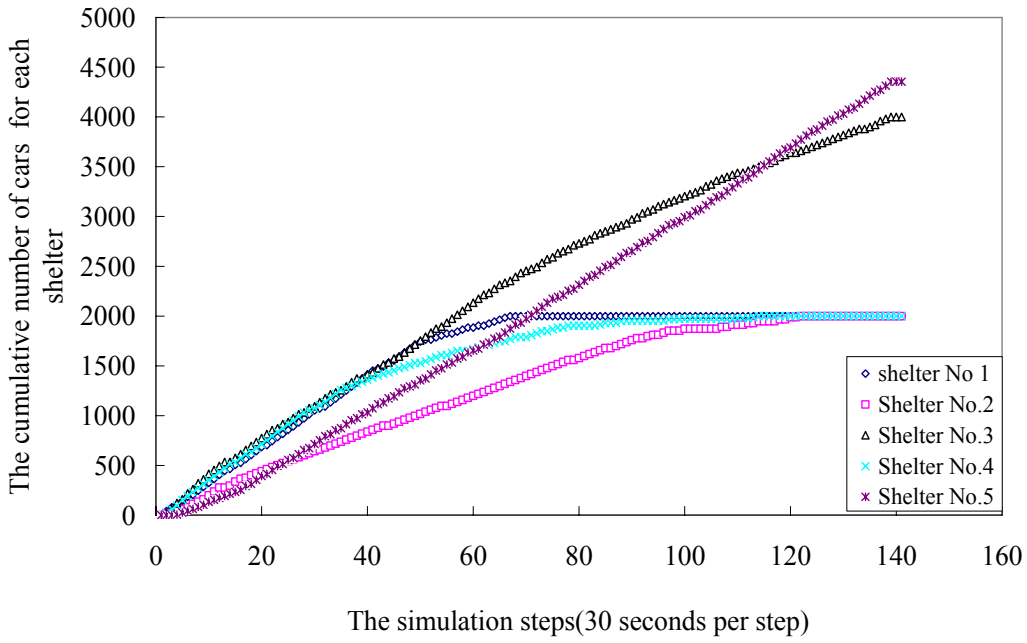


Fig.6. 13 Cumulative number of cars arriving at each shelter

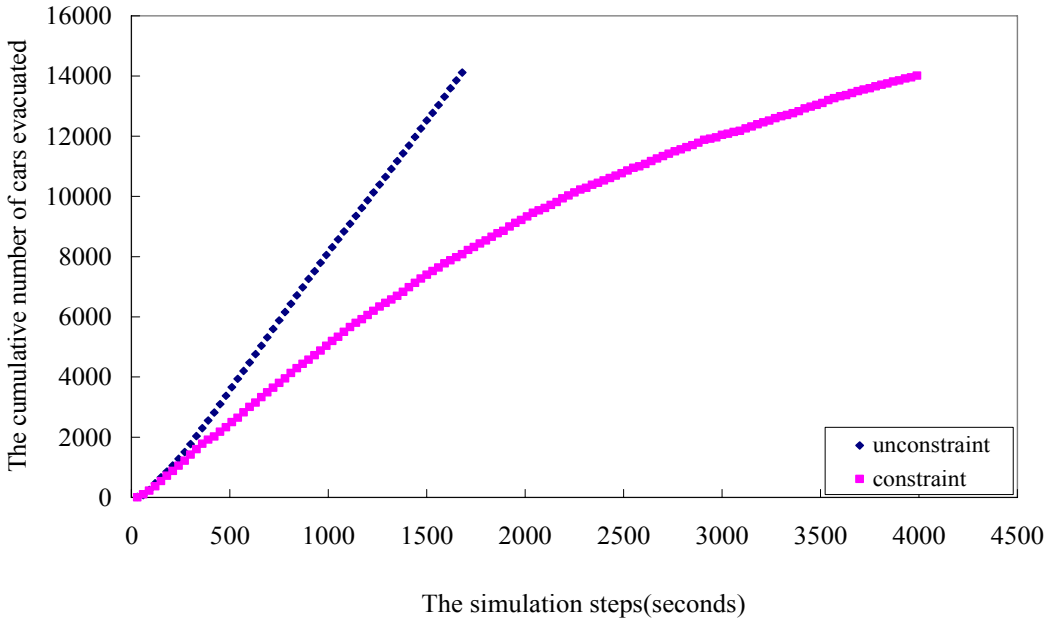


Fig.6. 14 Constrained and unconstrained evacuation problems compared.

Figure 6.15 gives the cumulative percentage of cars loaded at each

simulation step. It shows that all traffic will be loaded within 3870 seconds, 70% within 1440 seconds, and 95% within 2730 seconds. The optimal load schedule of the constrained problem is much slower than that for the unconstrained. The optimal load time for the latter case is 450 seconds.

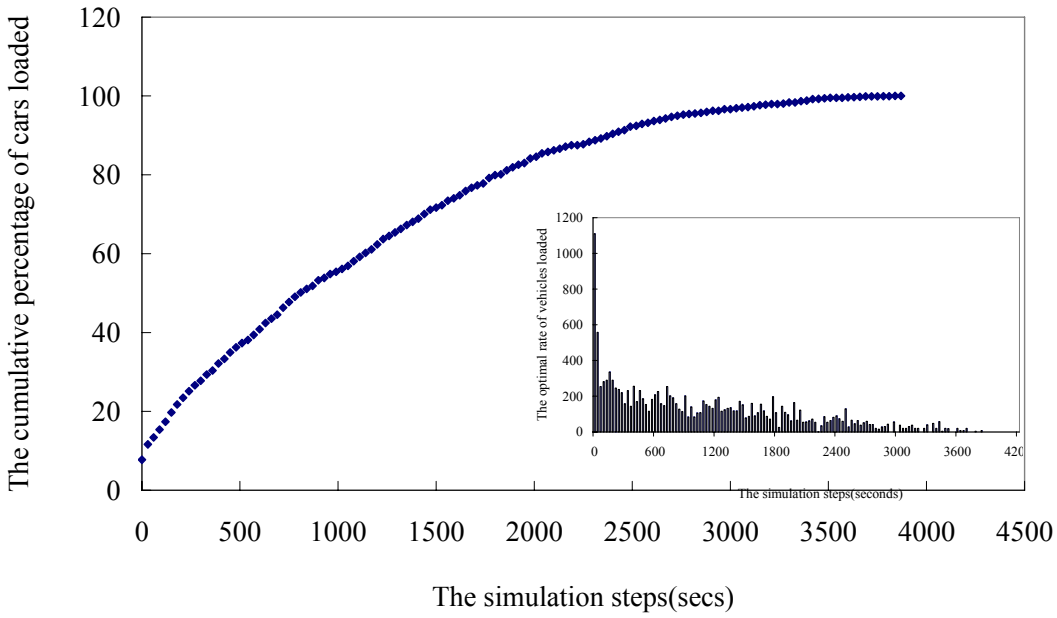
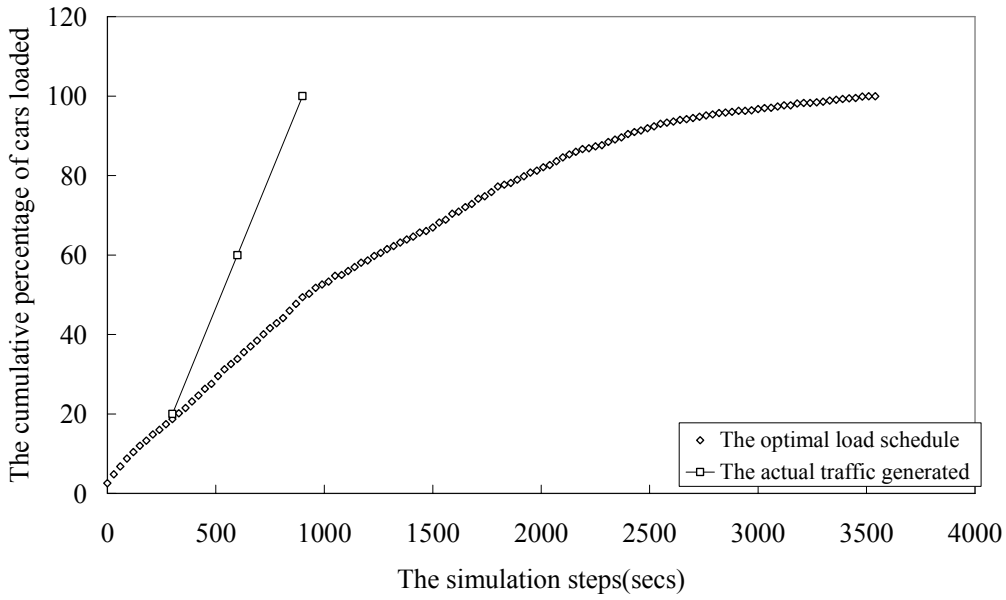


Fig.6. 15 Optimal load schedule for capacity evacuation problem (LT=0)



The optimal load schedule for LT=900 is shown in Figure 6.16. There is significant difference between the traffic load actually generated and the optimal load at each time. The latter is much slower than the former. In other words, due to the constraints of the network, more traffic demand is produced than the network can accommodate at each step and some of the traffic is required to wait for a while in its initial position. With the increase of the LT, the difference between actual traffic and the optimal loaded decreases, as shown in Figure 6.17 and Figure 6.18. For LT=2700, no significant difference was observed.

The relationship between the optimal load schedule and load time (LT) for the constrained evacuation problem is quite different to that for the unconstrained evacuation problem.

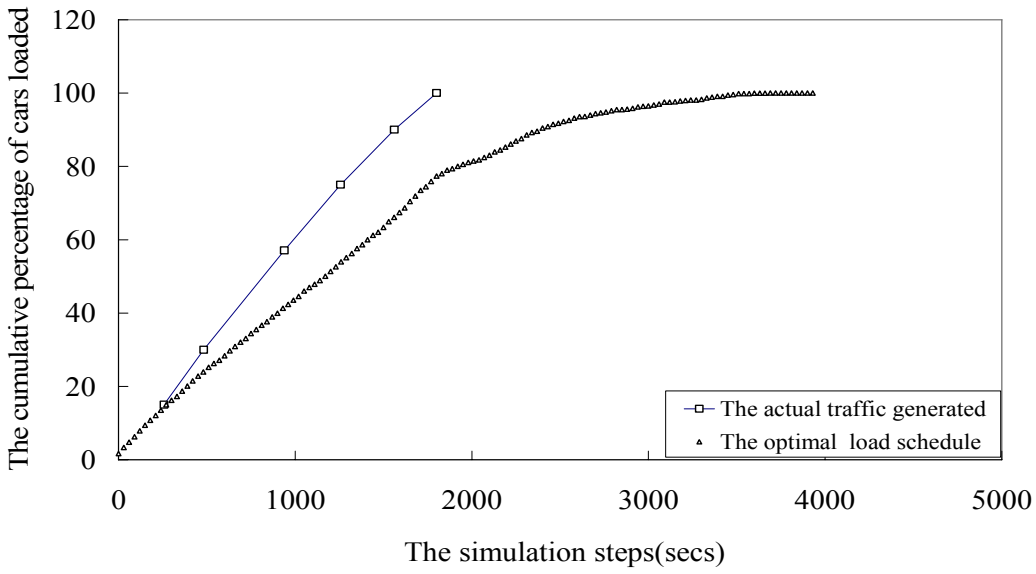


Fig.6. 17 Optimal schedule for load time (LT) =1800 seconds

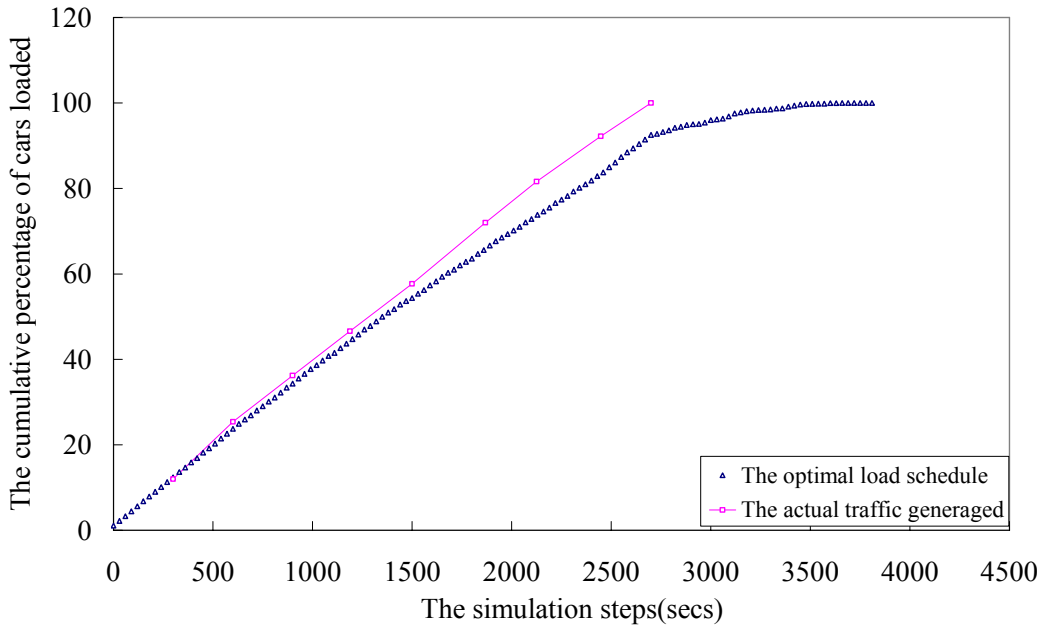


Fig.6. 18 Optimal schedule for load time (LT) =2700 seconds

The evacuation processes with different load processes are shown in Figure 6.20. The increase in load time has no discernable influence on the TET in the constrained evacuation problem. The relationship between the EET and load time (LT) for constrained evacuation problem is quite different from the unconstrained problem. The traffic load on each road is shown in Figure 6.21 and the evacuation map is given in Figure 6.22. A comparison of the traffic load patterns for constrained and unconstrained problems is given in Figure 6.23. The congestion patterns of the two scenarios are quite different.

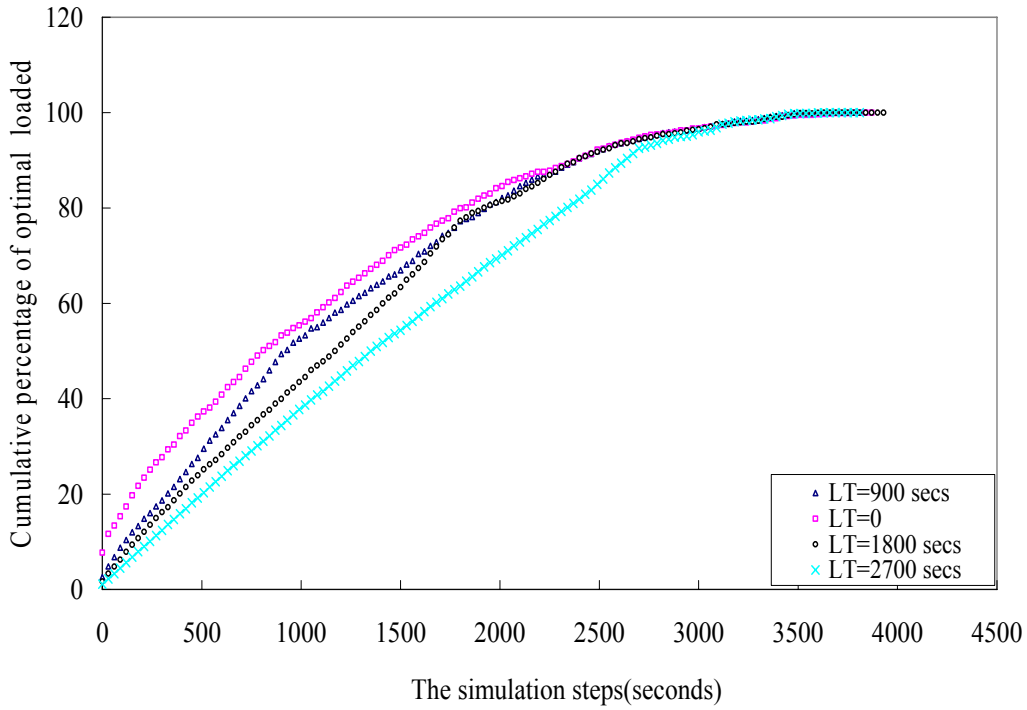


Fig.6. 19 Comparisons of the optimal schedule for different LT

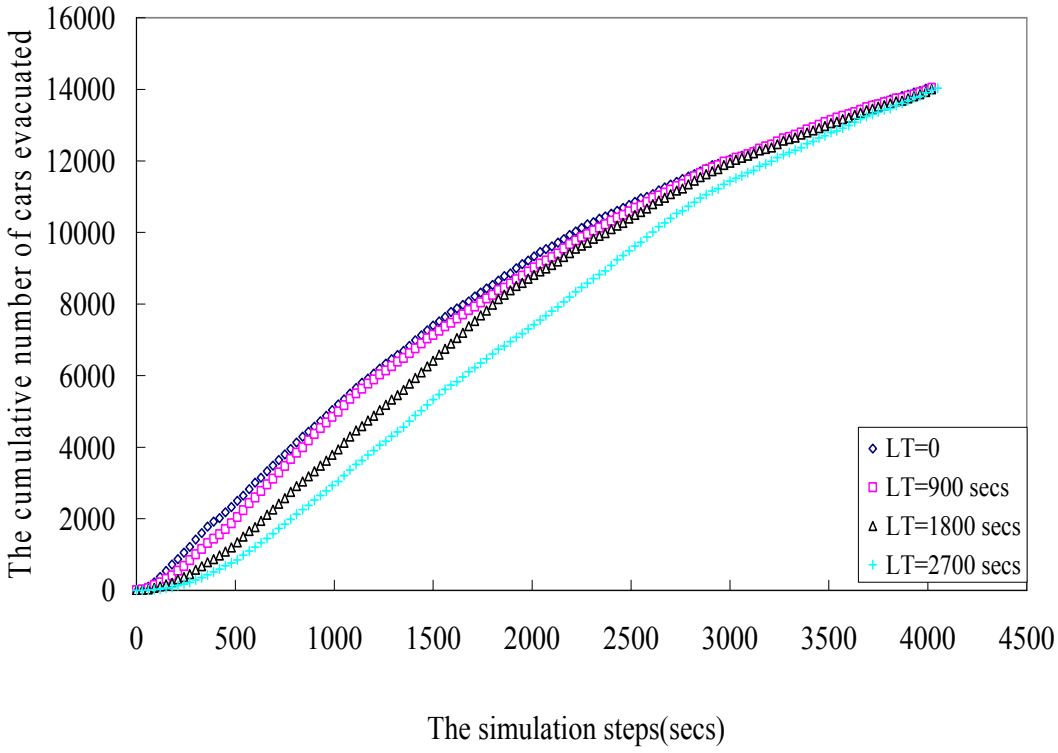


Fig.6. 20 Comparisons of the evacuation process for different LT

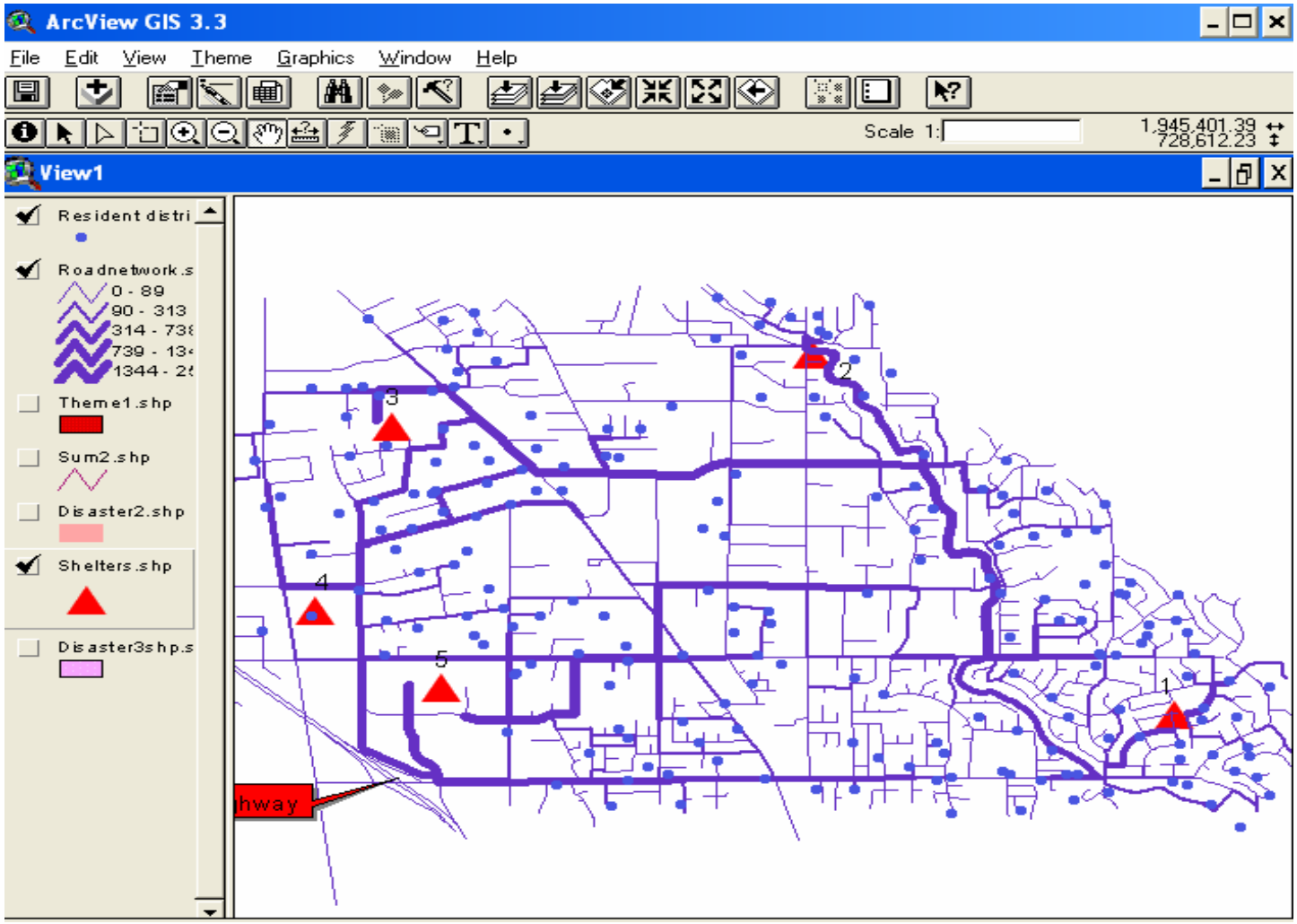


Fig.6. 21 Traffic loads with capacity constraints of shelters

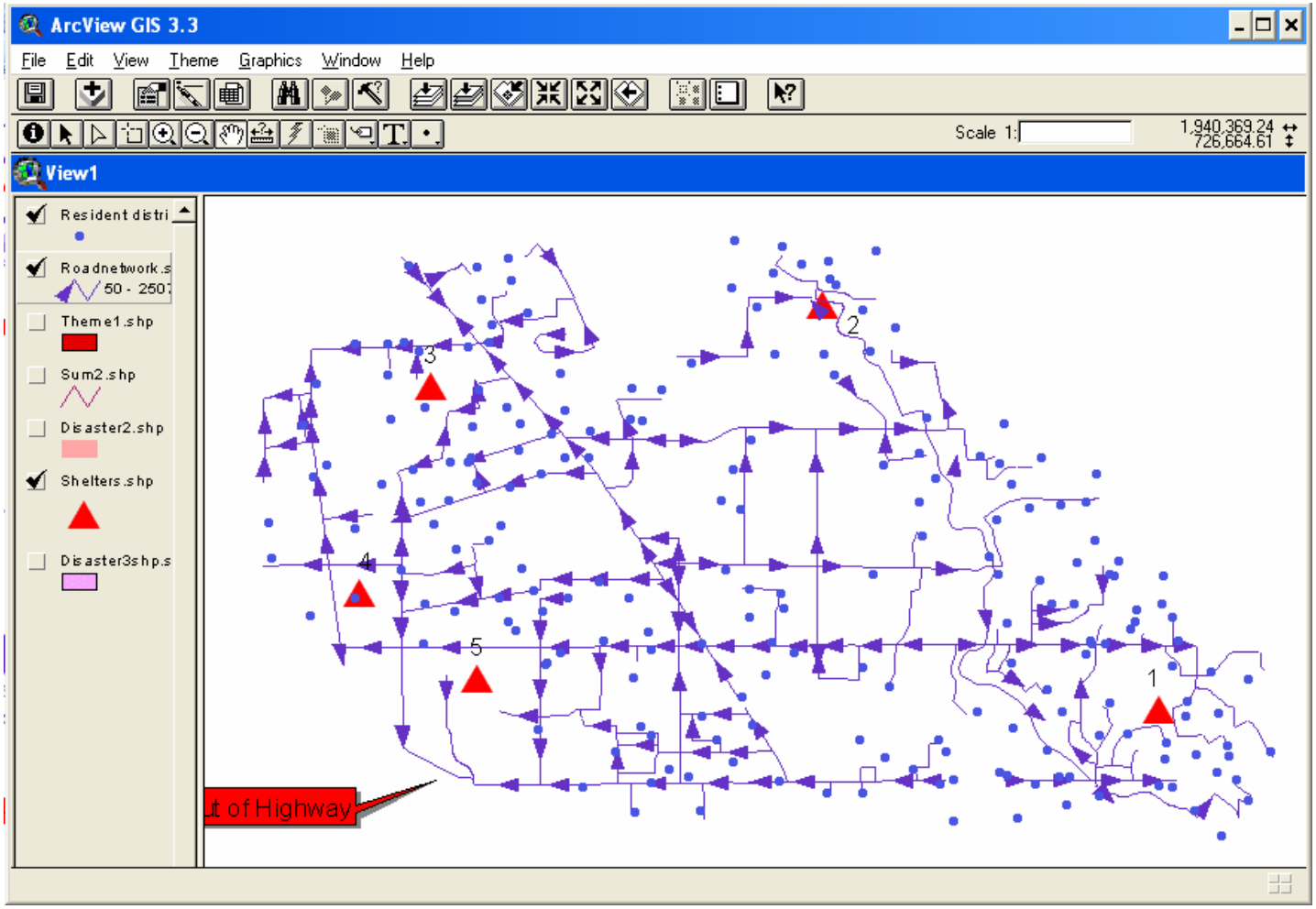
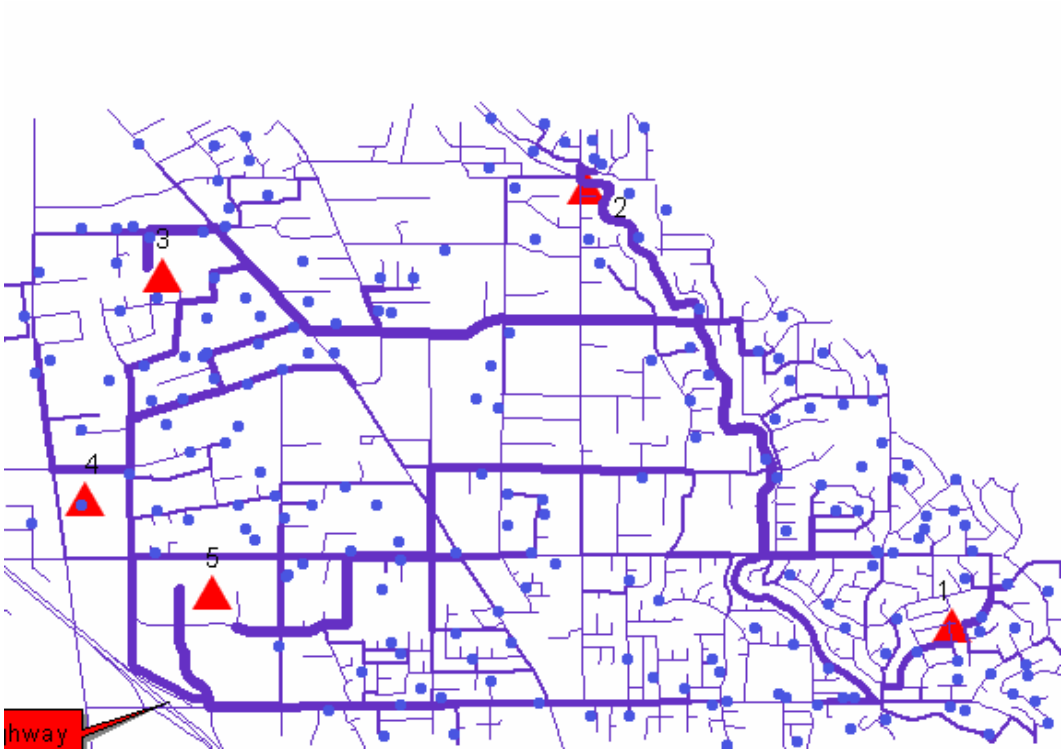
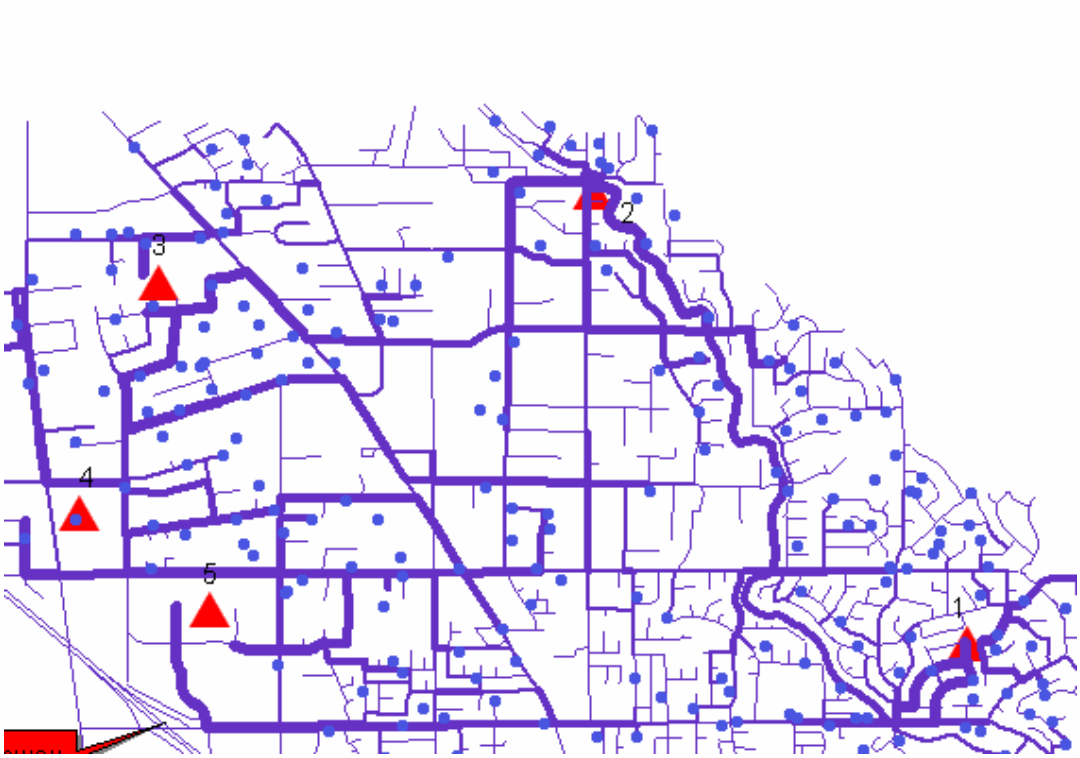


Fig.6. 22 Evacuation route for the constrained evacuation scenario



(a) The constrained evacuation scenario



(b) The unconstrained evacuation problem

Fig.6. 23 Comparison of traffic load at each link for constrained problem and unconstrained problem

6.7 A Hybrid Evacuation Model

As noted in the Chapter 2, most evacuation models can either be categorized as optimization-based models, which assume that evacuees are well-informed and act cooperatively from a global perspective, or as simulation-based models, which focus on modeling the behavior of individual entities on a road. Both kinds of models have advantages and disadvantages: optimization models give the best guidance strategy in real applications, but they ignore reductions in road capacity due to increases in traffic density, and the behavior of evacuees. Simulation is a powerful tool for evaluating traffic by providing us with a limited number scenarios possible in real circumstances, but it does not explicitly allow for optimization and cannot give us an optimal strategy for reducing clearance time.

A hybrid model which combines the best features of simulation-based models and optimization-based models was established. The schematic structure of this hybrid model is illustrated in Figure 6.24.

The hybrid model was based on the Geological Information System, which provides, stores, and displays basic information about an area of interest. The topological network was first extracted from GIS geological data, and then the traffic demand was estimated according to the GIS attribute data. Then, a time-varying quickest flow algorithm, based on dynamic network flow, was adopted to optimize the evacuation plans, including evacuation schedule, shelters and routes. Finally, the meso-scopic simulation model described in Chapter 4, was adopted to simulate the movement of evacuees according to the established plans. Once this procedure was complete, strategies for improving the efficiency of the evacuation could be proposed.

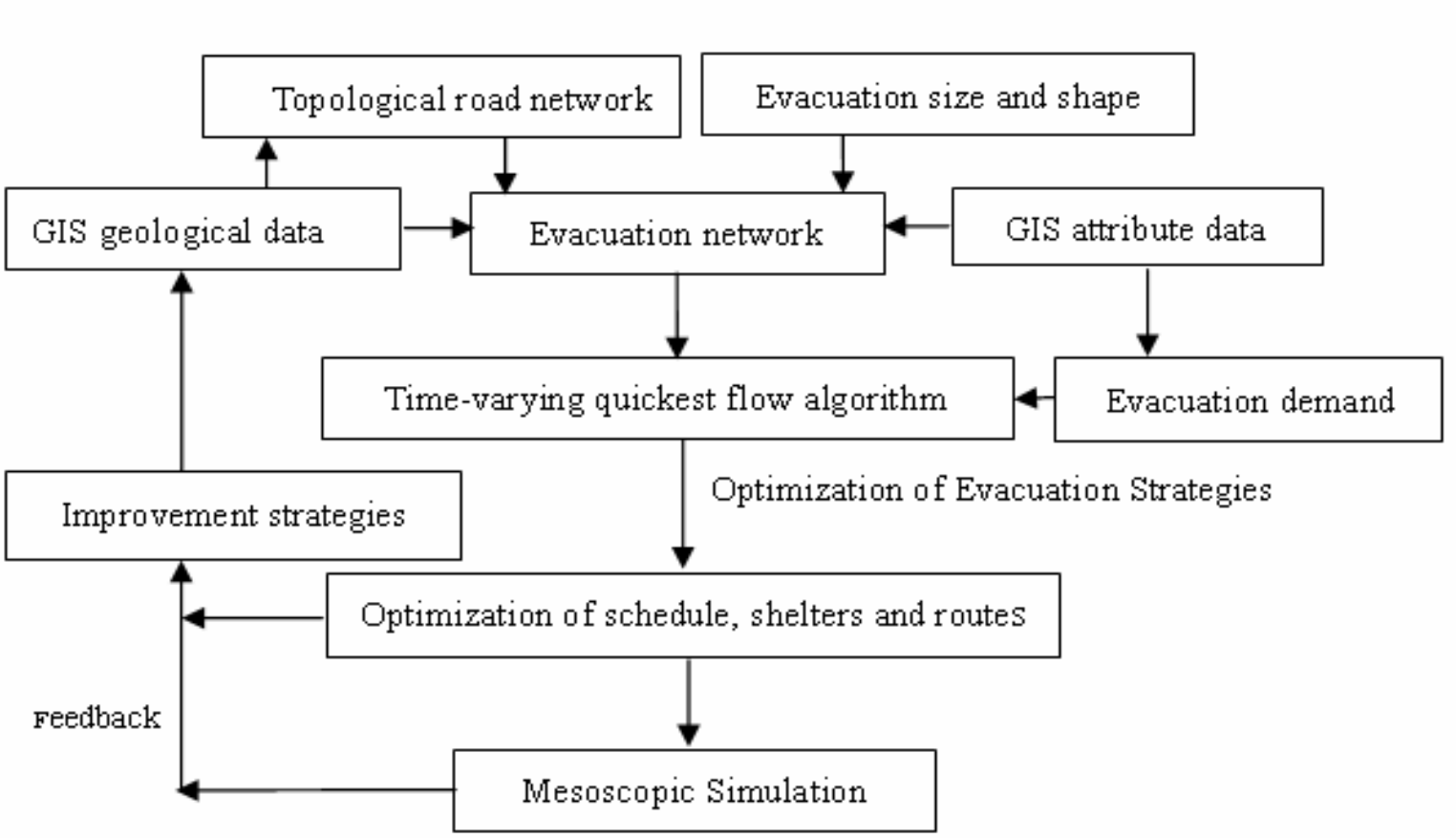


Fig.6. 24 Schematic structure of hybrid evacuation model

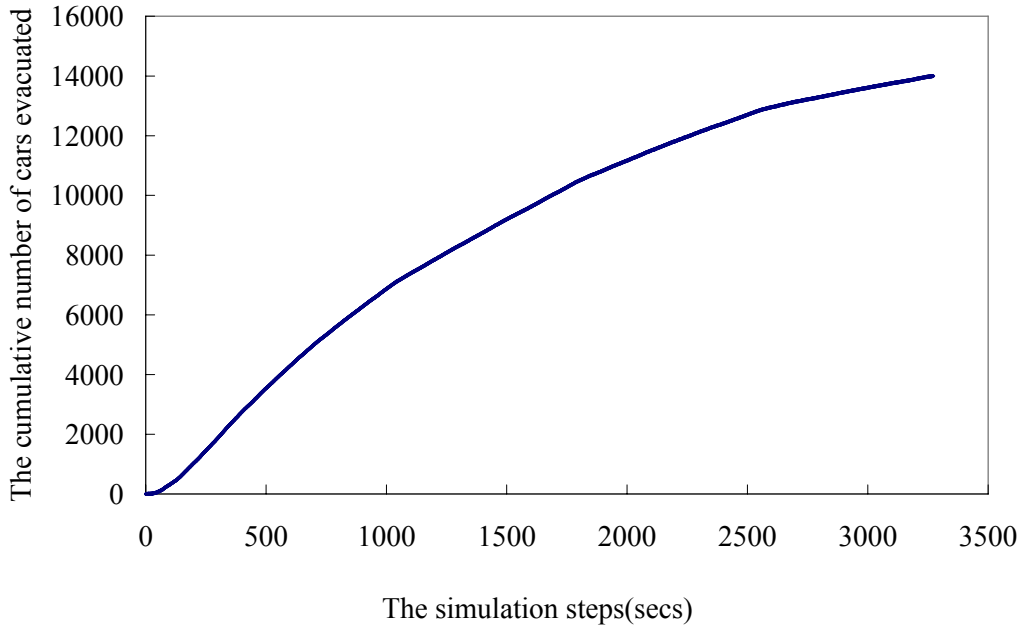


Fig.6. 25. Evacuation process in an iterative assignment simulation

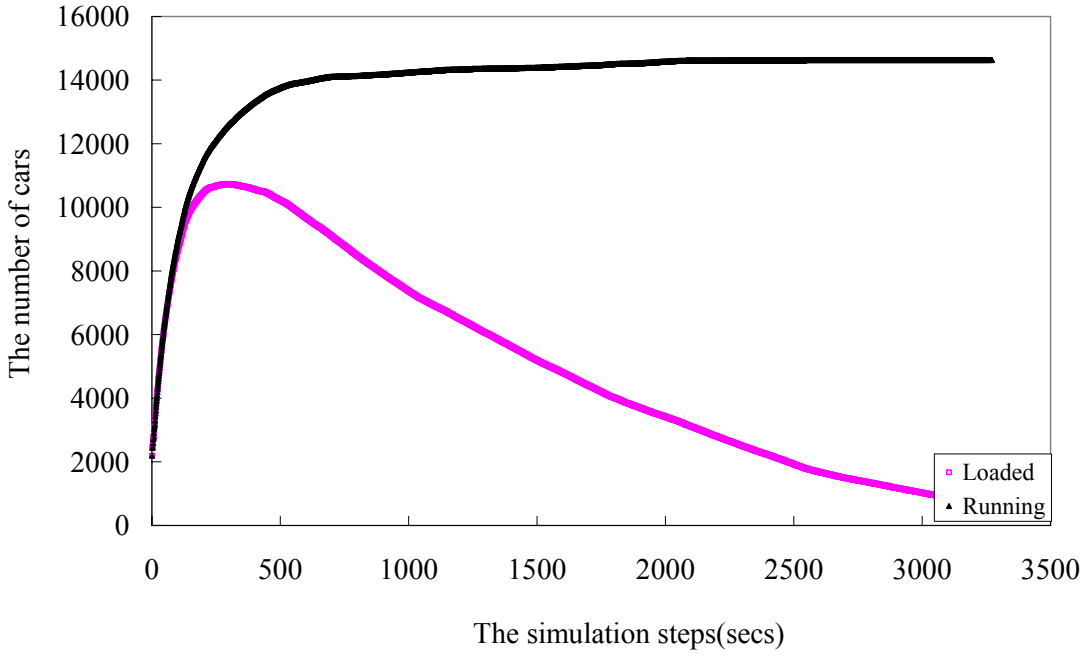


Fig.6. 26 Cumulative number of cars loaded and running at each step

For a better comparison, three approaches, simulation-based, optimization-based, and the hybrid model, were adopted to simulate the evacuation plans. As stated in previous section of chapter, the iterative assignment evacuation model is only suitable for the unconstrained evacuation problem, so the unconstrained problem was studied first by using model developed in Chapter.4. Let LT=0 and the results are shown in Figure 6.25. The TET was 3300 seconds. Figure 6.26 gives the cumulative number of cars loaded and the number of cars running per simulation step.

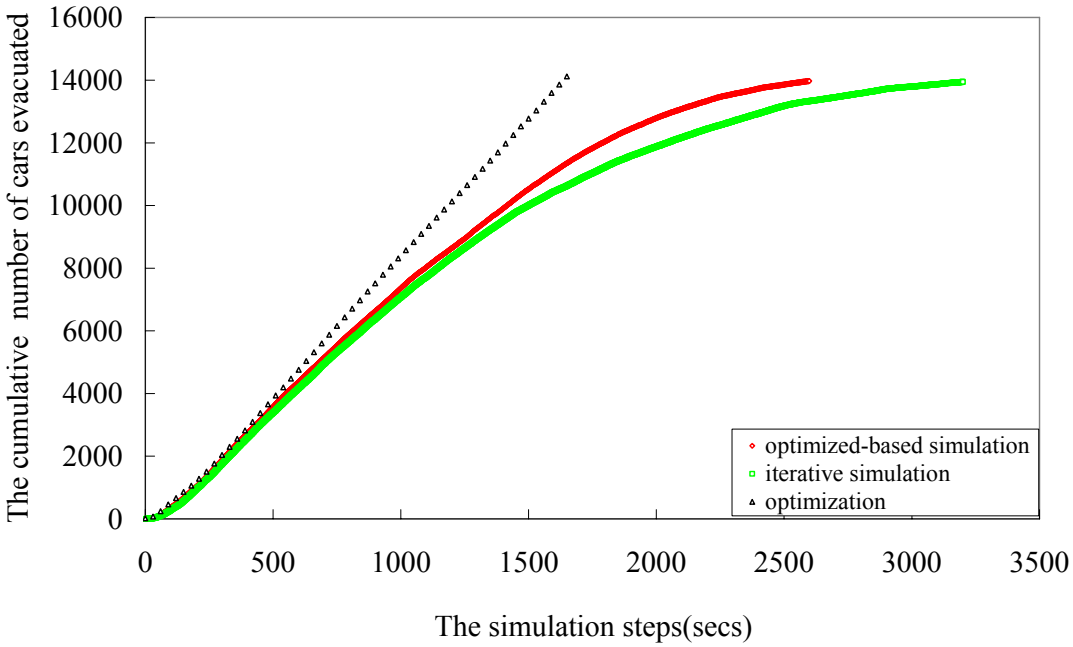


Fig.6. 27 Comparison of evacuation process for unconstrained evacuation

Then, the hybrid evacuation model, according to the optimized schedule, shelters, and routes, was performed with the same parameters and the simulation results are shown in Figure 6.27. The TET is 2600 seconds and it showed that after adoption of the optimized strategies, there is a 20% reduction in the total

evacuation time. As expected, the optimization-based model gives the shortest evacuation time, the simulation-based model gives the longest clearance time, and the hybrid evacuation model, gives the clearance time between of the two values.

Then the hybrid evacuation model was applied by taking consideration of the capacity constraint of shelters. Still, the optimization model was conducted first to compute the evacuation routes, schedule and shelters. Results of the hybrid model were given in Figure 6.28. The TET is 4020 seconds. The results agree well with those of by optimization model.

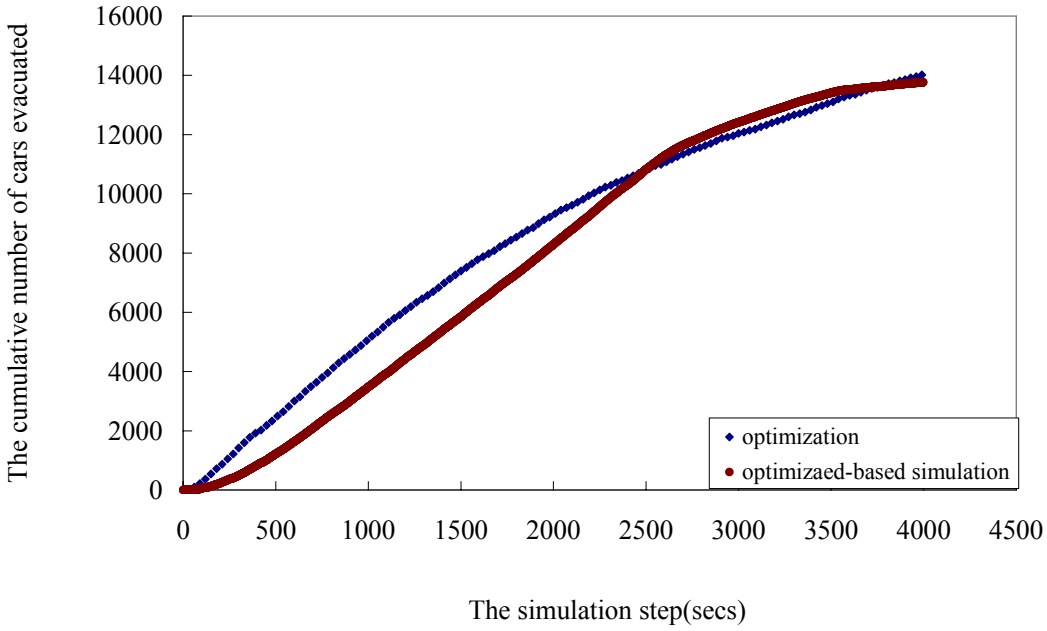


Fig.6. 28 Comparison of evacuation processes for constrained evacuation

6.8 Summary

This chapter has discussed the application of a quickest flow algorithm to the optimization of the evacuation planning of a city. This algorithm was based on a dynamic network and can simultaneously optimize the evacuation shelters,

routes and schedule. The optimization algorithm of shelter-route-schedule was applied to urban evacuation planning scenarios.

Two important types of evacuation problems, constrained and unconstrained, have been addressed. The former takes into account the capacity constraint of shelters while the latter does not. Our studies revealed that shelter capacity has an impact on the total clearance time: generally speaking, an evacuation happens much more quickly under unconstrained conditions. The influence of load time on the total evacuation time was analyzed under these two conditions and it was found that, under unconstrained conditions, the TET increases with the duration of LT. However, under constrained conditions, LT has little effect on the TET within a time interval.

In the last section of this chapter, we proposed a hybrid evacuation model which integrated the optimization model and the simulation model. The optimization model was used to optimize the evacuation routes, schedules, and shelters and provided a global optimal solution. The simulation model, by taking into consideration the interaction of individual entities, provides us with detailed evacuee behavior. The hybrid evacuation model was applied and results were discussed and analyzed.

The whole evacuation system was integrated with ArcView and MapObjects. The integration with GIS can provide a versatile and easy-to-use way to operate our model and display results graphically.

Chapter 7

Conclusion

7.1 Summary

The significance of emergency evacuation, either on foot or by vehicular traffic, has been underestimated for the past few decades. Piecemeal studies have been performed and are concentrated in various fields, such as transportation engineering, operational research, psychology and sociology. However, a systematic approach has rarely been carried out.

The major aim of the current study was to establish a decision support system which integrates simulation models, visualization tools, GIS, and optimization algorithms for managing large-scale evacuations of densely populated regions in disastrous events. The decision system proposed in this dissertation can be adopted to improve the design of transportation network, devise efficient evacuation plans and establish effective evacuation management strategies at place-in-use stage. The dissertation has presented a detailed discussion on the design, development, and application of evacuation models. A brief description of the contents of each chapter was given below.

In Chapter 1, the background to the research was briefly presented, and a conceptual review on the importance and mechanism of emergency evacuation was given. The aims, objectives of the research and methodology adopted were described. The overall structure of this dissertation was outlined.

In Chapter 2, a literature review for the studies of people/ crowd movement

was addressed. It was reviewed from two aspects: movement by means of vehicles and on foot. Then, a comprehensive review on the development of evacuation models is given. A total of 56 evacuation models, covering both building and regional evacuation, were examined and their merits and shortcomings are summarized.

In Chapter 3, a microscopic simulation evacuation, an improved random walker model, was developed and it can model the detailed behavior of each evacuee during evacuation process, such as the route and destination selection. As random walker model ignores the lane change behavior, a modified cellular automaton was presented to simulate the bi-direction pedestrian flow. It can model the lane formation and deadlock phenomena of crowd movement. As the computational demand for the model is reasonable, it was further developed for evacuation analysis. In order to facilitate the pre-processing of the model, an automatic process for transforming computer-drawn architectural plans into input data was embedded to the model. The model was adopted to simulate the evacuation of the passengers in an underground rail station and an interesting and counter-intuitive phenomenon, known as the Braess's Paradox, had been observed in the people's moving network. Provision of alternative routes is a significant issue for analyzing an evacuation network. The phenomenon explains why the addition of links may result in deterioration of the throughput of the whole network, i.e. a road network may suffer worse congestion after improvements have been made to it. The study also showed that the selection of appropriate evacuation network is vital for ensuring that a model mimics a scenario accurately.

In Chapter 4, a mesoscopic evacuation model, based on queue model was

established. The algorithm of this model consisted of two-link scanning processes, which check the dynamic capacity and static capacity respectively at each step. The mesoscopic model simplifies the lane change behavior of drivers on roads and focused on the behavior of drivers at intersections. It attempts to combine the best features of both macroscopic models and microscopic models by filling the gap between the aggregate level approach of macroscopic models and the individual interactions of the microscopic ones and it provides a cost-effective way to evaluate the evacuation planning in real time application. It is also capable of modeling the congestion and spillback process during an emergency evacuation.

Two types of assignment, all-or-nothing assignment and simulation-based iterative assignment were further implemented in the meso-simulation model. The former allocates the evacuees to their shortest routes and the latter distributes the evacuees to quasi-optimal routes. The performance of the two approaches was compared and it was found that the iterative assignment decreased the evacuation clearance time greatly, especially under congestion conditions. Iterative assignment can help making full use of the evacuation network, thus facilitating the movement of evacuees. Sensitivity analysis of the regional evacuation model was performed. This evacuation model was integrated with Netengine, a GIS component, which can provide all kinds of network algorithms. The GIS-based meso-evacuation model can provide a cost-effective way to simulate and evaluate the safety of a population in an area in terms of Totoal evacuation time(TET), and can also be used to guide and control the evacuation traffic during a real-time evacuation.

In Chapter 5, a time-varying quickest flow problem (TVQFP), based on

dynamic network flow, was developed to optimize the evacuation plan. TVQFP is different from its prototype problem, the quickest flow problem, in that all parameters associated with a network, such as travel time, capacity etc., are time-dependent. These time-varying features make TVQFP particularly suitable for evacuation planning as the through capacity of roads or intersections may decrease or become zero due to the effects of adverse environments such as fires, floods or lethal gas. Dynamic networks can reflect these time-varying features and optimize the evacuation process.

As evacuation problem is a multi-source-multi-sink problem, where sources are places where residents are located when an evacuation order is first issued and sinks are emergency shelters or places where the residents will move. The multi-source and multi-link situations can be resolved to a single-source-single-sink problem by addition of a super-source, a super-sink and associated virtual links which connect the super nodes with actual sources and sinks by appropriate definition of travel time and capacity of virtual links. The dynamic network algorithm considers the holding capacity at nodes and capacity constraints at intersections. The quickest flow problem was transferred to its equivalent, the earliest flow problem, which maximizes the flow arriving at sinks for each step over a time period. Then the algorithm was solved based on successive shortest augmenting paths on dynamic residual networks and the capacity of each arc in the dynamic residual network is updated for each run. In the chapter, a building evacuation and an urban evacuation were simulated by adopting TVQFP.

Phased evacuation is an arrangement for the evacuation of an area in the event of disaster whereby occupants will be evacuated in accordance with the

level of risk and the network pattern. A lexicographically quickest flow problem, based on time-varying quickest flow problem (TVQFP) was further proposed in the study to determine the minimal clearance time required to evacuate all residents and, at the same time, to maximize the output of higher priority people. The approach can suggest a process that can minimize the number of people located in the most dangerous place, and at the same time optimize the total evacuation time in the system optimization. It can be adopted to establish movement schedules and routes during a phased evacuation from multi-compartment buildings or cities.

In Chapter 6, the time-varying quickest flow problem (TVQFP) was adopted to optimize the evacuation shelters, evacuation routes and evacuation schedule simultaneously. Two kind of evacuation problems, unconstrained (unlimited capacity of shelters-temporary safe places) evacuation problem and constrained (limited capacity of shelters) were discussed. Our studies revealed that shelter capacity has an important impact on the total clearance time. In general, the evacuation time under unconstrained condition is quicker than under constrained condition. The influence of load time on the total evacuation time was analyzed under these two conditions and it was found that, under unconstrained conditions, the total evacuation time(TET) increases with the duration of load time LT. However, under constrained conditions, LT has little effect on the TET.

In the last section of this chapter, a hybrid evacuation model, which integrated the optimization model and the mesoscopic evacuation model developed in Chapter 4, was proposed. The optimization model was used to optimize the evacuation routes, schedules, and shelters simultaneously and

provided a global optimal point of view for the whole evacuation process. The simulation model, by taking into consideration the interaction of individual entities, provides us with detailed evacuee pattern. The hybrid model combines the advantages of both optimization model and simulation model. An urban evacuation problem was presented as an example to illustrate the feasibility of our algorithm for large scale evacuation problem. The following issues were discussed:

- Minimal clearance time
- Optimal evacuation route
- Optimal departure time
- Optimal capacity of each shelter.

The TVQFP was adopted to identify bottlenecks during an emergency evacuation process and assess the effectiveness of alternative traffic control strategies for alleviating congestion. The integration of the model with GIS can facilitate data input and provide a vivid and interactive analytical tool.

As a conclusion, the contribution of the study can be summarized as follows:

- A time-varying quickest flow problem (TVQFP), based on dynamic network flow, had been developed to optimize the evacuation plan. This algorithm can be adopted to optimize the evacuation shelters, evacuation routes and evacuation schedule simultaneously. It can effectively simulate the effect of unconstrained (unlimited capacity) and constrained (limited capacity) shelters – temporary safe places. TVQFP is particularly suitable for evacuation planning as through capacity of roads or intersections may decrease or totally be blocked due to the effects of adverse environments such as fires, floods, or lethal gas. Dynamic

network can reflect theses time-varying features and optimize the whole evacuation process to a system optimum.

- A lexicographically quickest flow was presented and it can minimize the number of occupants located at the most dangerous place, at the same time optimize the total evacuation time in the system optimization. It can be used to arrange the schedules and routes during a phased evacuation in multi-compartment buildings or cities.
- A microscopic simulation evacuation was developed and it can model the detailed behavior of each evacuee during evacuation process, such as the route and destination selection. The evacuation model incorporated many distinctive features of human behavior, such as competitiveness and cooperation. The model is quite simple and computational efficiency. The model had been adopted to simulate the evacuation of a subway and an interesting and counter-intuitive phenomenon, known as the Braess's Paradox, had been observed in the people's moving network.
- A mesoscopic level evacuation model, based on the queue model has been established on a GIS platform to model a regional traffic evacuation. This model simplified the lane change behavior of drivers on roads and focused on the behavior of drivers at intersections. It provides a cost-effective way to evaluate the evacuation planning in real time application. Despite its simplicity, it can model the congestion and spillback process during an emergency evacuation. Two types of assignment were implemented in the meso-simulation model, the all-or-nothing assignment and the simulation-based iterative assignment. This regional evacuation was integrated with Netengine, a

GIS component, which can provide all kinds of network algorithms. The GIS-based meso-evacuation model can provide us a cost-effective way to simulate and evaluate the safety of population in an area in terms of TET, and can also be used to guide and control the evacuee's traffic during a real-time evacuation subject to any kinds of disasters.

A hybrid evacuation model, integrating the dynamic network flow optimization approach and simulation, had been established in this study. The optimization model was used to optimize the evacuation routes, schedules, and shelters. The simulation model took the optimized strategies and provided a description about the evacuation behavior under emergency situations. The hybrid model made full use of the advantages of both simulation-based model and dynamic network flow based optimization model

7.2 Limitations and future Considerations

It was my intent to establish a spatial decision support system which integrates simulation models, visualization tools, GIS, and optimization algorithms for managing and optimization large-scale evacuation. However, in view of the time constraint for the study, the models developed have some limitations which require further works in future.

The performance of evacuation models should be studied further. This dissertation has included only a cursory examination of the models' response to changes in evacuation parameters. There is much to be learned about the model itself as well as about its behavior during real evacuations.

Additional investigation of the route selection process under emergency evacuation conditions is necessary. At present, only the optimal routes or semi-

optimal routes are selected. However, in real situations, people may not select the optimal routes. Route selection process may relate to the behavior of human beings.

The currently optimization algorithm, the quickest flow algorithm, only considers a single commodity flow. In fact, during urban evacuations many kinds of flow interact with each other, such as the pedestrian flow, traffic flow, and emergency rescue traffic and so on. Accordingly, a more complicated, multi-commodity quickest flow problem should be developed to provide more accurate results.

Current optimization algorithms assume flow-independence. In fact, the travel time and flow capacity depends a great deal on the traffic volume at each link. So a more complicated algorithm should be a flow-dependent dynamic algorithm.

In our traffic model, pre-timed signals and actuated signals are adopted at intersections. However, the operation of actuated controllers varies according to the current observed volume at an intersection. A more complicated optimization algorithm should therefore be developed in order to provide an effective optimization of traffic signals.

Mixed evacuation, which involves crowd flow and vehicle flow, should be studied further. The intersection of pedestrian traffic and vehicle traffic not only occurs at intersections but also on each section of road if there are no barriers. Furthermore, in a large scale evacuation, pedestrians will first travel to a point of assembly such as a plaza prior to being evacuated by vehicles. In the circumstance, a multi-mode evacuation model should be developed to simulate these scenarios.

Since evacuation is a dynamic process, the spread and development of hazardous constituents greatly affects the planning of evacuation. However, the current evacuation models do not consider the process of the spread and development of the constituents of the disasters. Thus, an attempt to include disaster models, such as gas dispersion models, flood dynamic models and fire dynamic models, should be explored.

Evacuation is a stochastic process, not only because human behavior is stochastic, but also the components of the network, such as throughput capacity and travel time, may be characterized by some stochastic properties. Accordingly, reliability analysis should be implemented to give a probability distribution of TET and other parameters.

Finally, a regional vulnerability map based on GIS should be developed. It should take into account the following factors: evacuation time, frequency and intensity of hazards and the affected population. This vulnerability map could be used to identify the most vulnerable regions and propose improvement measurements.

References

Aoki, Y., Osaragi, T. & Hashimoto, K. (1992) A Simulation Model of Evacuation Behavior in the Fire-Spread Urban Area Following Earthquake.Effects of Hearsay Information Process and Geographical Urban Image. *Journal of Architecture Planning Environment Engineering,* 440**,** 111-118.

Aronson., J. E. (1989) A survey of dynamic network flows. *Annals of Operations Research,* 20**,** 1-66.

Batty, M., Desyllas, J. & Duxbury, E. (2003) The discrete dynamics of small-scale spatial events: agent-based models of mobility in carnivals and street parades. *International Journal of Geographical Information Science,* 17**,** 673-697.

Ben-Akiva, M., Bierlaire, M., Koutsopoulos, H. & Mishalani, R. (1998) DynaMIT: a simulation-based system for traffic prediction. *DACCORD Short Term Forecasting Workshop.*

Bensilum, M. & Purser, D. (2002) GridFlow: an object-oriented building evacuation model combining pre-movement and movement behaviors for performance-based design. *7th International Symposium on Fire Safety Science.* Worcester Polytechnic Institute, Worcester, MA.

Benthorn, L. & Frantzich, H. (1996) Fire alarm in a public building: how do people evaluate information and choose evacuation exit? *Report LUTVDG/TVBB，3082 SE, Lund University.*

Blue, V. J. & Adler, J. L. (1998) Emergent Fundamental Pedestrian Flows from Cellular Automata Microsimulation. *Transportation Research Record,* 1644**,** 29-36.

Boyce, K., Fraser-Mitchell, J. & Shields, J. (1998) Survey Analysis and Modelling of Office Evacuation Using the CRISP Model. IN SHIELDS, T. J. (Ed.) *Human Behavior in Fire Proceedings of the First International Symposium.*

Breaux, J., Canter, D. & Sime, J. (1976) Psychological Aspects of Behavior of People in Fire Situations. *University of Surrey, Guilford, UK.*

Burghout, W. (2004) Hybrid microscopic-mesoscopic traffic simulation.

Stockholm, Sweden, Royal Institute of Technology.

Burkard, R. E., Dlaska, K. & Klinz., B. (1993) The quickest flow problem. *ZOR Methods and Models of Operations Research,* 37**,** 31--58.

Burstedde, C., Klauck, K., Schadschneider, A. & Zittartz, J. (2001) Simulation of pedestrian dynamics using a 2−dimensional cellular automaton. *cond-mat/0102397.*

Cai, X., Sha, D. & Wong, C. K. (2001) Time-Varying Minimum Cost Flow-Problems. *European Journal of Operational Research,* 131**,** 352-374.

Cappuccio, J. (2000) Pathfinder: A Computer-Based Timed Egress Simulation. *Fire Protection Engineering,* 8**,** 11-12.

Carroll, L. J., Koss, L. L. & Brumley, A. T. (2003) EvacuShip Analysis based on IMO Test Cases and other Benchmark Comparisons. IN E.R.GALEA (Ed.) *Second International Conference in Pedestrian And Evacuation Dynamics.* London.

Cetin, N., Nagel, K., Raney, B. & Voellmy, A. (2001) Large scale multi-agent transportation simulations. *Proceedings of the Computational Physics Conference 2001.* Aachen.

Chalmet, L. G., Francis, R. L. & Saunder, P. B. (1982) Network models for building evacuation. *Management Science,* 28**,** 86-105.

Chen, Y. L. & Chin, Y. H. (1990), the Quickest Path Problem. *Computers and Operations Research,* 17**,** 153-161.

Choi, W. (1987) Network flow models of building evacuation problems with flow-dependent arc capacities. University of Florida.

Choi, W., Francis, R. L., Hamacher, H. W. & S.Tufekci (1988) Modeling of Building Evacuation Problems by network flows with side constraints. *European Journal of Operational Research,* 35**,** 98-110.

Choi, W., Francis, R. L., Hamacher, H. W. & Tufecki, S. (1984) Network Models of Building Evacuation Problems with Flow Dependent Exit Capacities. *Operational Research,* 1047-1059.

Church, R. L. & Cova, T. J. (2000) Mapping evacuation risk on transportation networks using a spatial optimization model. *Transportation Research Part C,* 8**,** 321-336.

Corbin, J. (2003) Strategies to Improve Management of Travel for All Planned Special Events in a Region. *Presented at the 82nd Annual Meeting of the*

Transportation Research Board. Washington, D.C.

Cova, T. J. & Church, R. L. (1997) Modeling community evacuation vulnerability using GIS. *International Journal of Geographic Information Science,* 11**,** 763-784.

Cova, T. J. & Johnson, J. P. (2003) A network flow model for lane-based evacuation routing. *Transportation Research Part A,* 37**,** 579-604.

Cruz, F. R. B., Smith, J. M. & Medeiros, R. O. (2005) An M/G/C/C state-dependent network simulation model. *Computers & Operations Research,* 32**,** 919-941.

Cruz, F. R. B., Smith, J. M. & Queiroz, D. C. Service and Capacity Allocation in M/G/c/c State Dependent Queueing Networks. *Computers & Operations Research,* 32**,** 1545-1563.

De Silva, F. N. & Eglese, R. W. (2000) Integrating simulation modelling and GIS: Spatial decision support systems for evacuation planning. *Journal of the Operational Research Society,* 41**,** 423-430.

Di Gangi, M., Russo, F. & Vitetta, A. (2003) A Mesoscopic Method for Evacuation Simulation on Passenger Ships: Models and Algorithms. IN E.R.GALEA (Ed.) *Second International Conference in Pedestrian And Evacuation Dynamics.*

Drager, K. H., Lovas, G., Wiklund, J. & Soma, H. (1992) A Comprehensive Evacuation Simulation Tool. IN J.D.SULLIVAN (Ed.) *Proceedings 1992 International Emergency Management And Engineering Conference.* Florida.

Drager, K. H., Soma, H. & Orset, S. (2001) EVAC and LBL The Mustering and Evascuation Computer Models Resulting from the BriteEuram Project MEPdesign. IN SCHRECKENBERG, M. & SHARMA, S. D. (Eds.) *Pedestrian and Evacuation Dynamics.*

Fahy, R. F. (1991) EXIT89:An Evacuation Model for High-Rise Buildings. *Proceedings of the Third International Symposium on Fire Safety Science.*

Fahy, R. F. (1996) EXIT89: High-rise Evacuation Model -Recent Enhancements and Example Applications Interflam. *Interflam '96, International Interflam Conference 7th Proceedings.* Cambridge, England.

LO, S, Fang, Z. &. M. (2000) A Spatial-grid evacuation model for buildings.

Journal of Fire Science, 18**,** 376-394.

Farahmand, K. (1997) Application of simulation modeling to emergency population evacuation. *Proceedings of the 1997 Winter Simulation Conference.*

Ferrante, M., Napolitano, F. & Ubertini, L. (2000) Optimization of Transportation Networks During Urban Flooding. *Journal of the American Water Resources Association,* 36**,** 1115-1132.

Fleischer, L. (2001) Universally maximum flow with piecewise-constant capacities. *Networks,* 38**,** 115-125.

Ford, L. R. & Fulkerson, D. R. (1958) Constructing maximal dynamic flows from static flows. *Operations Research,* 6**,** 419- 433.

Ford, L. R. & Fulkerson, D. R. (1962) *Flows in Networks*, Princeton University Press, Princeton, NJ.

Fraser-Mitchell, J. (2001) Simulated Evacuations of an Airport Terminal Building, Using the CRISP model. *2nd International Symposium in Human Behavior in Fire.* Boston, MA.

Fu, H. Q. (2004) DEVELOPMENT OF DYNAMIC TRAVEL DEMAND MODELS FOR HURRICANE EVACUATION. *Agriculture and Mechanical College.* Louisiana State University.

Galea, E. R. & Galparsoro, J. M. P. (1994) A Computer Based Simulation Model for the Prediction of Evacuation from Mass Transport Vehicles. *Fire Safety Journal,* 22**,** 341 - 366.

Galea, E. R. & Galparsoro, J. M. P. (1994) EXODUS: An Evacuation Model for Mass Transport Vehicles. *Fire Safety Journal,* 22**,** 341-366.

Galea, E. R. & Markatos, N. C. (1991) The mathematical modelling and computer simulation of fire development in aircraft. *Int.J.Heat Mass Transfer,* 34**,** 181-197.

Gawron, C. (1998) An Iterative Algorithm to Determine the Dynamic User Equilibrium in a Traffic Simulation Model. *International Journal of Modern Physics C,* 339**,** 393-408.

Gawron, C. (1998) An iterative algorithm to determine the dynamic user equilibrium in a traffic simulation model. *International Journal of Modern Physics C,* 9**,** 393-407.

Gawron, C. (1998) Simulation-Based Traffic Assignment. der Mathematisch-

Naturwissenschaftlichen Fakultät.

Gawron, C. (1998) Simulation-Based Traffic Assignment -- Computing User Equilibria in Large Street Networks.

Gazis, D. C., Herman, R. & Rothery, R. W. (1961) Nonlinear Follow-the-Leader Models of Traffic Flow. *Op. Res,* 9**,** 545-567.

Gipps, P. G. & Marksjo, B. (1985) A Micro-Simulation Model for Pedestrian Flows. *Mathematics and Computers in Simulation,* 27**,** 95-105.

Gwynne, S. & Galea, E. R. (1999) Review of modeling methodologies used in the simulation of evacuation. *Journal of Building and the Environment,* 34**,** 441-749.

Gwynne, S., Galea, E. R., Lawrence, P. J., Owen, M. & Filippidis, L. (1999) Adaptive Decision-Making in buildingEXODUS. *Journal of Applied Fire Science,* 8**,** 265-289.

Hall, R. W. (1986) The fastest path through a network with random time dependent travel times. *Transport, Sci.,* 20**,** 181-188.

Hamacher, H. W. & Tjandra, S. (2002) Earliest Arrival Flow with Time Dependent Capacity for Solving Evacuation Problems. *Pedestrian and Evacuation Dynamcis.* Springer Verlag.

Hamacher, H. W. & Tjandra, S. (2002) Mathematical Modeling of Evacuation Problems: State of the Art. *Pedestrian and Evacuation Dynamcis*.

Hamacher, H. W. & Tjandra, S. A. (2002) Earliest arrival flow with time dependent capacity for solving evacuation Problems. IN SHARMA, S. D. (Ed.) *Pedestrian and Evacuation Dynamics.* M. Schreckenberg.

Hamacher, H. W. & Tjandra, S. A. (2002) Mathematical modeling of evacuation problems: state of the art. IN SHARMA, S. D. (Ed.) *Pedestrian and Evacuation Dynamics 2002.* Schreckenberg.

Hamacher, H. W. & Tufekci, S. (1987) On the use of lexicographic min cost flows in evacuation modeling. *Naval Research Logistics,* 34**,** 487-503.

Han, A. F. (1990) TEVACS, decision support system for evacuation planning in Taiwan. *Journal of Transportation Engineering,* 116**,** 821-830.

Helbing, D. (1992) A fluid-dynamic model for the movement of pedestrians. *Complex Systems,* 6**,** 391-415.

Helbing, D. (1997) Active walker model for the formation of human and animal trail systems. *Physical Review E,* 3**,** 2527.

Helbing, D. (2001) Traffic and related self-driven many-particle systems. *Reviews of Modern Physics,* 73**,** 1067-1141.

Helbing, D., Farkas, I. & Vicsek, T. (2000) Freezing by heating in a driven mesoscopic system. *Physical Review Letters***,** 1240-1243.

Helbing, D., Farkas, I. & Vicsek, T. (2000) Simulating dynamical features of escape panic. *Nature,* 407**,** 487-490.

Helbing, D. & Molnar, P. (1995) Social Force Model for pedestrian dynamics. *Physical Review E,* 51**,** 4282-4286.

Hendrickson, C. & Kocur, G. (1981) Schedule Delay and Departure Time Decision in a Deterministic Model. *Transporation Science,* 15.

Hobeika, A. G. & Jamei, B. (1985) MASSVAC: A model for calculating evacuation times under natural disasters. *Emergency Planning. Simulation Series,* 15**,** 23-28.

Hobeika, A. G. & Jamei, B. (1985) MASSVAC: a model for calculating evacuation times under natural disasters. *Emergency Planning, Simulations Series,* 15**,** 23-28.

Hobeika, A. G. & Kim, C. (1998) Comparison of traffic assignments in evacuation modeling. *IEEE Transactions on Engineering Management,* 45**,** 192-198.

Hobeika, A. G., Kim, C. & Beckwith, R. E. (1994) A Decision Support System For Deleloping Evacuation Plans around Power Stations. *Interfaces,* 24**,** 22-35.

Hooks, E. M. & Patterson, S., S. (2004) On solving quickest time problems in time-dependent dynamic networks. *Journal of Mathematical Modeling and Algorithms,* 39-71.

Hoppe, B. & Tardos, E. (1994) Polynomial time algorithms for some evacuation problems. *In Proc. of 5th Annual ACMSIAM Symp. on Discrete Algorithms***,** 433-441.

Huang, S. F., Wei, Y. M., Yang, C. J. & ZHang, J. T. (1998) Network Model for Victim Dispatching and Its Simulation Based on Geographic Information System. *Journal Of Natural Disasters,* 7**,** 65-70.

Hughes, R. L. (2002) A continuum theory for the flow of pedestrians. *Transportation Research Part B,* 36**,** 507-535.

Hughes, R. L. (2003) THE FLOW OF HUMAN CROWDS. *Annul. Rev. Fluid*

Mech., 35**,** 169-182.

Hurdle, V. F. (1974) The Effect of Queuing on Traffic Assignment in a Simple Road Network. *Proc. 6th Int. Symp.on Transportation and Traffic Theory.* Sydney.

Imamura, F. & Katada, T. (1999) Study of Human Damage and Evacuation Behavior in the case of heavy flood in the eastern Japan in1998. *Annual Disas. Pre.Res.Inst. Kyoto Univ.,* 42**,** 13-21.

Kawata, Y. & Koike, N. (1995) Emergency Management And Evacuation Manual for Tsunami Disaster. *Annual Disas. Pre.Res.Inst. Kyoto Univ.,* 38.

Kelley, H. H., Condry, J., Dahlke, A. E. & Hill, A. H. (1965) Collective behavior in a simulated panic situation. *Journal of Experimental Social Psychology.,* 1**,** 20-54.

Kerbache, L. & Smith, M. J. (2000) Multi-objective routing within large scale facilities using open finite queueing networks. *European Journal of Operational Research,* 121**,** 105-123.

Kerridge, J. M. & McNair, N. (1999) PEDFLOW - A System for Modeling Pedestrian Movement using occam. *Proceedings of WoTUG-22: Architectures, Languages and Techniques for Concurrent Systems.* Barry M. Cook.

Ketchell, N., Cole, S. S. & Webber, D. M. (1993) The EGRESS code for human movement and behaviour in emergency evacuation. IN SMITH, R. A. & DICKIE, J. F. (Eds.) *Engineering for Crowd Safety.* Elsevier Oxford.

Kimura, M. & Sime, J. D. (1989) Exit choice behaviour during the evacuation if two lecture theatres. *Proceedings of the Second International Symposium，Fire Safety Science.*

Kirchner, A. & Schadschneider, A. (2002) Simulation of evacuation processes using a bionics-inspired cellular automaton model for pedestrian dynamics. *Physica A,* 312**,** 260-276.

Kisko, T. M. & Francis, R. L. (1985) EVACNET+: A Computer Program to Determine Optimal Building Evacuation Plans. *Fire Safety Journal,* 9**,** 211-220.

KLD Associates, I. (1984) Formulations of the DYNEV and I-DYNEV Traffic

Simulation Models Used in ESF. *Prepared for the Federal Emergency Management Agency.*

Klinz, B. & Woeginger, G. J. (1995) Minimum cost dynamic flows: the series-parallel case. *Networks,* 43**,** 153 - 162.

Klote, J. H. (1993) Method for Calculation of Elevator Evacuation Time. *Journal of Fire Protection Engineering,* 5**,** 83-96.

Klüpfel, H. (2003) A Cellular Automaton Model for Crowd Movement and Egress Simulation. *Institut für Physik.* Universität Duisburg-Essen.

Klupfel, H. & Meyer-Konig, T. (2003) Characteristics of the PedGo Software for Crowd Movement and Egress Simulation. *2nd International Conference in Pedestrian and Evacuation Dynamics.*

Ko, S. Y. (2003) Comparison of Evacuation Times Using Simulex and EvacuatioNZ Based on Trial Evacuations. *Department of Civil Engineering.* University of Canterbury.

Kostreva, M. M. & Wiecek, M. M. (1993) Time Dependency in Multiple Objective Dynamic Programming. *Journal of Mathematical Analysis and Applications,* 173**,** 289-307.

Kostreva, M. M., Wiecek, M. M. & Getachew, T. (1991) Optimization Models in fire Egress Analysis for Residential Buildings. *Fire Safety Science Proceedings of the Third International Symposium.* London.

Lee, D., Park, J. H. & Kim, H. (2004) A study on experiment of human behavior for evacuation simulation. *Ocean Engineering,* 31**,** 931-941.

Levin, B. M. (1998) EXITT, A Simulation Model of Occupant Decisions and Actions in Residential Fires. *Proceedings of the Second International Symposium on Fire Safety Science.*

Lighthill, M. J. & Whitham, G. B. (1955.) On Kinematics Waves (Part II):A Theory of Traffic Flow on Crowded Roads. *Proceedings of the Royal Society.*

Lo, S. M. (1996) People in Fires-A study of the behavioral reaction of people in a fire incident in Hong Kong. *Fire Engineers Journal,* July.

Lo, S. M., Fang, Z., Lin, P. & Zhi, G. S. (2004) An evacuation model: the SGEM package. *Fire Safety Journal,* 39**,** 169-190.

Lovas, G. G. (1994) Modeling And Simulation Of Pedestrian Traffic Flow. *Transportation Research B,* 28**,** 429-443.

Lovas, G. G. (1995) On performance measures for evacuation systems. *European Journal of Operation Research,* 85**,** 352-367.

Lovas, G. G. (1998) Models of wayfinding in emergency evacuations. *European Journal of Operational Research,* 105**,** 371-389.

Lovas, G. G. (1998) On the Importance of Building Evacuation System Components. *IEEE Transactions on Engineering Management,* 45**,** 181-191.

Ludmann, J., Neunzig, D. & Weilkes, M. (1996) Traffc Simulation with Consideration of Driver Models. Theory and Examples. *Proceedings of the EUROMOTORSeminar on Telematics, Vehicle and Environment.* Aachen.

M.H.Poon, S.C.Wong & Tong, C. O. (2004) A dynamic schedule-based model for congested transit networks. *Transportation Research Part B,* 38**,** 343-368.

Mamada, S., Makino, K. & S.Fujishige (2003) The evacuation problem in tree dynamic networks with multiple exits. *International Symposium on Systems & Human Science For Safety, Security, and Dependability.*

Mamada, S., Makino, K., Takabatake, T. & Fujishige, S. (2004) Evacuation Problem and Dynamic Network Flows. *SICE Annual Conference.*

May, A. D. (1990) *Traffic Flow Fundamental*, Prentice Hall, New Jersey.

Meyer, J. E. (1995) Evacuation Planning in An intergated Information Environment. *Civil Engineering.*

Minieka, E. (1973) Maximal, lexicographic, and dynamic network flows. *Operations Research,* 21**,** 517-527.

Moeller, M. P., Urbanik II, T. & Desrosiers, A. E. (1981) CLEAR (Calculated Logical Evacuation and Response): A Generic Transportation Network Model for the Calculation of Evacuation Time Estimates. *Prepared for the Nuclear Regulatory Commission by Pacific Northwest Laboratory,NUREG/CR-2504.*

Muramatsu, M., Irie, T. & Nagatani, T. (1999) Jamming transition in pedestrian counter flow. *Physica A,* 267**,** 487−498.

Muramatsu, M. & Nagatani, T. (2000) Jamming transition in two-dimensional pedestrians traffic. *Physica A,* 275**,** 281-291.

Murosaki, M. & Yamada, T. (1980) Research on A Resident's Evacuation Area

Selection. *Journal of the City Planning Institute of Japan,* 15**,** 259-264.

Murosaki, Y. & koizumi, s. (1993) A study of regional evacuation plannings of urban municipalities. *Annual Disas. Pre.Res.Inst. Kyoto Univ.,* 36**,** 179-193.

Nagatani, T. (1993) Jamming transition in the traffic flow model with two level crossing. *Phys. Rev. E,* 48**,** 3290.

Nagel, K. (2001) Multi-modal traffic in TRANSIMS. *Conference on Pedestrian and Evacuation Dynamics, Proceedings of PED'01.*

Nagel, K. (2003) *Handbook on networks*.

Nagel, K. & Schreckenberg, M. (1992) A Cellular Automaton Model for Traffic Flow. *J. Physique I,* 2**,** 2221- 2229.

Nagel, K., Wolf, D. E., Wagner, P. & Simon, P. (1998) Two-lane traffic rules for cellular automata: A systematic approach. *Phys. Rev. E,* 58**,** 1425.

Okazaki, S. (1979) A Study of Pedestrian Movement in Architectural Space, Part 1: Pedestrian Movement by the Application on of Magnetic Models. *Transactions of Architectural Institute of Japan,* 283**,** 111-119.

Okazaki, S. & Matsushita, S. (1993) A study of simulation model for pedestrian movement with evacuation and queuing. *Proceeding of the International Conference on Engineering for Crowd Safety.*

Orda, A., Rem, R. & Sidi, M. (1993) Minimum Delay Routing in Stochastic Networks. *lEEFJACM TRANSACTIONS ON NETWORKING,* 1.

Orda, A. & Rom., R. (1990) Shortest-Path and Minimum-Delay Algorithms in Networks with Time-Dependent Edge Length. *Journal of the ACM,* 37**,** 607-625.

Ozel, F. (1985) A Stochastic Computer Simulation of the Behavior of People in Fires: An Environmental Cognitive Approach. *Proceedings of the International Conference on Building Use and Safety Technology.*

Pas, E. & Principio, S. L. (1997) Braess's Paradox: Some New Insights. *Transpn Res.-B,* 31**,** 265-276.

Perry RW, L. M., Greene MR (1981) Evacuation Planning in Emergency Management. *Lexington Books, Massachusetts, Toronto*.

Petruccelli, U. (2003) Urban evacuation in seismic emergency conditions. *ITE Journal,* 73**,** 34-38.

Pidd, M., De Silva, F., N. & Eglese, R. (1996) A simulation model for

emergency evacuation. *European Journal of Operational Research,* 90**,** 413-419.

Pidd, M., Eglese, R. & de Silva, F. N. (1997) CEMPS: a prototype spatial decision support system to aid in planning emergency evacuations. *Transactions in GIS,* 1**,** 321-334.

Poon, L. S. & Beck, V. R. (1994) Evacsim: Simulation Model Of Occupants With Behavioural Attributes In Emergency Evacuation Of High Rise Buildings. IN KASHIWAGI, T. L. (Ed.) *Proceedings Of Fourth International Symposium On Fire Safety Science.*

Poon, M. H., Wong, S. C. & Tong, C. O. (2004) A dynamic schedule-based model for congested transit networks. *Transportation Research Part B,* 38**,** 343-368.

Post, B., Schuh & Jernigan, Inc. (2000) Hurricane Floyd Assessment: Review of Hurricane Evacuation Studies Utilization and Information Dissemination. Tallahassee, Florida.

Post, B., Schuh & Jernigan, Inc. (2000) Southwest Louisiana Hurricane Evacuation Study: Transportation Model Support Document. Tallahassee, Florida.

Pradillon, J. Y. (2003) ODIGO: A Crowd Movement Simulation Tool for Passenger Vessels. *Conference Proceedings, COMPIT'03, 2nd International EuroConference on Computer and IT Applications in the Maritime Industries.* Hamburg.

Proulx, G. (1993) A Stress Model for People Facing a Fire. *Journal of Environmental Psychology,* 13**,** 137-147.

Quarantelli, E. L. (1984) Evacuation Behavior and Problems: Findings and Implications from the Research Literature. *DRC Final Project Report, 27.* Disaster Research Center University of Delaware.

Quarantelli, E. L., Hutchinson, D. C. & Phillips, B. D. (1983) Evacuation Behavior:case study of the TAFT, Louisiana Chemical tank explosion incident. *Disaster research center Miscellaneous Report#34.*

Radwan, A., Hobeika, A. & Sivasailam, D. (1985) A Computer Simulation Model for Rural Network Evacuation Under Natural Disasters. *ITE Journal***,** 25-30.

Ran, B. & Boyce, D. E. (1996.) *Modeling Dynamic Transportation Networks.*,

Springer, 2 edition.

Reisser-Weston, E. (1996) Simulating Human Behaviour in Emergency Situations. *International Conference Of Escape, Fire And Rescue.*

Rhodes, N. & Hoffman, N. A. (1997) Virtual reality and visualisation tools to assess evacuation times from trains and stations. *Escape From Trains.* Heathrow, UK, Independent Technical Conferences Ltd.

Rickert, M. (1997) Traffic Simulation on Distributed Memory Computers. *Mathematisches Institut.* Universität zu Köln.

Rickert, M., Nagel, K., Schreckenberg, M. & Latour, A. (2004) Two Lane Traffic Simulations using Cellular Automata. *LANL Report No. LA-UR 95-4367.*

Sattayhatewa, P. & Ran, B. (2000) DEVELOPING A DYNAMIC TRAFFIC MANAGEMENT MODEL FOR NUCLEAR POWER PLANT EVACUATION. *Transportation Research Board Annual Meeting.*

Schneider, V. (2001) Application of the Individual-Based Evacuation Model ASERI in Designing Safety Concepts. *2nd International Symposium on Human Behavior in Fire, Boston.*

Schneider, V. & Konnecke, R. (2001) Simulating Evacuation Processes with ASERI. *International Conference on Pedestrian Evacuation Dynamics.* Duisburg.

Sekizawa, A., Ebihara, M., Notake, H., Kubota, K., Nakano, M., Ohmiya, Y. & Kaneko, H. (1999) Occupants: Behaviour in Response to the High-rise Apartments Fire in Hiroshima City. *Fire and Materials,* 23**,** 297-303.

Sekizawa, A., Nakahama, S., Notake, H., Ebihara, M. & Ikehata, Y. (2003) Study on Feasibility of Evacuation using Elevators in a High-rise Building -- Is Use of Elevator in Evacuation Really Effective for General People? *ASME International.*

Sheffi, Y., Mahmassani, H. & Powell, W. B. (1982) A transportation network evacuation model. *Transportation Research,* 16A**,** 209-218.

SHERALI, H. D., CARTER, T. B. & HOBEIKA, A. G. (1991) A location-allocation model and algorithm for evacuation planning under hurricane/flood conditions. *Transportation Research B,* 25**,** 439-452.

Shestopal, V. O. & Grubits, S. J. (1994) Evacuation Model for Merging Traffic Flows in Multi-Room and Multi-Story Buildings. *Fire Safety Science* -

Proceedings of the 4th International Symposium.

Shin, M. S., Ran, B., Oh, R. S. & Choi, K. (1998) DEVELOPING AN EVALUATION TOOL FOR A REAL TIME DTA SYSTEM. *1999 Transportation Research Board Annual Meeting.*

Sime, J. D. (1992) Human behavior in fires: Summary report, BUSRU. *Fire and Emergency Planning Department.* London.

Sime, J. D. (1994) Escape behavior in fires and evacuations. IN STALLORD, P. & JOHNSTON, L. E. (Eds.) *Design Against Fire: An Introduction to Fire Safety Engineering Design.* London.

Simon, P. M. & Nagel, K. (1999.) Simple queuing model applied to the city of Portland. *International Journal of Modern Physics C,* 10**,** 941-960.

Sinuany Stern, Z. & Stern, E. (1993) Simulating the evacuation of a small city: the effects of traffic factors. *Socio-Economic Planning Sciences,* 27**,** 97-108.

Smith, M. J. (1991) State-Dependent Queueing Models in Emergency Evacuation Networks. *Transportation Research Part B,* 25**,** 373-389.

Southworth, F. (1991) Regional evacuation modeling: a state-of-the-art review. *Oak Ridge National Laboratory ORNL-11740, Tennessee.*

Stern, E. & Sinuany-Stern, Z. (1989) A behavioral-based simulation model for urban evacuation. *Papers of the Regional Science Association,* 66**,** 87-103.

Still, G. K. (2000) *Department of Mathematics.* University of Warwick.

Tajima, Y. & Nagatani, T. (2001) Scaling behavior of crowd flows outside of hall. *Physica A,* 292**,** 545-554.

Tajima, Y., Takimoto, K. & Nagatani, T. (2001) Scaling of pedestrian channel flow with a bottleneck. *Physica A,* 294**,** 257-268.

Takahashi, K., Tanaka, T. & Kose, S. (1988) An Evacuation Model for Use in Fire Safety Designing of Buildings. *Fire Safety Science, Proceedings of the 2nd International Symposium.*

TAKAHASHI, T. & NAKAGAWA, H. (1990) ASSESSMENT OF EVACUATION SYSTEMS FOR WATER OR MUD FLOODS: A COMBINED SIMULATION OF FLOODING AND THE ACTION OF RESIDENTS. *Journal of Natural Disaster,* 12.

Takahashi, T., Nakagawa, H. & Higashiyama, M. (1989) Assesment of

Evacuation System Based on the Simulation of Inundation and Action of Residents. *Annual Disas. Pre.Res.Inst. Kyoto Univ.,* 32**,** 757-780.

Takeda, M., Inove, K., Toda, K.-i. & Kawaike, K. The Study of the Hazard Map for Storm Surges and the Evacuation System. *Annual Disas. Pre.Res.Inst. Kyoto Univ.,* 40**,** 445-460.

Takimoto, K. & Nagatani, T. (2003) Spatio-temporal distribution of escape time in evacuation process. *Physica A,* 320**,** 611-621.

Talebi, K. & Smith, M. J. (1985) Stochastic network evacuation models. *Compuf. Ops Res.,* 12**,** 559-577.

Talebi, K. & Smith., M. J. (1985) Stochastic network evacuation models. *Compuf. Ops Res.,* 12**,** 559-577.

Tanaboriboon, Y., Hwa, S. S. & Chor, C. H. (1986) Pedestrian Characteristics study in Singapore. *ASCE Journal of Transportation Engineering,* 112**,** 229-235.

Thompson, P. A. & Marchant, E. W. (1993) Molding Techniques for Evacuation. *Engineering for Crow safety.*

Thompson, P. A. & Marchant, E. W. (1995) Computer Model for the evacuation of large building populations. *Fire Safety Journal,* 24**,** 131-148.

Thompson, P. A. & Marchant, E. W. (1995) A Computer Model the Evacuation of Large Building Populations. *Fire Safety Journal,* 24.

Thompson, P. A. & Marchant, E. W. (1995) Testing and Application of the Computer Model 'SIMULEX'. *Fire Safety Journal,* 24**,** 149-166.

TOSHISUKE, H. (1983) Development of a Network Flow Simulator (NESSY-IV) for Analyses of Mass Evacuation in Case of Emergency. *Journal of Information Processing,* 6**,** 001.

Tufekci, S. & Kisko, T. M. (1991) Regional evacuation Modeling System (REMS): A Decision Support System for Emergency Area Evacuations. *Computers Industrial Engineering,* 21**,** 89-93.

Tweedie, S., Rowland, J., Walsh, S. & Rhoten, R. (1986) A Methodology for Estimating Emergency Evacuation Times. *The Social Science Journal,* 23**,** 189-204.

Urbanik II, T., M.P.Moeller & K.Barnes (1988) Benchmark Study of the I-DYNEV Evacuation Time Estiamte Computer Code. *NUREG/CR-4873.* Pacific Northwest Laboratory.

Vassalos, D., Kim, H., Christiansen, G. & Majumder, J. (2001) A Mesoscopic Model for Passenger Evacuation in a Virtual Ship-Sea Environment and Performance-Based Evaluation Pedestrian and Evacuation Dynamics. IN SCHRECKENBERG, M. & SHARMA, S. D. (Eds.).

Whiteheada, J. C. (2000) Hurricane Evacuation Behavior: A Preliminary Comparison of Bonnie, Dennis, and Floyd. Department of Sociology, East Carolina University.

Whiteheada, J. C., Edwardsb, B., Willigenb, M. V., Maiolob, J. R., Wilsonb, K. & Smith, K. T. (2000) Heading for higher ground: factors affecting real and hypothetical hurricane evacuation behavior. *Environmental Hazards,* 2**,** 133-142.

Wilkinson, W. L. (1971) An algorithm for universal maximal dynamic flows in a network. *Operations Research,* 19**,** 1602-1612.

Wohl, M. (1970) A Methodology for Forecasting Peak and Off-peak Travel Volumes. *Highway Res. Rec.,* 322**,** 183-219.

Wolfram, S. (1986) *Theory and Applicnrions of Cellular Automata*, Singapore: World Scientific.

Wood, P. G. (1990) *A survey of behaviour in fires,* Fulton, London.

Yamada, T. (1996) A network flow approach to a city emergency evacuation planning. *International Journal of Systems Science,* 27**,** 931-936.

Zhi, G. S., Lo, S. M. & Fang, Z. (2003) A graph-based algorithm for extracting regions and loops from architectural floor plans for a building evacuation model. *Comput-Aided Des,* 1-14.