Evaluation of Emergency Evacuation Strategies in case of a Chemical Disaster for an Urban Area using a Traffic Simulation Model

Evaluation of Emergency Evacuation Strategies in case of a Chemical Disaster for an Urban Area using a Traffic Simulation Model

A thesis submitted to the Department of Civil Engineering
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Abstract

Due to the increase of both man made and natural disasters and the expansion of human activity to vulnerable areas, emergency evacuation seems to be more important than ever. It is still one of the few feasible strategies that can be undertaken in response to these type of disasters. This is also reflected into the large amount of research and knowledge already existing regarding this subject. However, the point of interest originally aimed at preventive or short-notice evacuations due to for example natural disasters. Recently, especially due to the higher risk for man made disasters, the point of interest is moving toward the no-notice evacuations.
This research is part of the PACER Project from the Urban Chemical Disaster Simulation Federation. Goal of this project is to develop a fully integrated emergency evacuation model to develop solution for the protection of critical infrastructure in the USA. Points of interest of this research are the way in which traffic simulation software can contribute to a better understanding of emergency evacuation and the development of evacuation strategies.

The microscopic traffic simulator AIMSUN was used to study the effect of different evacuation strategies for the evacuation of the Central Business District in Baltimore City (Maryland, USA) in case of a chemical disaster. Unfortunately it was not possible to calibrate the final dynamic simulation model used, because evacuation field date was not available. However, the results give a sufficient impression of the effects of the different strategies.

This report discusses the results of the different evacuation strategy simulations, which showed that the Management strategy, in which traffic is distributed over the available exits regarding their capacity and the shortest route, is the most effective one. The Management strategy results in a total evacuation time for the area of 5.08 hours. The staged evacuation strategy, in which the area is evacuated in different phases, showed very promising results, however it was less effective than the management strategy. Measures of Effectiveness are total evacuation time, total travel time and lost vehicles.
Subsequently the Management strategy without an implemented signal control plan for the entire area showed very promising results with a total evacuation time of only 3 hours.
Finally, additional simulations showed the positive effect of a limited number of network zonal entrance points and available routes. These simulations showed the desired traffic pattern: no crossing but only converging and some diverging traffic flows. Although the total travel time and the number of lost vehicles are decreased tremendously, the total evacuation time increases. However, this increase is caused by a limited number of delayed/congested zones.

It is recommended to implement more detail and calibrate the developed model to increase it’s validity. Also a sensitivity analyses regarding the behavior characteristics should be carried out.
Furthermore, development of the PACER model should not only focus on the traditional uncertainties like human behavior, traffic demand, response, accidents, etc. Especially in an no-notice emergency evacuation recourses like personnel, equipment and communication facilities will be very limited and there will be no time to wait for them. Integrating these aspects into the model will finally lead to better and more useful evacuation strategies.
Finally, an additional developed problem approach based on new insights gathered during this research is recommended. Regarding this approach we are not looking for a strategy resulting in the fastest route from A to B, but for the one resulting in a trip from A to B using the shortest travel time through threatened area.

Acknowledgements

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1 Introduction

Due to the increase of both man made and natural disasters and the expansion of human activity to vulnerable areas, emergency evacuation seems to be more important than ever. It is still one of the few feasible strategies that can be undertaken in response to these type of disasters. This is also reflected into the large amount of research and knowledge already existing regarding this subject. However, the point of interest originally aimed at preventive or short-notice evacuations due to for example natural disasters. Recently, especially due to the higher risk for man made disasters, the point of interest is moving toward the no-notice evacuations. Despite the high technological evolution nowadays, fully integrated emergency evacuation models are still not available. These models nowadays available are used for both pre-planning or real time operations.
This research is part of the PACER Project from the Urban Chemical Disaster Simulation Federation. Goal of this project is to develop a fully integrated emergency evacuation model to develop solution for the protection of critical infrastructure. The FAU was assigned to gather insight into the way in which traffic simulation software can contribute to a better understanding of emergency evacuation and the development of evacuation strategies, which is this research's point of interest.

In this chapter the background, principle and location of the research problem will be discussed, finally resulting in the formulation of the research objective and related questions in section 1.1. Section 1.2 describes the different steps that are followed to accomplish the required result and quality. The chosen research strategy, which will be followed during the research, is of great influence on the executed research. An explanation for the chosen strategy is given in section 1.2.1. Finally, in section 1.3 the outline of the thesis is given.

1.1 Problem Domain

1.1.1 Background

Disasters due to natural phenomena as extreme weather conditions (hurricanes, heavy rainfall, wildfires caused by drought), springtide and geological phenomena (earthquakes, volcanism, tsunami), but also human activities such as industrial accidents, failure of hydraulic structures, accidents with the transportation of hazardous goods and possible politically motivated attacks have the potential to cause great loss of life and extreme property damage. Especially when human activities expand to vulnerable areas. Emergency evacuation is often the most feasible strategy that can be undertaken in response to these types of disasters.
The evacuation process is one of the key elements for a successful and effective evacuation plan. During the occurrence of crisis, people, in general, are panic and lose composure. They compete for the egress routes without considering others. Therefore, the roadway network may not be efficiently utilized. Thus, a well-established evacuation plan can play a major role in controlling and maximizing the network utilization.
In the United States emergency evacuation research is highly advanced. Especially due to various emergency evacuations as a result of the yearly attacks of several areas by hurricanes. Also The Nuclear Regulatory Commission (NRC) requires since 1975 that all electric utilities develop and update evacuation plans for the areas surrounding their nuclear power plants. Planning, management and operation of hurricane evacuation plans was traditionally nearly exclusively executed by emergency management officials. Since hurricane Floyd in 1999, which precipitated in some of the largest evacuations in the history of the United States and perhaps its largest traffic jams, the level of coordination between en involvement of agencies,

including transportation agencies at the federal, state and local levels, is increased. One of the most notable of these groups are Departments of Transportation (DOTs).
Since the involvement of transportation professionals in evacuation, it is not surprising that the level of understanding of evacuation issues and terminology in the transportation community is somewhat limited. However there is still a lot of work to do. Wolshon (2001, 2005) executed several surveys to hurricane evacuation in the United States and the central issue confronting transportation engineers and planning practice as related to hurricane evacuation and emergency management in general is: 'trying to maintain a balance between the needs of evacuation and the enormous need for limited transportation resources for routine conditions'.

1.1.2 Principal Agency

Department of Homeland Security (DHS) is one of the main principals within this research. After 9/11 the topic of Emergency Evacuation is becoming more and more important in the Transportation Sector. Central to the department's mission is supporting effective critical infrastructure security investments. The 'FY08 Budget' requests funding for initiatives to support strengthening national chemical plant security, protecting high risk rail shipments, and cultivating partnerships with industry owners and operators.

Critical Issues DHS: How to Evacuate Downtown Traffic for an "Unexpected" Emergency Event (DHS, 2007).

FY 08 Budget Priorities: Protecting Critical Infrastructure (DHS,2007). On of the major priority focuses is the interior of the United States, so protecting the infrastructure and systems that keeps the nation and her economy running smoothly from an attack inside the United States. The federal government does not own most of the nation's critical infrastructure like the dams, the bridges, the transportation systems, the electrical and the nuclear facilities. The DHS needs to work in partnership with the private sector and with state and local government to evaluate vulnerabilities in these systems, increase protection, and build resiliency in the event of an attack or disruption.
From a total budget of $106 million, $30 million is spend for the 'Securing the Cities Implementation' initiative. Activities include the development of regional strategies, analyses of critical road networks, mass transit, maritime, and rail vulnerabilities (DHS, 2007).
Another important player is the earlier mentioned PACER Project. The FAU was assigned for this project to:

- Gather insight into the way in which Traffic Simulation Software Models can contribute to a better understanding of Emergency Evacuation Scenario's and development of Emergency Evacuation Strategies;
- Development of Emergency Evacuation Strategies in case of an evacuation by undertaking a case study to the city of Baltimore, FL.

1.1.3 Case Study Area

The research, determined by the DHS, is an economic important and vulnerable area alongside the railroad in the centre of Baltimore City in the state of Maryland.

Baltimore
Baltimore is a metropolitan city on the east cost located in the state of Maryland in the United States of America, see Figure 1. The city is situated alongside the Patapsco river at the Chesapeake Bay, see Figure 2.

Figure 1: Map of USA highlighting Maryland (University of Texas Libraries, 2007)

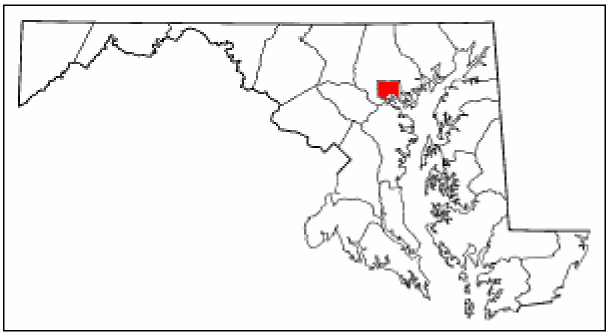

Figure 2: Map of Maryland highlighting Baltimore (University of Texas Libraries, 2007)

As of 2005, the population of Baltimore City was 641,943 and the Baltimore-Towson metropolitan area (MSA) had approximately 2.6 million residents. Baltimore is also part of the even bigger Baltimore-Washington Metropolitan Area (CMSA) of approximately 8.1 million residents. Baltimore is the largest city in Maryland and the fourth largest city on the East Coast, after New York City, Philadelphia and Jacksonville; its metropolitan area is the 19th largest in the country.
The city is a major U.S. seaport, situated closer to major Midwestern markets than any other major seaport on the East Coast. Baltimore is also an increasing modern service economy. Although deindustrialization took its toll on the city, costing residents many low-skill, high-wage jobs, the city is a growing financial, business, and health service base for the southern Mid-Atlantic region (Baltimore, 2007).

Vulnerable Area
Figure 3 and Figure 4 illustrates the mail road infrastructure for Baltimore County and Baltimore City respectively. The research area (blue shaded in Figure 4; also known as Regional Planning District (RPD) 118 or Central Business District (CBD)) has two major entrances/exits. The first one is U.S. Highway 83 (I83) which starts in the north-east part of the area and goes up to the north. The second one is U.S. Highway 395 (I395) which starts in the south-west corner and connect to U.S. Highway 95 (I95) down to the south of the area.

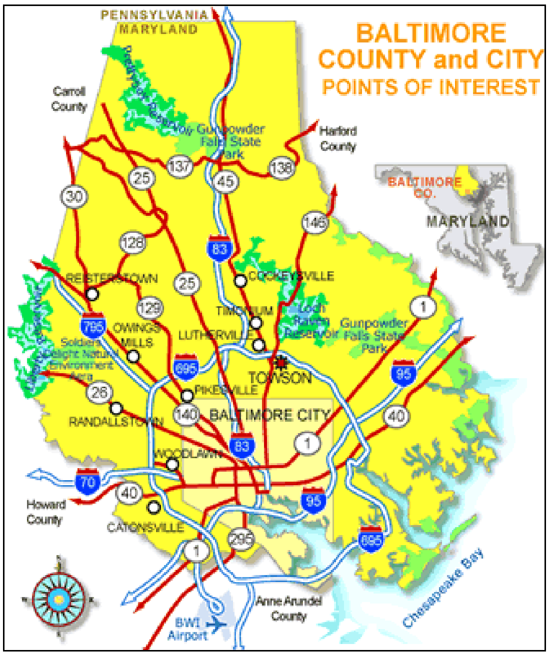

Figure 3: Baltimore County main road infrastructure (BMC, 2007)

Figure 4: Baltimore City main road infrastructure with blue shaded case study area (BMC, 2007)

The land use in Baltimore City is illustrated by Figure 5, which concludes that the research area (red shaded) mostly consist of commercial and a little bit urban area. Land to the south of the research area is mostly used for industry/harbor (gray hatched) and the disaster is located on the rail road (straight black lines) through this area to the south west of the research area.
Figure 6 illustrates the original research area ‘box’ with a approximate size of 2.3 km by 2.3 km, so 5.29 square km (1.43 miles by 1.43 miles, 2.05 square miles). The finally chosen research area is shaded by the red line.

Figure 5: Land use Baltimore City with red outlined case study area and disaster location (BMC, 2007)

Emergency Situation

The emergency situation considered in the present context is a chemical explosion on the railroad in the south-west area of Baltimore City, close to the defined area, during a south-west wind. The railroad transports freight to and from the harbor, which is generally located in the south-east part of the city.

Due to this explosion the south exit of the area, the I395 and further on the I95, will be out of order. This means that only the main exits at the north will be available for an evacuation, certainly causes large traffic problems.

As with a nuclear accident or a hurricane, a chemical explosion and the related evacuation is a very complex situation. This complexity is caused because time, location, accident characteristics and weather conditions are not exactly known. In other words, there is hardly clarity regarding the total threat and the area to evacuate. Because reasonable predictions regarding time, location and strength of a hurricane can be made hours before the actual appearance, hurricane evacuation is called ‘notice’ evacuation. Evacuations due to chemical of nuclear accident are ‘no-notice’ evacuation, which means time is very limited to determine the total threat and evacuation area.

Figure 6: Map of the case study area (red delineation) in Baltimore City (Google Maps, 2007)

1.1.4 Research Objective

Based on the background, nature of the problem and the case study area described, the research objective for the thesis can be formally stated as follows:

> *Determine the most suitable evacuation strategy for the Baltimore City Center in case of a chemical accident on the railroad.*

However, the stated research objective is still not useful for further research. Before continuing, a definition for 'the most suitable evacuation strategy' needs to be determined.
In most of the emergency evacuation research, the most suitable evacuation strategy is described as the strategy which enables the shortest evacuation time of the total population, or a defined percentage, in the evacuation area. Often minimization of the total amount of

kilometers traveled is also demanded, because this increases the accident risks which cause a considerable increase in travel time.
In case of a chemical or nuclear emergency it is not only a manner of minimizing the exposure time. It is an offset between exposure concentration, number of people and time. Due to differences of interests this will cause various scenario's. If for example minimization of the total amount of casualties (death people) is most important, goal is to reach at least an equal exposure time for the total population to evacuate, below a time that causes death or lasting trauma. This can cause however a lot of wounded people. On the other hand, if minimization of the number of wounded people is more important, minimizing the total evacuation time would be an important goal. This can cause however a lot of death people, for who the exposure time was to long.
Finally, emergency evacuation can be characterized as an efficiency problem: maximize the positive effect for all of the evacuees with the limited recourses available. Regarding this and the above mentioned, the following definition for 'the most suitable evacuation strategy' is chosen: 'the evacuation strategy which minimizes the number of people with physical damage'.

The research objective will be rewritten as follows:

Determine the most suitable evacuation strategy for the Baltimore City Center in case of a chemical accident on the railroad, which minimizes the number of people with physical damage.

1.1.5 Research Question

The above stated research objective lead to the following research question:

What is the most suitable evacuation strategy for the Baltimore City Center in case of a chemical accident on the railroad, which minimizes the number of people with physical damage?

This research question can be divided into the following sub research questions:

1. What is the state-of-the-art of emergency evacuation traffic modeling and simulation?

2. Which evacuation strategies for the Baltimore City Center in case of a chemical accident on the railroad can be developed?

3. What are the appropriate indices that support the simulation of the defined evacuation strategies?

4. What are the criteria to determine the most effective evacuation strategy that minimizes the number of people with physical damage?

5. Which evacuation strategies for the Baltimore City Center in case of a chemical accident on the railroad is the most effective?

1.1.6 Scope

Initially the research will be restricted to the defined network, question 1. up to and including 5., due to the maximum available time and feasibility. The research objectives and questions are strongly related to the case study area. However, the used modeling approach can be used for research to the evacuation of any city or system. This also means that generalization of the final results can answer the same questions and objectives for any system or city with approximately the same characteristics as the case study area.

1.2 Research Methodology

1.2.1 Research strategy

According to Verschuren (2005) a research strategy is a group of related decisions about the way of carrying out research. In other words it is the strategy how to acquire and process data to answer the research questions. The chosen research strategy depends on three key decisions.

1. Profound or broad?
   To determine the optimal evacuation routes and develop alternatives for optimizations, both a broad and profound research is necessary. The broad research will gather insight into the subject of emergency evacuation and related traffic simulation software models. Profound research on the other hand is necessary to gather insight into the problem area.
   To generalize the determined evacuation routes and developed optimizations, also both a broad and profound research is required.

2. Quantify or qualify?
   The undertaken research will have both a qualitative and quantitative character. Main target of the research is to determine emergency evacuation routes and develop alternatives for optimization of these routes. In general this will be undertaken in a qualitative way, with a traffic simulation software model.
   The generalization of determined evacuation routes and developed optimizations on the other hand, will be undertaken in a quantitative and interpreting way.

3. Empiric or non-empiric?
   Determination of evacuation routes and the implementation of optimization alternatives will be accomplished by a case study, which means the research has a empiric character.

After these decisions are made, a research strategy can be chosen. According to Verschuren (2005) there are five main strategies:

- Survey;
- Experiment;
- Case study;
- Theoretical founded approach;
- Desk research.

To answer the research questions a desk research in combination with a case study is the most appropriate.

1.3 Outline of the Thesis

After discussing the research problem in chapter 1, the literature review in the next chapter will give an overview of the existing knowledge related to emergency evacuation in general and emergency evacuation traffic simulation and modeling more specific.
Chapter 3 starts with the discussion of a global procedure for design of an evacuation plan. After determination of the objective function for the Baltimore case study, the evacuation process is explained. Finally, the possible evacuation strategies for the case study area will be explained.
In chapter 4 the developed modeling approach will be discussed, followed by the setup of the simulation model in chapter 5.
The simulation results will be shown and analysed in chapter 6 and the final conclusions and recommendations are given in chapter 7.

2 Literature Review

In section 1.1.1 there is already given a short introduction into emergency evacuation and its related characteristics. The amount of undertaken emergency evacuation research, especially in the traffic management sector in the USA, is almost unlimited. The approach of this research has different perspectives. The first groups points of interest are the development and improvement of traffic modeling and simulation, to better predict emergency evacuation scenario's. The second group is mainly using these developed simulation models to develop and improve emergency evacuation plans. The final group is doing research from a more planning and management point of view.
This chapter shows the result of the executed literature review. First the emergency evacuation process will be explained in section 2.1. Next in section 2.2 the actual knowledge about emergency evacuation in relationship with traffic management will be discussed. Finally, in section 2.3 the development of traffic simulation and modeling for emergency evacuation will be discussed.

2.1 The Emergency Evacuation Process

2.1.1 Definitions

Before describing the process of emergency evacuation it is important to gain accordance within the different definitions.

Emergency
According to DHS (2004) the Stafford Act defines an emergency as "any occasion or instance for which, in the determination of the President, Federal assistance is needed to supplement State and local efforts and capabilities to save lives and to protect property and public health and safety, or to lessen or avert the threat of a catastrophe in any part of the United States". Simplified, an emergency is "a situation that poses an immediate threat to human life or serious damage to property".

Evacuation
DHS (2004) defines an evacuation as "an organized, phased, and supervised withdrawal, dispersal, or removal of civilians from dangerous or potentially dangerous areas, and their reception and care in safe areas".

Emergency Evacuation
Regarding the above-mentioned definitions, emergency evacuation can be defined as "an organized, phased, and supervised withdrawal, dispersal, or removal of civilians from areas effected by a situation that poses an immediate threat to human life or serious damage to property, and their reception and care in safe areas".

Emergency Management
According to Hwang (1986) emergency management can be described as "the total set of measures that minimize the damages and losses from natural or man-made disasters".

Evacuation Plan
An evacuation plan can be described as "the set of measures to fully control withdrawal, dispersal, or removal of civilians from areas effected by a situation that poses an immediate threat to human life or serious damage to property, and their reception and care in safe areas".

From a traffic management point of view this can be translated as "the set of measures to fully control departure times, destinations and routes of civilians from areas effected by a situation that poses an immediate threat to human life or serious damage to property".

The Emergency Evacuation Problem
The general emergency evacuation problem is well described by Wolshon (2005) (stated earlier in a different context): 'trying to maintain a balance between the needs of evacuation and the enormous need for limited transportation resources for routine conditions'.

2.1.2 The Timeline of Evacuation

The four steps of emergency management proposed by Hwang (1986) are mitigation, preparedness, response, and recovery. Evacuation is one of the most crucial elements of preparedness and response.
The process for an evacuation can be outlined in a timeline, illustrated in Figure 7. This timeline is suitable for a preventive evacuation, in case of for example a hurricane or flood. The decision to start an evacuation is made in advance of the emergency, based on the estimation of time and place of the emergency and the time necessary for preventive evacuation. The decision makers need to find a balance between an early decision (when the organization of an evacuation is not yet critical, but an evacuation could be redundant) and a late decision (when the organization of an evacuation is critical and casualties could happen).

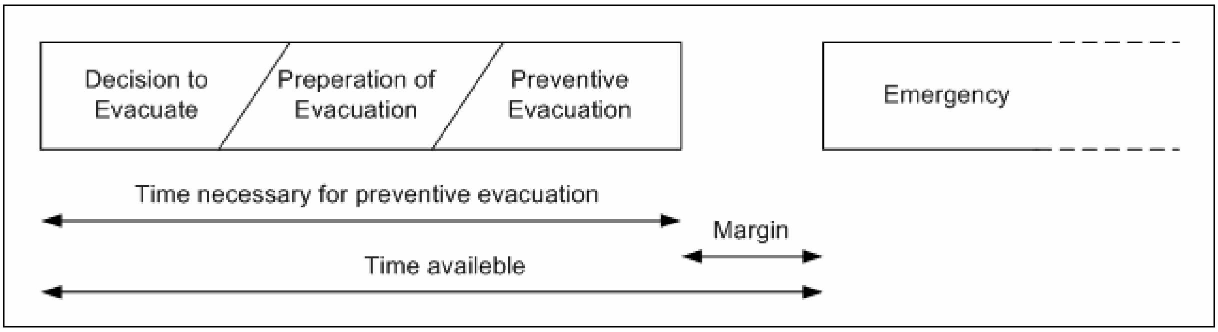

Figure 7: Timeline of a preventive evacuation (Zuilekom, 2007)

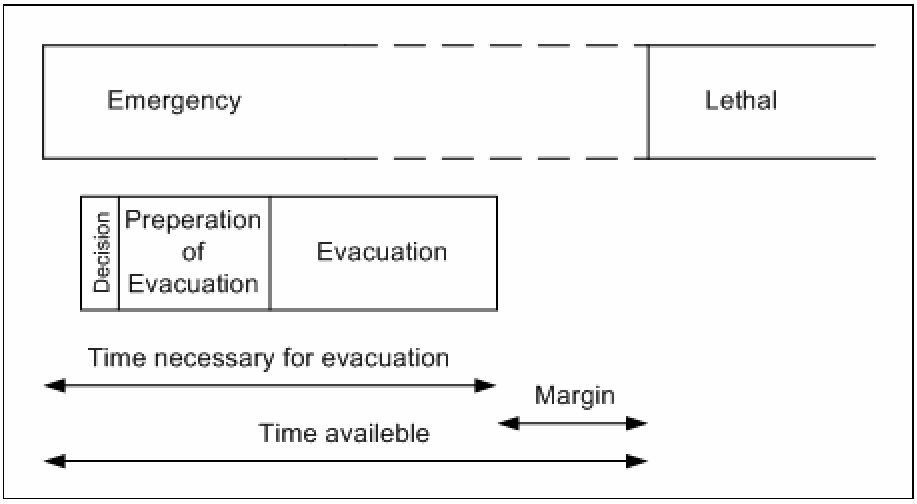

Figure 8: Timeline of an unexpected evacuation

In case of an unexpected chemical or nuclear disaster, the emergency and the decision to start the related evacuation almost take place at the same moment. In Figure 8 the timeline of the evacuation process in case of an unexpected disaster is illustrated.
The total time available for the evacuation depends on the total time necessary for the evacuation and the time span between the occurrence of the emergency and the moment of a deadly exposure.

2.1.3 The Decision to Evacuate

According to DHS (2004) the first line of responsive action to emergency conditions is the responsibility of local and State authorities. In most instances, evacuation operations are ordered on the local level in coordination with state officials. For evacuations that necessitate crossing State boarders, participating State agencies are responsible for coordinating evacuation operations. If deemed necessary, Local and State Departments of Transportation (DOTs) may institute contraflow operations in coordination with highway patrol or state police (FHWA, 2007).
The Federal government assists in evacuation operations when the resources of local and State authorities are overwhelmed. When the necessity arises, the DOTs enacts Emergency Support Function #1 (ESF-1). ESF-1 is designed to provide transportation support to assist emergency management (FHWA, 2007). According to the DHS (2004), ESF-1 does the following under emergency evacuation conditions:

- Provides technical assistance to Federal, State, local, and tribal government entities in evacuation or movement restriction planning, and determining the most viable transportation networks to, from, and within the incident area, as well as alternative means to move people and goods within the area affected by the incident;
- Coordinates and implements, as required, emergency-related response and recovery functions performed under DOT statutory authorities, including the prioritization and/or allocation of civil transportation capacity, to include safety- and security-related actions concerning movement restrictions, closures, quarantines, and evacuations;
- Coordinates the provision of Federal and private transportation services to support State and local governments;
- Provides staffing and liaisons for ESF-1 functions in headquarters, region, and local emergency facilities;
- Manages financial aspects of emergency transportation services.

2.1.4 Evacuation seen by the Evacuee

The different evacuation stages as seen by the evacuee are illustrated in Figure 9. According to Lindell (2005) the efficiency of an evacuation depends largely on the response of the evacuating public. Response to emergency conditions is dependent upon several factors. The manner in which these factors are considered and addressed has a direct effect upon travel demand, thus impacting the characteristics of evacuation operations. The following factors influence public response to emergency situations:

- Personal perception of risk
- Previous experience in emergency situations;
- Information source and type;
- Local authority action;
- Household location and structural characteristics;

- Gender and age;
- Presence of children or disability in the household;
- Emergency-specific threats;
- Time of day;
- Provision of evacuation transportation assistance;
- Development and dissemination of traffic management plans.

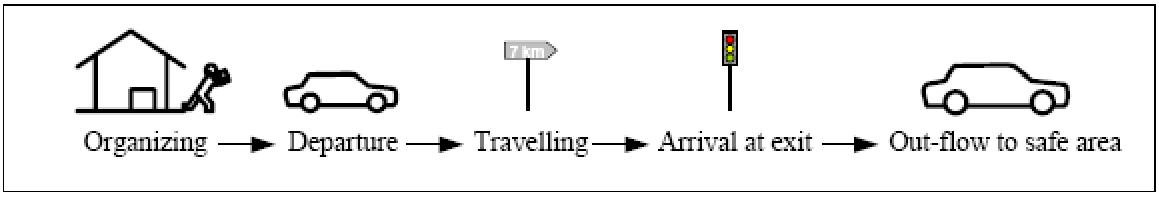

Figure 9: Evacuation stages seen by the evacuee (Zuilekom, 2007)

According to Moriarty (2006) personal perception of risk and emergency-specific threats are difficult to model accurately. Each incident possesses unique characteristics and prompts a wide variety of human response. Human response also varies from person to person. Emergency management planners have yet to understand the response of the public to emergency conditions, as their actions are not predictable. Human response is largely based on previous experience in emergency situations. Based on this prior experience, decisions are made whether or not to act. Once a decision has been made to evacuate, the time required to actually do so depends on preparation time. Evacuation preparation time is defined as "the time needed to prepare to leave from work, travel from work to home, gather all persons who would need to evacuate, pack items needed while gone, protect property from storm damage, shut off utilities, secure the home, and reach the main evacuation route (Lindell, 2005)." For example, during hurricane Opal in October 1995 in the USA, people left their homes about three hours later than the slowest estimate as illustrated in Figure 10.
According to Murray (2002) as a result of this preparation people moving toward the danger in stead of away from it. Not capturing this pattern in evacuation models, leads to longer-than-expected evacuation times.

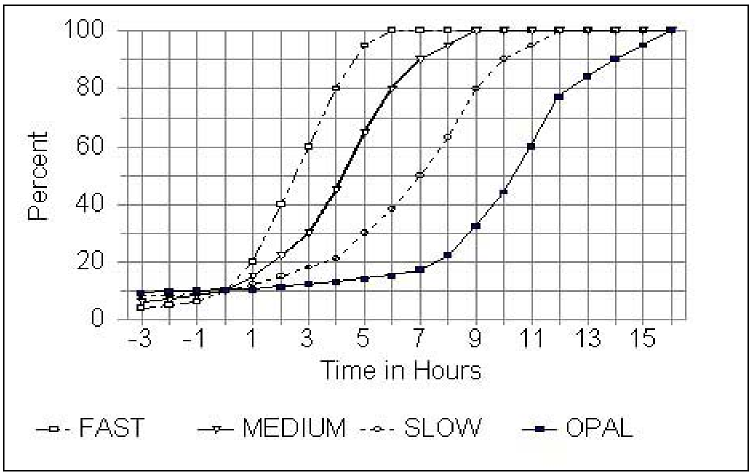

Figure 10: Alabama hurricane evacuation response rates. Estimates (fast, medium and slow) and actual response rate during hurricane Opal (Alabama, 2007)

In case of a preventive evacuation, there is no immediate threat available of visible. It is assumed that traffic behavior is normal. The usual assumptions for modeling traffic behavior are applicable. During the occurrence of crisis, people, in general, are panic and lose composure. They compete for the egress routes without considering others. In the latter situation the usual behavioral assumptions no longer suffice. In that case driver behavioral characteristics in panic conditions akin to those formulated in Hamdar (2005) should be adopted in the modeling (Zuilekom, 2007).

2.1.5 The General Process

Figure 11 illustrates the general evacuation process according to Liu (2005), which indicates that after a disaster has occurred or is predicted, the responsible agency will determine the start time of the evacuation process. This start time will directly determine the spatial distribution of all related activities right before evacuation and also affect the dispersion of evacuation order.

As mentioned earlier, most evacuees tend to meet their family and start evacuation as a single unit when necessary. Thus, practitioners have to identify these intermediate destinations for family reunion, which may greatly affect the network traffic pattern.

Based on estimated evacuation demand and target destinations, one can project the actual network traffic conditions in the evacuation process. The estimation approach should consider the available network capacity, various control strategies, and the response of evacuees under different information penetration levels.

Another two issues might also require proper consideration in this process. The first is the routing of emergency response teams, if necessary. This issue is critical as an efficient arrival of these responsive teams might limit the expansion of the zone in danger, but the network capacity they require may restrict the control strategies for evacuation traffic. The second issue is about real-time operations, which basically involve a feedback process of obtaining actual network traffic conditions with traffic surveillance systems and adjusting control strategies in a timely manner.

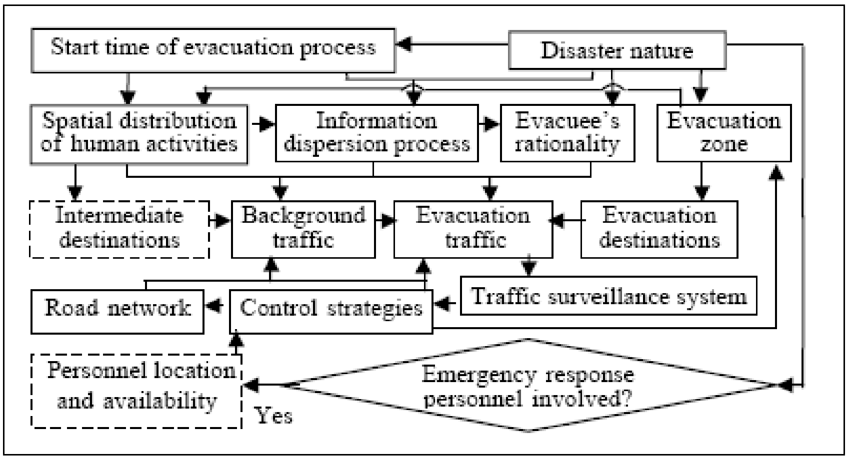

Figure 11: General evacuation process (Liu, 2005)

Note that Figure 11 presents some critical evacuation components, which have not been adequately addressed in the literature. Those include efficient design of control strategies, reliable estimate of network traffic, modeling information dispersion process, projecting the response of evacuees, and properly handling emergency response traffic.

2.2 Actual Knowledge and Results

2.2.1 Hurricane Evacuation

An important researcher in the field of hurricane evacuation is Brian Wolshon from the LSU Hurricane Centre and he has undertaken several 'reviews of policies and practices for hurricane evacuation' in the United States. These reviews, Wolshon (2001, 2005) determine what the latest policies and strategies are regarding evacuation plans, how they differ from one location to another, and try to increase the level of knowledge and awareness of these new evacuation practices. Key issues and problems identified by the reviews are:

- Limited involvement from and awareness within the professional transportation community in the field of evacuation;
- Limited interagency coordination for regional and cross-state evacuations;
- Limited consistency between states in the both the authority structure and planning/design processes for hurricane evacuation;
- Limited planning (at the DOT level) for the evacuation of low-mobility groups;
- Less than adequate use of the available transportation infrastructure during evacuations;
- A need to better coordinate construction work zone activities on hurricane evacuation routes;
- Obvious need for education and greater exchange of information;
- A need for standards and best practices for evacuation plans, which also allow room for flexibility;
- A need for reliable and u-to-date weather and traffic information;
- Many newly developed plans and policies are not put into actual practice.

Schwartz (2006) and Durham (2006) have also evaluated recent hurricane evacuations. Most of the issues and problems identified by these reviews are compared to the results of Wolshon (2001, 2005). However, they discovered also:

- Overuse of single occupied cars is one of the major causes of failure;
- Evacuation plan and criteria are too general and lax in nature and will do little to address and overcome the many unexpected happenings around an emergency event;
- Disadvantages of Flow: hinders movement of emergency vehicles and supplies, intensive use of law enforcement and other personnel and hinders evacuation of special needs population;
- Bad incident management;
- Lack of consideration from human behavior.

2.2.2 Developed Evacuation Efficiency Measures

According to Yuan (2006), routes exiting an evacuation area are often limited in number and insufficient in capacity to handle the unusual surge in demand due to concurrent evacuation activities. In most cases, constructing new routes and increasing roadway capacity are simply too cost-prohibitive to be considered. Therefore, it is essential to improve or optimize the planning and operational aspects of the evacuation process in order to best utilize the existing transportation network and available roadway capacity.

In general, evacuation efficiency can be improved by optimizing the destination and route assignments in the network over the evacuation time-horizon, or by reducing the delay on individual evacuation routes through effective traffic control. Existing evacuation research has been approached from different perspectives, including staged departure time, contra flow

operation, real-time signal control and coordination, and special routing consideration for heavy vehicles.
Most important is to adopt the alternatives in a well established evacuation plan with a high compliance rate.

Contra Flow
A very popular emergency evacuation measure is the 'contra flow' operation, also known as 'lane reversal'. According to Tagliaferri (2005) implementation of lane reversal, if transitioning is situated at a major signalized intersection, leads to a significant increase in throughput and decrease in queue.
However, there are also some negative side effects. According to Tagliaferri (2005) it leads to congestion on crossing streets. As stated earlier, contra flow hinders movement of emergency vehicles, supplies and evacuation of special needs population, and intensive use of law enforcement and other personnel is required. According to Wolshon (2005) contra flow is not, however, a magic solution. It has many inherent difficulties and poses challenges to both supervising agencies and evacuating drivers. It requires close cooperation between numerous agencies across political boundaries and jurisdictions both within and between participating states, something that has not been effectively accomplished in the past

Road Closure
According to Kwon (2005) closing arterial streets to downtown can be as effective as closing freeways or contra flow operations.

Routing
Route traffic over predetermined routes for a more efficient usage of the available infrastructure during evacuation. This can be accomplished in a passive or active way, for example with a predetermined routing plan or traffic lights respectively.
The integration of real-time data into evacuation models can contribute positively to route traffic more efficient over these predetermined routes.

Signal Timing
According to Chen (2005) signal control can greatly impact traffic flow in an evacuation. The undertaken research studied approaches for signal timing to facilitate evacuation and response in the event of a no-notice urban evacuation. Simulation results indicated that significant trade-offs exist in setting timing plans as long cycle lengths can lead to reduced evacuation times, but at the expense of delay on minor roadways. Best compromise plans employ cycle lengths greater in length than used in ordinary peak hour plans, giving significantly more green time to the main evacuation routes than to minor roadways as used in peak hour plans.

Staged Evacuation
Chen (2006) investigated the effectiveness of simultaneous and staged evacuation strategies using agent-based simulation. In the simultaneous strategy, all residents are informed to evacuate simultaneously, whereas in the staged evacuation strategy, residents in different zones are organized to evacuate in an order based on different sequences of the zones within the affected area. This study uses an agent-based technique to model traffic flows at the level of individual vehicles and investigates the collective behaviors of evacuating vehicles. They conducted microscopic simulations on three types of road network structures under different population densities. The three types of road network structures include a grid road structure, a ring road structure, and a real road structure from the City of San Marcos, Texas. Default rules were used for trip generation, destination choice, and route choice. Simulation results

indicate that: (1) there is no evacuation strategy that can be considered as the best strategy across different road network structures, and the performance of the strategies depends on both road network structure and population density; (2) if the population density in the affected area is high and the underlying road network structure is a grid structure, then a staged evacuation strategy that alternates non-adjacent zones in the affected area is effective in reducing the overall evacuation time.

Speed Limits
According to Pal (2002) the least traffic congestion during a hurricane evacuation occurred when speeds were limited to 60 mph on interstates and 40 mph on other roads.

2.3 Emergency Evacuation Simulation and Modeling

2.3.1 Introduction

As stated earlier in this chapter the approach of emergency evacuation research has different perspectives. In this part of the research the development and improvement of traffic modeling and simulation, regarding evacuation, will be discussed.
The common used term ‘traffic simulation models’ is confusing one, because a distinction can be made between ‘simulation software’ and ‘simulation modeling’. The first, ‘simulation software’, is the software package that is used for the simulation. Those packages are commercial or non-commercial and sometimes specially developed for emergency evacuation purpose. ‘Simulation modeling’, on the other hand, is the method of approach of the problem, resulting in specific ‘simulation models’. Those models are generally used in combination with simulation software, most often as an improvement, that’s why ‘simulation software’ and ‘simulation models’ have a strong inter-relationship. The combination of a developed ‘modeling approaches’ and ‘simulation software packages’, can be summarized as a ‘traffic simulation models’.
Due to the reoccurrence of catastrophic events, by nature or man-made, numerous simulation models and software packages have been developed to assist in the design, operation, management and evaluation of emergency evacuation plans and policies. Biggest advantage of traffic simulations is their ability to provide a low-cost, low-risk environment to test various assumptions and alternatives and to see their effects immediately. As mentioned the current risks for natural and man-made disasters have recently resulted in several papers on evacuation modeling, which will be discussed below.

2.3.2 Traditional Traffic Model

According to Chang (2003) the emergency evacuation models that have been developed are largely based on the conventional trip-based, four-step, traffic demand model, see Figure 12.
Below the different steps of the Model will be discussed. The knowledge used is mainly derived from Immers (1998).

1. *Trip Generation*
   Trip generation is the number of person-trips to and from each Traffic Analysis Zone (TAZ), also known as trip-ends. These can be calculated with production and attraction models, often based on a regression analyses method. For more accurate models, it is important to make a distinction between the trip motive. Regarding this motive, trips can be characterized as forced (for example work, education or evacuation) or optional (for example leisure).

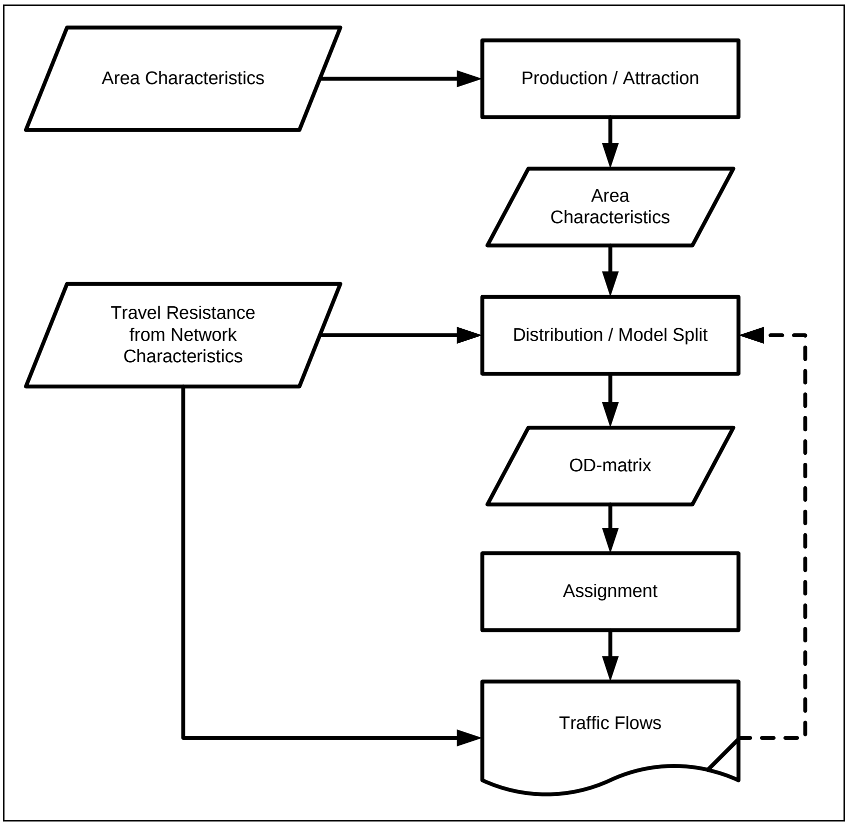

Figure 12: Traditional traffic model (Immers, 1998)

Factors of influence for the production of a zone are:

- social-economical (family) characteristics like income, composition and car ownership;
- demographical characteristics like land use, land price and level of urbanization;
- accessibility.

Factors of influence for the production of a zone are:

- employment;
- demographical characteristics like industry, education, retail surface, balance of goods and services and recreation;
- accessibility.

Unfortunately, most of the models used to determine production and attraction don't take the last factor, accessibility, into account. This is an important short coming of these models, because in this case changes in the transportation system will not have an effect on production or attraction. This is off course not true compare to reality.
Summarized, demographical characteristics are important factor in determining production. On the other hand, employment and land use characteristics are important factors in determining attraction.
For home-based trips the zone in which the house is located is responsible for the production and the activity zone is responsible for attraction. During evening rush-hour however traffic flows are going the opposite direction, but the above-mentioned definition of production and attraction will be maintained.

2. *Trip Distribution*
   Goal of trip distribution is to distribute trips from a specific origin over all the available destinations and distribute trips to a specific destination over all the origins, which results in a complete Origin Destination matrix (OD-matrix). The 'basic trip distribution problem' can be defined as: there are more unknowns than equations, the system is indefinite. In other words, the number of solutions that answer to the given boundary conditions is infinite.

   The OD-matrix can be determined in numerous ways, but they all rely on the principle of 'travel resistance', which can be defined as: a OD relation with a low resistance will attracts more traffic than one with a high resistance.

   As stated earlier, the OD-matrix can be determined in numerous ways, which can be divided into two main groups:
   - Growth Rate Model (GRM);
   - Synthetic Model (SM).

   The GRM is using a basis OD-matrix, based on historical data. Together with additional OD data a new OD-matrix will be defined. This process will finally result in a growth rate.
   The SM is using a friction function, which is describing the effect of the travel resistance on the distribution of the trips. Travel resistance is expressed in time and is made up of travel distance and travel time. Generally, travel distance is expressed in costs and therefore a cost-time function is necessary to convert it. An emergency evacuation is a deadly situation and because of that evacuees will not worry about the travel distance related costs.
   According to several researchers, among others Cova (2003), intersections in urban areas are mainly responsible for traffic delay. To reduce traffic delay as much as possible, crossing traffic flows needs to be avoided, which can be accomplished by distributing the trips regarding the shortest path. The shortest path is in this case the route with the shortest travel time. Only converging and some diverging traffic flows will appear.

3. *Model Split*
   Model split can be described as the classification of trips in terms of different traffic modes. Usually, travelers can choose the preferred mode for a trip to make. Factors influencing this decision are: the availability of the mode and several rational considerations of the decision-maker. Those considerations are related to the characteristics of the traveler, the traffic mode and the trip. Travelers who are not able to choose, for example if a place is only accessibly by car, are called captives.
   Traffic mode choice can be implemented in the trip distribution process, which will produce several traffic mode based OD-matrices.

4. *Trip Assignment*
   Assignment models finally assigns the trips to the various routes in the network. In fact route choice is very important in these models. It is obvious that travelers will choose the shortest-path to a specific destination. That is why algorithms for defining the networks shortest-path are the main element in assignment models.
   Traffic demand, represented as the trips in the OD-matrix, is varying in time. Also the network characteristics, among other things as a function of this traffic demand, are varying in time. Assignment models can be distinguished in their ability to handle these

time aspects. In general Dynamic Assignment Models (DTA) do and Static Assignment Models (STA) do not.
The oldest and most simplest STA models assume constant traffic demand and network characteristics, what is off course not true compare to reality. In the past various STA models are developed, which are to a certain extend able to handle time aspects, in an attempt to produce more realistic results.
The last decade however, DTA models are popular to estimate time-varying network conditions by capturing traffic flow and route choice behavior. DTA models are obvious superior, since they relax more assumptions and capture more realities than the static approach.

5. *Feedback*
   Traffic modeling must be seen as an highly iterative process, indicated by the dotted feedback-loop in Figure 12.

2.3.3 Emergency Evacuation Modeling

Application
According to Chang (2003) emergency evacuation models serving three main purposes: pre-planning analysis, real-time operation, and post-planning procedure.
Pre-planning analysis is the most common application of evacuation modeling for emergency purposes. The information provided is used to identify evacuation routes that minimize total evacuation time. The same information is also used to develop strategies to disseminate information to the endangered population regarding evacuation procedures.
Real-time simulation models can be continuously updated by employing a series of automated road detection systems. From this data, situation reports can be developed for each evacuation route. This information can then be dispersed to evacuees, guiding them to alternatives for faster evacuations.
Post-planning procedure uses the model output to evaluate evacuation operations. Output based on extensive historical data is most effective in this application of model use. The results can later be used as a reference to improve evacuation operations for a given area or to modify the model for future emergency planning.
According to Chang (2003) most of the models are mainly used for pre-planning and post-planning rather than real-time operations. The main reasons include the limited data for inputting, few trained staff, minimum calibration and limited field application to data.

Approach
According to Zuilekom (2006) processes like evacuation can be modeled by adopting a 'What if' or a 'How to' approach as discussed by Russo (2004). See Figure 13 for the 'global procedure for the design of an evacuation plan'.
In a 'What if' approach, a scenario is modeled and the results are analyzed. The situation is then iteratively adjusted until no further improvements seems possible. The final result is interpreted and translated into an evacuation plan. The final result depends on the interpretation and adjustments of the modeler. The quality of the result is, by lack of a formal objective function, unclear. It is possible to use detailed and complex models in this approach. The modeler will focus on those aspects of the model that are important for the problem.
On the contrary, in a 'How to' approach, the result is determined by the objective function, the constraints and structure of the model. An optimal solution cannot be guaranteed in all cases (due to local optima for example). The objective function, constraints and solution

techniques may limit the complexity of the model. Moreover, the focus on an objective function can overshadow other difficult quantifiable objectives.

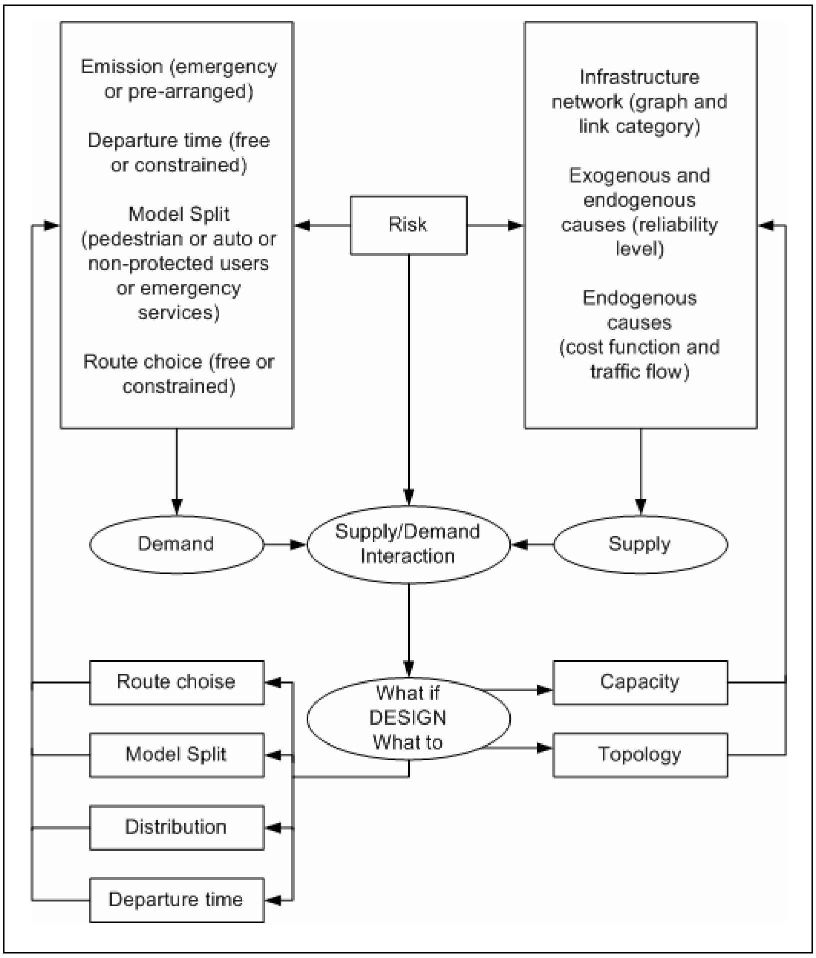

Figure 13: Global procedure for the design of an evacuation plan (Russo, 2004)

As stated by Zuilekom (2006) each modeling approach has it specific qualities. A distinction can be made between the type of distribution, the modeling environment, assignment and routing as the key elements in classification of the approaches.

- *Distribution*
  An important issue for the authorities is to what extend people can or should be directed to the several exits. Conflicts can arise between the preferred exits of the evacuees and the feasibility of the destination to accommodate these evacuees. At the same time there are limitations for the authorities to direct the evacuees.

- *Modeling environment*
  The scale of the area, the required level of detailing and accuracy will determine the modeling environment (microscopic/macroscopic, static/dynamic). Macroscopic dynamic models combine the advantages of microscopic dynamic models (using the dynamic interference of cars) with the ease of macroscopic static models (limited data need and relative fast computation).

- *Assignment*
  The nature of an evacuation makes a dynamic handling of time the preferred one. Dynamic assignment gives the best insight into the process and the best estimate of the

evacuation time. However, in the process of designing an evacuation plan there is a need to investigate a series of scenarios. In that case static assignment will give enough insight to select the most relevant scenarios for further, in-depth (dynamic) analysis.

- *Routing*
  Routing will be an important issue in an evacuation plan. The main concern is to avoid unnecessary disturbances and at the same time to best use the capabilities of the network. Here the challenge is to use the limited resources of the authorities and the autonomy of individual drivers' best.

Modeling Environment
Traffic models can be conducted on macroscopic and microscopic level. According to Tagliaferri (2005) microscopic simulation models more rigorously analyze a network by tracking individual vehicle trajectories stochastically with varying random number seeds, resulting in greater detail and performance measures aggregated over the entire sample of drivers and vehicles. Macroscopic models analyze platoons of uniform vehicles throughout a network, mostly using the cell transmission model by Daganzo (1993), which could be advantageous in oversaturated conditions.

Traffic Assignment: Static or Dynamic
Existing models are limited to take individual human behavior into account. This causes limitation to real-world applications and to overcome this, most actual research is executed into the topic of trip assignment. According to Ziliaskopoulos (2001) the various developed traffic assignment models for emergency evacuation modeling can be divided into two groups: Static Traffic Assignment Models (STA) and Dynamic Traffic Assignment Models (DTA).

The traffic assignment models are usually based on Wardrop's (1952) principles:

- User Equilibrium (UE) principle (closer to reality):
  At equilibrium, for each OD pair the paths that are used have equal travel cost (travel time) and the remaining paths have higher travel cost. This principle represents more realistically the travel behavior of travelers.
- System Optimal (SO) principle (not realistic):
  The total travel cost of the network is minimized. This principle assumes that travelers will obey some higher authority and follow paths such as to minimize the total network wide cost. This assignment is usually used as a guideline as what could be achieved if travelers were assigned optimally. Under this assignment some travelers of the same OD pair may experience lower costs and some will experience higher cost.

The STA models utilizes analytical travel cost functions to produce estimates of the travel time on each link of the network. The most traditional travel cost function used is the one developed by the Bureau of Public Roads (1960), which monotonically increases with the total flow, will produce a unique equilibrium solution. It is now well recognized that these travel time functions violate the basic principles of traffic flow theory: traffic volume reaches capacity and then declines in an unstable form within the over saturation region.
Furthermore, in STA models travelers are assumed to follow the same routes regardless of any changes in signal timing or link capacity. We know that this is not true, as travelers, once they learn of these changes in a few days or weeks they will change their paths until they

realize they can no-longer do better. This is the substantial difference between using DTA model versus a simply a traditional STA model.
DTA models are used to estimate time-varying network conditions by capturing traffic flow and route choice behavior. DTA models are typically classified into four broad methodological groups: mathematical programming, optimal control, variational inequality, and simulation-based. In general, simulation-based DTA models iterate between a traffic simulation module, a time-dependent shortest path module, and a network-loading module.
According to Ziliaskopoulos (2001) the use of DTA models should not be discouraged due to their inability to reach unique solutions but it should be looked upon as a positive step in modeling more realistic traffic conditions. In conclusion, DTA models are obvious superior, since they relax more assumptions and capture more realities than the static approach.
Because of this there is currently a heightened interest for DTA models. However, one of the aspects that fosters unanimity among researchers is that the general DTA problem is inherently characterized by ill-behaved system properties that are imposed by the need to adequately represent traffic realism and human behavior. This is further exacerbated by time-dependency and randomness in system inputs. A fundamental consequence of this reality is that a theoretical guarantee of properties such as existence, uniqueness, and stability can be tenable only through compromising and depicting traffic theoretical phenomena and potentially restrictive assumptions on driver behavior. Viewed from the complementary perspective, an ability to adequately capture traffic dynamics and driver behavioral tendencies precludes the guarantee of the standard mathematical properties. This inherent complexity of DTA has spawned a clear dichotomy of approaches that range from the analytical to the simulation-based. A short and incomplete discussion of these approached is given below.

Network flow optimization models, particularly the so-called ‘system optimal traffic assignment models’, have recently been applied to generate initial evacuation plans for emergency response. These optimization-based models are generally believed to be more capable of finding a good scheme among numerous alternatives than the earlier ‘evaluate-then-pick’ tools (e.g., OREMS, IMDAS, NETSIM), in which a limited number of evacuation plans are evaluated and compared. Hobeika (1985) proposed an evacuation planning model based on the static system optimal traffic assignment. To capture the dynamic features of network flows, Sattayhatewa (1999) formulated a system optimal dynamic traffic assignment (SO-DTA) model using the optimal-control theory. Liu (2006) encapsulated a similar SO-DTA model into an adaptive control framework for emergency evacuation. Chui (2005) generated the best possible evacuation scheme by the SO-DTA module of Dynasmart-P. Sbayti (2006) adopted a bi-level evacuation planning framework in which the combination of desired departure times, routes, and destination choices are produced by the SO-DTA module of Dynasmart-P. Recently, Ziliaskopoulos’s (2000) cell-based SO-DTA model has been applied by a number of authors to solve the emergency evacuation problem. This model is built on the well-embraced ‘Cell Transmission Model’ (CTM) (Daganzo, 1993) to represent traffic dynamics, and has an appealing simple Linear Programming (LP) structure. Ziliaskopoulos (2004) extended his work by introducing a reversibility ratio to yield the optimal evacuation contraflow. A heuristic solution algorithm using the tabu-search was proposed in a subsequent paper (Ziliaskopoulos, 2006). Lui (2005) conducted a case study by employing a simplified cell-based SO-DTA model. In their next paper (2006), binary variables are introduced to the model to optimize staging orders. Chiu (2005) proposed to reduce the multiple-destination SO-DTA into a single-destination one by using a “super-zone”. Shen (2006) proposed a dynamic network simplex method for solving the simplified SO-DTA model which represents traffic flow propagation by a point-queue model. Making full use of the networks structure, the algorithm is able to identify an optimal solution without holding, which is much easier and less costly to implement in emergence response.

Emergency Evacuation Models

The last decades there are developed numerous Traffic Simulation Models. Some of them are developed especially for Emergency Evacuation Modeling (or another specific topic), while others are developed for Traffic Modeling in general. However, both sorts of models are used for Emergency Evacuation Modeling.

Initially, efforts were made to develop evacuation traffic models on a macroscopic scale. In 1985, Hobeika developed the macroscopic MASSVAC 3.0 model to simulate the evacuation of a nuclear disaster. This model was enhanced in 1998 with the addition of the user-equilibrium (UE) assignment algorithm. This algorithm was not truly a dynamic assignment but was a major step in O-D mapping (Hobeika, 1985). NETVACI, also developed in the 1980s was one of the earliest evacuation planning tools which can simulate the evacuation process based on mathematical relationships between flows, speeds, densities, queue lengths, and other important traffic parameters (Sheffi, 1982).

In an effort to better analyze evacuation systems, further work was performed to investigate evacuation traffic patterns on a microscopic scale. The Oak Ridge Evacuation Modeling System (OREMS), developed by the Oak Ridge National Laboratory (ORNL), utilized the traffic modeling capabilities of the microscopic simulation model CORridor SIMulation (CORSIM) in conjunction with unique evacuation-related performance measures (such as clearance times) in order to analyze traffic flow in a defense-related emergency (Wolshon, 2001). Microscopic simulation models are preferred in this type of analysis due to their ability to model individual driver behaviors.

Widely-existing traffic simulation software models have been employed for evacuation planning: CORSIM (Liu, 2006 and Tagliaferri, 2006 and Chen, 2005), Paramics (Chen 2006), Dynasmart-P (Kwon, 2005 and Yuan, 2006 and Murray, 2006), Omnitrans (Zuilekom, 2006) and VISSIM (Yuan, 2006 and Tagliaferri, 2006); however, in many cases, extensive modifications were required. Jones (2004) compared three micro-simulation software products (SimTraffic (version 5.0), CORSIM (version 4.32), and AIMSUN (version 4.2)) based on system requirements, ease of coding, data requirements, reliability of output, and versatility. They concluded that each package had strengths and weakness in terms of its suitability for various applications.

According to Alsnih (2004), who performed a canvas of the state of the art in emergency evacuation modeling in order to determine the capability of existing models to accurately depict the deficiencies of a highway network in an evacuation scenario, current modeling procedures “do not incorporate all aspects of evacuation behavioral analyses, and some of the models used do not contain a dynamic traffic assignment, a critical feature that will more accurately depict evacuee behavior on the transport network”. In addition, “to develop microscopic simulation models that incorporate dynamic traffic assignment, more accurate relationships expressing human travel behavior are needed. To date, no microscopic simulation model is able to incorporate a dynamic traffic assignment while also adapting to the emergency-evacuation scenario”.

Human Behavior and Accident Management

According to Santos (2004) it is useful to think of evacuation behavior during emergencies, as having three distinct analytical dimensions:

- The physical location of the evacuation (the environment and its configuration from which to evacuate, as well as the configuration of the hazard);

- The existing management of the location (the managerial policies, procedures, and controls deployed at evacuation);
- The social psychological and social organizational characteristics impacting the response of persons and collectivities that participate in the evacuation.

It is much more common in the literature to find consideration of the first two dimensions than of the third, despite the fact that real advances in understanding of emergency evacuations will depend on their holistic integration.

According to Chang (2003) use of Traffic Simulation Models is intended to assist emergency management officials in decision-making as well as help the evacuating population obtain important information regarding evacuation operations. Many simulation packages exist to model so-called “normal” traffic conditions, but more and more emergency evacuation models have been developed yet. The existing emergency evacuation models provides a means to estimate evacuation times, develop traffic management and control strategies, and identify evacuation routes. According to Moriarty (2006) these models develop the ways and means to move an endangered public in the most effective manner possible. Unfortunately their not able to accurately represent human behavior in response to emergency conditions, and to account for occurrence of traffic accidents or impediments along evacuation routes. According to Moriarty (2006) it is recommended that future research be conducted for evacuation modeling purposes, focusing on accurately characterizing human behavior under emergency conditions.
Also the occurrence of accidents or other traffic obstructions deserve future consideration in evacuation modeling. According to Moriarty (2006) accidents under normal traffic conditions are cause for significant delays in traffic flow. Accidents or traffic impediments under emergency conditions, however, can be much more of a serious obstruction.
Firstly, evacuees are already experiencing psychological stress to get out of danger as quickly as possible. An accident on an evacuation route would further prolong evacuation time and cause for increased tensions in human behavior.
Secondly, emergency rescue personnel must be able to respond to the scene. The mass traffic volume existing on the highway already restricts the ability to do so.
Lastly, the new conditions need to be handled appropriately by emergency managers. In order to keep the evacuation moving in a safe and efficient manner, alternative plans need to quickly be developed based on the altered operational characteristics of the highway.

According to Liu (2006) evacuation planning gives hardly good predictions of future evacuation scenarios due to the highly dynamic and uncertain features involved in such extreme events. According to Chang (2003) one of the solutions to develop more useful evacuation models, is to explore potential investments into real-time data integration capabilities. Also larger databases, through modifying and uniform standard, can contribute in a positive way.

2.4 Conclusions

An Emergency Evacuation can be defined as “an organized, phased, and supervised withdrawal, dispersal, or removal of civilians from areas effected by a situation that poses an immediate threat to human life or serious damage to property, and their reception and care in safe areas”.
In an attempt to manage Emergency Evacuation in a successful way, Evacuation Plans are developed. An Evacuation Plan can be described as “the set of measures to fully control withdrawal, dispersal, or removal of civilians from areas effected by a situation that poses an

immediate threat to human life or serious damage to property, and their reception and care in safe areas". From a traffic management point of view this can be translated as "the set of measures to fully control departure times, destinations and routes of civilians from areas effected by a situation that poses an immediate threat to human life or serious damage to property".
In general there is still need for well established evacuation plans that will be fulfilled by all the participants. Nowadays most of the developed evacuation plans are lacking and to solve this problem, full cooperation between the various participants or their representatives is necessary.

More specifically, since the involvement of transportation professionals in evacuation, the level of understanding of evacuation issues and terminology in the transportation community is somewhat limited. However, the various number of emergency evacuation simulation models developed, to better predict emergency evacuation scenario's, are still a stereotype reflection of reality. They do not incorporate all aspects of evacuation behavioral analyses, and some of the models used do not contain a dynamic traffic assignment, a critical feature that will more accurately depict evacuee behavior on the transport network. In addition, to develop microscopic simulation models that incorporate dynamic traffic assignment, more accurate relationships expressing human travel behavior are needed. To date, no microscopic simulation model is able to incorporate a dynamic traffic assignment while also adapting to the emergency evacuation scenario. Summarized, there is still need for emergency evacuation models that are able to accurately represent human behavior in response to emergency conditions, and accidents or traffic impediments under emergency conditions. One of the most important and promising solutions for this problem at the moment is the integration of real-time date into evacuation models.

3 Evacuation Strategies

Before starting with the case study it is very important to develop different evacuation scenario's to research. The almost most important part of an evacuation strategy is the 'objective function', because this will greatly influence the research results and their usefulness. The development of evacuation strategy has a strong inter-relationship with the development of a modeling approach.
In case of an emergency evacuation there are many uncertainties: like the number of people in the area during the threat of a disaster, the number vehicles involved; the time of departure, the state of the network at the time of evacuation, and the route choice. Therefore it is not functional to focus on a maximum level of model accuracy. It may be appropriate to use a model with limited complexity, but high flexibility.
As stated earlier in the literature review, the numerous developed modeling approaches have their specific qualities. A distinction can be made between the **type of distribution, the modeling environment, assignment and routing** as the key elements in classification of the approaches. Distribution and routing are strongly related to the chosen evacuation control strategy.
The procedure for design of an evacuation plan, see Figure 13 in section 2.3.3, which is developed by Russo (2004) will be used as a basis for the development of different evacuation strategies and/or modeling approaches.

In section 3.1 the procedure for design of an evacuation plan will be discussed. Which will be followed by the description of the total evacuation process for the research area and this chapter will be concluded with the description of the different evacuation strategies in section 3.3. The discussed evacuation process and the developed strategies are strongly related to the case study area. However, some aspects are very general and therefore applicable for more areas or systems.

3.1 Procedure for the Design of an Evacuation Plan

Evacuation traffic is a result of the interaction between evacuation traffic demand and supply. An occurred risk (emergency) can 'influence' the demand, supply and also their interaction in many different ways. Some of these 'influences' are unchangeable, but others are.
An evacuation plan (evacuation strategy) tries to change those changeable influences with a set of measures to fully control departure times, destinations and routes of evacuees. Main goals is to reach the desired evacuation situation, which will be defined as an objective function.
According to the procedure developed by Russo (2004) strategies to control the evacuation traffic demand are route choice, model split, distribution and departure time. On the other hand the evacuation supply can be controlled by changing the network capacity and topology. Those will change the infrastructure network graph and link category, reliability level and cost function. Various evacuation strategies can be developed by adopting different control strategies.
An important requirement for the development of an evacuation strategy is that the strategy itself is feasible in case of a pending disaster, particularly in terms of people and resources. Several approaches to determine an evacuation strategy can be developed. Theoretically, full control over the departure times, destinations and routes of all people will be most ideal. However, for more feasible and practical approaches decreasing control over destination and route choice processes by the authorities for individuals is required (for example reflected in different evacuation strategies).

3.2 The Emergency Evacuation Process

The necessary model inputs can be found in the upper segment of the procedure, see Figure 13. These inputs can be summarized as demand characteristics, risk characteristics and network characteristics. The best way to determining those characteristics is by describing the evacuation process. In this case the evacuation process developed by Liu (2005) will be used. Different decisions and assumptions will lead to numerous evacuation strategies.

3.2.1 The Disaster Nature [1]

Because the tender stage of the project there is not much known about the characteristics of the disaster. However, good and realistic assumptions can be made.
The disaster can be characterized as a chemical explosion on the railroad due to an accident or a terrorist attack. The railroad, located to the south-west of the Baltimore City center, is the connection between the harbor and the hinterland. Due to a north-east wind, a part of the city will be affected by a cloud of chemical material and needs to be evacuated.
First we assume that an evacuation is necessary in any case. The characteristics of an evacuation are largely a result of the harmfulness of the disaster, which depends on:

- Type of material;
- Concentration;
- Material Density;
- Visibility;
- Weather, distribution conditions;
- Location.

A complete study can be undertaken to determine the effects of these parameters on the harmfulness and various scenario's can be developed, but this exceeds the scope of this research. However, some important assumptions can be made about the characteristics of the chemical cloud.
First we assume that the concentration of the chemical material in the cloud affecting the area is constant. Of course this is not true, because the concentration will decrease by moving further away from the source. However, the affected area is considered to small to cause a big concentration difference.
Secondly, the south part of the area is effected first and the north part effected last. In other words, it takes time until whole the area is covered by the chemical cloud. This means that there is more time for evacuation of the zones far away from the disaster than for the more closer zones. This is an interesting observation for the further development of an evacuation plan.
Finally assumptions need to be made about the exposure time until a certain level of damage will occur and the time the chemical cloud needs to reach the first and last zone.

3.2.2 Evacuation Zones [2]

Due to the disasters nature [1], specific zones of the affected area need to be evacuated. In this case the affected area to evacuate is predefined, namely the Baltimore city centre. To produce a manageable model, the research area needs to be divided into different zones. Goal is to make a distinction between homogeneous social-economical zones. The Transportation Analysis Zones (TAZs) from the Baltimore Metropolitan Council, see Figure 14, is chosen as a valid and reliable distinction. The black shaded TAZs, 114 – 129 and 136 – 141 (totally 22), correspond to the research area and are all part of Baltimore Downtown, also known as

Regional Planning District (RPD) 118. Figure 15 illustrates the location of RPD 118 in Baltimore City and the location of the case study area is indicated by the black outline. Social-economical data can provide information about the amount, characteristics and trip motives of the people in the different zones.

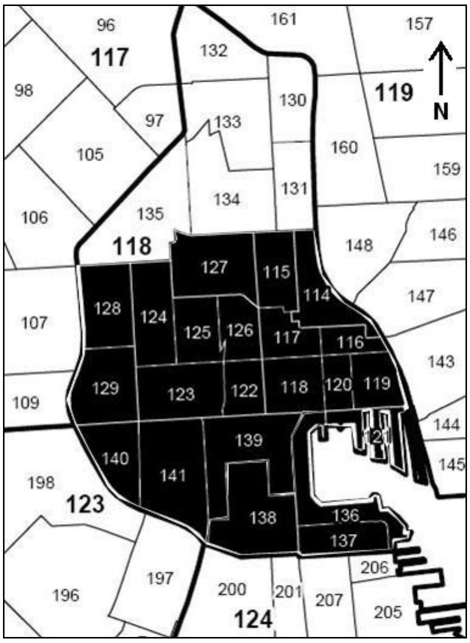

Figure 14: Case study area (black shaded TAZs) in RPD 118 (BMC, 2007)

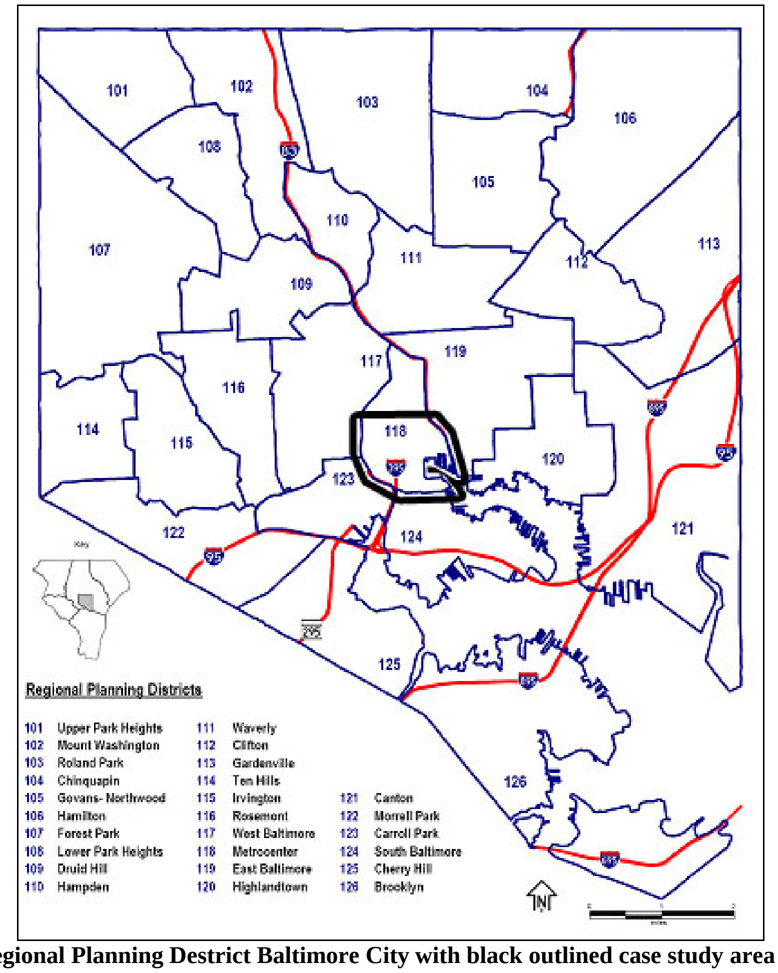

Figure 15: Regional Planning Destrict Baltimore City with black outlined case study area (BMC, 2007)

3.2.3 Evacuation Destinations [3]

All the zones which surround the zones to evacuate are possible evacuation destinations, also called safe area's. An important decision in emergency evacuation it is to allocate the exits of the evacuation area and the safe area's.
The I395 on the south and the I83 on the north, both freeways, are the major roads to exit the Baltimore City Center. Due to the disaster the south exit will be out of order for evacuation, leaving the I83 as the only available major exit, certainly cause largely traffic problems and congestion. Figure 16 illustrates the 10 available exit roads for the evacuation, note that road 1 and 5 are separated into two different sections. In reality there are more exits, but the ones considered are the most important.
Finally, 6 exits will be taken into account, because some exit roads are merging together outside the drawn network. This will of course influence the total capacity of the exits. The final result is illustrated in Table 1.
After the traffic passes the exit, it is assumed that it has reached safe area, with an infinite capacity. Of course this is not in accordance with reality, but it exceeds the research objective to take this also into account.

Figure 16: Detailed map case study area (red delineation) in Baltimore City (Google Maps, 2007)

Case Study Area Exits Capacity				
Exit #	***Roads # + Namen***	***# of Lanes***	***Capacity (veh/h)***	***Total Capacity (veh/h)***
1	1 Franklin Street US 40	2	3000	
	1 Franklin Street US 40	3	4500	4500
2	2 MLK Jr. Blvd.	3	2700	
	9 Pennsylvania Ave.	1	900	
	3 N. Paca St.	3	2700	2700
3	10 Park Ave.	2	1800	
	4 Calvert St	3	2700	4500
4	5 Jones Falls Expy I83	2	3000	
	5 Ramp I83	1	900	4500
5	6 Orleans St. US40	3	4500	
	7 N. Gay St.	3	2700	4500
6	8 W. Fayette St.	2	1800	1800

Table 1: Case study area exits capacity

3.2.4 Start Time of the Evacuation Process [4]

In the worst case the disaster will occur when there are as much people as possible in the affected area. For a city centre, like the proposed research area, this will occur in the afternoon just before the start of the evening rush hour.
Due to the nature of the disaster the occurrence of the disaster and the start time of the evacuation will be not simultaneously. As stated earlier in this report the first line of responsive action to emergencies is the responsibility of local and State authorities. In most instances, evacuation operations are ordered on the local level in coordination with state officials. In case of the chemical disaster in Baltimore, evacuation of the city centre will be ordered by local authorities. The decision to evacuate is difficult because knowledge and time are limited and the responsibility is enormous. A structured and established decision-making structure is essential to make good en fast decisions, but this exceeds the scope of this research. It will be necessary to make an assumption about time necessary to make the discussion. Also assumptions need to be made about the way in which the evacuation will be ordered.

3.2.5 Spatial Distribution of Human Activity [5]

The spatial distribution of human activity [5] depends on the start time of the evacuation process [4] and the specific evacuation zones [2]. It is logical that the spatial distribution of human activity dependents both on the time of the day and the specific area.
In a worst case scenario, the disaster and evacuation will occur when there are as much people as possible in the affected area. For the Baltimore City Center, which can be characterized as a business district, this will be the case around noon during a weekday. The Baltimore Metropolitan Council collected occupancy and classification counts of vehicles entering the Baltimore Central Business Districts (RPD 118) between 7:00 AM and 9:00 AM on a average weekday (Tuesday through Thursday) between April and July of 2003 (BMC, 2003). Together with the Community Profile – RPD 118 (BMC, 2006) the number of people inside the area can be determined.
According to the available data it is most likely to assume the start of the evacuation at 9:00 AM.

3.2.6 Intermediate Destinations [6]

Due to the spatial distribution [5] intermediate destinations [6] will occur. As stated earlier especially families first need to prepare (drive to home, gather al the family members, et cetera) before they leave. This preparation causes intermediate destinations [6].
Due to the spatial distribution of human activity [5] in the evacuation area and the seriousness and deadly disaster nature, no intermediate destinations [6] are taken into account.

3.2.7 Information Dispersion Process [7]

The information dispersion process [7] depends on the start time of the evacuation process [4] and the disaster nature [1] and the spatial distribution of human activity [5]. Because of the small time frame of the disaster and the evacuation the information dispersion process [7] will be poor. This information dispersion process [7] can be for example stimulated by informing people about evacuation plans.

3.2.8 Evacuee’s Rationality [8]

The evacuee’s rationality [8] depends on the information dispersion process [7] and the disaster nature [1]. Because of the poor information dispersion process and the seriousness and deadly disaster nature, evacuees are panic and loose composure. They compete for the egress routes without considering others. Hamdar (2005) researched the driver behavioral characteristics in panic conditions. However, it is known that evacuees don’t act like they normally do, but there is also no clarity regarding their panic behavior. From this point of view it is more likely to implement the known characteristics under normal conditions and take it into account in the conclusions.
The evacuee rationality will also influence the departure profile. As stated earlier it is known that evacuees during an evacuation will not leave the area immediately. A poor information dispersion process can both lead to a small or broad departure profile. However, if people are panic and loose composure a small departure profile is more likely.

3.2.9 Road Network [10]

The road network [10] is the total set of characteristics which determine the available network capacity. Most important characteristics are the network geometry, road capacities, speed limits and signal timing plans.
In emergency evacuation modeling it is important to choose the desired road network detail. In this research the main arterial roads of the area will be taken into account. Most of these roads are shaded yellow in the red delineation in Figure 16. Table 2 lists the boundaries of the research area and Table 3 the main arterial roads.

Boundary Roads Case Study Area	
Direction	***Street***
North	W. Franklin St. and Orleans St.
West	N./S. Martin Luther King Junior Blvd
East	Jones Falls Expy (IS 83) and S. President St.
South	IS 395, W. Conway St. and E. Pratt St.

Table 2: Boundary roads case study area

Main Arterial Streets Case Study Area	
East / West	***North / South***
W. Mulberry St.	N. / S. Greene St.
E. Pleasant St.	N. / S. Paca St.
E. Lexingtons St.	N. / S. Howard St.
E. / W. Fayette St.	Park Ave.
E. / W. Baltimore St.	Hopkins Pl.
E. / W. Lombard St.	N. Liberty St.
E. / W. Pratt St.	Cathedral St.
E. / W. Conway St.	St. Paul St. / St. Paul Pl.
	Light St.
	N. / S. Calvert St.
	N. Gay St.
	N. Frederick St.
	IS 295

Table 3: Main arterial streets case study area

The network also contains a high density bus system and a metro and light rail line. It is assumed that people who are using the metro or light rail to enter the research area, will also use it for the evacuation. Because both metro and light rail end up far to the north of the city centre. People using the bus system to enter the area are expected to take the bus for evacuation. However, a bus system will not be integrated in the simulation network, bus trips will be taken into account in the total traffic demand.
On many roads in the Baltimore City Center both outside lanes are reserved for parking. In the case cars are. If cars are indeed parked here, this will decrease the road capacity drastically. Initially this will not be taken into account in this research.

3.2.10 Evacuation Traffic [11]

Evacuation Traffic [11] is the amount of traffic flows generated by the evacuation. The characteristics of this so called evacuation traffic [11] directly depends on the traffic demand, evacuation destinations [3] and the road network [10]. The traffic demand directly depends on the available background traffic [9], spatial distribution of human activity [5], information dispersion [7] and evacuee's rationality [8].

3.2.11 Traffic Surveillance System [12]

If available in the road network [10] traffic surveillance systems [12] can provide information about the evacuation traffic [11]. This information can be used to adjust control strategies [13] in real-time or post-planning.

3.2.12 Emergency Response Personnel Location and Availability [9]

If there is emergency response personnel involved [9] in the evacuation depends on the disaster nature [1]. Routing of emergency response teams, if necessary, is critical as an efficient arrival of these responsive teams might limit the expansion of the zone in danger, but the network capacity they require may restrict the control strategies for evacuation traffic.
It is likely that emergency response personnel is involved in the evacuation. They will especially assist in the evacuation process, keep order and help delayed and obstructed evacuees. Emergency Response Personnel to limit the expansion of the zone in danger, for example fireman who resist the actual disaster, are not located and available in the evacuated area. The site of the actual disaster is located a certain distance from the evacuation area.

3.2.13 Control Strategies [13]

Control strategies [13] are the possibilities to control the evacuation traffic [11]. Generally this will lead to a different distribution or routing of traffic.

Possibilities for manipulating the Evacuation Traffic Demand are:

1. Time of departure. This can be influenced by means of information and direct orders;
2. Trip distribution. It is possible to instruct evacuees to go to a specific exit;
3. Mode of travel. In general, people with access to a car will use it. For people without own means of transport, the authorities will be responsible for supplying public transport;
4. Route choice. It will be possible to guide the traffic by means of information and instructions.

It will not be possible to influence the number of evacuees.

Possibilities for manipulating the Evacuation Network Supply are:

1. Capacity. It is possible to increase the network capacity by increasing the number of lanes available for evacuation traffic.
2. Typology. It will be possible to increase the networks level of reliability, regarding endogenous of exogenous causes, by changing the typology.

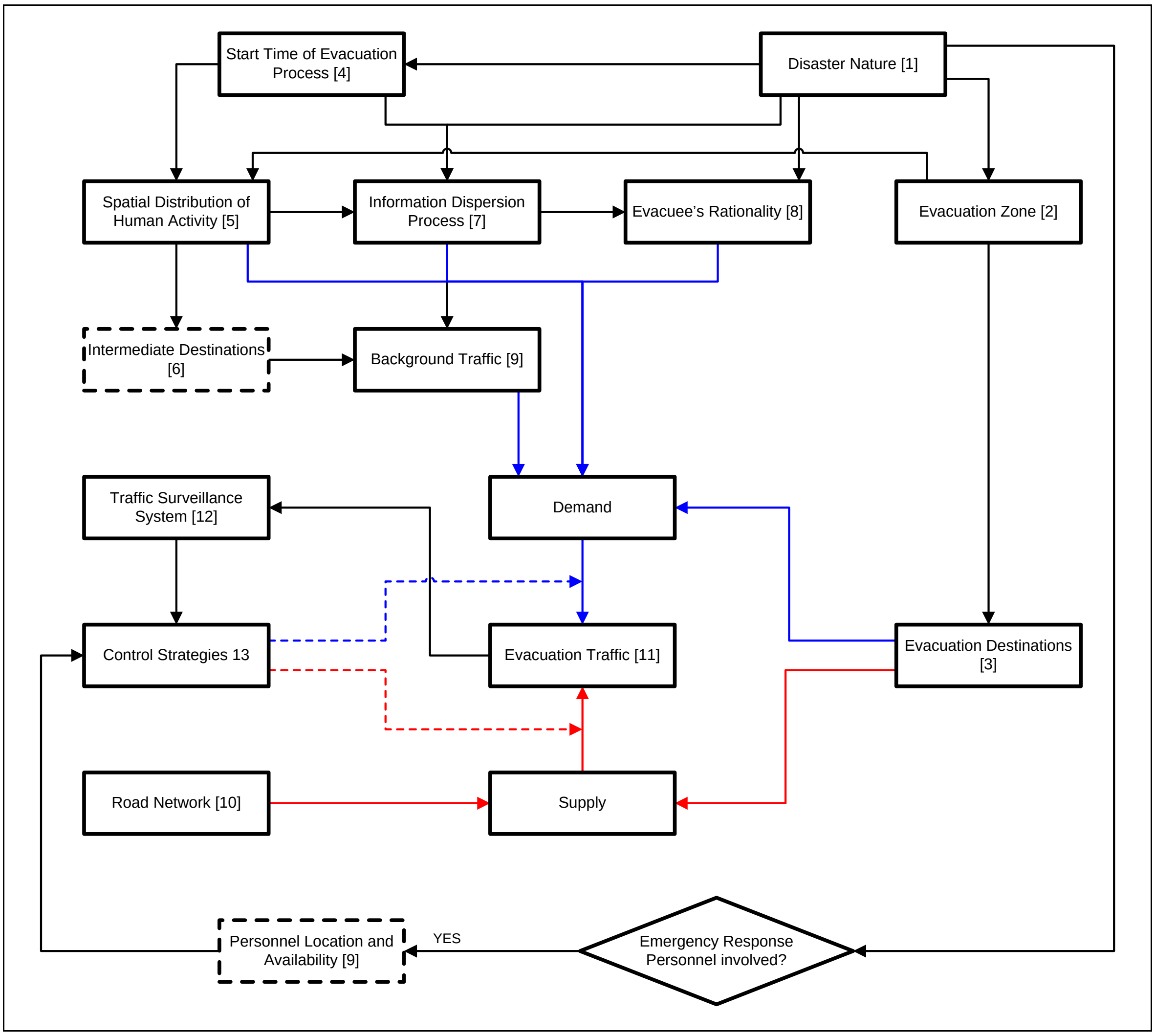

Figure 17: The Evacuation Process

3.2.14 Summary

After a disaster has occurred or is predicted [1], the responsible agency will determine the start time of the evacuation process [4]. This start time will directly determine the spatial distribution of all related activities [5] right before evacuation and also affect the dispersion of evacuation order [7]. These aspects, along with the information on the location, size of those evacuation action zones [2] to be cleared, evacuee's rationality [8], and evacuation destination [3] will decide the total evacuation demand as well as its loading pattern onto the network. As well recognized in the behavioral research, most evacuees tend to meet their family and start evacuation as a single unit when necessary. Thus, practitioners have to identify these intermediate destinations [6] for family reunion, which causes background traffic [9] and may greatly affect the network traffic pattern. The evacuation demand and loading pattern (demand = blue arrows in Figure 17), together with the road network characteristics [10] and the evacuation destinations [3] (supply = red arrows in Figure 17), will decide the evacuation traffic [11]. With control strategies [13] the traffic demand or supply can be manipulated to change the evacuation traffic [11].

3.3 Strategies

In a brainstorm session with the supervisors of this research, the following evacuation strategies where selected to investigate:

- Doing nothing / Nearest Exit;
- Destination Capacity / Management;
- Reference;
- Staged Evacuation.

The strategies will be described regarding the boundary conditions set in the previous part of this research.

3.3.1 Doing Nothing / Nearest Exit

In the 'Doing Nothing' strategy it is assumed that a pre-defined evacuation plan is not available. This will cause a low information dispersion process, what will result in a low rationality of the evacuees.
Because of this low rationality evacuees are panic and loose composure. They compete for the egress routes without considering others. Driver behavioral characteristics in panic conditions akin to those formulated in Hamdar (2005) should be adopted in the modeling (Zuilekom, 2007). Another result of this low rationality is that the evacuees will evacuate as soon as possible.
The evacuees will be distributed to the nearest exit, regardless of their capacity. They are free to choose their route within the available network area, however the usable exits are constrained, see Figure 16 for the available exits.
A sub-strategy of this 'Nearest Exit' strategy will be the 'Nearest Two Exits' strategy. In this strategy the evacuees will be distributed to the nearest two exits, while the rest of the conditions is the same as in the first strategy. The difference between the shortest exit and second shortest exit is almost always tight, see Table 8 on page 55.

3.3.2 Destinations Capacity / Management

In this strategy it is assumed that a pre-defined evacuation plan is available. This evacuation plan will only tell the evacuees which exit to use, based on the exits capacity. This will cause a small increase in the information dispersion process according to the 'Doing Nothing' strategy. As a result the evacuees rationality will increase.

However, the rationality is still low, causing panicking evacuees who are loosing composure. They still compete for the egress routes without considering others and evacuate as soon as possible.

The evacuees will be distributed over the available exits regarding their capacity, in a certain way to minimize the total vehicle kilometers. To accomplish this, the shortest path is taken into account in the calculation. The shortest path is in this case the route with the shortest travel time. This will result in only converging and some diverging traffic flows, what decreases the traffic delay at intersections.

Same as in the 'Doing Nothing' strategy the evacuees are free to choose their route within the available network area and the usable exits are constrained.

3.3.3 Reference

The evacuees will be distributed over the available exits regarding their relative attraction. The relative attraction of some specific exits is larger than others, because these exits are related to major roads, which are able to lead traffic out of the urban area. It is assumed that evacuees incline to use these exits more. It is also possible that a pre-defined evacuation plan will tell the evacuees which exits are more likely to use than others

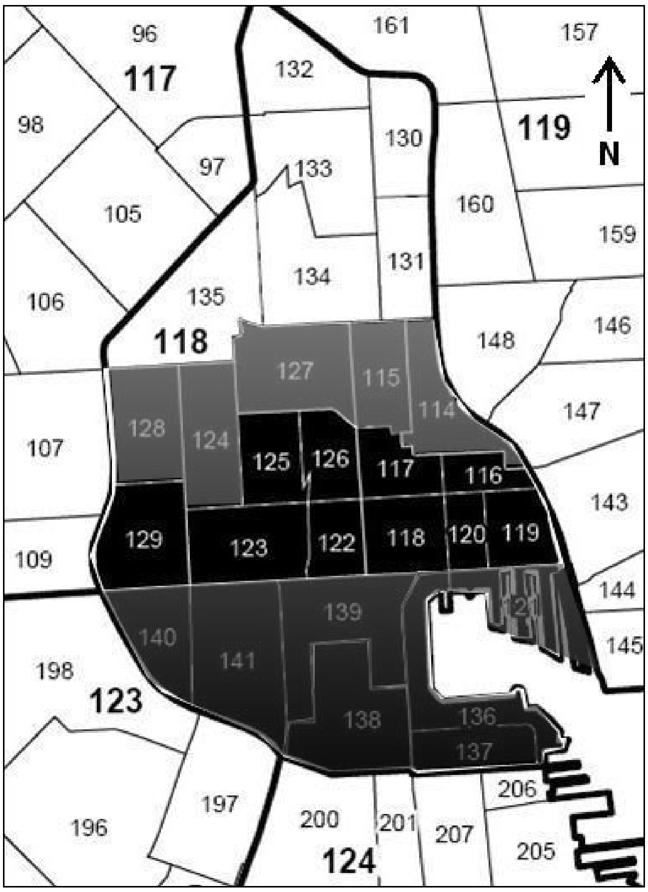

Figure 18: Different stages (Upper, Center and Bottom) evacuation case study area

3.3.4 Staged Evacuation

Same as in section 3.3.2 but than with a different departure profile for certain sections of zones. Numerous sub-strategies can be developed, by adopting a different evacuation order for the sections.
The evacuation area will be divided into three different groups: (1) Upper, (2) Center and (3) Bottom, see the different shaded area's in Figure 18.
According to Chen (2006) a staged evacuation strategy that alternates non-adjacent zones in the affected area is effective in reducing the overall evacuation time, if the population density in the affected area is high and the underlying road network structure is a grid structure.
Because the population density in the research area is high and the road network structure is a grid structure, first section (1) and (3) will be evacuated and the evacuation of section (2) will follow after a delay of 2 and 1.5 hours.

3.3.5 Additional Strategies

Three additional strategies will be add to the most effective evacuation strategy according to the simulations executed. These strategies are: Parked Cars, Contra Flow and Traffic Lights.

Parked Cars

One of the major obstacles in the Baltimore City Center are parked cars on the outside lanes of the roads, decreasing the road capacity drastically. According to satellite images (Google Earth, 2007) the outside lanes of several main arterial streets are occupied by parked cars. To gain insight into the effect of this capacity reduction, the right most lane of Paca Street, Greene Street, Baltimore Street, Fayette Street, St. Paul Street, Calvert Street and Gay Street will be closed for the first two hours of the evacuation. It is assumed that all the parked cars are departed after two hours.

Contra Flow

As stated earlier a popular emergency evacuation measure is the contra flow operation, especially during hurricane evacuation. To gain more insight into the effect of this measure for the evacuation of the Baltimore City Center, the Jones Falls Expy (I83) will be deployed for the Contra Flow operation. The total capacity of Exit 4 will increase therefore with 4500 Personal Car Unit (PCU)/hour, 9000 PCU/hour totally. A reconstruction of the Jones Falls Expy and East Fayette Street is inevitable. This reconstruction is illustrated in Figure 31 in Appendix 9.3. The changes don't influence the original shortestpath-matrix (Table 8).
Note that the implementation of a control flow operation is very difficult to organize and takes a large amount of recourses. This results automatically in a long preparation time. This preparation time will not be taken into account in the strategy. In reality a control flow operation will not double the capacity, but somewhat lower, because the driving conditions on the contra lane are different compare to the normal situation.

Signal Control

As stated earlier (Chen, 2005) signal control can greatly impact traffic flow in an evacuation. Significant trade-offs exist in setting timing plans as long cycle lengths can lead to reduced evacuation times, but at the expense of delay on minor roadways. Unfortunately it was not possible to change the signal timings for all the intersection, especially due to time limitations. However three sub-scenario's are developed to gain more insight into the effect of this measure and signal control in general:

1. Cycle length and green times of 60 intersections on the boundary and three internal roads, Martin Luther King Jr. Blvd, Franklin Street, Mulberry Street, Jones Falls Expy (IS 83) / President Street, Conway Street, Pratt Street, Lombard Street and Gay Street, are doubled.
2. Cycle length and green times of 12 intersections on the boundary roads Martin Luther King Jr. Blvd. and Jones Falls Expy (IS 83) / President Street are doubled;
3. No signal control plan for the entire network.

4 Modeling Approach

Before discussing the results in the next chapter an overview of the total developed modeling approach will be given in this chapter. First decision regarding model environment and assignment are discussed, followed by information regarding the used simulation software in section 4.1. Next in section 4.2 a short review will summarize the typical characteristics of the developed model and evacuation strategies. Furthermore the most important assumptions and the related limitations of the model will be outlined in section 4.3. Finally in section 4.4, the objective function and criteria to evaluate the results will be discussed.

4.1 Model Environment and Assignment

As discussed earlier a distinction can be made between the type of distribution, the modeling environment, assignment and routing as the key elements in classification of the modeling approaches. Decisions regarding the distribution and routing are strongly related to the chosen evacuation control strategy. However, also decisions about the modeling environment and assignment need to be made. Key factors in this decisions are:

- Level of detail available inputs;
- Desired level of detail outputs;
- Network size;
- Available time;
- Available money.

4.1.1 Model Environment

The scale of the area, the required level of detailing and accuracy will determine the modeling environment. Traffic models can be conducted on macroscopic and microscopic level. As stated earlier, microscopic simulation models resulting in greater detail and performance measures aggregated over the entire sample of drivers and vehicles. Macroscopic models analyze platoons of uniform vehicles throughout a network, resulting in more general detail and performance measures. On the contrary, macroscopic models require limited data and have a relative fast computation. For this research a microscopic model is chosen as the most appropriate one.

4.1.2 Trip Assignment

As stated in the literature review, the nature of an evacuation makes a dynamic handling of time the preferred one. Dynamic assignment gives the best insight into the process and the best estimate of the evacuation time. However, in the process of designing for example an evacuation plan there is a need to investigate a series of scenarios. In that case static assignment will also give good insight to select the most relevant scenarios for further, in-depth (dynamic) analysis. For this research a dynamic assignment is chosen as the most appropriate one.

4.1.3 Simulation Software

As stated in section 2.3.3 there are numerous traffic simulation software packages available and some of them are especially developed for emergency evacuation. Research however concluded that each package have strengths and weakness in terms of its suitability for various applications, but that a so called ‘best software package’ is not existing.
Full versions of the software packages VISSIM, CORSIM and AIMSUN where available for this research. Finally AIMSUN NG Version 5.1.5 is chosen as the most suitable software

package. AIMSUN NG is integrated suite of traffic and transportation analysis tools. Therefore it can be used for transport planning, microscopic traffic simulation and demand, and traffic data analysis. It provides a platform for both static and dynamic modelling. AIMSUN NG is developed by TTS – Transport Simulation Systems from Barcelona, Spain. Motives for the decision to use AIMSUN NG are the ability to model large networks (regarding the long term of the research project), the microscopic environment and the dynamic assignment possibilities.

4.2 Model Overview

As originally demanded by the research principals the focus of this research is concentrated on the southern part of RPD 118, also known as the Central Business District of Baltimore City. Due to the early stage of the research project this research is part of, major goal was to providing a first impression of the possible evacuation strategies and their effect on the evacuation process. This resulted in the development of a model, which is composed of only the main arterial roads of the research area. Due to the assumed disaster, a chemical explosion to the south west of the research area, only 12 roads are available to exit the area, leading to 6 safe areas. Only the traffic demand produced by RPD 118 itself at 9:00 AM is taken into account and is represented by simply one modality, namely the car.

Overview Evacuation Strategies			
Strategy	*Traffic Demand*	*Distribution*	*Comment*
Nearest Exit 1	Nearest Exit: Table 27	Regarding the nearest exit	
Nearest Exit 2	Nearest Exit: Table 27	Regarding the nearest two exits	Traffic demand proportional divided over the 2 exits
Reference	Reference: Table 29	Regarding relative attraction exits	
Management	Management: Table 28	Regarding capacity exits and minimize distance traveled	
Staged 1	Management: Table 28	Regarding capacity exits and minimize distance traveled	Delay time phase 2 is equal to 2 hours
Staged 2	Management: Table 28	Regarding capacity exits and minimize distance traveled	Delay time phase 2 is equal to 1.5 hours
Contra Flow	Contra Flow: Table 30	Regarding capacity exits and minimize distance traveled	Capacity Exit 4 9000 PCU/hour instead of 4500.
Parked Cars	Management: Table 28	Regarding capacity exits and minimize distance traveled	Parked cars on right lane of 7 internal roads for the first 2 hours
Signal Control 1	Management: Table 28	Regarding capacity exits and minimize distance traveled	Doubled cycle length and green times for 60 intersections on both boundary and three internal roads
Signal Control 2	Management: Table 28	Regarding capacity exits and minimize distance traveled	Doubled cycle length and green times for 12 intersections on MLK Jr. Blvd. and Jones Falls (boundary roads)
Signal Control 3	Management: Table 27	Regarding capacity exits and minimize distance traveled	No signal control plan for the entire network

Table 4: Overview evacuation strategies

Because a first impression is asked for, a macroscopic and static model would be sufficient to produce usable results. However a microscopic dynamic model is developed in an attempt to produce more reliable results and because of future prospects.
Originally four different evacuation strategies were developed and implemented in the model. During the simulation process 11 sub-strategies were developed or derived from the original strategies. Table 4 gives an overview of the different strategies and/or sub-strategies and their major characteristics.
In an attempt to provide consistent results, for every simulation the same set of parameters was used. Unfortunately it was impossible to calibrate those parameters due to the unavailability of specific field data and a limited amount of time.

4.3 Assumptions and Limitations

The assumption made before conducting the experiment will result in limitations in the model output. These assumptions where necessary in order to limit the amount of input data, which can be in case of an urban network almost unlimited, and number of simulation results that had to be performed to reach usable results. Also assumption were necessary because of the limited available input data. The following list summarizes the limitations to these assumptions:

- *Major arterial roads:* Only these roads are taken into account in the model, which will limit the available (shortest) routes. However, only a small percentage of the drivers will use these routes through residential area's. Therefore this assumption will have a minor effect on the final result. Signalized intersection with arterial roads and smaller residential area roads are implemented in the model.

- *RPD 118 traffic demand:* In reality the traffic demand in the model during an evacuation will not be only produces by RPD 118, but also traffic from surrounding RPDs will join the network. The effect on the final result is somewhat limited because a large percentage of this traffic will only use the boundary roads and there don't occur the biggest problems. Also the signal configuration on these boundary roads is still assuming traffic from surrounding RPDs.

- *One modality:* Although the total traffic demand is defined for RPD 118, it is only related to one modality, namely the car. Due to time limitations it was necessary to reduce the number of import actions. In reality the traffic will be less uniform, but the effect on the results will be minor because the total demand in PCU is used, slow driving conditions and the high percentage of cars in the original traffic demand.

- *Start time 9:00 AM:* In reality an emergency can occur 24 hours per day. An evacuation started at a different time then the time set in the model will result in a different evacuation process. However, 9:00 AM can be considered as the worst case scenario in a business district like RPD 118.

- *Empty Network:* At the start of the evacuation an empty network is assumed. In reality there will be a certain amount of traffic available in the network that is not arrived on their destination yet or still needs to leave the area. This will increase the total traffic demand.

- *No intermediate destinations:* In reality a certain percentage of people will not leave the network directly or will enter the network heading for an intermediate destination to pick-up family for example. These intermediate destination are not taken into account in the model, because it will increase the complexity of the model, and the related reliability. However the number of people heading for intermediate destinations will be limited, both because of the severity of the emergency and the low percentage of large (more then 2 members) families, few people will do. This will increase the total traffic demand.

- *6 safe destinations:* Only 12 exit roads leading to 6 safe destinations are implemented in the model. In reality this number can be larger, however also smaller. A different exit and safe area configuration can cause major changes in the results.

- *Limited and fixed origin centroid connectors:* In reality traffic will enter the network more evenly. However, fixed entering points largely exist due to parking garages and parking lots and large amounts of traffic will normally enter the network by using first residential area roads. However these roads are not implemented in the model, their intersections with main arterial roads are, and the origin centroid connectors are connected to these intersections. Therefore the effect of the limited number of fixed entrance points will have a minor effect on the final results.

- *Fixed PM-peak control plan:* Only the fixed PM-peak control plan was implemented into the model. For RPD 118 also an AM-peak and Noon control plan exists, however the PM-peak control plan was assumed as the most appropriate one for evacuation of the area. Implementing one of the other control plans will lead to a different, probably worse, evacuation process.

- *Recourses:* The model assumes full availability of recourses, for example public transport for people without a car or personnel to assist in the evacuation plan. In reality however this will take time or isn't possible at all. Also complete acceptance of evacuation plans is assumed in the different strategies, which isn't realistic. Results will therefore be more optimistic than the reality.

- *Calibration:* Because of unavailability of evacuation field data and time limitation to work with the simulation software is was not possible to calibrate the model properly. Parameter settings are largely based the engineering insight in traffic mechanics.

- *Multiple replications*: The stochastic nature of AIMSUN makes it necessary to perform multiple simulation replications in order to get valid results. In this case only three runs for each simulation were performed. It wasn't possible to execute more runs since the time available for simulations was limited. The result is that some results could have minor variations to it's mean values.

4.4 Objective Function and Evaluation Criteria

As stated earlier, see section 2.3.3, the procedure for designing an evacuation plan contains a 'What if' or a 'How to' approach. Both approaches have their specific pros and cons, but it was found that using a 'What if' approach the quality of the result is unclear by lack of a formal objective function. Research is useless if the quality of the results is unclear, so a 'How to' approach is preferred.

This means however that a formal objective function needs to be determined. As stated by the research objective we are looking for the most effective evacuation strategy for the Baltimore City Center in case of a chemical accident on the railroad, which minimizes the number of people with physical damage. This means we are looking for a system optimal solution in stead of an user optimal. Regarding this the formal objective function can be described as: determine a system optimal evacuation strategy.
To give an effective analysis of the results extracted from the simulation, evaluation criteria are introduced. As Measure of Effectiveness (MOE), as a result of the objective function, the total evacuation time and the total travel time will be analysed. This last MOE can be extracted from the network summary table provided by AIMSUN. The total evacuation time can be extracted from the database. Because data is collected with an interval of 15 minutes, the total evacuation time obtained contains the same interval.

During the simulations it was discovered that a certain amount of vehicles is getting lost in the network. This is a result of the vehicles knowledge of the next turning movement and the maximum give-way time.
According to TSS (2006) until now the assumption was made that a vehicle driving along a section only has knowledge of its next turning movement, that is the turning it will take when arriving at the end of the current section. This means that the lane changing decisions of each particular vehicle are made according to the next turning movement in the next junction or join. In urban networks where there are short sections or in a freeway situation where weaving sections may be relatively short, it is possible that some vehicles will not reach the appropriate turning lane and consequently miss the next turn, and finally get lost. This situation could occur when traffic conditions are very congested and if only the next turning movement in the lane changing decisions is taken into account. In order to avoid this undesirable behavior as much as possible, a look ahead model is integrated in AIMSUN, whose main purpose is to make the vehicles reach the turning lane earlier. The idea is to provide vehicles with the knowledge of additional next turning movements, rather than just one, enabling them to make decisions based not on the immediate next turning movement, but on a set of next turning movements. For the purposes of reducing computing time and memory requirements, in AIMSUN this set is reduced to two turning movements ahead. This is not considered as a limitation, as very few lane-changing decisions are made while considering more than the next two turns.
In the developed model the three turning movements ahead are set, however vehicles are still getting lost. This is a result of the maximum give-way time. If there is no available gap in the off-ramp side lane because of a heavily congested exit, a vehicle may even come to a full stop and wait for a gap in order to not to miss its desired exit. The time a vehicle is willing to wait in this situation is limited by the vehicle parameter maximum give-way time. This period is also used in the lane-changing model as the time that a vehicle accepts being at a standstill while waiting for a gap to be created in the desired turning lane before giving up and continuing ahead. Because of the high congested traffic conditions, many vehicles have to wait longer than their maximum give-way time, miss the desired exit or turning lane and get lost. A minor increase of the maximum give-way time, see Table 12, did not cause a major reduce of lost vehicles. Because of the short time frame it was decided to take the number of lost vehicles into account as a third MOE. Because the number of lost vehicles is directly related to congestion, a high number of lost vehicles indicates high congestion and therefore a less effective evacuation strategy.

The obtained MOEs will be used to provide a comparison between the different evacuation strategies. In order to give an evaluation of the performance of the different strategies, a pair comparison is carried out. Three different weight settings are used for the different MOEs, see Table 5.

Weight Configuration Pair Comparison			
	Evacuation Time	***Total Travel Time***	***Lost Vehicles***
Weight = 1	1	1	1
Weight Travel Time = 2	1	2	1
Weight Evacuation Time = 2	2	1	1

Table 5: Weight configuration pair comparison

5 Simulation Model Setup

In this chapter the developed simulation model for the evacuation of the Baltimore City Center will be discussed. First in section 5.1 the determination and calculation of the model input data will be discussed, followed by an explanation regarding the construction of the network in section 5.2. Finally, this chapter will be concluded with the calibration and validation of the model in section 5.3.

5.1 Model Input Data

5.1.1 Trip Production

To determine the trip production social-economical data is very important. In this case, especially data from the Community Profile – RPD 118 (BMC, 2006) and the Baltimore CBD Trip Characteristics (BMC, 2003) was used. For this last one, BMC collected occupancy and classification counts of vehicles entering the Baltimore Central Business Districts (CBD), also known as RPD 118, between 7:00 AM and 9:00 AM on an average weekday (Tuesday through Thursday) between April and July of 2003. See for the total trip production calculation Appendix 9.1.

In the trip production calculation a distinction is made between Activity/Not Live in RPD 118 Trips, Activity/Live in RPD 118 Trips, No-Activity/Live in RPD 118 Trips. Below the most important assumptions made in the calculation are listed.

General

- All the people in RPD 118 need to be evacuated;
- Final results are rounded up.

Activity/Not Live in RPD 118

- Travelers using public transport (bus, metro or light rail) to enter RPD 118 will also use this traffic mode for the evacuation;
- TAZs employment percentages are used to assign vehicle classification data to the different TAZs.

Activity/Live in RPD 118

- The traffic mode usage percentages for people both living and working in RPD 118 is equal to the percentages for people only working in RPD 118;
- Bus occupation factor is 21 trips per bus;
- Number of motorcycles is set to zero.
- TAZs employment percentages are used to assign vehicle classification data to the different TAZs.

No-Activity/Live in RPD 118

- RPDs 118 total labor force is not at home during the evacuation;
- There is no unemployment;
- There are no other activities;
- Number of persons per household is 1.52;
- Households with more than one vehicle available will only use one;
- Households with no vehicle available will use the bus;

- TAZs population percentages are used to assign vehicle classification data to the different TAZs;
- Bus occupation factor is 21 trips per bus.

For the total vehicle classification data for RPD 118 at 9:00 AM see Table 6. The bold figures correspond to the actual research area.

Total Vehicle Classification Data RPD 118						
TAZ	***Total Motor-cycles***	***Total Autos***	***Total SUVs***	***Total Buses***	***Total Trucks***	***Grand Total All Vehicles***
114	3	1597	647	32	72	**2351**
115	3	1373	556	28	62	**2022**
116	3	1542	625	30	70	**2270**
117	6	3515	1424	68	159	**5172**
118	9	5266	2133	103	234	**7745**
119	3	1413	572	28	64	**2080**
120	2	841	342	18	38	**1241**
121	2	814	331	17	37	**1201**
122	5	2715	1099	52	123	**3994**
123	7	3684	1492	71	164	**5418**
124	2	766	312	18	30	**1128**
125	4	2393	969	47	107	**3520**
126	3	1719	697	36	73	**2528**
127	3	1543	627	34	60	**2267**
128	3	1722	698	35	75	**2533**
129	8	4406	1785	86	197	**6482**
130	1	597	245	18	15	876
131	2	942	383	22	36	1385
132	1	511	208	12	23	755
133	3	1639	666	35	66	2409
134	2	1455	592	34	53	2136
135	1	821	334	22	27	1205
136	1	605	246	15	25	**892**
137	1	430	176	11	16	**634**
138	2	909	371	24	28	**1334**
139	3	1355	550	28	60	**1996**
140	1	312	128	10	9	**460**
141	1	375	153	9	17	**555**
Total	85	45260	18361	943	1940	66589
Total	**75**	**39295**	**15933**	**800**	**1720**	**57823**

Table 6: Total vehicle classification data RPD 118 at 9:00 AM

5.1.2 Trip end Calculation

The total capacity of the exits, see Table 1, together is 22500 vehicles/hour, which is equal to 22500 PCU/hour. See Table 7 for the assumed PCU configuration. Together with the results from Table 6 this will finally result in 64308 PCU. The evacuation will therefore need at least 2 hours and 52 minutes.

PCU Configuration	
Vehicle	***PCU***
Motorcycle	0.75
Auto	1.0
SUV	1.25
Bus	2.0
Truck	2.0

Table 7: PCU configuration

5.1.3 Trip Distribution

Evacuation Calculator

For the trip distribution calculation the Evacuation Calculator (EC) developed by the Transportation Department of the University of Twente was used. The EC was originally developed as a tool to calculate an OD-matrix for the evacuation of a dike ring area.

The EC takes the following input factors into account:

- The area's social economical characteristics;
- The trip production coefficients
- The departure profile
- The distance to exits;
- The average speed;
- The exits capacity;
- The evacuation process.

In the EC the network is reflected by the friction-matrix, the so-called shortestpath-matrix. This matrix indicates the length of the shortest paths regarding time assuming regular free-flow speeds.

The shortestpath-matrix was created with the 'Statistic Shortest Path' tool in AIMSUN and is illustrated in Table 8. Note that this matrix is incomplete, because for example the shortest path between TAZ 114 and TAZ 127 is not important for this research.

		Statistics shortestpath-matrix (km)					
		Exit					
		1	*2*	*3*	*4*	*5*	*6*
TAZ	*114*	1.812	1.593	0.231	0.205	0.205	0.766
	115	0.950	0.725	0.142	0.779	0.295	1.074
	116	1.703	1.484	0.727	0.362	0.361	0.290
	117	1.395	1.176	0.648	0.630	0.590	0.580
	118	1.690	1.485	0.820	0.834	0.794	0.784
	119	2.089	1.870	1.114	0.601	0.578	0.568
	120	1.984	1.766	1.030	0.596	0.556	0.546
	121	2.114	1.895	1.160	0.606	0.794	0.585
	122	1.586	1.382	0.957	0.989	0.949	0.939
	123	1.013	0.809	0.751	1.456	0.993	1.406
	124	0.490	0.262	0.498	1.458	0.753	1.408
	125	0.581	0.376	0.377	1.383	0.619	1.333
	126	0.933	0.707	0.373	0.698	0.615	0.993
	127	0.488	0.262	0.374	1.086	0.295	1.381
	128	0.393	0.364	1.100	1.883	1.355	1.833
	129	0.850	0.821	1.290	1.792	1.547	1.742
	136	2.226	1.989	1.253	1.245	1.222	1.212

	137	2.178	1.974	1.334	1.326	1.303	1.293
	138	1.824	1.619	1.433	1.425	1.402	1.393
	139	1.824	1.619	1.264	1.278	1.237	1.228
	140	1.384	1.345	1.673	2.161	1.915	2.111
	141	1.363	1.159	1.260	1.738	1.502	1.689

Table 8: Statistic shortestpath-matrix in kilometers

Parameter Settings

Various parameters can be set in the EC and the general parameter settings are illustrated in Table 9.

Evacuation Calculator General Parameter Settings			
Intervals per hour	***Non-response***	***Mean speed (km/h)***	***Vehicle categories***
6	0.0	10.0	5

Table 9: Evacuation calculator general parameter settings

According to VVR (2006) the average evacuation speed should be chosen conservative, low, therefore an average speed of 10.0 km/h is assumed. Later during the simulations this assumption was confirmed.
Table 6 and Table 7 are used as the social economical data and the general category information respectively. No correction factors for average speed and exit capacity are used.

Evacuation Methods and Results

Three different evacuation methods are simulated with the EC, namely: Reference, Nearest Exit and Traffic Management. The evacuation methods and the results will be discussed below.

Nearest Exit

The evacuees will be distributed to the nearest exit, regardless of their capacity. The method results in an total evacuation time of 17 hours and 40 minutes. Cause of this enormous evacuation time are the unused exits 1 and 4, because from every TAZ there is no shortest paths to these exits. The results, an Arrival-Departure Profile and an OD-matrix, can be found in Appendix 9.2.

Traffic Management

The evacuees will be distributed over the available exits regarding their capacity, in a certain way to minimize the total distance traveled. This method will show the best result in case there is a large amount of evacuees compare to a limited exit capacity, which is reflected in the result. A total evacuation time of 3 hours and 20 minutes was found. The results, an Arrival-Departure Profile and an OD-matrix, can be found in Appendix 9.2.

Reference

The evacuees will be distributed over the available exits regarding their relative attraction, which are listed in Table 10.

Relative Attraction					
Exit 1	***Exit 2***	***Exit 3***	***Exit 4***	***Exit 5***	***Exit 6***
2	1	1	3	2	1

Table 10: Relative Attraction

The relative attraction of Exit 1, 4 and 5 is larger because these exits are related to major roads, which are able to lead traffic out of the urban area. It is assumed that evacuees incline to use these exits more. This method results in an total evacuation time of 4 hours and 20 minutes. The results, an Arrival-Departure Profile and an OD-matrix, can be found in Appendix 9.2.

5.1.4 Model Split

Originally the vehicle classification data was divided into 5 different vehicle categories, see section 5.1.1. The OD-matrix created by the EC shows only the total amount of PCU and doesn't make a distinction between vehicle categories. To reduce the amount of input data, it is decided to distribute the total traffic demand to one vehicle category only, namely the car.

5.2 Building the Network

The network is build with AIMSUN NG Version 5.1.5. The most important data used are a detailed map of the area extracted from Google Earth (2007) and a Synchro network file from the Baltimore Central Business District. This file was received from Sabra, Wang & Associates, Inc.:

Sabra, Wang & Associates, Inc.
1504 Joh Avenue
Suite 160
Baltimore, MD
21227
T: +14107376564 F: +14107371774
http://www.sabra-wang.com

A satellite map from Google Earth (2007) is used to build the network in the right scale. Road geometry and signal timings are derived from the Synchro file. The PM peak signal timing plan is chosen as the most appropriate for an evacuation. Because the research area is part of the CBD (RPD 118), it is assumed that the PM peak signal timing plan is especially designed to efficiently distribute the traffic out of the area.

The following rules are followed during the construction of the network, to construct a network with the highest validity possible:

- US 40, I83 and I395 are set as ring roads with a maximum speed of 80 km/h;
- The rest of the roads are set as arterial road with a maximum speed of 50 km/h;
- The network has a total of 6 exits centroids because some exits, as illustrated in Figure 16, are joined together. This will be discussed in more detail below;
- Every zone is represented by one centroid;
- Centroids have as much connectors to or from the road network as possible;
- Exit roads have a length of 100 meter after the last intersection;
- Entrance roads have a length of 50 meters, if not possible 25 meters;
- The same percentage of traffic is divided over the connectors of one centroid.

Finally this resulted in the following network characteristics:

- 475 Sections;
- 156 Intersections;
- 37 km. Section Length;
- 97 km. Lane Length
- 28 Centroids (22 zones and 6 exits)

An impression of the network as constructed in AIMSUN is illustrated in Figure 30, which can be found in Appendix 9.3.

5.3 Calibration and Validation

Model calibration is a critical step in the employment of a microscopic traffic simulator. Traditionally model parameters are adjusted until an acceptable correspondence between simulation results and field data has been achieved. The adjustment of parameters is based on engineering insight in traffic mechanics and trial and error methods. A more systematic approach includes the use of genetic algorithms were the model calibration is seen as an optimization process to search for the best fitting parameter set combination.

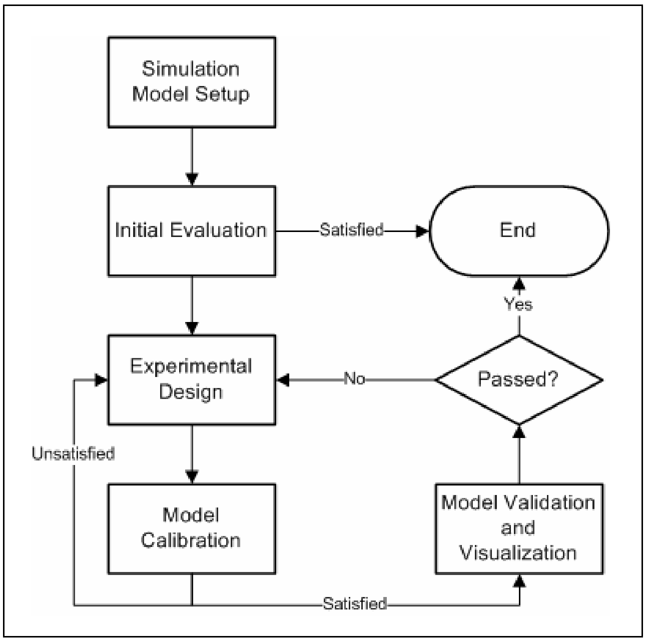

Figure 19: Calibration and Validation Flow Chart

Figure 19 gives an overview of the process and shows the necessity of seeing the calibration process as an iterative process. If the first calibration step doesn't fulfill it's expectations a new experiment has to be designed. It is prudent to select several best fitting parameter combinations for the new experimental design until the calibration achieves a satisfying goodness of fit otherwise potential parameter combination sets could be overlooked by discarding them in an early phase. The goal of the calibration process is to define the optimal parameter input set so that traffic simulator can produce results as close to reality as possible.
Because there is no evacuation field data available, calibration of the model is hardly impossible. The validity of the developed model relies totally on the engineering insight in traffic mechanics.

Validation of the calibrated model is the last step in the process. For the qualitative validation the animations showed by AIMSUN during the Interactive Simulations were reviewed. The quantitative validation traditionally consists of comparing model output to a new data set which has not yet been exposed to the calibration procedure. If satisfactory results can be established on both fronts the calibrated model can be defined as validated. As with the calibration, a proper quantities validation can not be carried out due to the lack of available field data.

5.3.1 Modeling Parameters

In AIMSUN a various set of modeling parameters can be adjusted. Some of these parameters are valid for the whole network, while others can be set on the level of vehicle type or section level. Basically, one set of parameter settings is used for all the simulations. While often default settings are used, some parameters are adjusted specifically for the situation of an emergency evacuation. As stated earlier, evacuees will be panicked and less patient, resulting in a more aggressive driving style compare to normal conditions. Only the most important parameter or adjusted parameter settings, see Table 11, will be discussed in this section.

The percentage overtake and recover are increased, because in this way a smaller speed difference is necessary unit a vehicle will make the decision to overtake.
The maximum number of turning regarding the Look Ahead model is increased, to reduce the number of lost vehicles.
ASAP is the generation model in which vehicles are entered in the network 'as soon as possible', i.e. as soon as there is some space available in the input section. This model is intended to make the most use of the network entrance capacity and is therefore extremely useful for simulating evacuation situations.

Case Study AIMSUN Modeling Parameter Settings			
Parameter	*Default*	*Adjusted*	*Unit*
Car Following			
Car Following Model	4.2	-	
Lane Changing			
Percent Overtake	90	95	%
Percent Recover	95	98	%
On Ramp Model	5.1.0	-	
Look Ahead			
Maximum Number of Turning	2	3	
Simulation Step			
Simulation Step	0.75	-	seconds
Reaction Time			
Reaction Time at stop	1.35	1.00	seconds
Arrivals			
Global Arrivals	-	ASAP	
Route Choice			
Cycle	10	15	minutes
Route Choice Model	-	C-Logit (Dynamic)	
Initial K-SPs	-	3	
Max number to Keep	-	10	
Maximum Number of routes	-	3	
Scale Factor	-	60	
Beta Factor	-	0.01	
Gamma Factor	-	1	

Table 11: Case study AIMSUN modeling parameter settings

The Route Choice model settings will be discussed in section 5.3.2. Also the vehicle characteristics are changed to realize a more aggressive driving style, see Table 12 for these changes (in gray). Main rules regarding these changes are a higher desired speed, faster acceleration, faster deceleration (because of a smaller reaction time), higher speed acceptance and a smaller minimum vehicle distance.

Car Settings Default vs. Changed (gray shaded)					
Name	***Mean***	***Deviation***	***Min***	***Max***	***Units/Info***
Length	4	0.5	3.4	4.6	meters
	-	-	-	-	
Width	2	0	2	2	meters
	-	-	-	-	
Max Desired Speed	110	10	80	150	km/h
	120	10	90	-	
Max Acceleration	3	0.2	2.6	3.4	m/s^2
	3.4	0.05	3.2	3.6	
Normal Deceleration	4	0.25	3.5	4.5	m/s^2
	4.5	-	4	5	
Max Deceleration	6	0.5	5	7	m/s^2
	-	-	-	-	
Speed Acceptance	1.1	0.1	0.9	1.3	
	1.2	-	1	1.4	
Min Distance Vehicle	1	0.3	0.5	1.5	meters
	0.75	0.2	0.3	1.2	
Give Way Time	10	2.5	5	15	secs
	20	-	15	25	
Guidance Acceptance	75	10	65	90	%
	-	-	-	-	

Table 12: Car settings default vs. changed (gray shaded)

5.3.2 C-Logit Route Choice

In AIMSUN Version 5.1.5. four different route choice models are implemented. They are used either when assigning the initial path for a vehicle at the beginning of its trip or when having to decide whether to change path en-route within dynamic modeling or not. These models are the Binomial, Proportional, the Multinomial Logit and the C-Logit models. The user can also define his/her own user-defined route choice model using the function editor. The C-Logit Route Choice model is used for the simulations and it's characteristics are discussed in Appendix 9.4.

The parameters initially chosen for the simulation are listed in Table 11. Because θ is greater than 1, the alternative choices are concentrated in very few routes. Because β is suggested in the shortest routes range $[t_{min}, t_{max}] = [0.0025, 0.0452]$, β is set to 0.01 for all the scenario's. With this low value for β, evacuees are not willing to take a longer and non-overlapping route, however they prefer a shorter and more overlapping route. It is assumed that evacuees will handle that way during an emergency evacuation. The maximum number of routes available is set to 3, assuming that people during an evacuation will choose for familiar routes, which are of course limited.

5.3.3 Replication

AIMSUN is a stochastic simulation model, which rely upon random numbers to release vehicles, assign vehicle type, select their destination and their route, and to determine their behaviors as the vehicles move through the network. Therefore, multiple simulation runs using different seed numbers are required and the median simulation run (based on a user-

specified measure) or the average results of several simulation runs can reflect the average traffic condition of a specific scenario.
In order to determine the required number of replications a calculation is carried out, which is explained in Appendix 9.4. This calculation is based on the student t-distribution and it was found that for almost all the strategies numerous replications, in a range of 3 till 218, are necessary to reach the required confidence interval of 95%. However, only three replications will carried out for each different strategy simulation. Due to time limitations it is not possible to increase this number.

6 Simulation Results and Analyses

In this chapter an overview of the results acquired from the AIMSUN simulations is given. The total simulation results for the different evacuation strategies can be found in Appendix 9.5. The delay time, density, flow, harmonic speed, speed, stop time, stops, total distance traveled, total travel time, evacuation time and lost vehicles from all the different replications are listed. Also average values are calculated and listed for the different evacuation strategy. For each strategy the total travel time is illustrated in a graph.

Final Simulation Result							
	Total Evacuation Time (h)		***Total Travel Time (h)***		***Total Distance Traveled (km)***		***Lost Vehicles #***
Strategy	*Mean Value*	*Std. Dev.*	*Mean Value*	*Std. Dev.*	*Mean Value*	*Std. Dev.*	*Mean Value*
Nearest Exit 1	4.83	0.14	25768.17	1092.63	70855.67	547.10	46279
Nearest Exit 2	5.50	1.39	20489.67	2754.48	70304.83	4423.17	29959
Reference	10.58	1.38	38873.30	7622.39	79975.73	5426.19	36293
Management	5.08	0.63	21334.70	862.13	69844.97	1086.38	29153
Staged 1	6.00	0.43	16809.43	496.58	78004.67	244.47	27318
Staged 2	5.58	0.29	16859.93	42.87	77886.37	1071.98	28390
Contra Flow	5.33	0.52	19699.83	2642.90	66737.03	6135.93	30977
Parked Cars	5.50	0.25	24705.13	846.07	68746.27	1089.03	30336
Signal Control 1	7.58	0.14	22735.60	2146.21	68136.10	3821.18	32133
Signal Control 2	4.67	0.29	23255.73	1358.51	71266.63	597.68	32002
No Control	3.00	0.00	14070.43	669.75	72602.27	1102.52	30056
No Control Fixed	3.00	0.00	13332.5	480.1	63551.4	1514.9	29581
No Control Fixed Best Entrance	6.75	0.00	3657.1	48.5	46249.2	154.0	11785

Table 13: Final Simulation Results

A summary of the simulation results regarding the MOEs described in section 4.4 is listed in Table 13. The result from the pair comparison of the main strategies are illustrated in Figure 20.

It can be concluded that the Reference strategy is not effective at all. Regarding the evacuation time the scores for the rest of the strategies are very tight. The results of the Nearest Exit 1 strategy however, are very unlikely compare to the results provided by the evacuation calculator. The short evacuation time is probably caused by the great loss of vehicles. The Nearest Exit 2 strategy, in which all the six exits are available in stead of four, produces more likely results. After all the Management strategy produces the best evacuation time results.

Regarding the total travel time both Staged strategies show very good results. Figure 36 and Figure 37 in Appendix 9.5.4 also illustrate that the traffic from phase 1, which includes the zones nearest to the emergency, has almost totally left the area after two hours of evacuation.

After all it can be concluded that the Management and both Staged strategies show promising results. Because it will be very difficult to implement an staged evacuation in reality, in a life threatening situation it will be almost impossible to delay people entering the network, the Management strategy is the most effective.

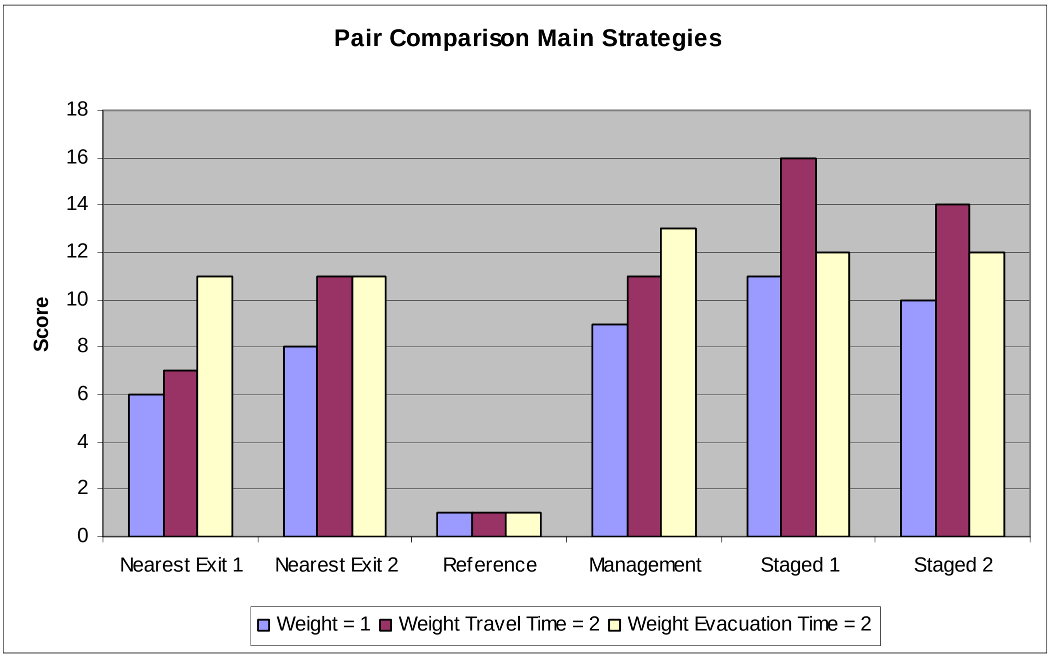

Figure 20: Pair comparison main strategies

As stated in section 3.3.5 three additional sub-strategies are add to the most effective main strategy. The results of the pair comparison of these strategies are illustrated in Figure 21. These results show that the availability of Parked Cars in the network will have a major negative effect on the effectiveness of the strategy. The effect of Signal Control 1 is even more negative, probably caused by the large disturbance of the optimized signal control plan. The Contra Flow and Signal Control 2 strategy are providing good results regarding total travel time and evacuation time respectively.
However, the No Control strategy is the most effective one for every weight configuration. The evacuation time is reduced to 3 hours, almost equal to the trip end calculation, and also the total travel time is reduced significant. A closer look to the 'Interactive Simulation' in AIMSUN shows very dangerous turn and merge actions made by vehicles. Initially both traffic lights and behavior characteristics influence this behavior. The absence of traffic lights results however in this dangerous behavior, which indicates that the behavior and vehicle parameters are not accurate.
Finally, the results indicate that the most effective strategy is to get rid of the actually signal control plan. It is probably better to develop a special signal control plan or control the traffic in a different way.

Two complementary sub-strategies are finally carried out to gain more insight into the limitations of the chosen C-Logit route choice model. Although only converging and some diverging traffic flows should appear because trips are distributed regarding the shortest path. A closer look to the 'Interactive Simulation' in AIMSUN indicates that many diverging and crossing traffic flows appear. Probably this is caused by the C-Logit route choice model which calculated new shortest routes every 15 minutes. The Fixed route choice model is static, calculates only once the shortest routes at the beginning of the simulation, and uses only one shortest route for each OD-pair. The No Control Fixed strategy shows better results, but not significant. Also the 'Interactive Simulation' still indicates many crossing and diverging traffic flows.
Initially, an equal and fixed percentage of vehicles is distributed over the origin centroid connectors. As a result of this some vehicles needs to make a detour to finally reach their

desired shortest route. To avoid this problem only the best origin centroid connectors are used in the final strategy; No Control Fixed Best Entrance. This strategies shows an significant decrease in total travel time, total distance traveled and lost vehicles. However, the total evacuation time is more than doubled up to 6.75 hour. A promising results however is that this delay is almost totally caused by a fraction of the evacuation traffic, indicated by the long flat tail of the graph in Figure 44 in Appendix 9.5.8. Closer research to the simulation results shows that this fraction almost totally consist of traffic from the TAZs 117 and 118. Specific measures to improve the evacuation of those two areas will probably decrease the evacuation time significant. Also the 'Interactive Simulation' indicates only converging and some diverging traffic flows.
Although these last two strategies are not close to the reality, because evacuees will not restrict themselves to only one (congested) route, they give a good impression of the network's possibilities.

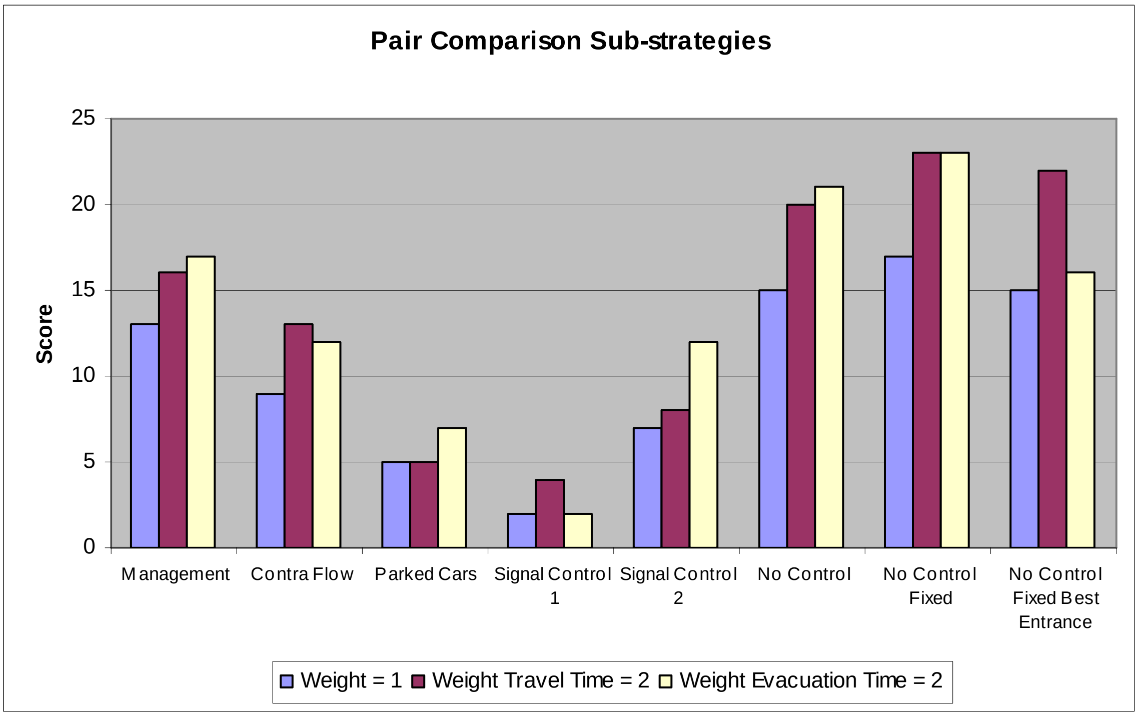

Figure 21: Pair comparison sub-strategies

7 Conclusion and Recommendations

For the Baltimore City Center initially four evacuation strategies are developed (Nearest Exit, Reference, Management, Staged) resulting in 12 sub-strategies. The trip end calculation found out that the evacuation of the area at least will take 2 hours and 52 minutes. The evacuation calculator calculated 17 hours and 40 minutes, 3 hours and 20 minutes, and 4 hours and 20 minutes of evacuation time for the nearest exit, management and reference strategy respectively.

Finally the different strategies / sub-strategies are implemented in the developed simulation model. This microscopic dynamic model contains only the mail arterial roads of the area, 22 origin zones, 12 exit roads leading to 6 safe destination zones, a 9:00 AM traffic demand and a fixed PM-peak control plan. Parameters for route choice and human behavior are set to emergency evacuation driver behavior. Due to the unavailability of emergency evacuation field data and sufficient time, quantitative calibration of the model was not possible. However with the result produced by the model the different strategies can be compared, which is sufficient regarding the goal of this research.

Pair comparison of the results from the different strategies regarding the three Measures of Effectiveness (evacuation time, total travel time and lost vehicles) concluded the management strategy as the most effective one. This strategy results in an evacuation time of 5.08 hours with a total travel time of 21335 hours. The staged evacuation time shows promising results, regarding the low total travel time of 16809 hours and it's ability to evacuate the people nearest to the disaster first.

Initially parked cars were not implemented in the simulation model. Implementation of the sub-strategy Parked Cars on the Management strategy, illustrated the major effect of road capacity decrease due to this phenomenon. The evacuation time increased with almost half an hour and the total travel time increased with more than 4500 hours. Signal control changes and the implementation of a contra flow operation didn't provide satisfying results. The first sub-strategy only illustrated the effect of the disturbance of an optimized signal control plan. However, removal of the signal control plan causes a substantial effectiveness increase. The No Signal Control strategy results in an total evacuation time of only 3 hours.

Finally two strategies with different route choice model (fixed) and origin centroid connector configuration (best entrance) are implemented. The use of only the best entrance point per TAZ and only one shortest route per OD-pair shows the desired traffic flow pattern (no crossing and only converging and some diverging traffic flows) and promising results regarding all the MOEs. Although this strategy is not close to reality, because evacuees will not restrict themselves to only one (congested) route, it gives a good impression of the network's possibilities.

The Management strategy, in which traffic is distributed to the exits regarding their capacity and with reduction of travel distance, is recommend as most effective. The Staged strategy showed really promising results regarding evacuation in case of a chemical disaster, because it is able to evacuate people nearest to the disaster first, which has a positive effect on the total exposure time. However the staged evacuation strategy showed promising results, the strategy will be almost impossible to implement in reality. Without the total assurance that an staged evacuation is better for everybody, evacuees are not willing to wait in a life threatening situation like a chemical disaster. This aspect should be taken into account within further research to staged evacuations.

The sub-strategy No Control additional to the Management strategy is the most effective. Therefore it is recommended to do further research to this strategy or to the development of a strategy with a specific evacuation signal control plan.

Because the No Control Fixed Best Entrance sub-strategy shows the desired traffic flow pattern (no crossing and only converging and some diverging traffic flows) and promising results regarding all the MOEs, it should be recommend to develop evacuation strategies which uses a limited number of zonal best entrance points and shortest routes per OD-pair. However, these strategies are not very close to reality, but better results can probably obtained by implementing a more detailed zonal configuration.

As stated in the report the initial objective function was to determine a system optimal evacuation strategy. Measure of Effectiveness for this objective function is an equal exposure time for all the evacuees. In this case it will be interesting to know the total evacuation time for the different origin zones alone. However, especially due to time limitations, it was not possible to extract this information from the generated databases. For further research it would be interesting to extract this information from the database and use a fourth Measure of Effectiveness in the comparison.

Afterwards the research it was concluded that a different problem approach would be more appropriate and probably lead to different results, conclusions and recommendation. Bottom-line regarding this approach is to reduce the total travel time in threatened area. A brief overview of this approach and its assumed influences on the obtained results is added to Appendix 9.6.

Furthermore, to provide more reliable results which are closer to reality better calibration of the model is inevitable. As with most of the emergency evacuation research this is very difficult because of the unavailability of field evacuation data. However, it is very likely that this sort of data will become available in the future, because of it's importance and the still growing technological development. Till then we need to make assumptions to model the very uncertain process of evacuation, due to unforeseen events like traffic accident and the difficulty to control human behavior.

However, a sensitiveness analyses can give more insight into the effect of changes in driver behavior parameters on the final simulation results. Comparing the results from different parameter settings with the results under normal conditions gives not only an indication for the most suitable behavior parameter settings, it also gives a model validity indication. If results from certain parameter settings are totally different than logically can be expected, question marks regarding the model validity are appropriate. Due to time limitations it was not possible to carry out a sensitiveness analyses. In an approach to better simulate panicked driver behavior, some model parameters are adjusted. The validity of these changes and the final results can only been proven with a sensitiveness analyses. Both calibration of the model and a sensitiveness analyses regarding the different model parameters are strongly recommended to increase the model validity.

Also more than three replications should be carried out to reach the required confidence interval for the obtained results. According to the calculations, replications in a range of 3 till 218 should be carried.

Further development of the PACER model should not only focus on the traditional uncertainties like human behavior, traffic demand, response, accidents, etc. Especially in an no-notice emergency evacuation recourses like personnel, equipment and communication facilities will be very limited and there will be no time to wait for them. Integrating these aspects into the model will finally lead to better and more useful evacuation strategies.

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9 Appendix

9.1 Trip Production

To calculate the trip productions, especially data from the Community Profile – RPD 118 (BMC, 2006) and the Baltimore CBD Trip Characteristics (BMC, 2003) was used. For this last one, BMC collected occupancy and classification counts of vehicles entering the Baltimore Central Business Districts (CBD; also known as RPD 118) between 7:00 AM and 9:00 AM on an average weekday (Tuesday through Thursday) between April and July of 2003.
In the trip production calculation a distinction is made between Activity/Not Live in CBD trips, Activity/Live in CBD trips, No-Activity/Live in CBD trips.

9.1.1 Activity/Not Live in CBD

This are person trips from people who are present in CBD for an activity but not live there. As stated earlier it is assumed that people who are using the metro or light rail to enter the research area, will also use it for the evacuation. Because both metro and light rail end up far to the north of the city centre. People who are using the bus system to enter the area are expected to take the bus for evacuation. However, a total public transport system will not be integrated in the simulation network, but bus trips will be taken into account in the total traffic demand.

Total Transit Trips Entering CBD						
Transit Mode	*7:00-7:30*	*7:30-8:00*	*8:00-8:30*	*8:30-9:00*	***Total Trips***	*Transit Pct.*
Heavy Rail (METRO)	1604	1582	2566	1903	**7655**	40.01%
Light Rail	575	792	701	683	**2751**	14.38%
MTA Bus	2070	2092	2621	1946	**8729**	45.62%
Total Transit Trips	**4249**	**4466**	**5888**	**4532**	**19135**	**100,00%**

Table 14: Total transit trips entering CBD (BMC, 2003)

Total Person Trips Entering CBD						
Mode	*7:00-7:30*	*7:30-8:00*	*8:00-8:30*	*8:30-9:00*	***Total Trips***	Mode Pct.
Transit	4249	4466	5888	4532	**19135**	21.68%
Motor Vehicle (Driver + Passengers)	14264	18373	18809	17661	**69123**	78.32%
Total Person Trips	**18513**	**22839**	**24697**	**22193**	**88258**	**100.00%**

Table 15: Total person trips entering CBD (BMC, 2003)

Vehicle Occupancy CBD Summary							
Vehicle Occupancy	*7:00-7:30*	*7:30-8:00*	*8:00-8:30*	*8:30-9:00*	***Tot. Veh.***	*Tot. Occ.*	*Pct. Occ.*
1-Occupant	10310	13217	13374	12268	**49169**	49169	71.10%
2-Occupant	1690	2223	2305	2238	**8456**	16912	24.50%
3-Occupant	130	170	185	211	**696**	2088	3.00%
4+Occupant	46	50	71	71	**238**	952	1.40%
Total Occupants	14264	18373	18823	17661		69121	100.00%
Total Above Vehicles	**12176**	**15660**	**15935**	**14788**	**58559**		
Total Occupants Ration	1.17	1.17	1.18	1.19		1.18	

Table 16: Vehicle occupancy CBD summary (BMC, 2003)

Summary of Vehicle Classification Data CDB						
Vehicle Classification	*7:00-7:30*	*7:30-8:00*	*8:00-8:30*	*8:30-9:00*	***Tot. Veh.***	*Pct.*
Total Motorcycles	20	13	21	18	**72**	0.10%
Total Autos	8460	11278	11447	10452	**41637**	67.90%
Total SUVs, Pickups, Vans	3696	4369	4467	4318	**16850**	27.50%
Total Buses	203	206	212	178	**799**	1.30%
MTA Buses	106	117	113	85	**421**	0.70%
Tourist & Other Buses	97	89	99	93	**378**	0.60%
Total Trucks	388	482	510	548	**1928**	3.10%
Light Trucks 4-Wheels	87	83	71	87	**328**	0.50%
Light Trucks 6-Wheels	176	271	324	337	**1108**	1.80%
Medium Trucks 3 Axles	78	82	67	81	**308**	0.50%
Medium Trucks 4 Axles	8	11	8	6	**33**	0.10%
Heavy Trucks 5+ Axles	39	35	40	37	**151**	0.20%
Grand Total all Vehicles	**12767**	**16348**	**16657**	**15514**	**61286**	**100.00%**

Table 17: Summary of vehicle classification data CBD (BMC, 2003)

Total Person Trips into CBD	*1997*		*2000*		*2003*	
Travel Modes	*No.*	*Pct.*	*No.*	*Pct.*	*No.*	*Pct.*
Transit Trips	20717	22%	*19887*	21%	19135	22%
Motor Vehicle Driver Trips	60484	64%	64320	66%	58560	66%
Motot Vehicle Pass. Trips	13007	14%	12987	13%	10563	12%
Total Person Trips into CBD	**94208**	**100,00%**	**97194**	**100%**	**88258**	**100,00%**

Table 18: Total person trips into CBD (BMC, 2003)

Projections for Transportation Analyses Zones (TAZs) CBD									
TAZ	***Population***		***Pct.***	***Families***		***Pct.***	***Employment***		***Pct.***
	2005	*2030*	*2005*	*2005*	*2030*		*2005*	*2030*	*2005*
114	165	375	0,93%	67	153	0,67%	5289	5397	3,68%
115	126	135	0,71%	85	94	0,85%	4548	4632	3,17%
116	0	0	0,00%	0	0	0,00%	5185	5185	3,61%
117	20	340	0,11%	3	128	0,03%	11811	11814	8,23%
118	638	2205	3,61%	107	387	1,07%	17400	18110	12,12%
119	0	0	0,00%	0	0	0,00%	4748	5465	3,31%
120	18	21	0,10%	102	524	1,02%	2814	3239	1,96%
121	0	0	0,00%	0	0	0,00%	2736	2879	1,91%
122	0	0	0,00%	0	0	0,00%	9128	9128	6,36%
123	393	1085	2,22%	294	847	2,93%	12197	12452	8,50%
124	713	1174	4,03%	347	720	3,46%	2227	2227	1,55%
125	185	1036	1,05%	100	581	1,00%	7957	7957	5,54%
126	801	934	4,53%	589	717	5,88%	5389	5389	3,75%
127	1519	1710	8,59%	861	997	8,59%	4450	445	3,10%
128	519	571	2,94%	128	136	1,28%	5535	5535	3,86%
129	306	499	1,73%	96	239	0,96%	14668	15237	10,22%
130	1848	1962	10,45%	1271	1404	12,68%	1108	1108	0,77%
131	1008	887	5,70%	686	630	6,84%	2678	2678	1,87%
132	103	105	0,58%	73	78	0,73%	1663	1684	1,16%
133	1360	1708	7,69%	1012	1326	10,10%	4848	4848	3,38%
134	2032	1871	11,50%	1225	1125	12,22%	3908	3908	2,72%
135	1604	1745	9,07%	775	877	7,73%	1982	1982	1,38%
136	434	1097	2,46%	177	448	1,77%	1819	1823	1,27%

137	532	468	3,01%	285	262	2,84%	1186	1188	0,83%
138	2097	1952	11,86%	1106	1016	11,04%	2040	3074	1,42%
139	262	266	1,48%	153	162	1,53%	4425	4990	3,08%
140	888	903	5,02%	406	431	4,05%	616	705	0,43%
141	105	106	0,59%	74	79	0,74%	1204	1378	0,84%
Total	**17676**	**23155**	**100,00%**	**10022**	**13361**	**100,00%**	**143559**	**148462**	**100,00%**

Table 19: Projections for Transportation Analyses Zones (TAZs) CBD (BMC, 2006)

Because Activity/Not Live in CBD based traffic will have strong interrelation with employment, an Activity/Not Live in CBD vehicle classification data Table for the different TAZs, see Table 20, can be made by multiplying Employment Percentage 2005 from Table 19 with the Total Vehicles from Table 17. The values in Table 20 are rounded up, which explains the little difference between the Totals in Table 17.

Activity/Not Live in CBD Vehicle Classification Data													
TAZ	***Total Motorcycles***	***Total Autos***	***Total SUVs***	***Total Buses***	*MTA Buses*	*Tourist Buses*	***Total Trucks***	*Light Trucks 4-Wheels*	*Light Trucks 6-Wheels*	*Medium Trucks 3 Axles*	*Medium Trucks 4 Axles*	*Heavy Trucks 5+ Axles*	***Grand Total All Vehicles***
114	3	1534	621	30	16	14	72	13	41	12	2	6	**2260**
115	3	1320	534	26	14	12	62	11	36	10	2	5	**1945**
116	3	1504	609	29	16	14	70	12	41	12	2	6	**2215**
117	6	3426	1387	66	35	32	159	27	92	26	3	13	**5044**
118	9	5047	2043	97	52	46	234	40	135	38	4	19	**7430**
119	3	1378	558	27	14	13	64	11	37	11	2	5	**2030**
120	2	817	331	16	9	8	38	7	22	7	1	3	**1204**
121	2	794	322	16	9	8	37	7	22	6	1	3	**1171**
122	5	2648	1072	51	27	25	123	21	71	20	3	10	**3899**
123	7	3538	1432	68	36	33	164	28	95	27	3	13	**5209**
124	2	646	262	13	7	6	30	6	18	5	1	3	**953**
125	4	2308	934	45	24	21	107	19	62	18	2	9	**3398**
126	3	1563	633	30	16	15	73	13	42	12	2	6	**2302**
127	3	1291	523	25	14	12	60	11	35	10	2	5	**1902**
128	3	1606	650	31	17	15	75	13	43	12	2	6	**2365**
129	8	4255	1722	82	44	39	197	34	114	32	4	16	**6264**
130	1	322	131	7	4	3	15	3	9	3	1	2	**476**
131	2	777	315	15	8	8	36	7	21	6	1	3	**1145**
132	1	483	196	10	5	5	23	4	13	4	1	2	**713**
133	3	1407	570	27	15	13	66	12	38	11	2	6	**2073**
134	2	1134	459	22	12	11	53	9	31	9	1	5	**1670**
135	1	575	233	12	6	6	27	5	16	5	1	3	**848**
136	1	528	214	11	6	5	25	5	15	4	1	2	**779**
137	1	344	140	7	4	4	16	3	10	3	1	2	**508**
138	2	592	240	12	6	6	28	5	16	5	1	3	**874**
139	3	1284	520	25	13	12	60	11	35	10	2	5	**1892**

140	1	179	73	4	2	2	9	2	5	2	1	1	**266**
141	1	350	142	7	4	4	17	3	10	3	1	2	**517**
Total	**85**	**41650**	**16866**	**811**	435	392	**1940**	342	1125	323	50	164	**61352**

Table 20: Activity/Not Live in CBD vehicle classification data

9.1.2 Activity/Live in CBD

This are person trips from people who are present in CBD for an activity and also live there. According to BMC (2000) 2.5% of the workers origin in CBD is CBD itself. Multiplying this percentage with the total person trips results in 2206 extra person trips. By using the percentages from Table 14 and Table 15, it is assumed that these percentages are valid for CBD, the number of vehicles can be calculated, see Table 21.

The number of busses is calculated by using a occupancy factor of 21 trips per bus. This number is derived from MTA Bus figures in Table 14 and Table 17. The total number of motorcycles is set to zero.

Activity/Live in CBD Vehicles		
	No.	*Vehicles*
Extra Trips	2206	
Transit Trips	**478**	
Heavy Rail (METRO)	192	
Light Rail	69	
MTA Bus	219	**11**
Motor Vehicle Trips (+ passenger)	**1728**	
Vehicles (Tot. Occ. Rat. = 1,18)	1464	
Total Motorcycles	2	**0**
Total Autos	1042	**1042**
Total SUVs, Pickups, Vans	422	**422**

Table 21: Activity/Live in CBD vehicles

Together with the Employment Percentage 2005 from Table 19 the Activity/Live in CBD vehicle classification data Table for the different TAZs can be produced, see Table 22.

Activity/Live in CBD Vehicle Classification Data					
TAZ	*Total Motor-cycles*	*Total Autos*	*Total SUVs*	*MTA Buses*	*Grand Total All Vehicles*
114	0	39	16	1	**56**
115	0	34	14	1	**49**
116	0	38	16	1	**55**
117	0	86	35	1	**122**
118	0	127	52	2	**181**
119	0	35	14	1	**50**
120	0	21	9	1	**31**
121	0	20	9	1	**30**
122	0	67	27	1	**95**
123	0	89	36	1	**126**
124	0	17	7	1	**25**
125	0	58	24	1	**83**
126	0	40	16	1	**57**
127	0	33	14	1	**48**

128	0	41	17	1	**59**
129	0	107	44	2	**153**
130	0	9	4	1	**14**
131	0	20	8	1	**29**
132	0	13	5	1	**19**
133	0	36	15	1	**52**
134	0	29	12	1	**42**
135	0	15	6	1	**22**
136	0	14	6	1	**21**
137	0	9	4	1	**14**
138	0	15	6	1	**22**
139	0	33	14	1	**48**
140	0	5	2	1	**8**
141	0	9	4	1	**14**
Total	**0**	**1059**	**436**	**30**	**1525**

Table 22: Activity/Live in CBD vehicle classification data

9.1.3 No-Activity/Live in CBD

This are person trips from people who are present in CBD because they live there. According to Table 19 the population of CBD in 2005 is 17676, divided over 10022 households/families. Because the total population needs to be evacuated, this will lead to 17676 trips. However, not all the people will be home during an evacuation.
First a certain amount of people who are living in CBD will not be home because of work in CBD itself. In section 9.1.2 we found that this is equal to 2206 trips. There is also a certain amount of people in a different area for work. According to BMC (2006) the total labor force of the population in 2000 was 9079. With a growth rate of 6.6% from 1990 to 2000 we assume a growth rate of 3.3% over the period 2000 – 2005. A total labor force of 9379 was found for 2005.
Assuming no unemployment and other activities, there are still 8297 people at home in CBD. Because people will evacuate as a group, it is important to know over how many households/families these people are divided. According to BMC (2006) every household in 2005 contained an average of 1.52 people. This results in a total of 5459 households.
From CTPP (2000) the vehicle availability for households in Baltimore City for 2005 can be derived, see Table 23.

Household Vehicle Availability Baltimore City								
	1990		***2000***		***Changes 1990/2000***		***2005 (estimated)***	
Vehicles Available	*No*	*Pct.*	*No.*	*Pct.*	*No.*	*Pct.*	*No.*	*Pct.*
Total households	275977	100.0	257788	100.0	-18189	-6.6	249281	100.0
No vehicle available	102985	37.3	90908	35.3	-12077	-11.7	85590	34.3
1 vehicle available	101813	36.9	104387	40.5	2574	2.5	105692	42.4
2 vehicles available	56234	20.4	49615	19.2	-6619	-11.8	46688	18.7
3 vehicles available	12074	4.4	10250	4.0	-1824	-15.1	9476	3.8
4 vehicles available	2332	0.8	1850	0.7	-482	-20.7	1659	0.7
5 or more vehicles available	539	0.2	778	0.3	239	44.3	950	0.4
Mean vehicles per household	0.95	(X)	0.95	(X)	>0	(X)	0.96	(X)

Table 23: Household vehicle availability Baltimore City

According this, assuming if there is more than one vehicle available the family will use only one vehicle and families without a car will use the bus, this will result in 3587 auto's and

2842 bus trips. Together with the population percentages in Table 19, a SUV percentage of 29.16 and a bus occupation of 21, this will result in the vehicle classification data illustrated in Table 24.

No-Activity/Live in CBD Vehicle Classification Data					
TAZ	***Total Motor- cycles***	***Total Autos***	***Total SUVs***	***MTA Buses***	***Grand Total All Vehicles***
114	0	24	10	1	**35**
115	0	19	8	1	**28**
116	0	0	0	0	**0**
117	0	3	2	1	**6**
118	0	92	38	4	**134**
119	0	0	0	0	**0**
120	0	3	2	1	**6**
121	0	0	0	0	**0**
122	0	0	0	0	**0**
123	0	57	24	2	**83**
124	0	103	43	4	**150**
125	0	27	11	1	**39**
126	0	116	48	5	**169**
127	0	219	90	8	**317**
128	0	75	31	3	**109**
129	0	44	19	2	**65**
130	0	266	110	10	**386**
131	0	145	60	6	**211**
132	0	15	7	1	**23**
133	0	196	81	7	**284**
134	0	292	121	11	**424**
135	0	231	95	9	**335**
136	0	63	26	3	**92**
137	0	77	32	3	**112**
138	0	302	125	11	**438**
139	0	38	16	2	**56**
140	0	128	53	5	**186**
141	0	16	7	1	**24**
Total	**0**	**2551**	**1059**	**102**	**3712**

Table 24: No-Activity/Live in CBD vehicle classification data

9.1.4 Total vehicles in CBD

The vehicle classification data from the different situations together (Activity/Not Live in CBD, Activity/Live in CBD, No-Activity/Live in CBD) results in the total vehicle classification data in CBD, see Table 25.

Total Vehicle Classification Data						
TAZ	***Total Motor-cycles***	***Total Autos***	***Total SUVs***	***Total Buses***	***Total Trucks***	***Grand Total All Vehicles***
114	3	1597	647	32	72	**2351**
115	3	1373	556	28	62	**2022**
116	3	1542	625	30	70	**2270**
117	6	3515	1424	68	159	**5172**
118	9	5266	2133	103	234	**7745**
119	3	1413	572	28	64	**2080**

120	2	841	342	18	38	**1241**
121	2	814	331	17	37	**1201**
122	5	2715	1099	52	123	**3994**
123	7	3684	1492	71	164	**5418**
124	2	766	312	18	30	**1128**
125	4	2393	969	47	107	**3520**
126	3	1719	697	36	73	**2528**
127	3	1543	627	34	60	**2267**
128	3	1722	698	35	75	**2533**
129	8	4406	1785	86	197	**6482**
130	1	597	245	18	15	876
131	2	942	383	22	36	1385
132	1	511	208	12	23	755
133	3	1639	666	35	66	2409
134	2	1455	592	34	53	2136
135	1	821	334	22	27	1205
136	1	605	246	15	25	**892**
137	1	430	176	11	16	**634**
138	2	909	371	24	28	**1334**
139	3	1355	550	28	60	**1996**
140	1	312	128	10	9	**460**
141	1	375	153	9	17	**555**
Total	85	45260	18361	943	1940	66589
Total	**75**	**39295**	**15933**	**800**	**1720**	**57823**

Table 25: Total Vehicle Classification Data

9.2 Evacuation Calculator

The legend for Figure 22 to Figure 29 is listed in Table 26.

Evacuation Calculator Graph Legend	
X-ax	Time in hours
Y-ax	PCU
Red line	Arrival
Green line	Departure

Table 26: Evacuation Calculator graph legend

9.2.1 Nearest Exit

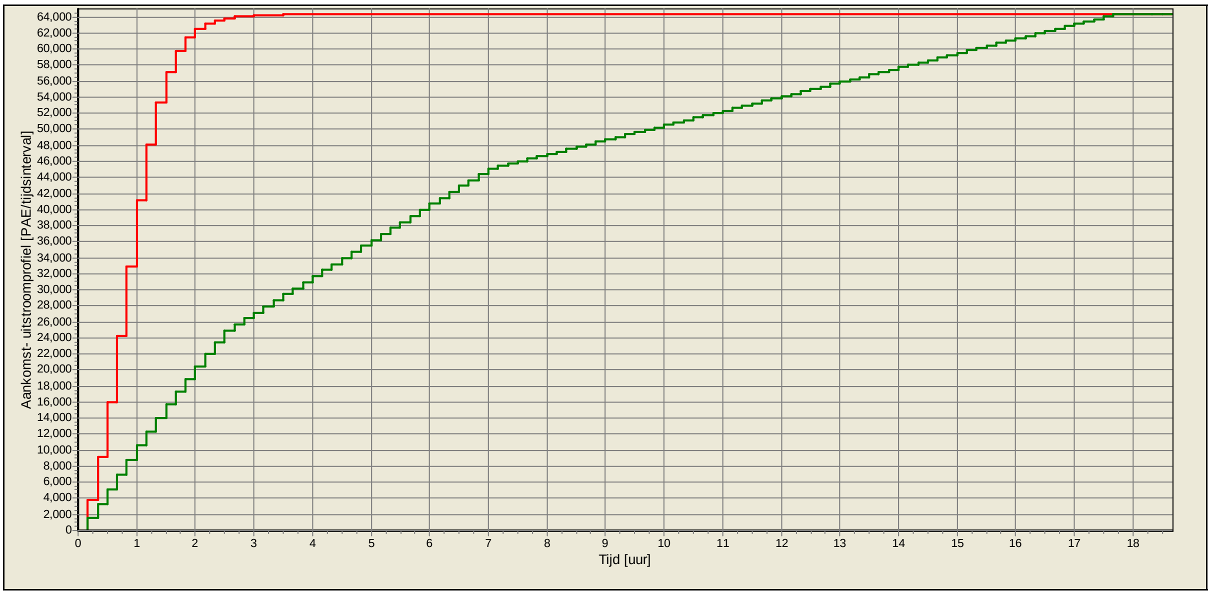

Figure 22: Cumulative Arrival-Departure Profile Nearest Exit all Categories

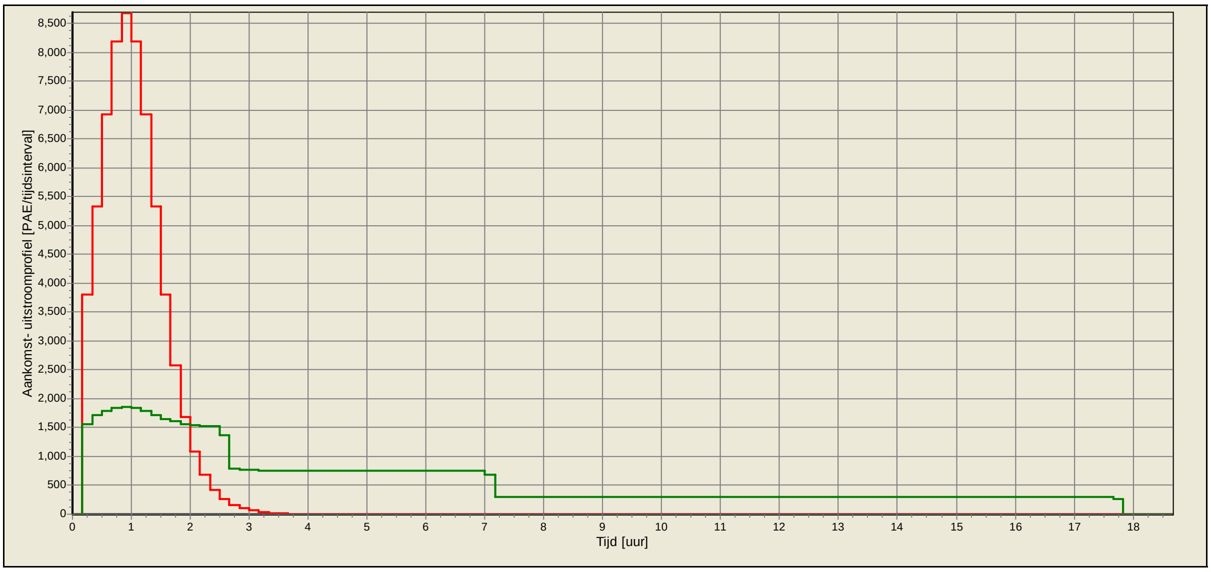

Figure 23: Arrival-Departure Profile Nearest Exit all Categories

		Nearest Exit OD-matrix						
		Exit 1	*Exit 2*	*Exit 2*	*Exit 4*	*Exit 5*	*Exit 6*	*Total*
TAZ	*114*					2616		**2616**
	115						2250	**2250**
	116						2526	**2526**
	117						5754	**5754**
	118						8613	**8613**
	119						2314	**2314**
	120						1382	**1382**
	121						1337	**1337**
	122						4443	**4443**
	123			6024				**6024**
	124		1254					**1254**
	125		3915					**3915**
	126			2811				**2811**
	127		2517					**2517**
	128		2817					**2817**
	129		7209					**7209**
	136						993	**993**
	137						705	**705**
	138						1478	**1478**
	139						2221	**2221**
	140		511					**511**
	141		619					**619**
	Total	**0**	**18842**	**8835**	**0**	**2616**	**34015**	**64308**

Table 27: Nearest Exit OD-matrix (PCU)

9.2.2 Traffic management

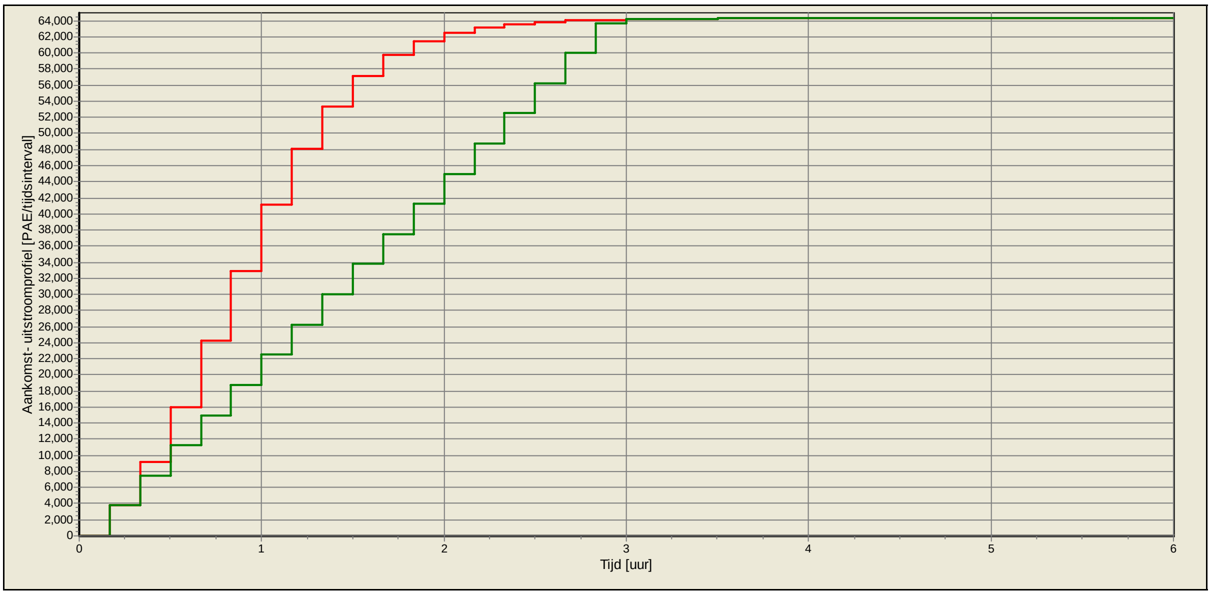

Figure 24: Cumulative Arrival-Departure Profile Management all Categories

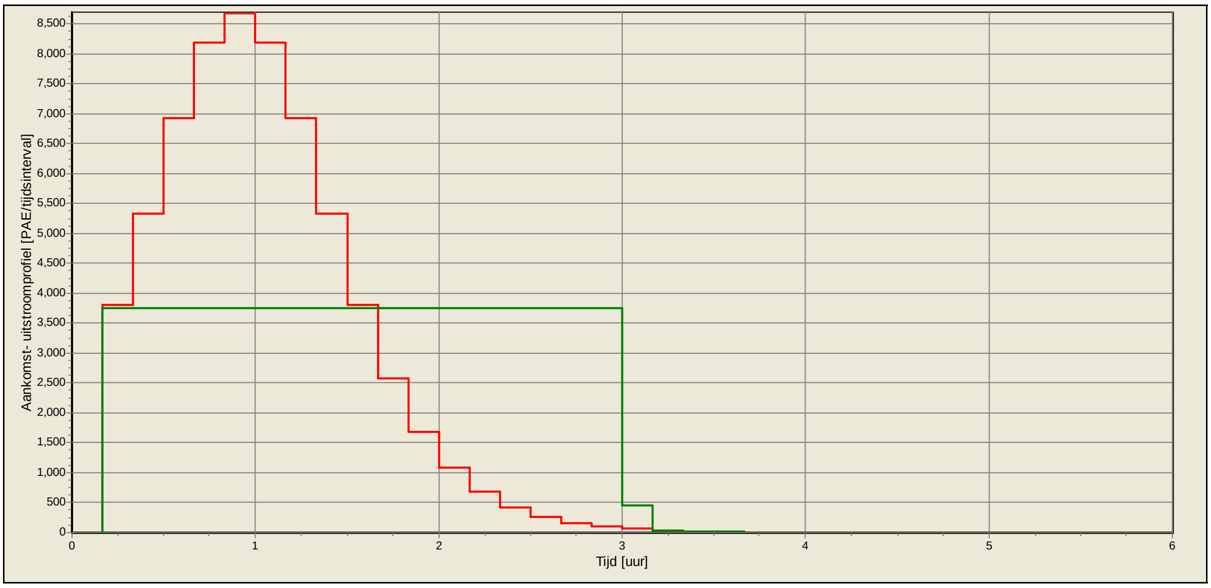

Figure 25: Arrival-Departure Profile Management all Categories

		Management OD-matrix						
		Exit 1	*Exit 2*	*Exit 2*	*Exit 4*	*Exit 5*	*Exit 6*	*Total*
TAZ	*114*				2616			**2616**
	115			2251				**2251**
	116						2526	**2526**
	117				3134		2619	**5754**
	118				284	8330		**8613**
	119				2314			**2314**
	120					1382		**1382**
	121				1337			**1337**
	122			3513		929		**4443**
	123	1706	31	4287				**6024**
	124		1254					**1254**
	125		3915					**3915**
	126			2811				**2811**
	127		2517					**2517**
	128	2817						**2817**
	129	7209						**7209**
	136				993			**993**
	137				705			**705**
	138				1478			**1478**
	139					2221		**2221**
	140	511						**511**
	141	619						**619**
	Total	**12862**	**7717**	**12862**	**12862**	**12862**	**5145**	**64308**

Table 28: Management OD-matrix (PCU)

9.2.3 Reference

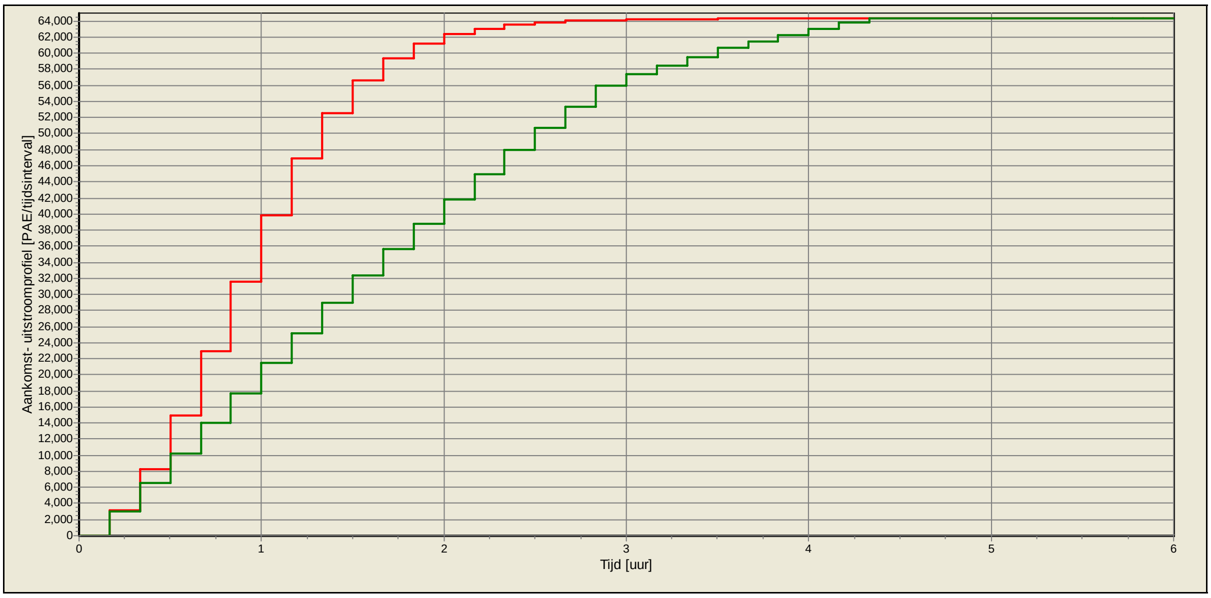

Figure 26: Cumulative Arrival-Departure Profile Reference all Categories

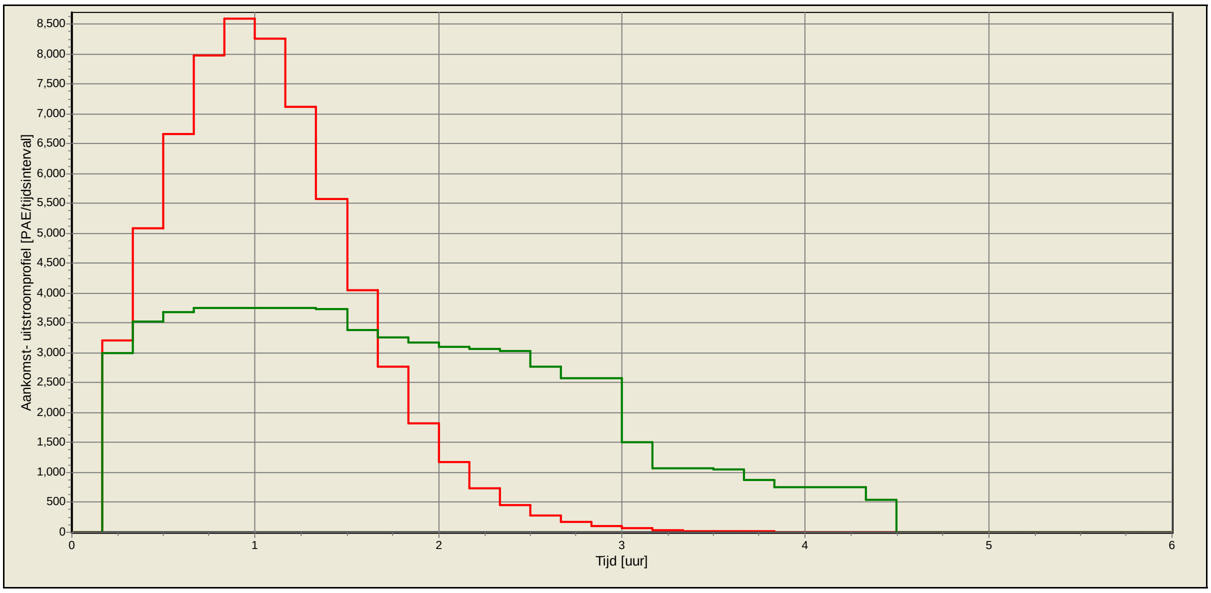

Figure 27: Arrival-Departure Profile Reference all Categories

		Reference OD-matrix						
		Exit 1	***Exit 2***	***Exit 2***	***Exit 4***	***Exit 5***	***Exit 6***	***Total***
TAZ	*114*	523	262	262	785	523	262	**2616**
	115	450	225	225	675	450	225	**2250**
	116	505	253	253	758	505	253	**2526**
	117	1151	575	575	1726	1151	575	**5754**
	118	1723	861	861	2584	1723	861	**8613**
	119	463	231	231	694	463	231	**2314**
	120	276	138	138	415	276	138	**1382**
	121	267	134	134	401	267	134	**1337**
	122	889	444	444	1333	889	444	**4443**
	123	1205	602	602	1807	1205	602	**6024**
	124	251	125	125	376	251	125	**1254**
	125	783	392	392	1175	783	392	**3915**

	126	562	281	281	843	562	281	**2811**
	127	503	252	252	755	503	252	**2517**
	128	563	282	282	845	563	282	**2817**
	129	1442	721	721	2163	1442	721	**7209**
	136	199	99	99	298	199	99	**993**
	137	141	70	70	211	141	70	**705**
	138	296	148	148	443	296	148	**1478**
	139	444	222	222	666	444	222	**2221**
	140	102	51	51	153	102	51	**511**
	141	124	62	62	186	124	62	**619**
	Total	**12862**	**6431**	**6431**	**19292**	**12862**	**6431**	**64308**

Table 29: Reference OD-matrix (PCU)

9.2.4 Contra Flow

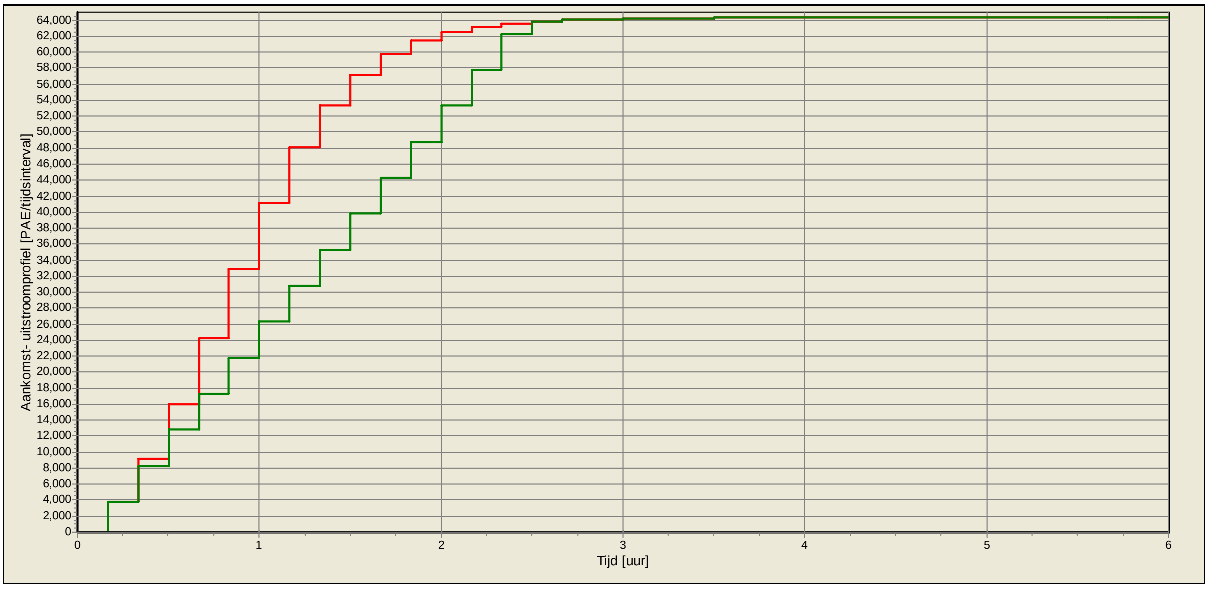

Figure 28: Cumulative Arrival-Departure Profile Contra Flow all Categories

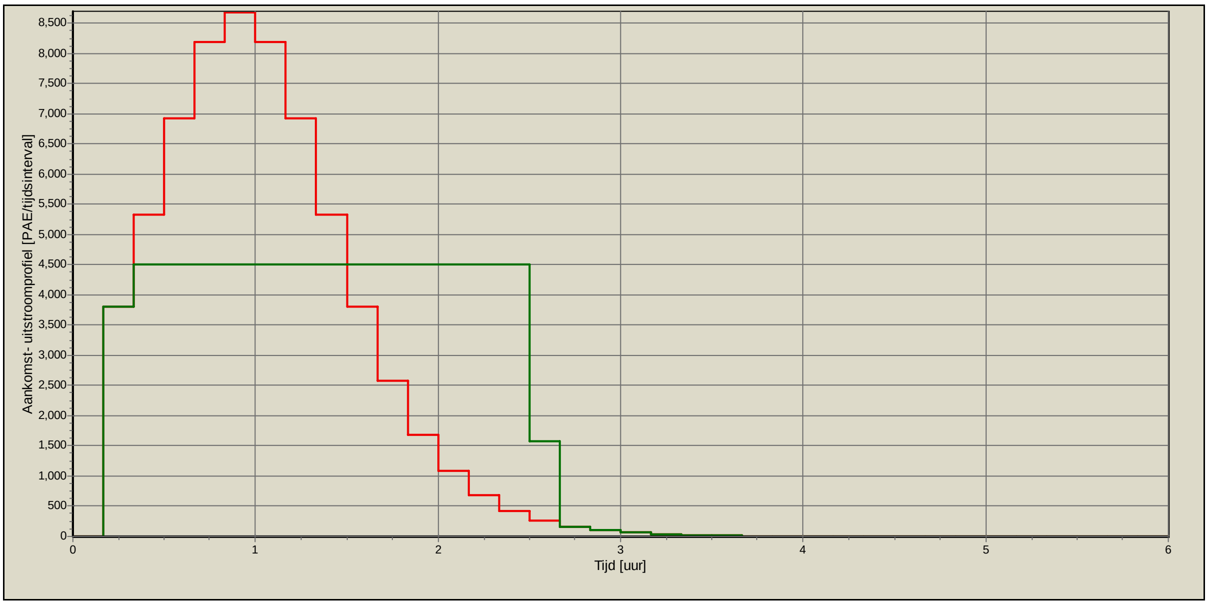

Figure 29: Arrival-Departure Profile Contra Flow all Categories

		Contra Flow OD-matrix						
		Exit 1	*Exit 2*	*Exit 3*	*Exit 4*	*Exit 5*	*Exit 6*	*Total*
TAZ	*114*				2616			**2616**
	115			1230		1021		**2250**
	116						2526	**2526**
	117				5754			**5754**
	118				2895	5718		**8613**
	119				2314			**2314**
	120					719	663	**1382**
	121				1337			**1337**
	122				3344		1099	**4443**
	123			6024				**6024**
	124		1254					**1254**
	125		3262	654				**3915**
	126			2811				**2811**
	127		1478			1039		**2517**
	128	2817						**2817**
	129	7209						**7209**
	136				993			**993**
	137				705			**705**
	138				1478			**1478**
	139					2221		**2221**
	140	511						**511**
	141	181	438					**619**
	Total	**10718**	**6431**	**10718**	**21436**	**10718**	**4287**	**64308**

Table 30: Contra Flow OD-matrix (PCU)

9.3 Network

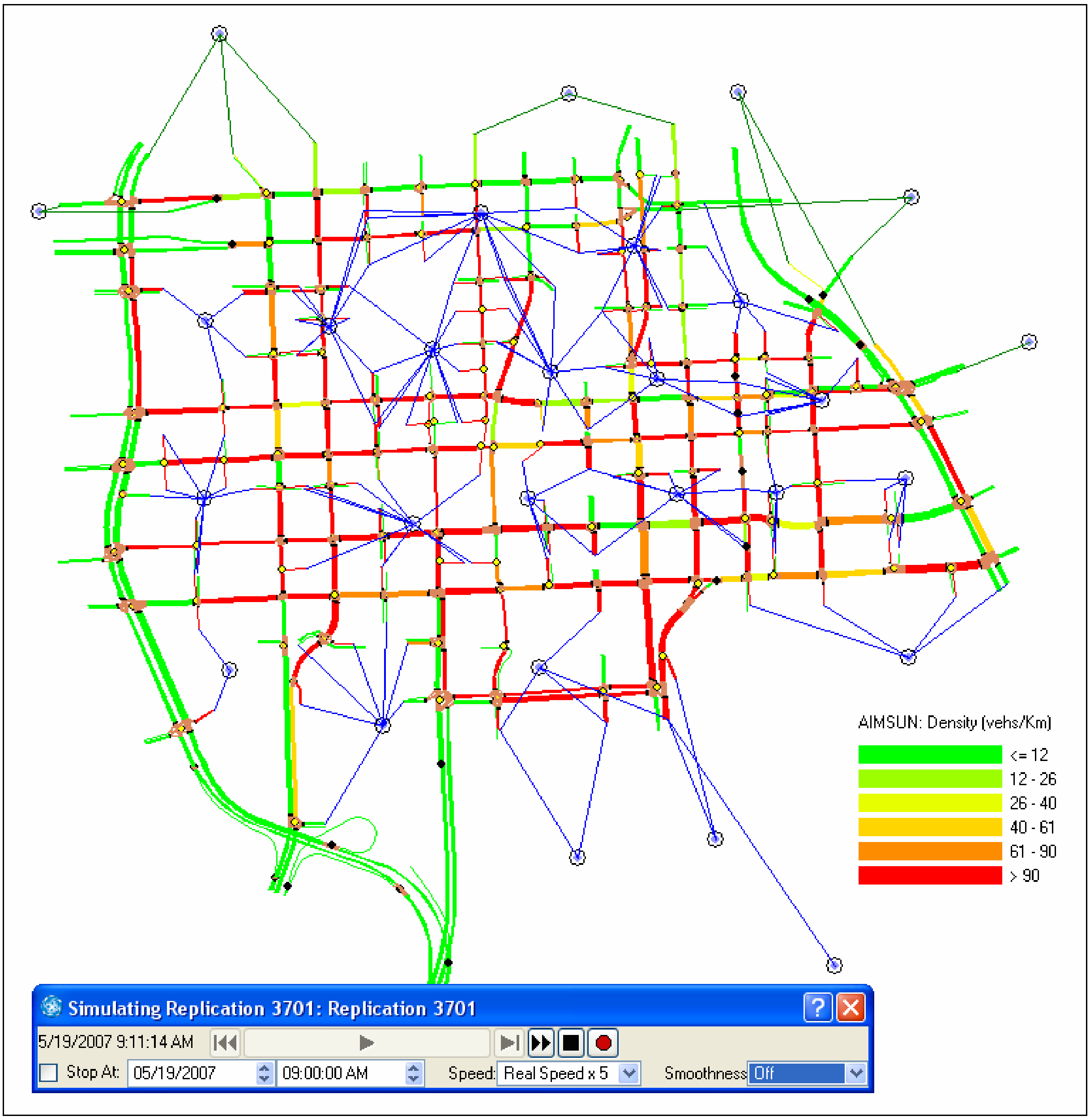

Figure 30: Network as constructed in AIMSUN

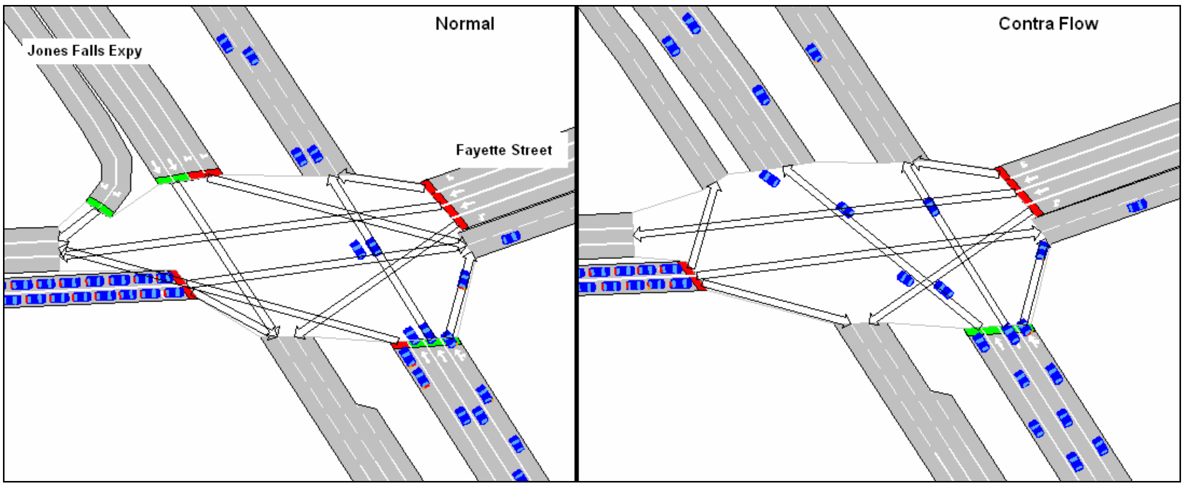

Figure 31: Intersection Jones Falls Expy/Fayette Street Normal vs. Contra Flow

9.4 Calibration and Validation

9.4.1 C-Logit Route Choice Model

In the C-Logit Route Choice Model the probability P_k of a given alternative path k, where $k \in K_i$, can be expressed as a function of the difference between the measured utilities of the path and all the other alternative paths:

$$P_k = \frac{e^{v_k \theta}}{\sum_{l \in K} e^{v_l \theta}} \qquad \text{[Equation 1]}$$

or its equivalent expression:

$$P_k = \frac{1}{1 + \sum_{l \neq k} e^{(v_l - v_k)\theta}} \qquad \text{[Equation 2]}$$

where V_i is the perceived utility for alternative path i and θ is a shape or scale factor. When taken $V_i = -CP_i/3600$ (function V_i is minus cost of path i, measured in hours). Assumed that the utility U_k^i of path k between O/D pair i is given by:

$$U_k^i = -\theta \cdot t_k^i + \varepsilon_k^i \qquad \text{[Equation 3]}$$

where:

θ is a shape or scale factor parameter;
t_k^i is the expected travel time on path k of O/D pair i;
ε_k^i is a random term.

The underlying modeling hypothesis is that random terms ε_k^i are independent identically distributed Gumbel variates. Under these conditions, the probability of choosing path k amongst all alternative routes of O/D pair i is given by the logistic distribution:

$$P_k^i = \frac{e^{-\theta \cdot t_k^i}}{\sum_l e^{-\theta \cdot t_k^i}} = \frac{1}{1 + \sum_{l \neq k} e^{-\theta \left(t_l^i - t_k^i\right)}} \qquad \text{[Equation 4]}$$

The scale factor θ plays a two-fold role, making the decision based on difference between utilities independent of measurement units, and influencing the standard error of the distribution of expected travel times:

$$Var\left(t_k^i\right) = \frac{\pi^2}{6\theta^2} \qquad \text{[Equation 5]}$$

that is:

$\theta < 1$ high perception of the variance, in other words a trend towards utilizing many alternative routes;
$\theta > 1$ alternative choices are concentrated in very few routes.

The Logit models exhibit a tendency towards route oscillations in the routes used, with the corresponding instability generating a kind of flip-flop process. There are two main reasons for this behavior: the properties of the Logit function, and the inability of the Logit function to distinguish between two alternative routes when there is a high degree of overlapping.
The instability of the routes used can be substantially improved when the network topology allows for alternative paths with little or no overlapping at all, changing the shape factor θ and re-computing the path very frequently. However, in large networks where many alternative paths between origin and destinations exist and some of them exhibit a certain degree of overlapping the use of the Logit function may still exhibit some weaknesses.
To avoid this drawback the C-Logit model has been implemented. In the C-Logit model, which is, in fact, a variation of the Logit model, the choice probability P_k, of each alternative path $k \in K_i$ of available paths connecting an O/D pair, is expressed as:

$$P_k = \frac{e^{\theta(v_k - CF_k)}}{\sum e^{\theta(v_l - CF_l)}} \qquad \text{[Equation 6]}$$

where V_i is the perceived utility for alternative path i and θ is the scale factor, as in the case of the Logit model. The term CF_k, denoted as commonality factor of path k, is directly proportional to the degree of overlapping of path k with other alternative paths. Thus, highly overlapped paths have a larger CF factor and therefore smaller utility with respect to similar paths. CF_k is calculated as follows:

$$CF_k = \beta \cdot \ln \sum \left(\frac{L_{lk}}{L_l^{1/2} L_k^{1/2}} \right)^{\gamma} \qquad \text{[Equation 7]}$$

where L_{lk} is the length of links common to paths l and k, while L_l and L_k are the length of paths l and k respectively. Depending on the two factor parameters β and γ, a greater or lesser weighting is given to the commonality factor. Larger values of β means that the overlapping factor has greater importance with respect to the utility V_i; γ is a positive parameter, usually taken in the range [0, 2], whose influence is smaller than β and which has the opposite effect.

As a rule of thumb, it is suggested factor β is in the range $[t_{min}, t_{max}]$, with:

$t_{\min} = Min_{k \in K_i}\left[CP_k\right]$ and $t_{\max} = Max_{k \in K_i}\left[CP_k\right]$.

Then β will become a kind of scaling factor for CF_k, which translates it into an order of magnitude similar to V_k in the formula V_k - C_k used for the exponential. And thus, when using larger values for β, it is possible that the commonality factor, CF_k, will have a greater influence on the choice probability than the utility (i.e. the travel time) itself, thus giving higher probability of choosing non-overlapped longer paths than heavy overlapped shortest paths (TSS, 2006).

9.4.2 Replications

In order to determine the number of required replications, we need to know the variance of a number of performance measures from simulation results, which are unknown before simulation. A number of simulation runs is needed to be executed first and then the required number of runs can be calculated according to the mean and standard deviation of a performance measure of these runs:

$$N = \left(t_{\alpha/2} \cdot \frac{\delta}{\mu \cdot \varepsilon} \right)^2 \qquad \text{[Equation 8]}$$

where μ and δ are the mean and standard deviation of the performance measure (MOE) based on the already conducted simulation runs, ε is the allowable error specified as a fraction of the mean μ and $t_{\alpha/2}$ is the critical value of the t-distribution at the confidence interval of 1-α.

We only considered the MOE Total Evacuation Time in calculating the required number of replications. A 95% confidence interval and a 5% allowable error were used in the calculation. The critical value of the t-distribution at the confidence interval of 95% depends on the degrees of freedom. The degrees of freedom is defined as *n-1*, with *n* as the number of initial replications. Because initially three replications where chosen, the degrees of freedom is equal to 2, resulting in a critical value of 2.92. The required replications for the different strategies are illustrated in Table 31. Note that the calculation of the required replications normally is an iterative process parallel with the simulation process. As more replications are carried out, the number of executed and required replications will converge to an optimum.

Strategy	***N***
Nearest Exit 1	3
Nearest Exit 2	218
Reference	58
Management	52
Staged 1	18
Staged 2	9
Contra Flow	32
Parked Cars	7
Signal Control 1	1
Signal Control 2	13
No Control	0
No Control Fixed	0
No Control Fixed Best Entrance	0

Table 31: Number of replications for the different strategies

As illustrated in Table 31 for almost all the strategies numerous replications, in a range of 3 till 218, are necessary to reach the required confidence interval of 95%.

9.5 Simulation Results

9.5.1 Nearest Exit

Nearest Exit 1 Simulation Results									
Replication	***3738***		***3739***		***3740***		***Average***		
	Value	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Unit*
Delay Time	1284.3	963.7	1447.3	1196.0	3023.6	4058.7	1918.4		sec/km
Density	27.4	30.4	26.0	32.1	26.9	32.7	26.8		veh.km
Flow	6401.0	7564.2	6430.9	7480.0	6430.9	7542.4	6420.9		veh/h
Harmonic Speed	2.9	2.9	2.8	2.8	2.5	2.6	2.7		km/h
Speed	6.6	5.6	6.3	5.5	5.9	5.2	6.3		km/h
Stop Time	1248.8	938.4	1411.3	1172.2	2988.2	4045.3	1882.8		sec/km
Stops	227.4		229.3		234.7		230.5		#/veh/km
Tot. Distance Trav.	70451.8		71478.3		70636.9		**70855.7**	**547.1**	km
Tot. Travel Time	24605.4		25925.5		26773.6		**25768.2**	**1092.6**	hours
Travel Time	1345.7	1006.9	1508.7	1235.4	3085.1	4082.3	1979.9		sec/km
Evacuation Time	4.75		4.75		5.00		**4.83**	**0.14**	hours
Lost Vehicles							46279		

Table 32: Nearest Exit 1 simulation results

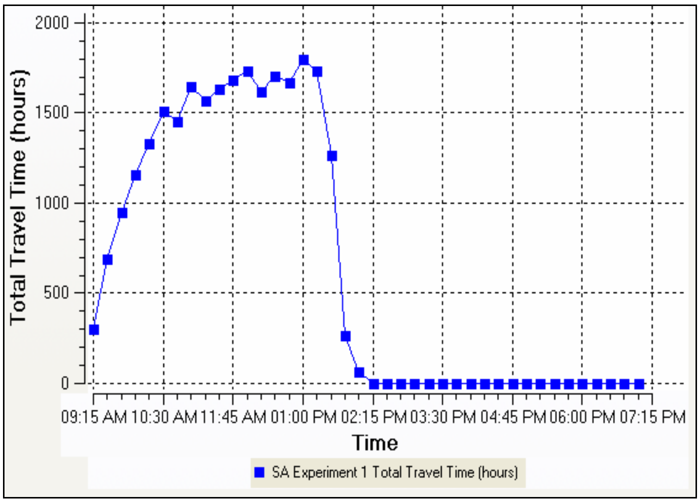

Figure 32: Total travel time Nearest Exit 1

Nearest Exit 2 Simulation Results									
Replication	***3730***		***3731***		***3732***		***Average***		
	Value	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Unit*
Delay Time	967.6	524.5	862.6	899.2	668.1	743.7	832.8		sec/km
Density	53.1	15.1	30.9	29.9	28.0	32.8	37.3		veh.km
Flow	7589.4	7228.4	7990.4	8215.0	8038.6	8897.1	7872.8		veh/h
Harmonic Speed	3.5	3.2	2.1	1.8	1.7	1.8	2.4		km/h
Speed	7.4	3.8	4.6	3.8	3.4	3.5	5.2		km/h
Stop Time	934.0	515.1	834.1	886.2	643.8	724.4	804.0		sec/km
Stops	313.7		232.1		201.5		249.1		#/veh/km
Tot. Distance Trav.	65354.8		71690.2		73869.5		**70304.8**	**4423.2**	km
Tot. Travel Time	17322.4		21821.3		22325.3		**20489.7**	**2754.5**	hours
Travel Time	1020.7	538.6	902.7	919.1	700.7	769.9	874.7		sec/km
Evacuation Time	7.00		5.25		4.25		**5.50**	**1.39**	hours
Lost Vehicles							29959		

Table 33: Nearest Exit 2 simulation results

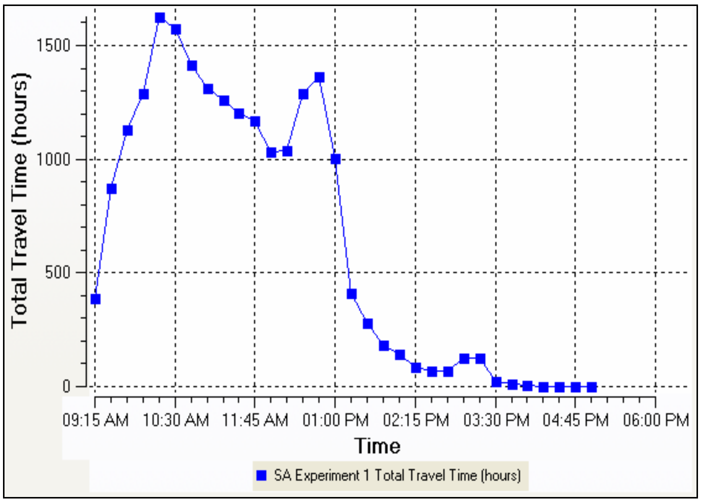

Figure 33: Total travel time Nearest Exit 2

9.5.2 Reference

Reference Simulation Results									
Replication	***3716***		***3717***		***3718***		***Average***		
	Value	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Unit*
Delay Time	4273.1	4974.8	2073.7	2081.4	2006.7	3868.8	2784.5		sec/km
Density	40.5	33.3	41.8	34.6	51.3	24.8	44.5		veh.km
Flow	5296.3	5357.6	5328.9	5156.9	5126.2	5616.1	5250.4		veh/h
Harmonic Speed	1.5	1.2	1.3	1.3	3.0	3.4	2.0		km/h
Speed	4.4	3.2	3.7	3.1	5.4	3.7	4.5		km/h
Stop Time	4239.9	4971.6	2044.5	2070.8	1975.3	3865.7	2753.2		sec/km
Stops	508.5		451.7		402.0		454.1		#/veh/km
Tot. Distance Trav.	82207.8		83929.9		73789.5		**79975.7**	**5426.2**	km
Tot. Travel Time	39823.9		45975.8		30820.2		**38873.3**	**7622.4**	hours
Travel Time	4330.7	4978.4	2119.4	2097.1	2056.4	3874.8	2835.5		sec/km
Evacuation Time	11.50		9.00		11.25		**10.58**	**1.38**	hours
Lost Vehicles							36293		

Table 34: Reference simulation results

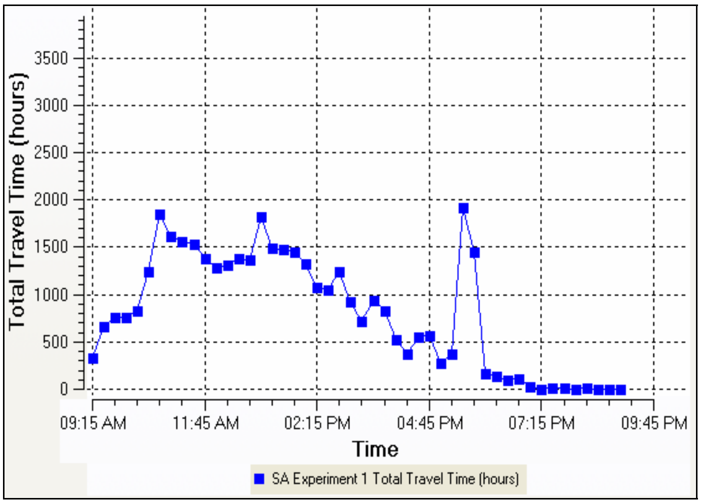

Figure 34: Total travel time Reference

9.5.3 Management

Management Simulation Results									
Replication	***3701***		***3702***		***3703***		***Average***		
	Value	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Unit*
Delay Time	1218.7	597.1	1052.1	387.6	1175.3	645.5	1148.7		sec/km
Density	41.6	28.8	44.5	25.5	40.5	30.3	42.2		veh.km
Flow	10614.3	8100.2	10529.5	7051.9	10646.3	8307.0	10596.7		veh/h
Harmonic Speed	3.1	1.9	3.6	1.6	3.1	2.2	3.3		km/h
Speed	6.2	3.4	7.5	2.6	6.5	4.0	6.7		km/h
Stop Time	1172.7	580.8	1009.2	382.9	1128.9	624.0	1103.6		sec/km
Stops	249.7		252.2		223.9		241.9		#/veh/km
Tot. Distance Trav.	69304.2		69135.1		71095.6		**69845.0**	**1086.4**	km
Tot. Travel Time	21697.9		20350.4		21955.8		**21334.7**	**862.1**	hours
Travel Time	1280.1	618.1	1113.7	394.9	1236.6	673.6	1210.1		sec/km
Evacuation Time	5.00		5.75		4.50		**5.08**	**0.63**	hours
Lost Vehicles							29153		

Table 35: Management simulation results

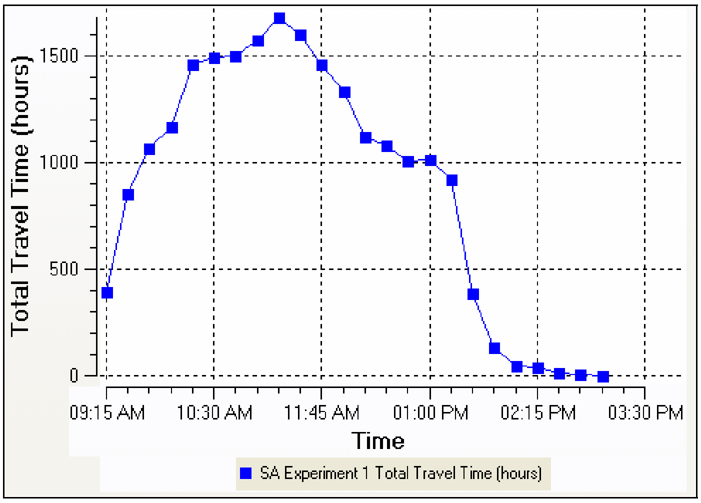

Figure 35: Total travel time Management

9.5.4 Staged

Staged 1 Simulation Results									
Replication	***3706***		***3707***		***3708***		***Average***		
	Value	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Unit*
Delay Time	955.2	878.6	761.3	377.6	956.6	985.3	891.0		sec/km
Density	25.2	19.3	26.7	17.3	24.4	19.5	25.4		veh.km
Flow	9176.6	6482.1	9109.6	6110.5	9179.4	6675.4	9155.2		veh/h
Harmonic Speed	4.6	3.0	5.1	3.3	4.7	3.0	4.8		km/h
Speed	7.9	4.7	9.0	4.5	8.0	4.6	8.3		km/h
Stop Time	908.0	867.0	716.1	364.5	908.9	976.9	844.3		sec/km
Stops	243.9		247.2		254.6		248.6		#/veh/km
Tot. Distance Trav.	78266.7		77964.6		77782.7		**78004.7**	**244.5**	km
Tot. Travel Time	17282.0		16291.9		16854.4		**16809.4**	**496.6**	hours
Travel Time	1016.6	893.2	822.8	395.7	1017.9	996.7	952.4		sec/km
Evacuation Time	5.75		6.50		5.75		**6.00**	**0.43**	hours
Lost Vehicles							27318		

Table 36: Staged 1 simulation results

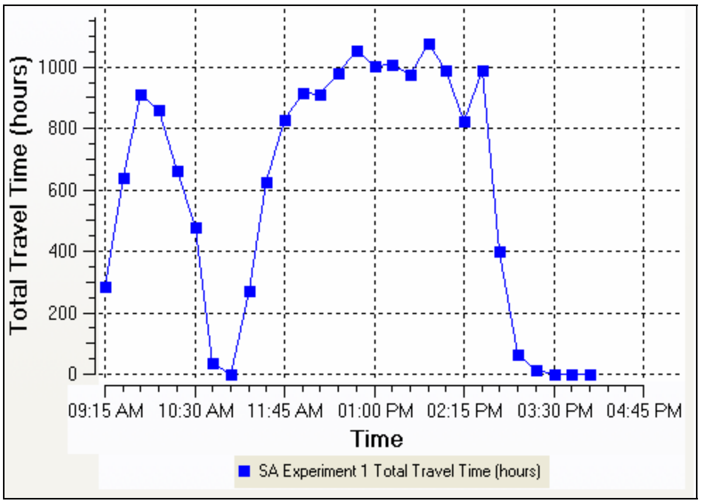

Figure 36: Total travel time Staged 1

Staged 2 Simulation Results									
Replication	***3726***		***3707***		***3708***		***Average***		
	Value	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Unit*
Delay Time	553.6	467.9	767.7	488.2	736.0	441.8	685.8		sec/km
Density	22.7	19.6	24.1	18.8	23.4	18.2	23.4		veh.km
Flow	8011.3	6992.7	7991.5	6587.1	7997.0	6554.8	7999.9		veh/h
Harmonic Speed	2.9	2.4	5.1	3.9	5.1	3.8	4.4		km/h
Speed	5.0	4.0	8.5	5.4	8.6	5.4	7.3		km/h
Stop Time	522.1	447.7	721.1	467.3	689.7	419.8	644.3		sec/km
Stops	239.9		244.4		243.9		242.7		#/veh/km
Tot. Distance Trav.	77168.6		77371.9		79118.6		**77886.4**	**1072.0**	km
Tot. Travel Time	16862.8		16901.3		16815.7		**16859.9**	**42.9**	hours
Travel Time	593.8	493.0	829.1	515.7	797.4	470.8	740.1		sec/km
Evacuation Time	5.25		5.75		5.75		**5.58**	**0.29**	hours
Lost Vehicles							28390		

Table 37: Staged 2 simulation results

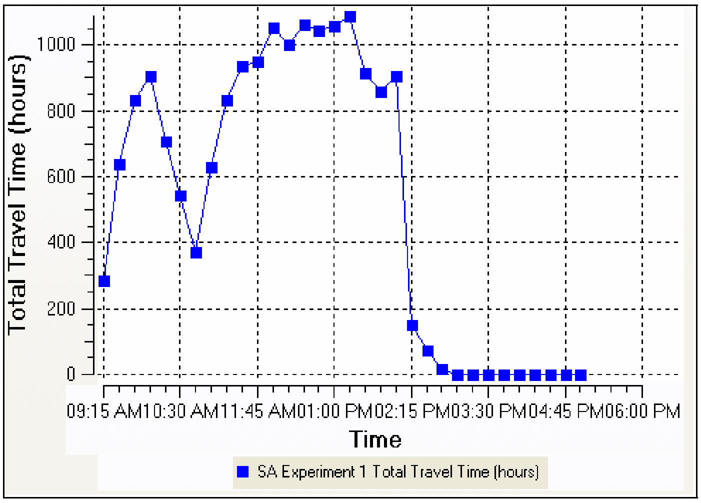

Figure 37: Total travel time Staged 2

9.5.5 Parked Cars

Parked Cars Simulation Results									
Replication	***3749***		***3750***		***3751***		***Average***		
	Value	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Unit*
Delay Time	1349.5	839.7	1740.2	1592.1	1610.4	1252.9	1566.7		sec/km
Density	35.3	27.6	35.3	28.3	41.3	25.9	37.3		veh.km
Flow	7963.5	7180.2	7981.5	7153.0	7912.8	6764.8	7952.6		veh/h
Harmonic Speed	2.8	2.3	2.7	2.3	2.6	2.1	2.7		km/h
Speed	6.9	4.9	6.3	4.5	7.0	4.5	6.7		km/h
Stop Time	1307.9	816.8	1699.1	1579.8	1569.1	1237.8	1525.4		sec/km
Stops	245.8		254.6		268.0		256.1		#/veh/km
Tot. Distance Trav.	67763.2		68558.7		69916.9		**68746.3**	**1089.0**	km
Tot. Travel Time	23816.8		24797.2		25501.4		**24705.1**	**846.1**	hours
Travel Time	1410.5	873.5	1801.1	1612.7	1671.3	1275.3	1627.6		sec/km
Evacuation Time	5.25		5.50		5.75		**5.50**	**0.25**	hours
Lost Vehicles							30336		

Table 38: Parked Cars simulation results

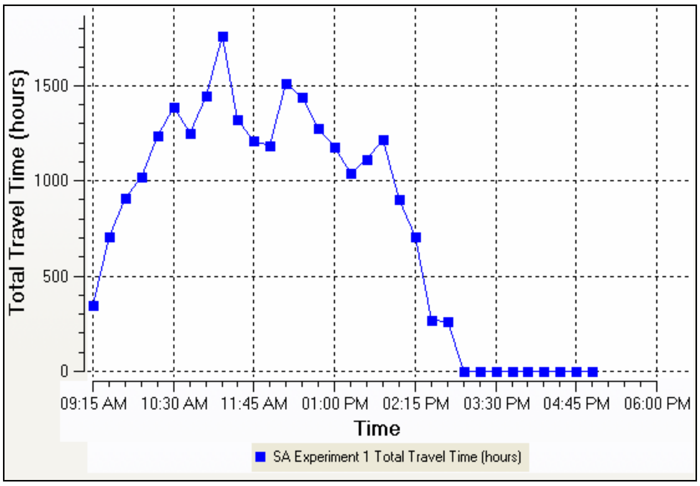

Figure 38: Total travel time Parked Cars

9.5.6 Contra Flow

Contra Flow Simulation Results									
Replication	***3749***		***3750***		***3751***		***Average***		
	Value	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Unit*
Delay Time	1507.3	1664.4	781.5	515.5	1546.5	1839.8	1278.5		sec/km
Density	55.2	15.3	39.1	29.2	43.8	27.6	46.0		veh.km
Flow	10169.5	7712.6	10637.2	8118.5	10605.8	7537.2	10470.8		veh/h
Harmonic Speed	3.1	1.4	3.4	3.2	2.7	1.4	3.1		km/h
Speed	6.7	3.0	6.4	4.2	6.2	3.0	6.5		km/h
Stop Time	1468.6	1665.4	746.3	500.1	1509.3	1839.7	1241.4		sec/km
Stops	259.2		215.7		239.7		238.2		#/veh/km
Tot. Distance Trav.	59852.0		71627.6		68731.5		**66737.0**	**6135.9**	km
Tot. Travel Time	16765.9		20439.5		21894.1		**19699.8**	**2642.9**	hours
Travel Time	1565.8	1667.0	830.0	535.0	1602.7	1844.7	1332.8		sec/km
Evacuation Time	5.75		4.75		5.50		**5.33**	**0.52**	hours
Lost Vehicles							30977		

Table 39: Contra Flow simulation results

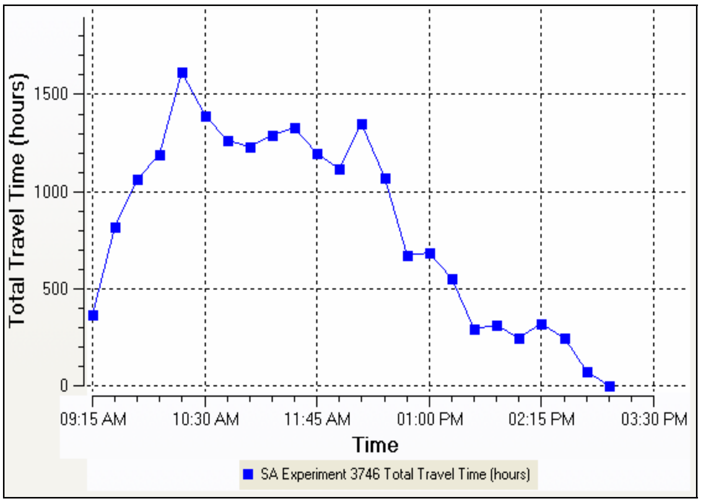

Figure 39: Total travel time Contra Flow

9.5.7 Signal Control

Signal Control 1 Simulation Results									
Replication	***3992***		***3750***		***3751***		***Average***		
	Value	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Unit*
Delay Time	3665.4	4994.5	3922.6	5382.4	2742.7	4235.0	3443.6		sec/km
Density	37.1	27.1	43.6	22.1	40.2	25.2	40.3		veh.km
Flow	7936.9	7088.4	7802.6	6893.7	7882.8	6704.3	7874.1		veh/h
Harmonic Speed	2.3	1.6	2.5	1.8	2.6	1.6	2.4		km/h
Speed	5.1	3.5	5.5	3.3	5.4	3.1	5.3		km/h
Stop Time	3630.3	4999.7	3886.6	5388.1	2704.9	4237.6	3407.3		sec/km
Stops	290.1		300.3		306.5		299.0		#/veh/km
Tot. Distance Trav.	70663.4		63740.2		70004.7		**68136.1**	**3821.2**	km
Tot. Travel Time	23628.4		20287.1		24291.3		**22735.6**	**2146.2**	hours
Travel Time	3722.6	4997.4	3981.9	5384.4	2799.9	4237.4	3501.5		sec/km
Evacuation Time	7.50		7.75		7.50		**7.58**	**0.14**	hours
Lost Vehicles							32133		

Table 40: Signal Control 1 simulation results

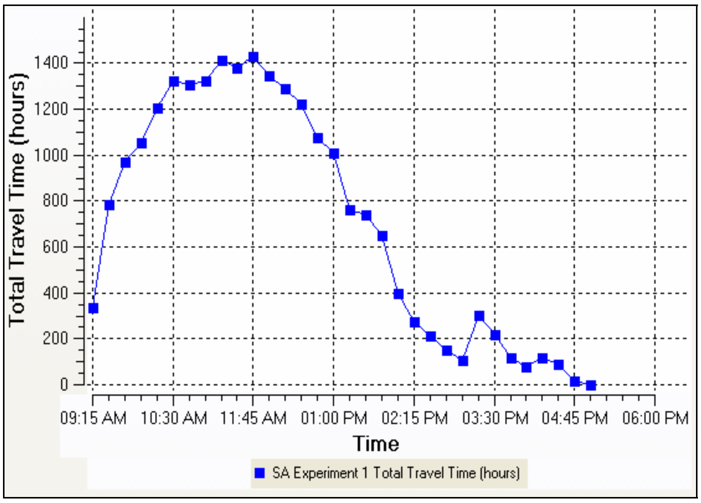

Figure 40: Total travel time Signal Control 1

Signal Control 2 Simulation Results									
Replication	***3754***		***3755***		***3756***		***Average***		
	Value	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Unit*
Delay Time	855.1	941.5	751.2	816.0	858.8	1146.0	821.7		sec/km
Density	32.6	30.6	31.7	32.4	31.0	34.0	31.8		veh.km
Flow	7974.4	8178.0	7999.9	8406.2	8038.6	8220.9	8004.3		veh/h
Harmonic Speed	1.9	1.8	1.7	1.7	1.6	1.6	1.7		km/h
Speed	3.9	3.4	3.5	3.4	3.4	3.4	3.6		km/h
Stop Time	826.6	925.2	724.9	796.6	833.3	1130.9	794.9		sec/km
Stops	229.5		215.9		215.5		220.3		#/veh/km
Tot. Distance Trav.	70584.1		71519.4		71696.4		**71266.6**	**597.7**	km
Tot. Travel Time	22090.8		22928.4		24748.0		**23255.7**	**1358.5**	hours
Travel Time	893.3	962.6	785.7	841.1	893.2	1166.4	857.4		sec/km
Evacuation Time	5.00		4.50		4.50		**4.67**	**0.29**	hours
Lost Vehicles							32002		

Table 41: Signal Control 2 simulation results

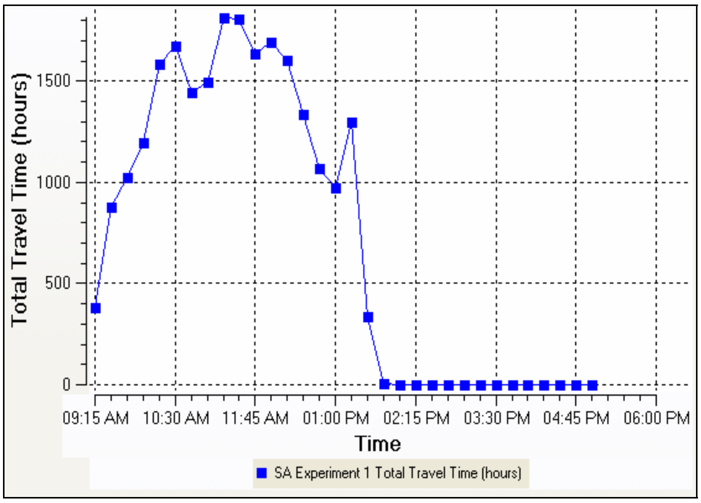

Figure 41: Total travel time Signal Control 2

No Signal Control Simulation Results									
Replication	***3754***		***3755***		***3756***		***Average***		
	Value	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Unit*
Delay Time	275.3	326.1	272.3	310.2	307.8	350.3	285.1		sec/km
Density	24.8	31.1	29.7	28.6	27.2	31.8	27.2		veh.km
Flow	10696	13019	10585	12972	10671	12777	10651		veh/h
Harmonic Speed	2.8	3.3	4.4	8.1	3.6	5.8	3.6		km/h
Speed	5.8	6.5	8.0	9.8	7.3	8.0	7.0		km/h
Stop Time	257.8	309.1	254.9	293.2	289.7	333.7	267.5		sec/km
Stops	136.7		131.4		136.7		135.0		#/veh/km
Tot. Distance Trav.	73732.4		71529.6		72544.8		**72602.3**	**1102.5**	km
Tot. Travel Time	14073.4		13399.2		14738.7		**14070.4**	**669.8**	hours
Travel Time	303.5	354.4	303.0	337.4	338.7	377.3	315.1		sec/km
Evacuation Time	3.00		3.00		3.00		**3.00**	**0.00**	hours
Lost Vehicles							30056		

Table 42: No Signal Control simulation results

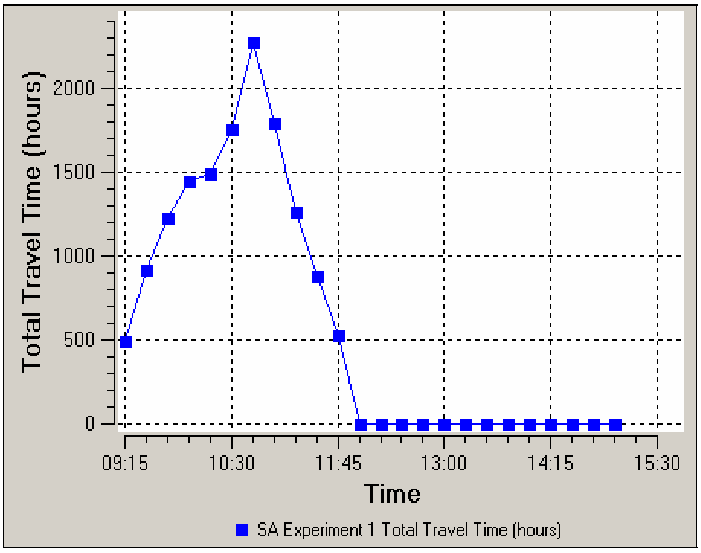

Figure 42: Total travel time No Signal Control

9.5.8 No Signal Control Fixed (time) Route Choice

No Signal Control Fixed Simulation Results									
Replication	***3754***		***3755***		***3756***		***Average***		
	Value	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Unit*
Delay Time	310.4	348.6	302.0	339.4	358.1	404.6	323.5		sec/km
Density	24.7	29.8	24.0	30.6	26.6	28.7	25.1		veh.km
Flow	10688	13229	10694	13588	10629	13343	10670		veh/h
Harmonic Speed	2.3	2.7	2.4	2.7	2.5	2.7	2.4		km/h
Speed	5.9	6.6	5.7	6.5	6.3	7.0	6.0		km/h
Stop Time	294.4	332.1	285.5	322.4	341.9	392.1	307.3		sec/km
Stops	135.3		134.8		142.7		137.6		#/veh/km
Tot. Distance Trav.	64344.3		64505.3		61804.7		**63551.4**	**1514.9**	km
Tot. Travel Time	13710.0		13495.2		12792.2		**13332.5**	**480.1**	hours
Travel Time	338.5	378.5	330.0	369.0	388.7	432.0	352.4		sec/km
Evacuation Time	3.00		3.00		3.00		**3.00**	**0.00**	hours
Lost Vehicles							29581		

Table 43: No Signal Control Fixed simulation results

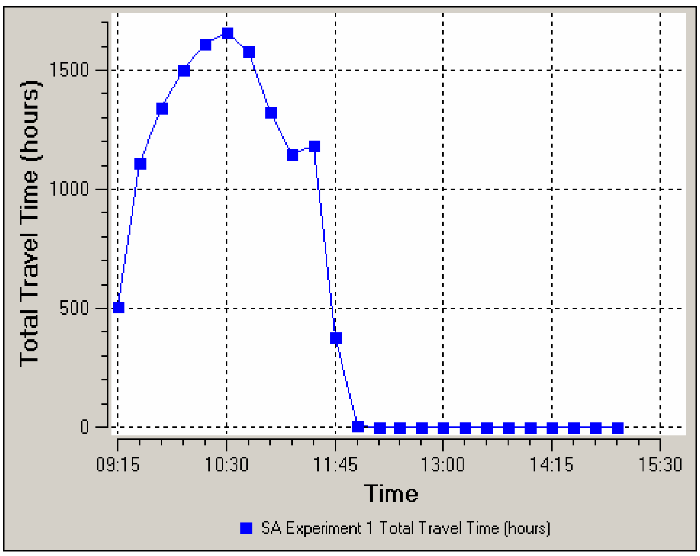

Figure 43: Total travel time No Signal Control Fixed

No Signal Control Fixed Best Entrance Simulation Results								
Replication	***3998***		***3755***		***3756***		***Average***	
	Value	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Value*	*St. De.*	*Unit*
Delay Time	83.7	87.9	86.1	91.2	85.5	89.5	85.1		sec/km
Density	4.5	7.8	4.6	8.0	4.6	7.9	4.6		veh.km
Flow	8038.6	9393.6	8038.6	9406.2	8038.6	9355.5	8038.6		veh/h
Harmonic Speed	23.1	13.4	23.0	13.5	22.9	13.4	23.0		km/h
Speed	26.8	12.5	26.6	12.5	26.7	12.5	26.7		km/h
Stop Time	57.6	77.9	59.4	80.9	59.1	79.2	58.7		sec/km
Stops	128.2		130.5		130.2		129.6		#/veh/km
Tot. Distance Trav.	46097.3		46245.1		46405.2		**46249.2**	**154.0**	km
Tot. Travel Time	3601.5		3690.4		3679.4		**3657.1**	**48.5**	hours
Travel Time	136.0	99.1	138.3	102.2	137.8	100.7	137.4		sec/km
Evacuation Time	6.75		6.75		6.75		**6.75**	**0.00**	hours
Lost Vehicles							11785		

Table 44: No Signal Control Fixed Best Entrance Simulation Results

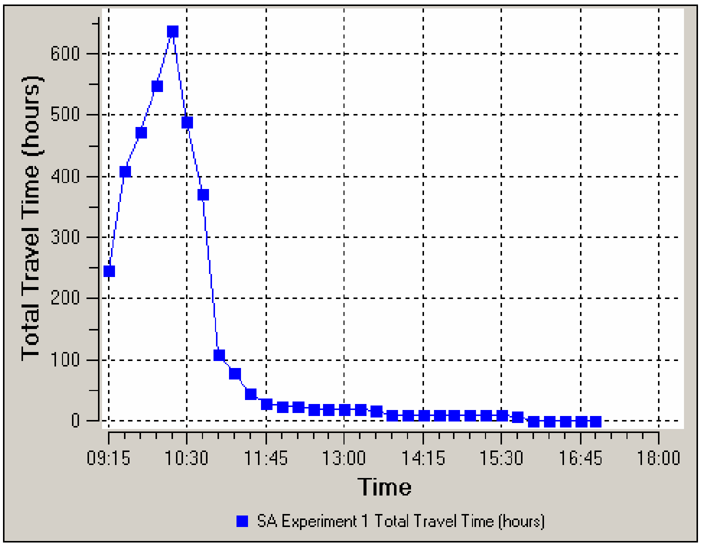

Figure 44: Total travel time No Signal Control Fixed Best Entrance

9.6 *Additional Problem Approach*

A simplification of the emergency problem, based on Baltimore City, is illustrated in Figure 45. A Central Business District, surrounded by high density residential areas, low density suburbs and harbor/industry areas can be distinguishable. The red ellipses illustrate the dispersion of the chemical air pollution, caused by the chemical explosion in the harbor/industry area.

In case of an air pollution it is important to know the concentration on ground level. Various models are developed to determine the dispersion, mostly based on the Gaussian Plume Model. This model assumes that emission from a single point source is transported by the average wind speed and dispersed by the atmosphere turbulence, in a certain way the concentration perpendicular to the wind direction can be described by the Gaussian Curve. However, the model also assumes that over short periods of time, 1 - 3 hours, steady state conditions exists with regard to air pollutant emissions and meteorological driving forces, i.e., stable wind speed and direction, stability class, mixing height, and temperature (Augustijn, 2003).
Summarized, the dispersion of an air pollutant emission depends on emission characteristics (amount and height), material characteristics (density) and meteorological driving forces (wind speed and direction, stability class, mixing height and temperature).
Normally the concentration on ground level decreases as the distance to the source increases. However, if the material is erupted high in the air, a low concentration close to the disaster is possible.

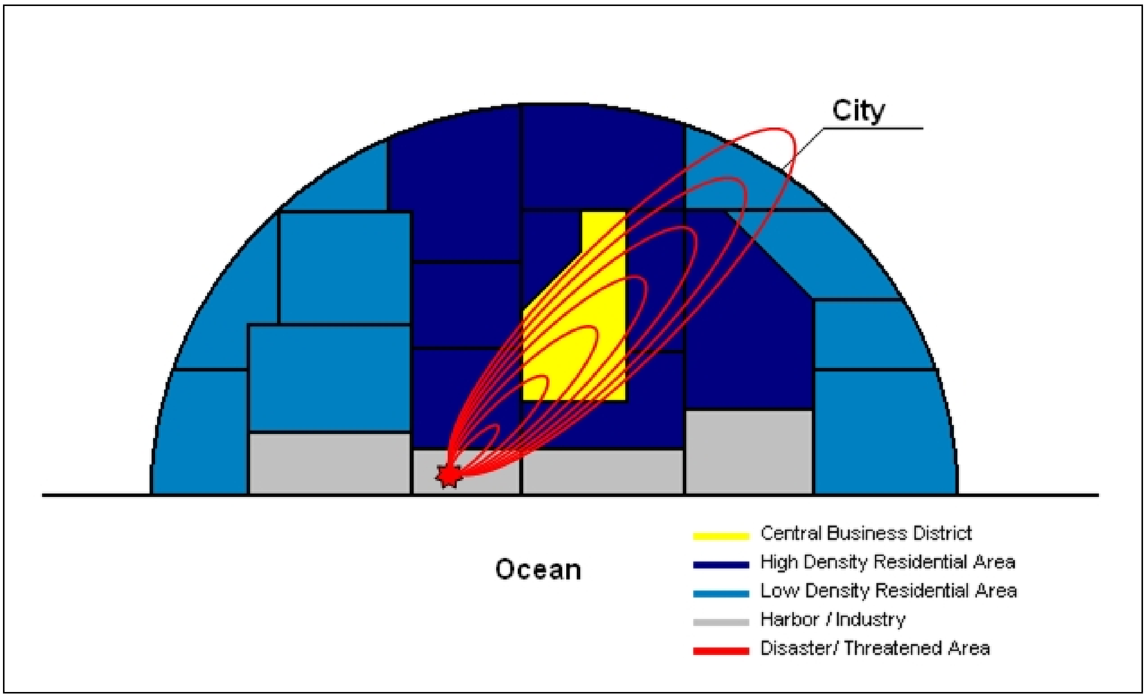

Figure 45: Simplified emergency problem with chemical air pollution dispersal

The total damage caused by an (chemical) air pollution can be characterized as follows:

$$\text{Damage} = \sum P_i \cdot c \cdot t \qquad \text{[Equation 9]}$$

With:

P_i = Population in *i;*
i = threatened area;
c = concentration;
t = exposure time.

The harmfulness of a chemical air pollution is a direct result of the concentration (*c*) and the exposure time (*t*), illustrated in Figure 46. For a certain concentration, damage will occur regardless of the exposure time. In case of a lower concentration, damage will only occur after a certain exposure time. Very low concentration require an almost infinite exposure time to cause any damage.

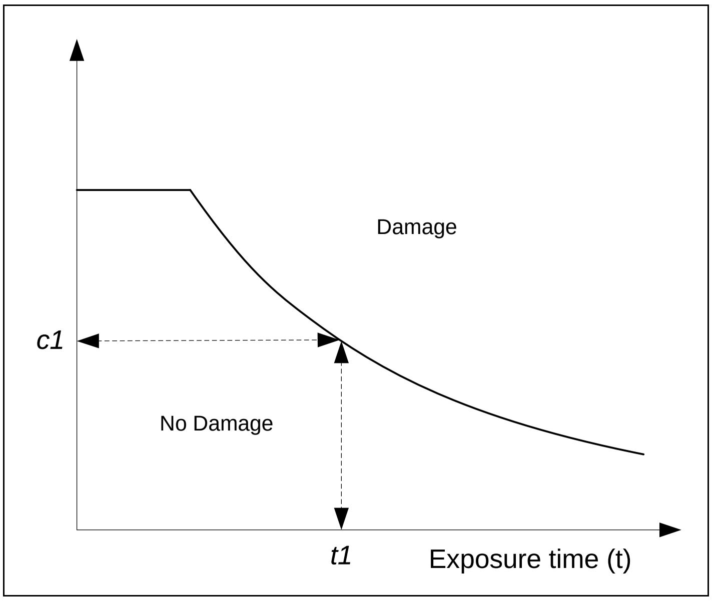

Figure 46: Chemical concentration and exposure time relationship

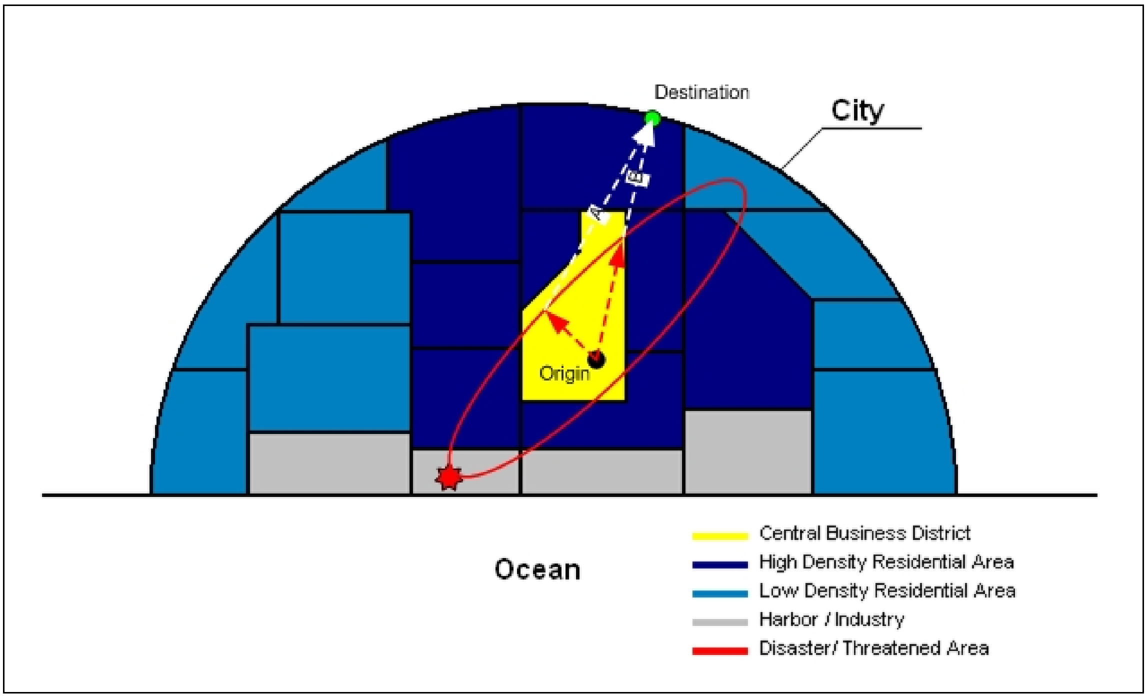

Figure 47: Simplified emergency problem with threatened area and routes A and B

During an evacuation, the first three variables in Equation 9 (*P*, *i* and *c*) can not be changed, however the last one (exposure time, *t*) can. This can be accomplished by minimization of the travel time through threatened area. From this point of view the longer route A in Figure 47 is better than the shorter route B. This results in the objectives: 'minimize total link (road) usage in time through the threatened area' and 'minimize total evacuation time of the threatened area'. Automatically resulting in the Measures of Effectiveness (MOEs): 'total link usage in time through the threatened area' and 'total evacuation time of the threatened area'.

These objectives can be reached by giving a penalty (for example by a low speed limit) to roads within the threatened area, which makes route A preferable compare to route B in Figure 47. It is also advisable to choose safe destinations perpendicular to the wind direction instead of downstream.

This approach will definitely lead to different result compare to the approach used in the research, because MOEs are changed and the penalties in the network will cause a different trip distribution and route choices. It is likely that evacuation times will be shorter, because the first priority is to exit the threatened area. Possibly the results are also closer to reality.

Note that this approach requires more detailed knowledge about the disaster characteristics and methodological conditions which finally results in the concentrations on ground level and the total threatened area. In case the selected research area is a smaller part of the total threatened area, and therefore penalties will not have their desired effect, it is still advisable to select those safe destinations perpendicular to the wind direction.