ABSTRACT

Title of Thesis: TRAFFIC SIGNAL TIMING FOR URBAN EVACUATION

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Significant effort has been expended to reduce the evacuation time in a geographic evacuation. The majority of these efforts have focused on freeways and it appears that there has been no systematic consideration of signal timing in evacuation planning for urban areas. However, signal control can greatly impact traffic flow in an evacuation. This thesis studies approaches for signal timing to facilitate evacuation and response in the event of a no-notice urban evacuation. A simulation model was constructed with data from Washington, D.C. Experimental results indicate 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.

TRAFFIC SIGNAL TIMING FOR URBAN EVACUATION

By

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Chapter 1. Introduction

1.1 Background

Due to high population density, urban populations are vulnerable in events of attack, natural disaster or accidental release of dangerous substances. In such events, emergency preparedness plays a vital role in mitigating the damage to property, personal injury and loss of life. One response action under such events is to evacuate. Evacuation-related research has flourished in the last several years, especially after 9/11 attack. However, few of these works have addressed the issues of urban evacuation and most have focused on evacuation with significant warning. This thesis focuses on no-notice evacuation from urban areas, where notification of a need for evacuation may be only minutes prior to the event that might cause the need for an evacuation.

The main objective of evacuation is to move people out from an endangered area as quickly as possible so as to avoid casualties. Thus, minimizing the evacuation time can play a critical role in minimizing the adverse effects of an event leading to an evacuation, e.g. fatalities and injuries. Numerous strategies have been proposed to assist in the quick movement of evacuees toward safety. One such strategy that has received little systematic study in the literature or in practice is to reset signal timing plans to aid in the evacuation. This is of particular utility in urban areas. By resetting the timing plans, it may be possible to increase the capacity of the traffic network, and likewise, reduce the evacuation time required to move all evacuees to safety.

There are many factors in evacuation that may complicate the design of suitable signal timing plans. Under ordinary traffic conditions, it is often very difficult to determine and implement optimal signal timing plans. Several factors that further complicate the determination and implementation of optimal timing plans in the context of no-notice evacuation include the following. (1) Traffic demand arises in a very short period of time after the evacuation is initiated especially under terrorist attacks. This leads to a greater concentration of demand than arises in ordinary operations and widespread saturation phenomena. (2) Significant inbound travel may cause considerable traffic congestion for travel in all directions. For example, family members may seek to travel together, requiring travel inbound, in the opposite direction of the evacuation and emergency vehicles may need to head inbound. (3) One would suspect that people's behavior may differ from ordinary circumstances. At a minimum, one would expect drivers to behave more aggressively than usual. With an increase in aggressive driving, one can expect more frequent traffic incidents as compared to ordinary conditions. This, in turn, may lead to reduced capacity of the evacuation routes. In addition, roadside parking along the evacuation routes can also seriously affect the available roadway capacity during an evacuation. (4) The mobility impaired and people who do not own vehicles may require some form of public transportation. While transit can potentially meet these special needs, it can also impact the available capacity for automobiles. If the signal timing plans and offsets do not suit these special classes of traffic that exist in an evacuation, significant delay may result. The determination of suitable signal timing plans for evacuation from an urban area produces significant challenges. Unfortunately, few studies have considered signal timing plans for this purpose. While some transportation agencies or researchers may have considered the potential impact of signal timing plans on successful evacuation, which plans will be most effective have not been systematically studied.

1.2 Research Goal and Objectives

A systematic study of methodologies used to set signal timing plans for evacuation was undertaken in this thesis to examine their effects. The ultimate goal of this study was to acquire useful findings in setting signals for evacuation and thereby assist traffic engineers in developing appropriate evacuation signal timing plans. Specifically, two objectives were involved in this study. The first was to assess the state-of-the-art and state-of-the-practice in setting signals during a no-notice evacuation in an urban environment. To achieve this objective, a literature review was completed and nationwide interviews with select experts on evacuation and representatives from various transportation agencies were conducted. The second was to test different signal timing plans and offsets that have been proposed or previously implemented as part of the plans for an evacuation. A simulation model was developed, composed of two evacuation routes in Washington D.C. The simulation model enables examination of the proposed plans and assessment of these plans under several evacuation scenarios. It further permits the identification of potential problems that could result from implementation of these plans.

1.3 Contribution and Organization

The primary contributions of this study are determination of the state-of-the-art and state-of-the-practice in setting signals for evacuation in the United States and a systematic assessment and comparison of the signal timing plans that have been proposed or previously implemented as part of the plans for use in an evacuation.

Subsequent chapters of this thesis are organized as follows. Chapter 2 provides a literature review of existing research related to signal timing for emergency evacuation of a geographic region. Summary of findings from nationwide interviews with experts on evacuation from around the United States and representatives from various agencies are also included in this chapter. Chapter 3 describes the study network on which the proposed signal timing plans were tested, as well as the details of each plan. Chapter 4 describes the development of two master scenarios in which an evacuation is required, i.e. terrorist attack near the Capitol building and federal shutdown. Each master scenario includes many sub-scenarios. Travel demand estimation for evacuation based on the census data is also given in this chapter. Chapter 5 provides the simulation results in terms of two select measures. Chapter 6 examines the effects of employing varying cycle lengths under different levels of traffic demand for evacuation. Findings and discussion are provided in Chapter 7.

Chapter 2. Literature Review

This chapter provides a summary of the English-written literature related to signal timing for emergency evacuation of a geographic region. The literature search revealed that few formal studies on this topic have been conducted. That is, while numerous works developed over two or three decades have addressed geographic evacuation, and while several researchers and agencies have noted the potential impact that traffic signal control may have on evacuation operations, very few studies have addressed this topic. In fact, it appears that only one small study has been published on signal timing for evacuation. This chapter includes a review of this study and other relevant articles and reports on geographic evacuation.

As the goal of this chapter is to provide the state-of-the-art and state-of-the-practice in signal timing for evacuation, a summary of findings from nationwide interviews with experts on evacuation from around the United States and representatives from various agencies conducted by Miller-Hooks and Tarnoff (2005) is included in this chapter for completeness.

2.1 The Literature

Human populations are faced with numerous natural (e.g. hurricanes, earthquakes, tornados, tsunamis, volcanic eruptions, flooding, mudslides, wildfires) and human-caused, whether accidental (e.g. a hazardous materials release or a nuclear power plant malfunction) or purposeful (e.g. terrorist attack), hazards that have the potential to cause significant devastation. Discussion of these hazards can be found in (Pidd et al., 1996; Petruccelli, 2003; and Sattayhatewa and Ran, 1999). The intensity and course of such a hazard event can be predicted with varying levels of accuracy. For example, a hurricane can often be predicted even longer than 24 hours in advance of its arrival at a particular location, while the first tremors of, or aftershocks from, an earthquake cannot be predicted in advance with any reasonable level of certainty (Petruccelli, 2003). Few if any such hazards can be perfectly predicted.

To cope with these hazards, society has adopted various methods of preparedness. One such protective action that is taken is to prepare in advance for evacuation of an affected area. See (Rathi et al., 1993) for additional discussion. Whether or not an evacuation is successful depends, in part, on the time it takes for the population to successfully reach safety. Further, the urgency with which the evacuation will take place depends on the amount of lead time. The initial warning to evacuate in preparation for the arrival of a hurricane may come even longer than a day prior to the hurricane's arrival. On the contrary, an evacuation that is required in response to a terrorist action or release of a biological, chemical or other hazardous substance into the atmosphere may force immediate evacuation without advanced warning. Such an evacuation is referred to herein as a no-notice evacuation and differs from evacuation due to hurricane in that the evacuation takes place after the incident. Both evacuations that come with notice and no-notice evacuations lead to enormous demands on the traffic network. The transportation infrastructure is often unable to adequately accommodate such high levels of demand (Wolshon et al., 2003) and long queues will form, negatively impacting the evacuation time for the area. While numerous studies have addressed advanced notice regional evacuation as might take place in preparation for a hurricane, few works have considered the specific issues that might arise in no-notice evacuations or evacuation of urban areas. It is hypothesized that traffic signal settings can effect the movement of people to safety from a hazardous urban region. The goal of this review is to determine the state-of-the-art in signal timing for evacuation with special attention given to no-notice evacuation.

Numerous works have addressed evacuation from a geographic area, but very few have considered traffic signal timing to facilitate evacuation. Thus, while the focus of this review is on works that address signal timing for evacuation, many other relevant works have also been reviewed. These works are loosely classified into several categories: human behavior and evacuation demand characteristics, evacuation routing, evacuation plans and policies, traffic simulation models for evacuation, evacuation and Geographic Information Systems (GIS), evacuation and Intelligent Transportation Systems (ITS), and signal timing for evacuation. The literature on building evacuation is not reviewed herein, but may also be of interest.

2.1.1 Human behavior and evacuation demand characteristics

Numerous articles and reports have been published that address human behavior and travel demand in geographic evacuation. Human behavior during evacuation can have a large impact on traffic patterns (Petruccelli, 2003). Evacuee behavior was first represented in a simulation model for urban evacuation by Stern et al. (1989). In their work, diffusion of evacuation instructions, represented by diffusion curves, and evacuation decision time (obtained from survey data) were analyzed. Chiu et al. (2005)

developed a real-time traffic management system for flooding-related disasters. The response of the evacuees to these management strategies was incorporated into the system to aid in refining the strategies.

The Center for Urban Transportation Research at the University of South Florida (1998) conducted an analysis of travel demand given historical data from prior evacuations. They used traffic count data to examine the temporal variation in traffic demand during Hurricanes Opal and Bertha and compared the actual counts with assumptions that were made in prior studies. Using the data collected in the Florida Keys after Hurricane Georges, Dash and Morrow (2001) examined the effects of heavy re-entry delays on future evacuation decisions (i.e. future decision on whether or not to evacuate). They noted that the fear of delays in returning had greater influence on future decisions to evacuate by the people who learned second-hand of the delays than it did on the decisions by those who had experienced the delays first-hand. Based on a survey of coastal South Carolina, Dow and Cutter (2002) investigated the impact of household decisions on evacuation demand during Hurricane Floyd. Four specific issues were considered: (1) number of vehicles taken by a household; (2) the timing of departures; (3) distances traveled in egress; and (4) the role of information in the selection of specific evacuation routes. Petruccelli (2003) examined behavior during an earthquake evacuation, i.e. a no-notice evacuation. An s-shaped curve was used to describe the behavioral aspects that influenced the cumulative volume loaded on the network. Alsnih et al. (2005) developed a travel demand model to predict when residents will decide to evacuate from a naturally occurring disaster, such as a bushfire.

2.1.2 Evacuation Routing

A critical issue in managing an evacuation is how to route people to safety. An efficient routing plan may greatly reduce the evacuation time (sometimes referred to as the network clearance time). Sheffi et al. (1982) considered the dynamic properties of route choice in the context of a simulation model of evacuation. In their model, they recognized that drivers would likely update their route selection while en route as actual traffic volumes and proportion of vehicles that are turning at given intersections are learned. Another approach is to model the evacuation problem as a network flow problem. Dunn (1992) proposed two algorithms for finding optimal evacuation routes, where the objective was to maximize the flow through a capacity constrained network, i.e. the problem was modeled as a maximum flow network flow problem.

Campos et al. (1999) proposed a method that identified k-optimal independent paths (i.e. with no points of intersection) for allocating traffic to the network in an evacuation. The use of such independent routes can aid in reducing crashes and can aid in permitting a continuous traffic flow. Cova et al. (2002) proposed a lane-based evacuation routing approach. A lane-based routing plan can aid in reducing traffic delays at intersections by limiting the number of merges and preventing crossing-conflicts. It is worth noting that while such an approach will reduce interactions at the intersections, the total distance traveled will likely increase. The approach was illustrated on a representation of Salt Lake City, Utah.

Lim and Wolshon (2005) used CORSIM, a traffic microsimulation tool, to model contraflow operations along freeways in the event of a catastrophic storm. Various contraflow termination designs were evaluated and compared to assess how termination point configuration might impact the effectiveness of these operations.

2.1.3 Evacuation Plans and Policies

The Federal Emergency Management Agency (FEMA) requires that every state in the U.S.A. have emergency evacuation plans that can address multiple hazards (Urbina et, al., 2002). Southworth (1991) proposed a five step process for regional evacuation. The steps include: trip generation, trip departure time selection, trip destination selection, trip route selection, and plan set-up. Liu et al. (2005) proposed an optimization model to identify the most likely optimal evacuation plan. The upper level problem seeks to maximize the throughput in a prescribed clearance time T, while the lower level problem seeks to minimize the total travel time for the specified evacuation demand. The model results in a set of evacuation plans that can be further evaluated with the use of simulation under multiple evacuation scenarios. Goldblatt (2004) reviewed and discussed a number of issues involved in the evacuation planning process. Steps in the planning methodology were explored, including, for example, identification of the evacuation area, estimation of the evacuation demand, evaluation of highway network, identification of intended destinations, computation of the evacuation routes, simulation of traffic flow, and traffic control and management. The methodology was applied in a study of the Indian Point Emergency Planning Zone in New York. On a related topic, Urbanik (2000) studied the estimation of evacuation time for nuclear power plants.

Other works have tested proposed evacuation plans. Rontiris and Crous (undated) analyzed existing evacuation plan for the Koeberg Nuclear Power Station under various evacuation demand scenarios. Sisiopiku et al. (2004) developed a region-wide emergency model employing CORSIM for testing proposed emergency preparedness plans and their impacts on the operation of the transportation network. A case study was implemented on Birmingham, Alabama. The study demonstrated the feasibility of micro-simulation modeling in developing and refining evacuation plans. Further discussion of this work is given in Section 2.1.7.

Preparedness concerns related to the threat from hurricanes have received considerable attention in the U.S.A., because hurricanes have continued to threaten and damage the eastern and gulf coastal states (FHWA, 2003). Thus, a significant portion of the works on geographic evacuation in the U.S.A. have addressed the specific concerns of improving transportation operations during hurricane evacuation. Shaw (1997) identified effective methods for increasing highway capacity during the hurricane warning response period to maximize the number of people who can be evacuated from Southern Florida. Sixteen operational improvements were proposed and the potential benefits of contraflow operations were emphasized. Wolshon (2001) studied the advantages and disadvantages of contraflow strategies on design, operation, and implementation. An overview of current plans in various states to use contraflow operations during an evacuation is given and recommendations are provided. A case study of the city of New Orleans was conducted as described in Wolshon (2002). Critical issues, such as roadway safety and work zones, are discussed. In another work, Wolshon (2003) presented the current research status on emergency evacuation from a transportation perspective. He discussed several areas that require attention: controlling evacuation travel demand, maximizing capacity of the existing infrastructure, improving communications and coordination, assisting low-mobility groups and addressing work zone issues.

In 2002, nine southeastern states were provided with grants from the Federal Highway Administration (FHWA) to improve hurricane evacuation management according to a report by SAIC (2003). The report provides details of state evacuation planning activities and lessons learned. Louisiana's cooperation with the U.S. Geological Survey to deploy Hydrowatch information stations to simultaneously monitor traffic and water levels is also discussed.

A comprehensive review of nation-wide evacuation policies and plans is provided in Urbina (2002) and Urbina and Wolshon (2003). These studies provide a literature review and results of a survey conducted among transportation and emergency management officials from the coastal states. A detailed description of the proposed use of contraflow operations and advanced technologies via Intelligent Transportation Systems (ITS) is also given. Current evacuation management policies, methods of information exchange and decision-making criteria are summarized.

2.1.4 Traffic Simulation Models for Evacuation

Numerous simulation models and software packages have been developed to assist in the design, operation, management and evaluation of emergency evacuation plans and policies. Southworth (1991) provided a review of many of the existing models. Radwan et al. (1985), Church and Sexton (2002), and Sattayhatewa and Ran

(1999) also review commonly-used evacuation models. NETVAC (Sheffi et al. MIT), DYNEV (KLD), and MASSVAC (Hobeika et al.) are some of the popular existing evacuation models. NETVAC is a macro-simulation model for simulating traffic patterns during emergency evacuations. The development of this model was motivated by the need to estimate the network clearance time for areas around nuclear power stations (Sheffi, 1982; Sheffi et al., 1982). DYNEV (KLD, 1984) is another widely known model for use in evacuation planning. It is based on a static equilibrium assignment (Sattayhatewa and Ran, 1999). MASSVAC (Hobeika et al.) is a macroscopic simulation model that can model numerous scenarios and operationally test various alternative traffic management strategies. It is designed to operate in real-time. More recent versions of this MASSVAC, e.g. MASSVAC 4.0, employ a user-equilibrium assignment algorithm (UE).

Hobeika et al. (1994) developed the Transportation Evacuation Decision Support System (TEDSS), a software package for use in analysis, evaluation, and development of evacuation plans around nuclear power stations. TEDSS relies on a knowledge-based system that stores evacuation expert rules, disaster-related information, area and transportation network characteristics, and a simulation module that contains several traffic assignment algorithms from which users can choose. Barrett et al. (2000) proposed a model for use in hurricane evacuation that relies on dynamic traffic assignment (rather than the static traffic assignment techniques that have been proposed in Hobeika et al. and other works).

Regional Evacuation Modeling System (REMS) (Tufekci and Kisko, 1991) is another software package that is capable of handling different emergency scenarios, such as hurricanes, chemical material spill or nuclear accidents. The software can animate the evacuation process over time and display the flow of traffic on the links of the transportation network in a time-lapsed manner.

To help develop evacuation plans for different scenarios, OREMS was developed at the Oak Ridge National Laboratory to simulate traffic flow during regional evacuations in response to both human-made disasters, such as nuclear reactor failures, airborne release of a toxic gas, dam-failure caused flooding, and naturally-caused disasters such as hurricanes and earthquakes (Rathi and Solanki, 1993).

Several evacuation-oriented software systems have been proposed to address specific needs. For example, TEVACS was developed by Han (1990) to consider the specific needs of the Taiwanese for public transportation as a means of evacuation and to model the characteristics of mixed traffic (i.e. passenger car, taxi, pick-up van, bus, truck, motorcycle, and bicycle). CEMPS (Configurable Emergency Management and Planning System) developed by Pidd et al. (1996), uses a Geographic Information System (GIS) linked to a simulation model. The simulation model was created to determine suitable evacuation plans given specific characteristics of the terrain and population.

Widely-existing traffic simulation software models have been employed for evacuation planning: CORSIM (Sisiopiku et al.), Paramics (Cova and Johnson, 2002, 2003; Church and Sexton, 2002), EMME/2 (Rontiris and Crous), NETSIM (Radwan and Hobeika, 1985), MITSIM (Yang and Koutsopoulos, 1996), WITNESS (Farahmand, 1997), SLAM (Stern and Sinuany-Stern, 1989), IMDE (Sumner and Zahn, 1996), Dynasmart-P (Kwon and Pitt, 2005), and VISSIM (Han and Yuan, 2005);

however, in many cases, extensive modifications were required. Jones et al. (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.

Radwan et al. (1985) employed NETSIM to develop a macroscopic computer simulation model for evacuating a rural highway network under the threat of a natural disaster. The model was applied to a small town in Virginia. Rontiris and Crous (undated) used the Cape Metropolitan Council (CMC)'s EMME/2 transportation demand model to model the expected traffic link flows resulting from the various evacuation demand scenarios tested around the Koeberg Nuclear Power Station. EMME/2 proved to be a valuable tool for the quick assessment of many possible scenarios. Witness was adopted by Farahhmand (1997) to build up a simulation model to predict with a certain degree of probability the optimal escape routes from the coastal areas of the Rio Grand Valley. Cova and Johnson (2002) presented a microscopic simulation method using Paramics to develop and test neighborhood evacuation plans in the urban-wildland interface.

2.1.5 Evacuation and Geographic Information Systems (GIS)

GIS is often used in emergency evacuation planning and evacuation management, because of its capability to integrate spatial data. Wilmot and Meduri (2005) proposed a procedure to establish evacuation zones that relies on GIS. Li and Wang (2004) developed a prototype of a GIS-based evacuation simulation system that integrates information on evacuee behavioral patterns, the transportation network and regional land-use for evacuation planning. Cova and Church (1997) and Church and Cova (2000) proposed the CCM (critical cluster model) to identify neighborhoods that might be of particular concern during an evacuation due to a fast moving hazard, such as a wildfire. The model was embedded in a GIS-based platform and a case study was conducted in Santa Barbara, California.

Lepofsky and Abkowitz (1993) proposed methods employing GIS with the capacity to perform transportation hazard analysis and incident management. Several case studies were provided involving highway operations in California to illustrate their implementation. The importance of GIS in planning, design, and operation of emergency management was also addressed in (PublicWorks, 2002). Alam and Goulias (1999) employed a database management system and GIS software to develop an evacuation management system with special emphasis on traveler behavior and land use patterns. Silva and Eglese (2000) designed a spatial decision support system, referred to as the Configurable Emergency Management and Planning Simulator (CEMPS), with an interactive evacuation simulator and dynamic graphics.

2.1.6 Evacuation and Intelligent Transportation Systems (ITS)

Several authors have considered the potential impact of the use of advanced technologies and ITS on evacuation. Baxter (2001) evaluated the potential real-time use of Intelligent Transportation Systems (ITS) technologies to improve safety and efficiency during hurricane evacuation in Florida. The potential use of ITS technologies to collect performance data during an evacuation and conduct post-evacuation analyses was also considered. Such analyses can aid in improving preparedness plans for future events requiring evacuation. Morrow (2002) similarly studied the implementation of ITS technologies to reduce the evacuation time when major storms threaten Florida. Zaragoza and Burris (1998) advocate for the importance of advanced technologies, specifically, traffic surveillance cameras and other related devices, for emergency management during hurricane evacuation. Urbina and Wolshon (2003) discuss the benefits of using ITS during hurricane evacuation based on a survey that they conducted.

2.1.7 Signal Timing for Evacuation

Traffic signal timing plans can greatly effect emergency management and response during an evacuation. Franzese and Han (2001) proposed a computer-based system to simulate traffic flow and evaluate the impacts of different traffic management alternatives on emergency evacuation. They suggested that traffic management could have a significant impact in the effectiveness of evacuation plans. Their focus was on traffic management strategies, such as contraflow operations. Sisiopiku et al. (2004) tested proposed evacuation plans and response actions employing CORSIM. In their work, the impact of signal timing optimization as a traffic management strategy was evaluated on a very small area in Birmingham, Alabama. They used SYNCHRO to establish the optimal signal timing plan and then input the resulting timing plans into their CORSIM model. The effect of adjusting the signal timing plans in this way under different scenarios was evaluated. The authors suggested that traffic signal optimization can significantly decrease delays and, thus, the evacuation time.

On January 27, 2005 a meeting on traffic operations was held in Florida. Participants identified a number of factors that could support traffic management operations in an evacuation. They suggested that traffic signal timing plans should be constructed in preparation for an evacuation.

Emergency vehicle preemption (EVP) can improve response times for emergency vehicles by providing favorable treatment for these vehicles at intersections. EVP can enhance the movement of emergency vehicles, but not without affecting other roadway users. Thus, it is necessary to evaluate the benefits and costs of implementing EVP as part of an evacuation plan. Bullock et al. (1998) used TSIS with a controlled hardware-in-the-loop environment to quantify the impact of EVP systems across three coordinated intersections on traffic in Loudon County, Virginia. In the simulation model, the emergency vehicle was treated as a passenger car with a very aggressive driver. The result showed that for the given signal timing plans and specified preemption strategies, EVP had a statistically significant, albeit relatively minor, negative effect on the entire network under some scenarios. McHale and Collura (2003) modeled emergency vehicles in CORSIM with the runtime extension. Data simulated from CORSIM with an optimal timing plan obtained through TRANSYT-7F was used to evaluate the influence of EVP on all travelers.

Louisell and Collura (2005) noted that the inherent limitations of simulation-based methods make them insufficient for evaluating the impact of EVP on network performance. Consequently, they empirically evaluated the benefits of EVP on the performance of an intersection or an emergency response corridor based on extensive field observations in the Northern Virginia Region. They considered the interaction among emergency vehicles, individual driver behavior and the impact of signal timing plans. They used such measures of effectiveness as the number of stops, delay and speed.

Unlike most of the above mentioned works that focused on decreasing the travel time of emergency vehicles via EVP, Louisell et al. (2003) proposed a conflict analysis method to evaluate the potential safety conflicts of EVP. Empirical analyses revealed that conflict points between the emergency vehicle's path and the interacting traffic stream have been largely reduced with EVP. Three types of conflict points were characterized in this study: conflict with concurrent traffic streams, perpendicular traffic streams, or opposing traffic streams. Furthermore, Louisell et al. (2004) developed a worksheet method to evaluate the safety benefits of EVP by considering the estimated crash reduction at a given intersection or along a corridor. By this method, which intersections or corridors would most benefit from EVP could be determined.

2.2 Summary of Interviews

Nationwide interviews with experts and representatives from federal, state and local agencies concerned with geographic evacuation within the United States were conducted by Miller-Hooks and Tarnoff (2005) between September 2004 and February 2005. The purpose of the interviews was to assess the state-of-the-practice in signal timing in an event requiring geographic evacuation.

The interviews revealed that there are currently four general approaches to setting signal timing for evacuation in practice in the United States: (1) set the signals on flash; (2) allow the police to direct traffic at critical intersections; (3) use PM peak (generally outbound) timing; (4) set the timing plans to the maximum cycle length on the evacuation routes as governed by the controllers, giving the majority of the green time to the major roadways. Furthermore, there appears to be no clear policy within or across the states on how to control traffic at signalized intersections during an evacuation. Decisions concerning signal timing in an evacuation are generally taken at a local level. Little, if any, coordination across jurisdictions in operating the signalized intersections exists.

2.3 Conclusions

Numerous works have addressed geographic evacuation and several have proposed methods for improving traffic operations to facilitate evacuation and emergency response. The majority of these works consider hurricane evacuation and evacuation due to a release or potential release at a nuclear power plant. Various models have been developed to simulate and analyze traffic conditions for different scenarios under different emergencies, and have, as such, provided useful insight for transportation engineers in developing evacuation plans and policies. While several researchers and agencies have noted the potential impact that traffic signal control may have on evacuation operations, very few studies have addressed this topic. All but one of these studies considered preemption for emergency vehicles. One work included a small study on signal timing for evacuation. Finally, it seems that in practice, four approaches to setting signal timing for evacuation are currently employed in the United States.

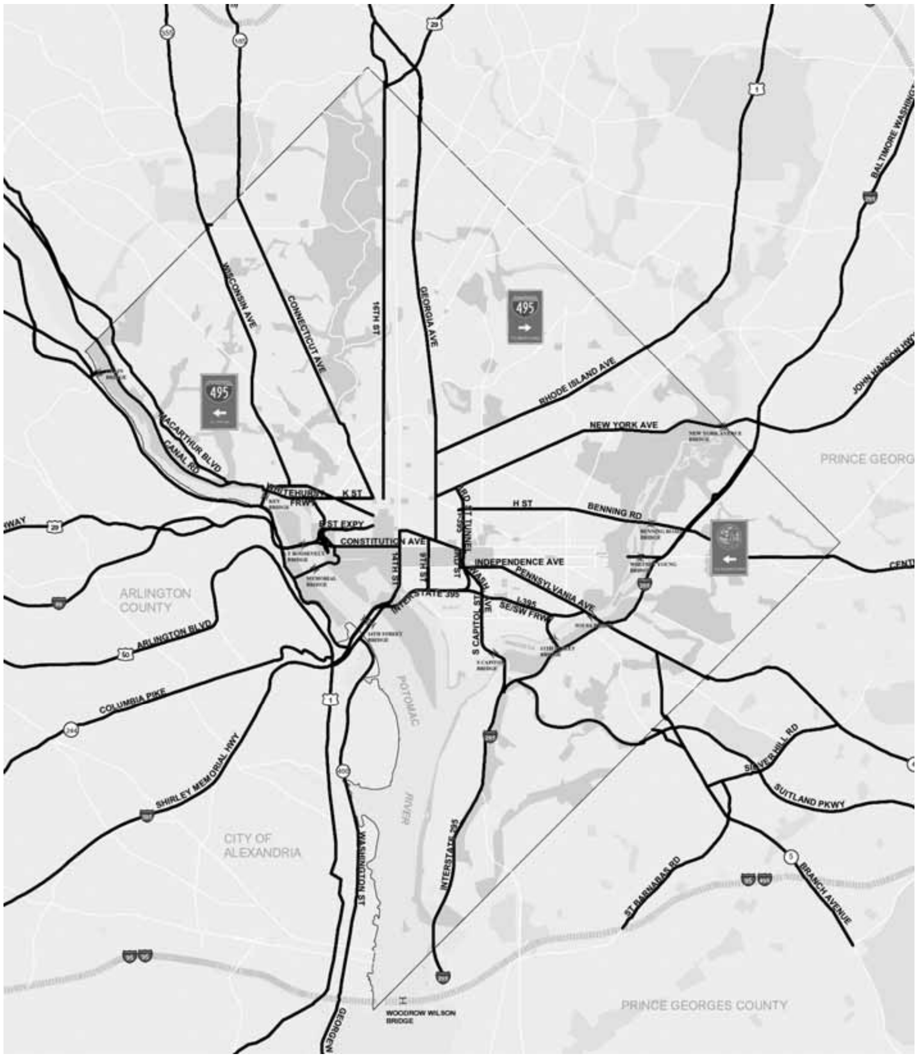
Chapter 3. Development of Simulation Model

A simulation model of the region within Washington D.C. was developed to assess the performance of the proposed signal timing plans under various evacuation scenarios. The model is composed of two primary evacuation routes, i.e. Connecticut Ave. and 16th Street. Details of the study network are provided in section 3.1. Three signal timing plans proposed for emergency management were tested and compared, each of which is described in detail in section 3.2. CORSIM, a microscopic traffic simulation software package with specifically designed capabilities for simulating traffic control systems, was employed to simulate traffic in this study. Details concerning the building of the proposed model in CORSIM are given in section 3.3.

3.1 Study Network

Post September 11, 2001, the District Department of Transportation (DDOT) established an evacuation plan intended to facilitate outbound traffic flow during an evacuation. The plan involves 25 primary evacuation routes, as depicted in Figure 3-1. These evacuation routes contain approximately 400 signalized intersections. The evacuation signal timing plans employ cycle lengths at their maximum value of 240 seconds (dictated by the controllers) with majority of the green time allocated to the major roadways.

Figure 3-1 Primary evacuation routes in Washington D.C. (shown in bold)



Two of the 25 evacuation routes were included in the study network, i.e. Connecticut Ave. and 16th Street, referred to herein as the study corridor. The DDOT provided the geometry data and signal timing plans for each evacuation route for use in this study. Several connecting roadways are also included in the study network, i.e., K-Street, L-Street, M-Street, Rhode Island Avenue, Massachusetts Avenue, New Hampshire Avenue, Military Road, Porter Street and Calvert Street-Euclid Street.

These connecting roadways create the possibility for the evacuees to change evacuation routes in response to roadway conditions and information received en route. Figure 3-2 shows the study network, details of which are provided in Table 3-1. Note that the Washington, D.C. borders with Maryland and Virginia are shown in the Figures 3-1 and 3-2.

Figure 3-2 Study network

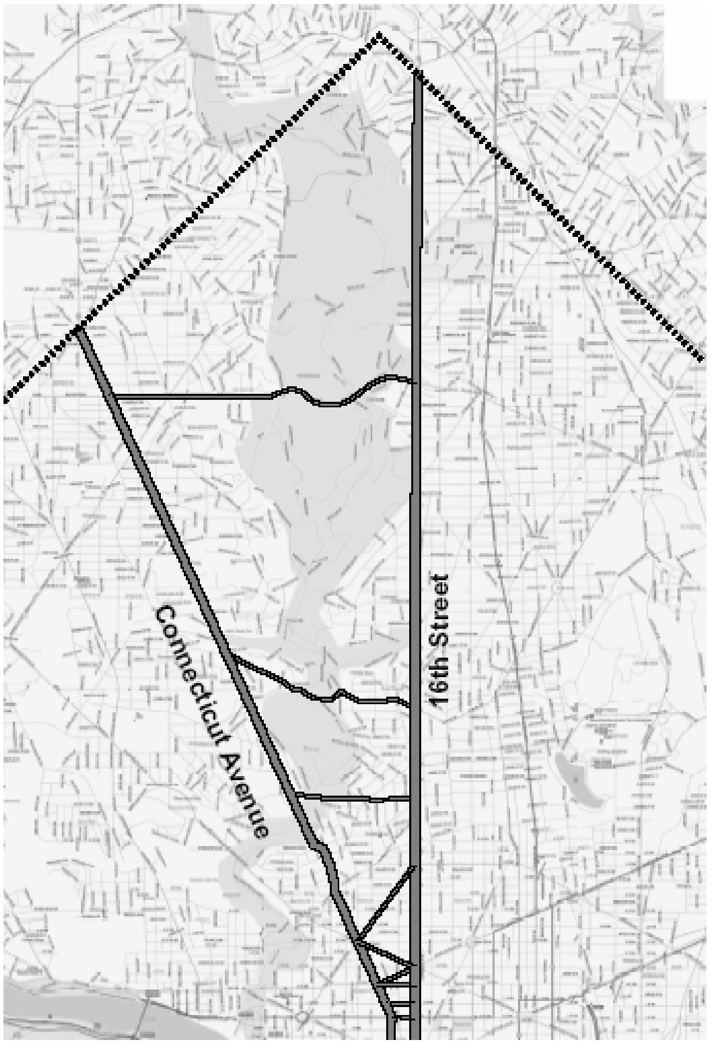
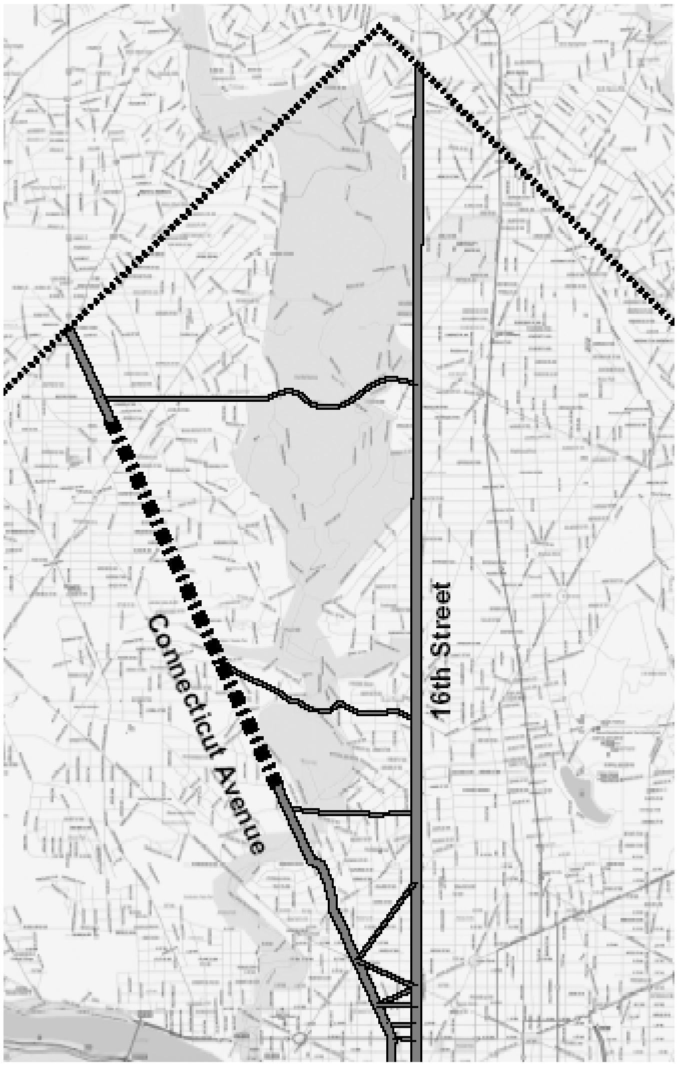


Table 3-1 Components of the study network

Street name	From	To	Length (mile)	# of lanes	# of cross Streets
Connecticut Ave.	K Street	Patterson Street	5.11	4-7	60
16th Street	K Street	N Portal	6.19	4	85
K Street	Connecticut Ave.	16th Street	0.17	6	N/A
L Street	Connecticut Ave.	16th Street	0.20	3	N/A
M Street	Connecticut Ave.	16th Street	0.25	1	N/A
Rhode Island Ave.	Connecticut Ave.	16th Street	0.28	5	N/A
Massachusetts Ave.	Connecticut Ave.	16th Street	0.40	4	N/A
New Hampshire Ave.	Connecticut Ave.	16th Street	0.59	2	N/A
Calvert St-Euclid St	Connecticut Ave.	16th Street	0.82	2	N/A
Porter Street	Connecticut Ave.	16th Street	2.59	1	N/A
Military Road	Connecticut Ave.	16th Street	2.53	3	N/A

The study network includes 124 intersections, 89 of which are signalized, and 35 of which are un-signalized. Among the 89 signalized intersections, 9 are actuated and the remaining are pre-timed. Traffic signals on the connecting roadways are not modeled in the network. Free flow speeds on the two evacuation routes and the minor roadways included in the study network are set to 30 miles per hour and 25 miles per hour, respectively. Contraflow operations (sometimes referred to as reversal lane strategies) are in daily use along a portion of Connecticut Ave., as shown in Figure 3-3. Two of the six lanes are designated as reversal lanes. These lanes are used for inbound traffic in the AM-peak hour and outbound traffic in the PM-peak hour.

Figure 3-3 Contraflow operations along Connecticut Ave.



3.2 Description of Proposed Signal Timing Plans

Nationwide interviews were conducted by Miller-Hooks and Tarnoff (2005) on the state-of-the-practice in traffic signal timing for evacuation. The interviews involved experts from universities, and representatives, traffic engineers from federal, state or local transportation agencies. The interviews revealed that four general methods are currently used in practice for setting signals for an evacuation in the

United States: (1) set the signals on flash; (2) allow the police to direct traffic at critical intersections; (3) set the signals on the PM-peak (outbound) setting; and (4) set the timing plans to the maximum cycle length on the evacuation routes as governed by the controllers, giving the minimum green time to the minor roadways. The use of flash mode, peak-hour plan and plan with maximum cycle length under several evacuation scenarios were assessed on the CORSIM model of the study network using signal timing plans provided by the DDOT. Details regarding each of these plans are given in sub-section 3.2.1 through 3.2.3.

3.2.1 PM-peak Plan

The peak-hour plan can be used in some cities and for some events precipitating an evacuation, such as an event that takes place in the central business district. For example, the DDOT employed the PM-peak timing plans to facilitate outbound traffic flow after the attack on the Pentagon on September 11, 2001. The PM-peak timing plan has a cycle length of 100 seconds.

3.2.2 240-s Plan

To facilitate the outbound flow of traffic along the arterials designated for Washington D.C. as evacuation routes post Sept. 11, 2001, the DDOT has developed signal timing plans for an evacuation, as discussed previously. These plans employed a longer cycle length than the PM-peak plans, i.e. 240 seconds as compared with 100 seconds, the maximum permitted by the controller. The majority of the green time is given to the major roadways. Similar maximum cycle length plans could be widely employed.

3.2.3 Flash Mode Plan

It is practice in many jurisdictions to set the traffic signals on flash mode during an evacuation. There are two general approaches for setting the signals on flash:

(1) Flash yellow on main roadway / flash red on minor roadway

In this approach, priority is given to traffic on the arterials to achieve a continuous flow, allowing the roadway capacity to be used more efficiently. A drawback of this approach is that extremely long delays may result for vehicles on the minor roadways. If delays are extremely long, drivers may not be willing to obey the traffic rules. This plan is referred to herein as the flash mode plan (YR).

(2) Flash red in all directions.

In this approach, vehicles at each intersection are served on a first-come first serve basis. While this approach may lead to greater equity in terms of delay for vehicles on the minor roadways, the capacity of the roadway will not be exploited. Such an approach will incur a great amount of loss time at each intersection, caused by the need for vehicles to come to a full stop before proceeding. This plan is referred to herein as the flash mode (4R).

3.3 Simulation Model Building

A simulation model of the evacuation corridor defined in section 3.1 was constructed using data supplied by the DDOT. In this section, details of the data format and how the data was converted to construct the CORSIM model are given.

The DDOT provided their signal timing plans by time of day for ordinary operations and evacuation plan for this study. These plans are built and stored in SYNCHRO, a traffic signal timing optimization package. Each plan on each evacuation route is stored in a single SYNCHRO file. The SYNCHRO files also contain all the desirable network data, including those describing the characteristics of each roadway section (length, number of travel lanes, lane width, grades, free flow speed, etc.) and those describing the characteristics of each intersection (number of lanes for each approach, lane channelization, lane alignment, etc.).

In CORSIM, a network is defined by a TRF file. To avoid building the network from scratch, which can be very tedious and time consuming, an effort was made to transform the network data directly from SYNCHRO to CORSIM. Small and necessary modifications were completed to make the files compatible with CORSIM. Since CORSIM has special rules for numbering the nodes, e.g. ID of entry nodes and exit nodes must start with 8 and ID of interface nodes must start with 7, nodes were renumbered in SYNCHRO before the transformation was carried out to accommodate this rule.

Network data for each evacuation route was originally stored in separate files, thus coordinates were adjusted so that several CORSIM files could be merged into a single file representing the integrated study network on which the signal timing plans were tested. Additional issues exist due to limitations on the input data as defined by CORSIM. For example, the maximum value of green time cannot exceed 120 seconds. To deal with such issues, phases with green time greater than 120 seconds were decomposed into two phases with the first one requiring no amber or red time.

The final TRF file that defines the study network in CORSIM is composed of approximately 4,000 records. The network consists of 326 nodes and 620 links, excluding entry (exit) nodes and entry (exit) links. To assist with the analysis of the simulation output and to correctly model the problem characteristics that vary over time, ten time periods, each representing one hour, were used. That is, all demand is assumed to arise within the first hour in all scenarios and the turning movement percentage in some scenarios differs between the first hour and remaining hours of the evacuation. Details regarding the setting of more parameters in the proposed model, such as those defining the aggressiveness of drivers and traffic incidents, are given in experimental design in chapter 4.

Chapter 4. Experimental Design

The evacuation corridor described in chapter 3 was modeled in CORSIM. The proposed signal timing plans were tested on the study network defined in chapter 3 under several evacuation scenarios. To systematically assess the performance of the proposed signal timing plans, various factors were considered when constructing the evacuation scenarios, i.e. time of day, percentage of traffic turning in the outbound direction onto the main evacuation routes from minor roadways (referred to herein as the turning movement percentage), aggressiveness of drivers, traffic incidents, contraflow operations, roadside parking along the evacuation routes during off-peak hours and transit operations. These factors can significantly impact the network clearance time and average vehicle delay, which are of significant concern to decision makers (state and local transportation agencies).

Two master evacuation scenarios were developed in this study, each of which is composed of many sub-scenarios. The first master scenario involves a terrorist incident, e.g. a bomb explosion that occurs around the Capitol building. The second involves the imposition of a federal government shutdown in which all the federal offices in Washington D.C. are closed and office workers must leave for home. Details of these two master scenarios and their corresponding sub-scenarios are given in section 4.1. The Census Transportation Planning Package (CTPP) 2000 was employed in this study to estimate the traffic demand on the roadways in the area of study. The demand was estimated by time of day and by type of incident. For each scenario, there is a worst case estimate and an average case estimate of demand. Details are provided in Section 4.2.

4.1 Development of Scenarios

Seven factors that may affect the resulting performance of the evacuation plans were considered when constructing these scenarios: time of day, turning movement percentage, aggressiveness of drivers, crashes and other traffic incidents, contraflow operations, roadside parking along the evacuation routes during off-peak hours and transit operations. Time of day plays a critical role in determining the magnitude of demand, i.e. demand during the off-peak hours in a highly commercialized area can be significantly larger than at midnight. Turning movement percentage may influence the evacuation efficiency. The phase and split of the timing plan at a particular intersection should be based on the turning movement percentage at that intersection. Aggressiveness of drivers may positively impact the efficiency with which roadway capacity is used, likely at the expense of traffic safety. Crashes and other traffic incidents, contraflow operations and roadside parking can significantly influence the available capacity of the evacuation routes. The use of transit in evacuation to assist those who do not possess a vehicle was proposed by several researchers (e.g. Brian 2003). While it can aid in the evacuation, it can also negatively impact the remaining capacity for automobiles. Twenty sub-scenarios were developed from the various combinations of these factors.

4.1.1 Scenario Construction

In this section, the factors considered in sub-scenario generation are discussed in detail.

4.1.1.1 Time of Day

The event initiating the evacuation is assumed to occur at three possible time periods during the day: midnight, off-peak hour, and AM-peak hour. The time period in which the event occurs affects magnitude and distribution of demand for the evacuation. For the AM-peak hour case, only those people who usually start working before the time of the emergency event are assumed to be in their offices. The remaining people who work in the affected area are assumed to be either on their way to their offices or are still at home. For the off-peak hour case, it is assumed that all workers are in their offices at the time of the event. Details concerning how the demand was estimated for this study are provided in section 4.2.

4.1.1.2 Turning Movement Percentage

Turning movement percentage is a factor that must be preset in the simulation model. The process of selecting an evacuation route is dynamic, as drivers decisions in this regard are affected by real-time traffic conditions (Sheffi et al. 1982). Moreover, some drivers may wish to head inbound to find family, save a pet, etc. Similarly, emergency vehicles may need to head inbound. Due to the limitations of the simulation software used in this study, such decisions are modeled through a random assignment that forces randomly chosen vehicles to turn at each intersection. The number that “choose” to turn at any intersection is generated by a preset turning movement percentage. This preset turning movement percentage is set identically at each intersection for a given run in this study. Three settings for the turning movement are considered: (1) In the first hour, 98% of the people choose the outbound direction and the remaining choose alternative directions. In later hours, 99.8% of the people choose the outbound direction and the remaining 0.2% choose alternative directions. (2) 100% of the people choose the outbound direction throughout the course of the evacuation. (3) 98% of the people choose the outbound direction throughout the course of the evacuation. Settings (2) and (3) are extreme cases and results of runs employing these settings can provide bounds that can be used in the analysis of runs employing the other more realistic setting. A higher percent of vehicles turning to go in a direction that is inconsistent with the evacuation in the first hour is considered in settings (1) to model activities, such as parents who must first pick up their children at school before leaving for a safe area.

4.1.1.3 Aggressiveness of Drivers

During a no-notice evacuation, drivers are likely to be more aggressive than in non-emergency circumstances. Aggressive driving may be characterized by faster speed and increased willingness to break traffic rules (Petruccelli, 2003). Such behavior can lead to more frequent occurrence of traffic accidents. On the other hand, a greater number of aggressive drivers may, in the absence of traffic incidents, lead to more efficient use of the available capacity. The aggressiveness of drivers is considered in the first set of scenarios (bomb explosion near the Capitol building). A set of parameters are set in the network properties of the developed CORSIM model.

The parameters indicate how likely a driver is to stop for amber signals and how likely the driver is to tolerate low speed of the lead vehicle or to cooperate with other drivers who are trying to change lanes. To model the aggressiveness of drivers in CORSIM, one can also change more parameters in NETSIM setup such as free flow speed and headways at which all drivers will attempt a lane change.

4.1.1.4 Crashes and Other Traffic Incidents

One might expect a greater frequency of crashes and other traffic incidents along the escape paths in an evacuation than might arise during normal traffic operations. Once a traffic incident occurs, one or more lanes will be blocked, resulting in reduced capacity of the evacuation routes. The impact of these incidents may persist for between several minutes and several hours depending on the severity of the incident and the capability to respond to the incident.

To examine how the occurrence of traffic incidents during an evacuation can affect the network clearance time, five cases are considered in constructing the scenarios: (1) no traffic incident occurs throughout the evacuation; (2) 14 minor traffic incidents occur during the evacuation, locations of which are distributed along both evacuation routes (Connecticut Ave. and 16th Street), each incident blocking one lane for a duration of 15 minutes; (3) 14 major traffic incidents occur during the evacuation, the locations of which are identical to case (2), but with a duration of one hour; (4) identical settings to case (3) with the exception that each incident blocks two lanes of traffic; and (5) identical settings to case (3) with the occurrence of an additional incident (shown in Table 4-1 as incident 15) along Connecticut Ave. Case (5) was intended to examine the impact of an incident that occurs at the bottleneck of the evacuation route. Figure 4-1 shows the distribution of these traffic incidents throughout the study network. The location and the time of occurrence of each of the 14 traffic incidents are given in Table 4-1. The starting time of the evacuation is assumed to be 0:00 in the table.

Figure 4-1 Distribution of assumed traffic incidents

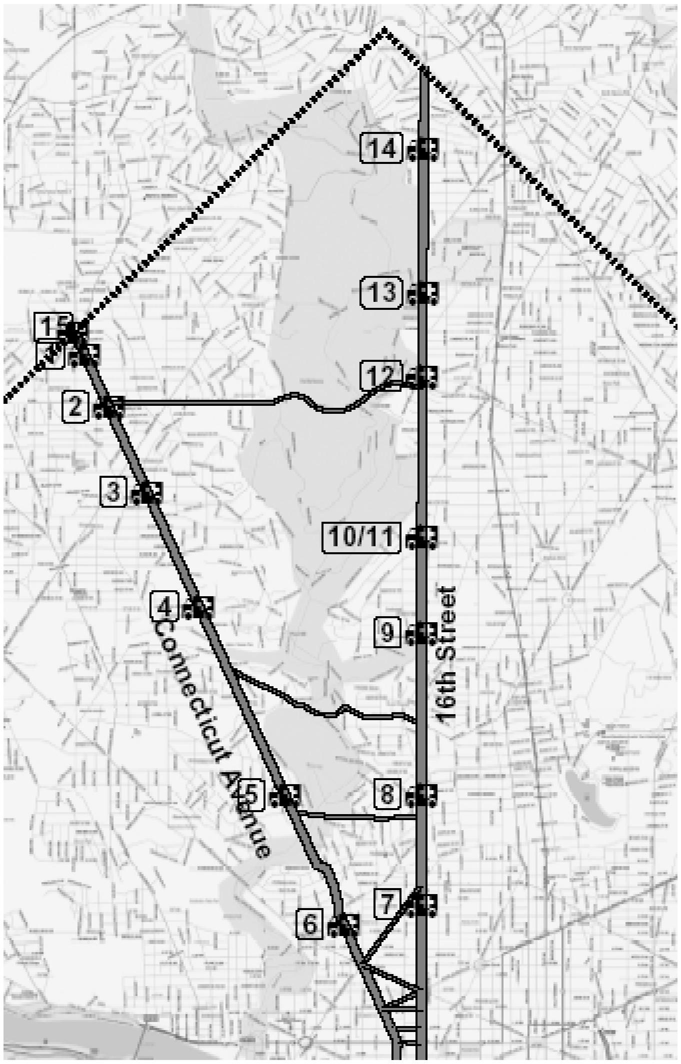


Table 4-1 Location and time of occurrence of the assumed 14 traffic incidents

Incident Number	Location	Starting Time
1	Connecticut Avenue between Northampton and Mckinley St.	2:30
2	Connecticut Avenue between Military Rd. and Kanawha St.	2:00
3	Connecticut Avenue between Ellicott St. and Davenport St	2:30
4	Connecticut Avenue between Veazey Terr. and Van Ness St.	1:00
5	Connecticut Avenue between Woodley Rd. and 24th St.	1:00
6	Connecticut Avenue between S St. and R St.	0:30
7	16th Street between S St. and T St.	0:15
8	16th Street between EUCLID St. and HARVARD St.	1:00
9	16th Street between SHEPHERD St. and UPSHUR St.	2:00
10	16th Street between EMERSON St. and DECATUR St.	1:00
11	16th Street between EMERSON St. and DECATUR St.	1:30
12	16th Street between Fort Stevens and Military Rd.	2:30
13	16th Street between Aspen St. and Van Buren St	1:30
14	16th Street between Kalmia Rd. and Holly St.	2:30
15	Connecticut Avenue between Patterson St. and Oliver St.	2:00

4.1.1.5 Contraflow Operation

Contraflow operations are employed along a portion of Connecticut Avenue in daily traffic operations, as described in chapter 3. Two vehicle travel lanes can be reversed and are used for inbound traffic in the AM-peak hours and for outbound traffic in the PM-peak hours. Whether or not contraflow operations along a portion of an evacuation route can affect the performance of the proposed signal timing plans in an evacuation is examined. Contraflow operations are modeled in eighteen sub-scenarios (the sub-scenarios are described in Section 4.1.2). Two remaining sub-scenarios are modeled without contraflow operations for comparison.

4.1.1.6 Roadside Parking Along the Evacuation Routes

Roadside parking is permitted along Connecticut Ave. in the off-peak hours. Capacity along this evacuation route will be greatly affected by the loss of one lane due to parked cars. In fact, the impact may last throughout the evacuation as long as one car is not cleared from a lane. Roadside parking is modeled in two of these sub-scenarios and the impact of allowing parking in the parking lane is examined.

4.1.1.7 Transit Operations

The operation of transit is necessary for evacuating those who do not possess a vehicle. Transit operations are modeled in all sub-scenarios. Such operations may negatively influence the available capacity for automobiles along the evacuation routes. Two transit routes (one for the inbound direction and one for the outbound direction) are assumed to operate on each of the two evacuation routes. The service frequency during the evacuation is set to 10 minutes. Only one stop is modeled within the evacuation region, as it is expected that the transit vehicle will not have the capacity to allow passengers to board at many intermediate locations.

4.1.2 Development of Sub-scenarios

Twenty sub-scenarios are constructed from various combinations of the factors discussed in Section 4.1.1. A complete list of the sub-scenarios is provided in Table 4-2. For each sub-scenario, a worst case and an average case demand were considered. Three signal timing plans (i.e. 240-s plan, flash mode plan (YR), PM-peak plan) were tested on each sub-scenario and an additional plan (flash mode plan (4R)) was tested on those indicated by (*).

Table 4-2 List of evacuation sub-scenarios

Sub-Scenario	Master Scenario	Time of Day	Turning Percentage	Traffic Incident	Contraflow Strategy	Roadside-parking
1(*)	1	midnight	1	1	yes	no
2	1	midnight	1	1	yes	yes
3	1	midnight	1	1	no	no
4(*)	1	midnight	1	2	yes	no
5	1	midnight	1	2	yes	yes
6	1	midnight	1	2	no	no
7(*)	1	midnight	1	3	yes	no
8	1	midnight	2	1	yes	no
9	1	midnight	2	2	yes	no
10	1	midnight	3	1	yes	no
11	1	midnight	1	4	yes	no
12	1	midnight	1	5	yes	no
13	1	off-peak	1	1	yes	no
14	1	off-peak	1	2	yes	no
15	1	AM-peak	1	1	yes	no
16	1	AM-peak	1	2	yes	no
17	1	AM-peak	3	1	yes	no
18	2	off-peak	1	1	yes	no
19	2	off-peak	1	2	yes	no
20	2	off-peak	3	1	yes	no

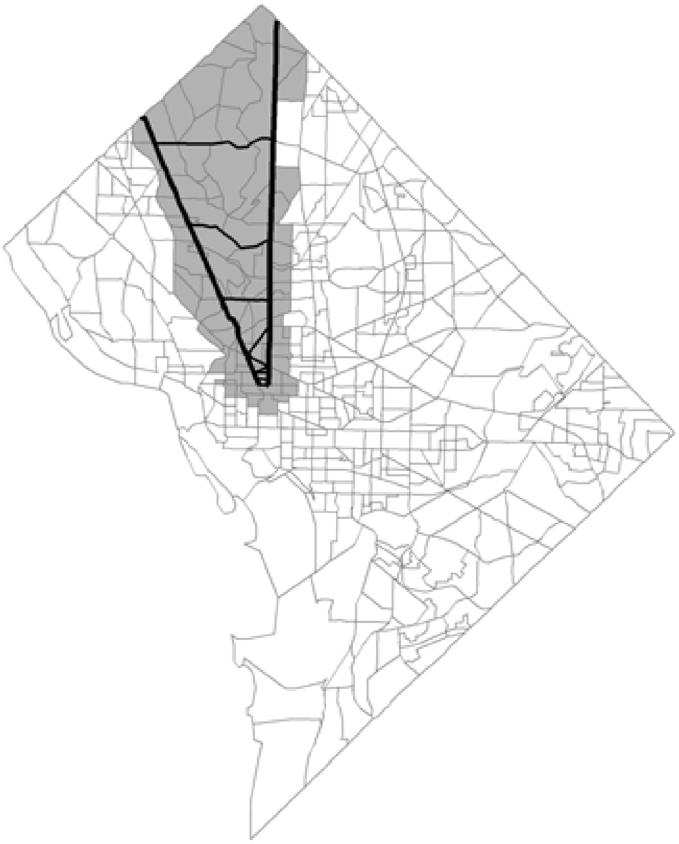
4.2 Evacuation Demand Estimation

The Census Transportation Planning Package (CTPP) 2000 obtained from the U.S. Census Bureau was employed to estimate the travel demand on the roadways in the area of study during an evacuation. The data set contains data by place of work, place of residence and commuter trips from home to work. Data related to population, employment, number of available vehicles and other relevant factors are provided in the CTPP 2000. Data based on place of work and place of residence were employed to estimate the travel demand during an evacuation. The data is reported in several geographic reporting units, including counties, tracts, traffic analysis zones (TAZs), and block groups. The demand estimation herein was based on TAZ level data.

In this study, all of Washington, D.C. (the District) is assumed to be affected by the event precipitating the evacuation. The District is composed of 458 TAZs. However, only a small region of the District (94 TAZs) is considered in this study, i.e. only the areas surrounding the evacuation study corridor are considered, as depicted in Figure 4-2.

The demand was estimated by time of day and by type of event (i.e. bomb explosion near the Capitol building or federal shutdown). As described in section 4.1.1.1, three possible time periods are considered in this study, i.e. midnight, off-peak hour and AM-peak hour. For the AM-peak hour case, it is assumed that the event occurs at 9:00 a.m. In each TAZ, it is assumed that four groups of people need to be evacuated: (1) those who stay at home; (2) those who work in their offices; (3) transient population, and (4) children who are at school. For each case, a worst case demand and an average case demand were estimated in terms of the total number of vehicles involved in the evacuation. The methods used to estimate the average case demand and the worst case demand for each scenario are described in sections 4.2.1 through 4.2.4.

Figure 4-2 Surrounding areas of the study corridor



The notation used to describe the techniques used for demand estimation are given in Table 4-3, including those representing the estimates of demand and variables employed in estimation. For each variable, e.g. P_i , W_i , the source table in CTPP2000 from which the data was obtained is also indicated in the table.

Table 4-3 Notation of estimates and variables used in demand estimation

Symbol	Description	Source Table
D_i^w	Total worst case demand in TAZ i,	estimate
$D_i^{w,h}$	Worst case demand in TAZ i, caused by at home population	estimate
$D_i^{w,w}$	Worst case demand in TAZ i, caused by at work population	estimate
$D_i^{w,t}$	Worst case demand in TAZ i, caused by transient population	estimate
$D_i^{w,s}$	Worst case demand in TAZ i, caused by at school population	estimate
D_i^a	Total average case demand in TAZ i,	estimate
$D_i^{a,h}$	Average case demand in TAZ i, caused by at home population	estimate
$D_i^{a,w}$	Average case demand in TAZ i, caused by at work population	estimate
$D_i^{a,t}$	Average case demand in TAZ i, caused by at transient population	estimate
$D_i^{a,s}$	Average case demand in TAZ i, caused by at school population	estimate
P_i	The number of residents in TAZ i	Table 1-047
P_i^w	The number of workers who reside in TAZ i	Table 1-001
$\overline{P}_\mathrm{i}^\mathrm{w}$	The number of workers who reside in TAZ i and leave home for work before 9 am	Table 1-001
P_i^s	The number of students who reside in TAZ i	Table 1-053
V_i	The number of vehicles possessed by residents in TAZ i	Table 1-063
V_i^c	The number of vehicles possessed by residents in TAZ i and used for commuter trips	Table 1-110
$\overline{V}_i^c$	The number of vehicles possessed by residents in TAZ i, which are used for commuter trips before 9 am.	Table 1-110
V_i^w	The number of vehicles attracted to TAZ i due to commuter trips	Table 2-050
$\overline{V}_\mathrm{i}^w$	The number of vehicles attracted to TAZ i before 9 am due to commuter trips	Table 2-050
W_i	The number of people who work in TAZ i	Table 2-001
$\overline{W}_i$	The number of people who work in TAZ i and arrive at work place before 9 am	Table 2-001
F_i	The number of federal government workers in TAZ i	Table 2-005
κ	Vehicle occupancy ratio	constant

4.2.1 Demand Estimation for Master Scenario 1 (midnight)

In the midnight sub-scenarios of master scenario 1, the event leading to an evacuation occurs at midnight. Consequently, the evacuation primarily involves residents who live in the affected area. The number of vehicles involved in the evacuation depends on the number of available vehicles for use and a chosen vehicle utilization ratio (i.e. percent of vehicles used in an evacuation), which is usually less than one due to the fact that family members are more likely to travel together in an evacuation. Baker (1979, 1987) found that the vehicle utilization ratio was equal to 0.75 from studies on hurricane evacuation. While Perry and Greece (1983) found that the ratio was equal to 0.52 from a survey associated with the eruption of Mount St. Helens. It is assumed in this study that: (1) in the worst case, all the available vehicles possessed by residents in each TAZ are used for the evacuation, i.e. the vehicle utilization ratio is equal to one and (2) in the average case, the vehicle utilization ratio is equal to 0.55. The demand for this scenario is estimated as given in equation 4-1 and 4-2.

$$D_i^w = V_i ; \tag{4-1}$$

$$D_i^a = 0.55 V_i \tag{4-2}$$

4.2.2 Demand Estimation for Master Scenario 1 (off-peak)

In the off-peak sub-scenarios of master scenario 1, the emergency incident occurs in the off-peak hour in a typical weekday. People who are employed, excluding those who work at home, are assumed to be in their offices and a few residents, including those who are unemployed and those who work at home, are assumed to be at home at the time of the event. Children who are enrolled in school are assumed to be at school. The demand for this scenario can be estimated as given in equations 4-3 and 4-4.

$$D_i^w = D_i^{w,h} + D_i^{w,w} + D_i^{w,t} + D_i^{w,s} \qquad (4\text{-}3)$$

$$D_i^a = D_i^{a,h} + D_i^{a,w} + D_i^{a,t} + D_i^{a,s} \qquad (4\text{-}4)$$

4.2.2.1 At home population, $D_i^{w,h}$ and $D_i^{a,h}$

The at home population consists of those people who are at home when the emergency incident occurs, including those who are unemployed and those who work at home. Available vehicles are assumed to be parked at or near the home except those used for commuter trips from home to work. It is assumed that in the worst case all the vehicles left at home are used for the evacuation and in the average case, the vehicle occupancy ratio (i.e. average number of passengers per vehicle) takes the value of 1.85 ($k = 1.85$) considering that family members who are at home are more likely to travel together. These demand estimates are computed by equations 4-5 and 4-6.

$$D_i^{w,k} = V_i - V_i^c \qquad (4\text{-}5)$$

$$D_i^{a,h} = (P_i - P_i^w - P_i^s)/k \qquad (4\text{-}6)$$

4.2.2.2 At work population, $D_i^{w,w}$ and $D_i^{a,w}$

The at work population consists of those who work in their offices when the emergency event occurs. People may take different means of transportation from home to work, e.g. private car (including driving alone and carpool) or public transportation. It is assumed that, in the worst case, all the people are evacuated by private cars no matter which means of transportation they take from home to work and the vehicle occupancy ratio takes the value of 1.25 ($k = 1.25$).I In the average case, only the commuter vehicles in the affected area are used for the evacuation. The at work population estimates are computed by equations 4-7 and 4-8.

$$D_i^{w,w} = W_i / k \tag{4-7}$$

$$D_i^{a,w} = V_i^w \tag{4-8}$$

4.2.2.3 Transient population, $D_i^{w,t}$ and $D_i^{a,t}$

The transient population includes those who are passing through the affected area when the emergency incident occurs and those who are visiting the area, i.e. they are attracted to the area by some special facilities, such as hotels, shopping malls, parks and recreation centers. In this study, it is assumed that transient population in a given TAZ has a linear relationship with the number of workers in that TAZ, as in equation 4-9. The vehicle occupancy ratio is assumed to be 1.25 ($k = 1.25$).

$$D_i^{w,t} = D_i^{a,t} = 0.1 \cdot W_i / k \tag{4-9}$$

4.2.2.4 At school population, $D_i^{w,\mathrm{s}}$ and $D_i^{a,\mathrm{s}}$

The at school population consists of the children who are at school at the time of the event. It is assumed that six children take one vehicle during an evacuation, i.e. the vehicle occupancy ratio is 6 ($k = 6$). The estimate is computed by equation 4-10.

$$D_i^{w,\mathrm{s}} = D_i^{a,\mathrm{s}} = P_{\mathrm{i}}^{\mathrm{s}} / k \tag{4-10}$$

4.2.3 Demand Estimation for Master Scenario 1 (AM-peak)

In the AM-peak sub-scenarios of master scenario 1, the incident causing the need for an evacuation was assumed to occur in the AM-peak hour (9:00 a.m.) in a typical weekday. Only those people whose work hours start before 9:00 a.m. are assumed to be in their offices and others are still at home or on their way to their offices when the emergency event occurs. The warning is assumed to reach the drivers via car radio. The demand is composed of four parts as given in equations 4-11 and 4-12.

$$D_i^{w} = D_i^{w,h} + D_i^{w,w} + D_i^{w,t} + D_i^{w,s} \tag{4-11}$$

$$D_i^{a} = D_i^{a,h} + D_i^{a,w} + D_i^{a,t} + D_i^{a,s} \tag{4-12}$$

4.2.3.1 At home population, $D_i^{w,h}$ and $D_i^{a,h}$

The at home population consists of people who are at home when the emergency event occurs. This population includes those who are unemployed, those who are employed but leave home after 9:00 a.m. and those who work at home. Children who are enrolled in a school are assumed to be at school. Vehicles are assumed to be parked at or near home except those used for commuter trips from home to work before 9:00 a.m. It is assumed that: (1) in the worst case, all vehicles left at home are used for the evacuation and (2) in the average case, the vehicle occupancy ratio takes the value of 1.85 ($k = 1.85$) considering that family members who are at home are more likely to travel together. The at home population estimates can be computed by equations 4-13 and 4-14.

$$D_i^{w,h} = V_i - \overline{V}_i^{c} \tag{4-13}$$

$$D_i^{a,h} = (P_i - \overline{P}_i^w - P_i^s)/k \qquad (4\text{-}14)$$

4.2.3.2 At work population, $D_i^{w,w}$ and $D_i^{a,w}$

The at work population includes those who work in their offices when the event occurs, i.e. those who arrive at their offices before 9:00 a.m. It is assumed that: (1) in the worst case, all the people who are in their offices are evacuated by private cars regardless of which means of transportation they take from home to work and (2) in the average case, only the commuter vehicles used by those workers who arrive at their offices before 9:00 a.m. are used in the evacuation. The vehicle occupancy ratio is set to 1.25 ($k = 1.25$). The at work population estimates for this scenario are computed by equations 4-15 and 4-16.

$$D_i^{w,w} = \overline{W}_i \big/ k \qquad (4\text{-}15)$$

$$D_i^{a,w} = \overline{V}_i^w \qquad (4\text{-}16)$$

4.2.3.3 Transient population, $D_i^{w,t}$ and $D_i^{a,t}$

As described in section 4.2.2.3, the transient population includes those who are passing through the affected area when the emergency incident happens and those who are attracted to this area by some special facilities, such as hotels, shopping malls, parks and recreation centers. Similar computation (equation 4-17) as described in sections 4.2.2.3 for off-peak hour case is employed here. The vehicle occupancy ratio takes the value of 1.25 ($k = 1.25$).

$$D_i^{w,t} = D_i^{a,t} = 0.1 \cdot W_i \big/ k \qquad (4\text{-}17)$$

4.2.3.4 At school population, $D_i^{w,s}$ and $D_i^{a,s}$

The at school population consists of the children who are at school at the time of the event. It is assumed that six children take one vehicle during an evacuation, i.e. the vehicle occupancy ratio takes the value of 6 ($k = 6$). As in the off-peak estimates, this population estimate is computed by equation 4-18.

$$D_i^{w,s} = D_i^{a,s} = P_i^s / k \tag{4-18}$$

4.2.4 Demand Estimation for Master Scenario 2

In master scenario 2, an evacuation of only a subset of the population is ordered. This is referred to herein as selective evacuation. The particular case of selective evacuation concerning a federal government shutdown is modeled. In such a selective evacuation, traffic demand will be lighter than in more general evacuations. Moreover, the locations from which the demand for the evacuation arises may be widely spread over the area, as would be the case in a federal government shutdown.

CTPP 2000 provides the number of federal government employees in each TAZ. These employees are distributed in 110 federal agencies and 1,967 federal buildings in Washington D.C (http://www.ncpc.gov/). The data from CTPP 2000 was used to estimate the traffic demand for evacuation in the sub-scenarios of this master scenario 2. The vehicle occupancy ratio is assumed to be 1.25 ($k = 1.25$) for the worst case and 1.85 ($k = 1.85$) for the average case. The demand for this scenario is estimated as given in equation 4-19 and 4-20.

$$D_i^w = F_i / k \tag{4-19}$$

$$D_i^a = F_i / k \tag{4-20}$$

4.2.5 Estimation Results

The estimation results of travel demand for evacuation are summarized in Table 4-4. The total number of vehicles that need to be evacuated along the two evacuation routes (i.e. Connecticut Ave. and 16th Street) for each scenario are provided in this table for the average and worst case scenarios. It is clear from the table that master scenario 1 (off-peak hour case) involves the largest number of vehicles in the evacuation. The distribution of demand over the region for each sub-scenario is illustrated in Figures 4-3 through 4-10.

Table 4-4 Results of the Demand Estimation

Scenario		Worst Case (number of vehicles involved)	Average Case (number of vehicles involved)
Master scenario 1 (bomb explosion near the Capitol building)	midnight	61,382	33,760
	off-peak	404,521	267,796
	AM-peak	167,080	114,121
Master scenario 2 (federal shutdown)		26,897	18,158

Figure 4-3 Average level of demand for midnight case of master scenario 1

Figure 4-4 Worst level of demand for midnight case of master scenario 1

Figure 4-5 Average level of demand for off-peak hour case of master scenario 1

Figure 4-6 Worst level of demand for off-peak hour case of master scenario 1

Figure 4-7 Average level of demand for peak-hour case of master scenario 1

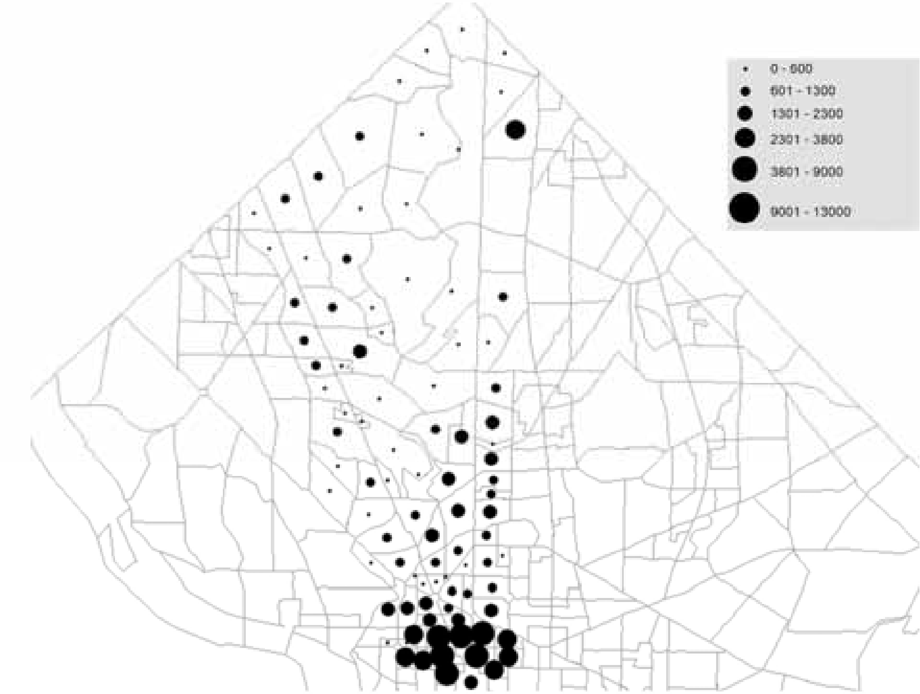


Figure 4-8 Worst level of demand for peak-hour case of master scenario 1

Figure 4-9 Average level of demand for master scenario 2

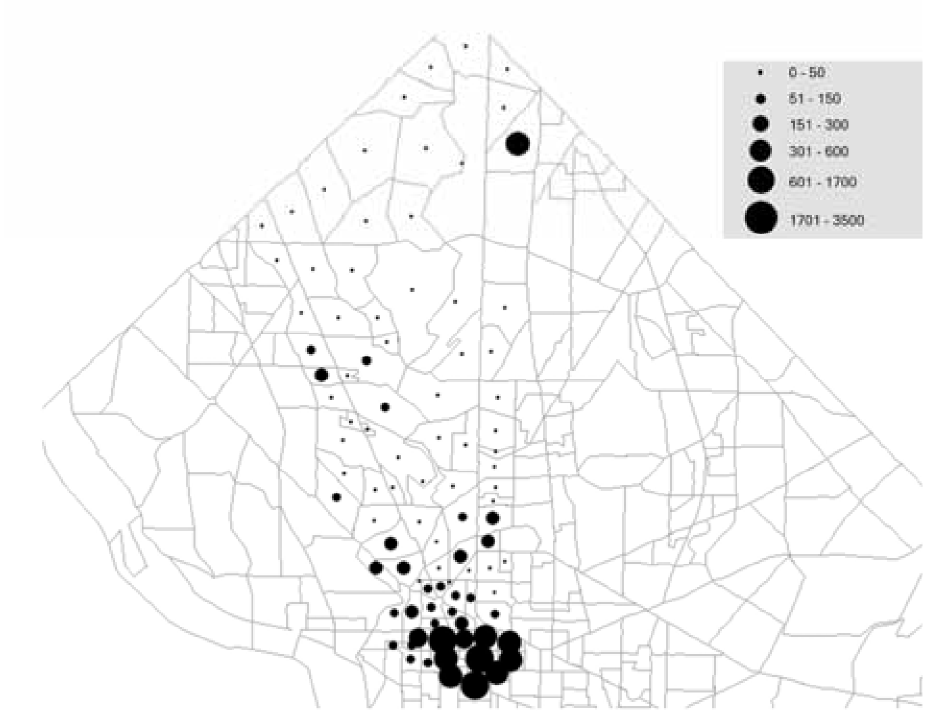
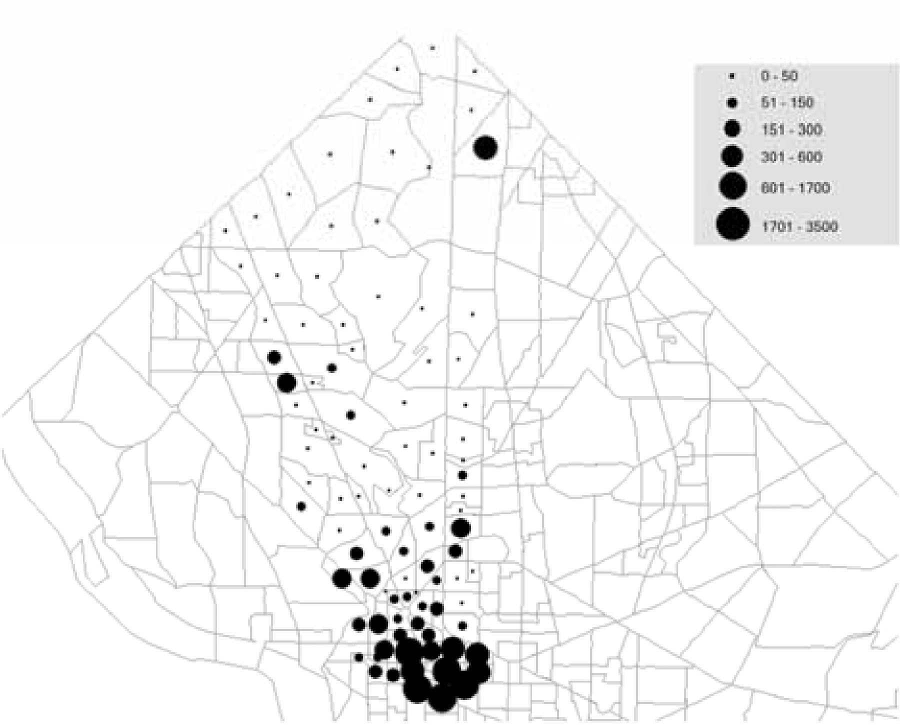


Figure 4-10 Worst level of demand for master scenario 2



Chapter 5. Simulation Results and Analysis of Existing Plans

In this chapter, results from simulation runs for the twenty sub-scenarios discussed in Chapter 4 are reported. To compare the proposed signal timing plans, two performance measures were employed: the total number of vehicles evacuated in a given time period and the average vehicle delay. Results in terms of these measures are given in sections 5.2. Findings of the analyses of the results are summarized in section 5.3.

5.1 Selection of Performance Measures

The goal of an evacuation is to quickly move people out of the affected area to avoid personal injuries and loss of life. Thus, a crucial measure in evaluating the performance of an evacuation is the network clearance time, i.e. the time until the last person (vehicle) escapes the affected area. Other measures that may also be of interest include average vehicle speed, total travel time, average vehicle delay, and number of vehicle stops. To obtain the network clearance time from the experiments in the simulation environment, it is necessary to set the simulation time sufficiently long to essentially guarantee that the network can be cleared. However, the traffic demand for evacuation in some sub-scenarios, such as sub-scenarios 15 through 18, is very large. As a result, the running time can be extraordinarily long, and as such, the total number of vehicles evacuated over a chosen duration of time is used in place of network clearance time. Specifically, in all the runs, the simulation time is set to 10 hours. The advantage of running the simulation for a limited duration is that if a single vehicle is unable to escape, the simulation will complete and the network clearance time will not be, in some sense, overestimated to account for this vehicle. Note that the network is entirely cleared in runs involving master scenario 2 within the limited time duration. As a result, the network clearance time is obtained in these runs, as discussed in section 5.2.1.4.

A vehicle is considered to be evacuated when it arrives at a safe location. In many studies of this nature, a vehicle that exits the network at any link that borders the study area (as depicted in Figure 5-1) is assumed to have made it to safety. In this study, because only a portion of the actual evacuation network for the District is modeled, only those vehicles that reach the Northern-most boundary of the evacuation corridor modeled in this study, as shown in Figure 5-2, are counted in the final number of vehicles to reach safety. All other vehicles that leave the study area along other boundaries are assumed to travel to alternate evacuation routes. Since it is not possible to “track” these vehicles once they exit the network, in the results given in this section the total number of vehicles counted as having evacuated at any point in time will understate the total number that exit the network. Thus, for example, the number counted as evacuated once the network is cleared may be significantly lower than the total initial demand for evacuation in the study corridor,

Figure 5-1 Possible boundary 1

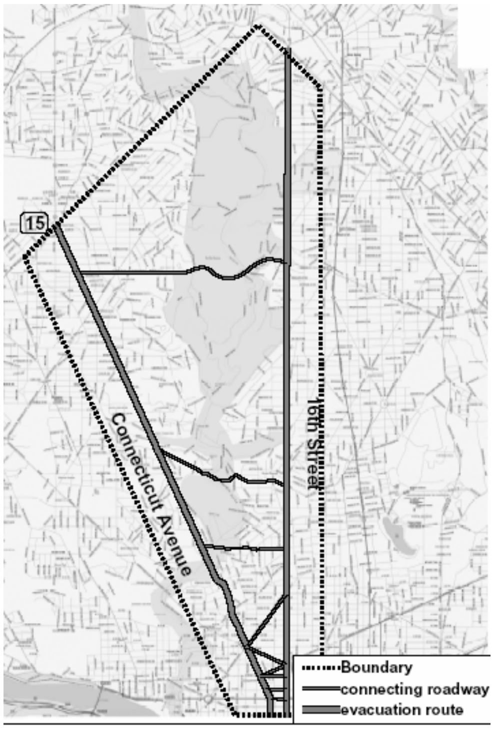
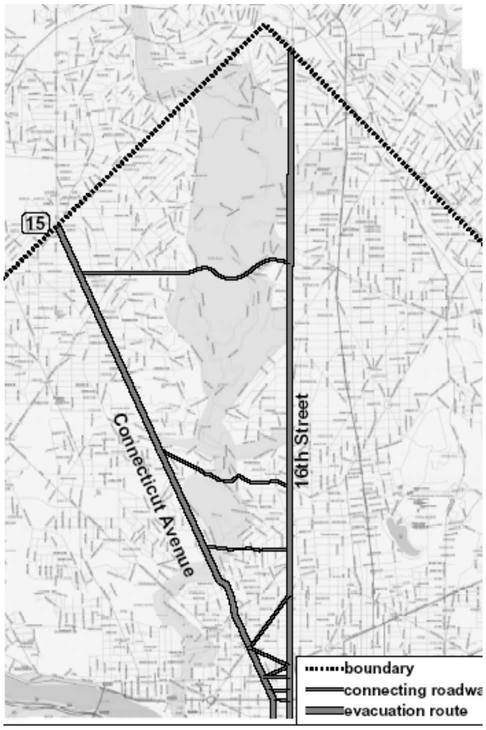


Figure 5-2 Possible boundary 2



In addition to the efficiency of an evacuation, other concerns such as fairness exist. These concerns stress the equal opportunity for people to escape in an evacuation. There are trade-offs between these two criteria. The most efficient evacuation plan might be achieved at the expense of fairness, which is unacceptable in our society and is difficult to implement in reality.

One measure of fairness is the average vehicle delay. Vehicle delay is defined as the difference between the actual time spent on a given network link and the time one could travel along that link if free flow speeds could be maintained (see the CORSIM manual for more details). It represents the time that vehicles are delayed as a result of not traveling at the free flow speed. The average vehicle delay is computed over two sets of links, i.e. links representing the evacuation corridor and links representing the minor roadways. Average vehicle delay along both sets of links is used to assess the fairness of each plan. The intent of this approach is to avoid giving too much priority to the vehicles traveling along the corridor while simultaneously sacrificing the right-of-way of those on the minor roadways.

5.2 Simulation Runs and Results

Ten simulation runs, each with a different random number seed, were made for each of the twenty sub-scenarios described in chapter 4, section 4.1.2. The results reported in this section are average values obtained from the ten runs. Results in terms of the first measure, the total number of vehicles evacuated in a ten hour time period, are given in Section 5.2.1 and results in terms of the second measure, the average vehicle delay, are given in Section 5.2.2. The tradeoffs between these two measures are discussed in assessing the various signal timing plans.

5.2.1 Results in Terms of Total Number of Vehicles Evacuated

In this section, the total number of vehicles evacuated in the first ten hours of the evacuation for each sub-scenario and signal timing plan is reported. The results of each sub-scenario for the average and worst case demand levels are provided in Figure 5-3 through 5-36 and Tables 5-8 through 5-10. Results from identical sub-scenarios are given in the same figure. In all the figures, each curve provides the results for one signal timing plan.

One will note that the total number of vehicles evacuated under each plan will vary from run to run and sub-scenario to sub-scenario, even for the same level of demand. This can be interpreted as a consequence of setting different turning percentage values in different time periods. Recall from chapter 4 that a higher percent of vehicles turning to go in a direction that is inconsistent with the evacuation in the first hour over succeeding hours is assumed in several of the runs. It was noted that setting the turning movement percentage in this way results in larger numbers of vehicles that leave the study corridor along minor roadways. Thus, a larger percentage of vehicles will be unaccounted for when obtaining the total number of vehicles that are evacuated from the area. The results obtained from sub-scenarios employing turning movement percentage settings (2) and (3) confirm this statement. See, for example, Figures 5-17, 5-19 and 5-21.

5.2.1.1 Master Scenario 1 (midnight case)

Figures 5-3 through 5-26 show the results of runs for the midnight case of master scenario 1. A list of the midnight sub-scenarios and the corresponding figures in which the results are presented is provided in Table 5-1. From the figures, it is quite clear that among all the proposed signal timing plans, the flash mode plan (YR) performs the best, the 240-s plan the second best and the flash mode (4R) the worst in terms of the total number of vehicles evacuated in a ten hour time period.

Table 5-2 shows the results of simulation runs for the average demand case of sub-scenarios 1, 4, 7, 11 and 12. These five sub-scenarios differ only in the settings of traffic incidents (see more details in chapter 4). From this table, one can see the performance of each plan in terms of the total number of vehicles evacuated within 10 hours is not significantly impacted if only one lane is blocked due to the occurrence of a traffic incident regardless of its duration time (15 minutes or one hour), as in sub-scenarios 4 and 7. If two lanes are blocked (sub-scenario 11) or the traffic incident occurs at the bottleneck of an evacuation route (sub-scenario 12), however, the total number of vehicles that can be evacuated in a given period of time is significantly decreased. Similar results were found for the worst demand cases of these sub-scenarios and other tested sub-scenarios.

Table 5-3 shows the results of simulation runs for the 240-s, flash mode (YR) and PM-peak plans for the average demand case of sub-scenarios 1 and 3. These two sub-scenarios differ only in whether or not contraflow operations are permitted. That is, contraflow operations are used in sub-scenario 1 but not in sub-scenario 3. From this table, no significant difference in the performance of each signal timing plan in terms of the total number of vehicles evacuated within 10 hours is found. Similar results were found in the worst demand case for these two sub-scenarios and in other tested sub-scenarios.

Table 5-4 shows the results of simulation runs for the 240-s, flash mode (YR) and PM-peak plans for the average demand case of sub-scenarios 1 and 2. These two sub-scenarios differ only in whether or not roadside parking is permitted. Specifically, sub-scenario 1 does not allow roadside parking, while sub-scenario 2 does. Results show that roadside parking significantly degrades the performance of each plan in terms of the total number of vehicles evacuated. However, the influence of roadside parking is consistent across plans, i.e. allowing roadside parking does not change the relative benefits of the tested signal timing plans. Similar results were found for the worst demand case for these two sub-scenarios and in other tested sub-scenarios.

Table 5-1 List of sub –scenarios and the corresponding figures for midnight demand case of master scenario 1

Sub-scenario	Turning Movement	Traffic Incident	Contraflow Operation	Roadside-parking	average case	Worst case
1	1	1	Yes	No	5-3	5-4
2	1	1	Yes	Yes	5-5	5-6
3	1	1	No	No	5-7	5-8
4	1	2	Yes	No	5-9	5-10
5	1	2	Yes	Yes	5-11	5-12
6	1	2	No	No	5-13	5-14
7	1	3	Yes	No	5-15	5-16
8	2	1	Yes	No	5-17	5-18
9	2	2	Yes	No	5-19	5-20
10	3	1	Yes	No	5-21	5-22
11	1	4	Yes	No	5-23	5-24
12	1	5	Yes	No	5-25	5-26

Figure 5-3 Total number of vehicles evacuated over 10 hours for the average demand case of sub-scenario 1

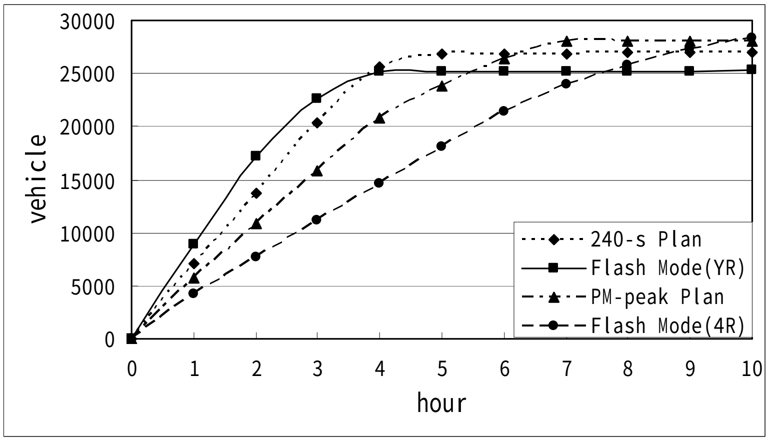


Figure 5-4 Total number of vehicles evacuated over 10 hours for the worst demand case of sub-scenario 1

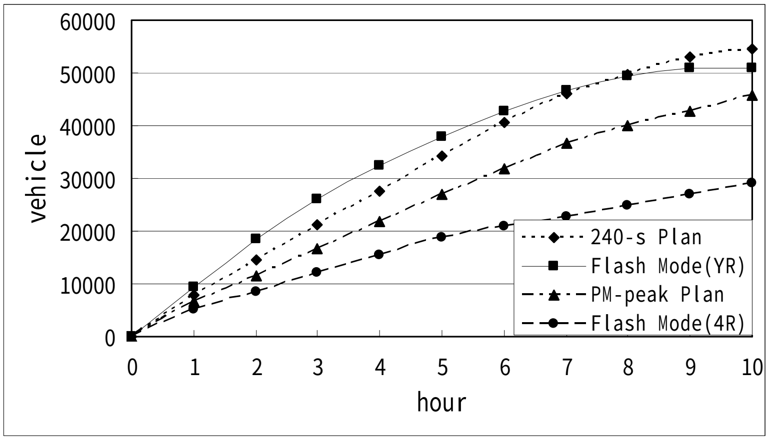


Figure 5-5 Total number of vehicles evacuated over 10 hours for the average demand case of sub-scenario 2

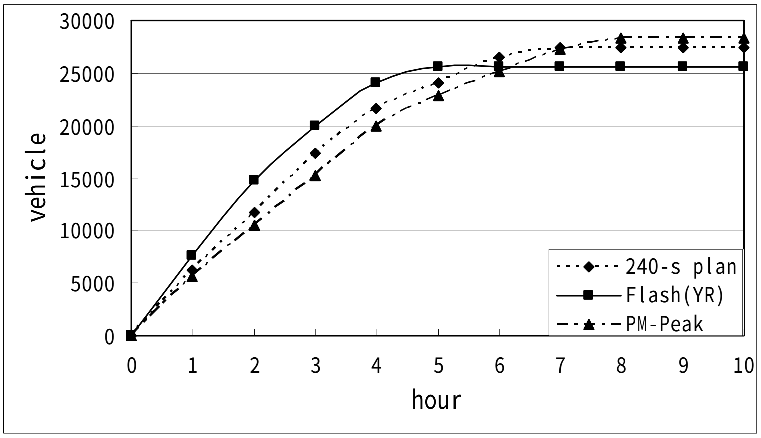


Figure 5-6 Total number of vehicles evacuated over 10 hours for the worst demand case of sub-scenario 2

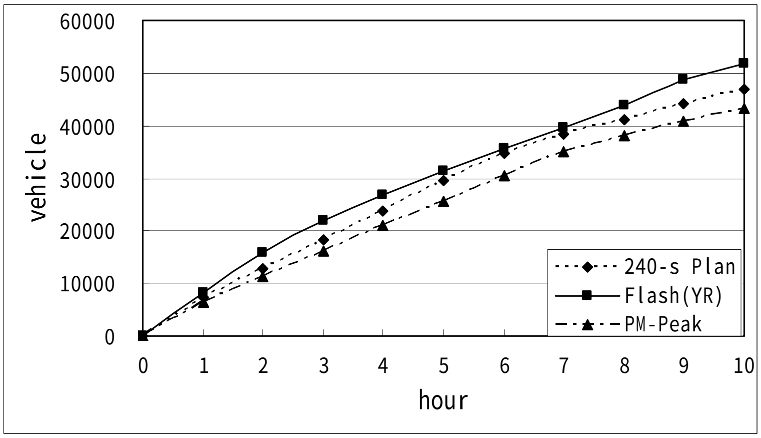


Figure 5-7 Total number of vehicles evacuated over 10 hours for the average demand case of sub-scenario 3

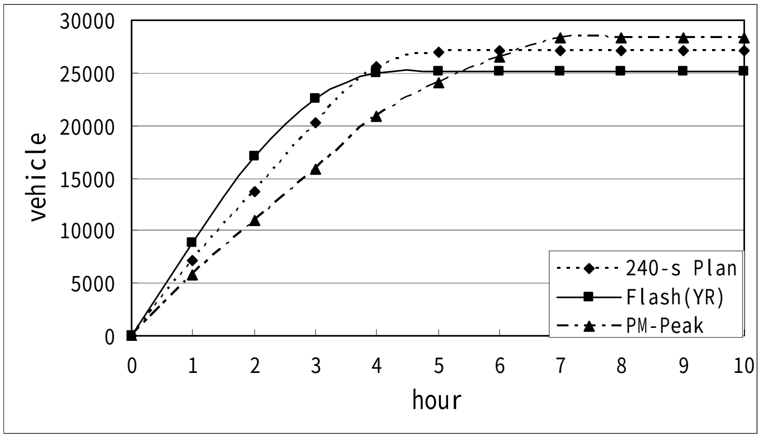


Figure 5-8 Total number of vehicles evacuated over 10 hours for the worst demand case of sub-scenario 3

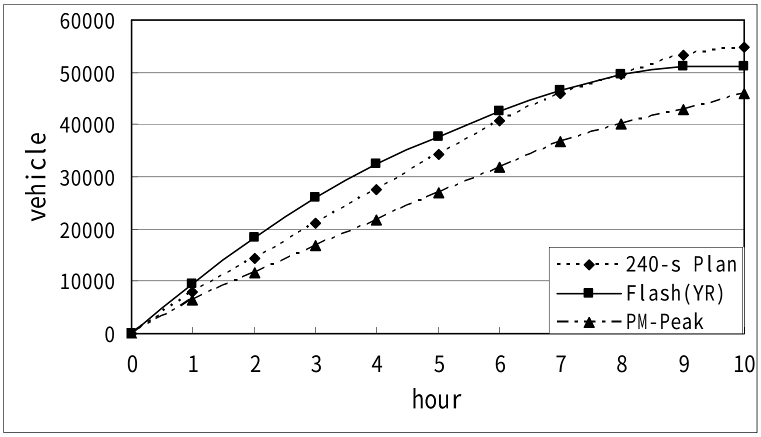


Figure 5-9 Total number of vehicles evacuated over 10 hours for the average demand case of sub-scenario 4

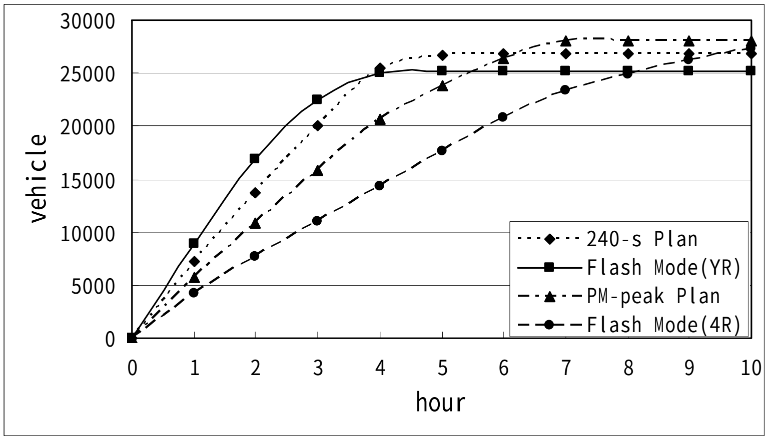


Figure 5-10 Total number of vehicles evacuated over 10 hours for the worst demand case of sub-scenario 4

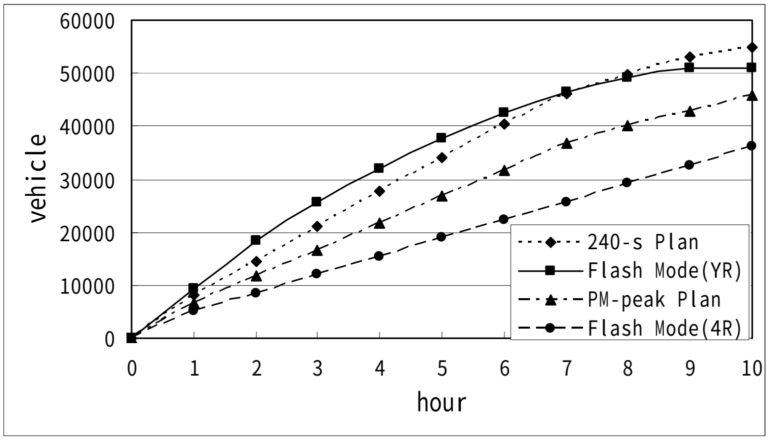


Figure 5-11 Total number of vehicles evacuated over 10 hours for the average demand case of sub-scenario 5

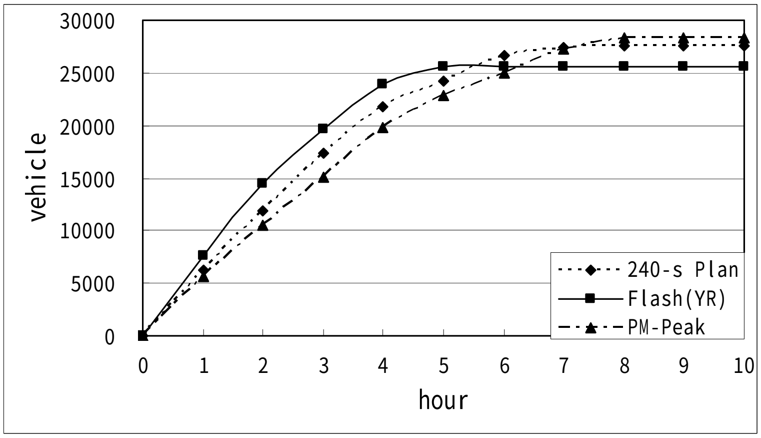


Figure 5-12 Total number of vehicles evacuated over 10 hours for the worst demand case of sub-scenario 5

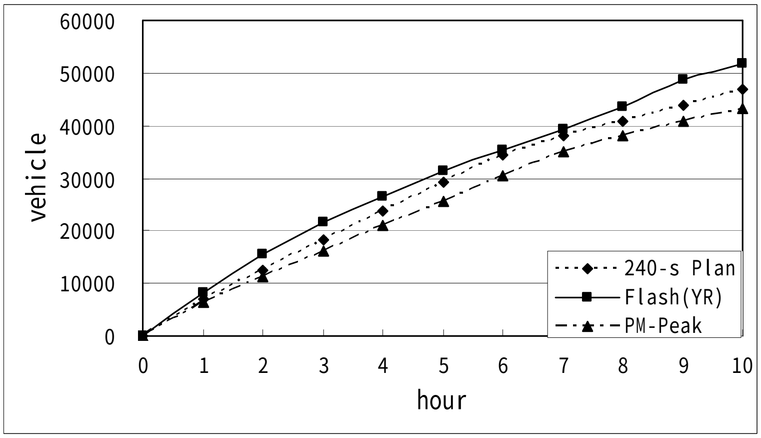


Figure 5-13 Total number of vehicles evacuated over 10 hours for the average demand case of sub-scenario 6

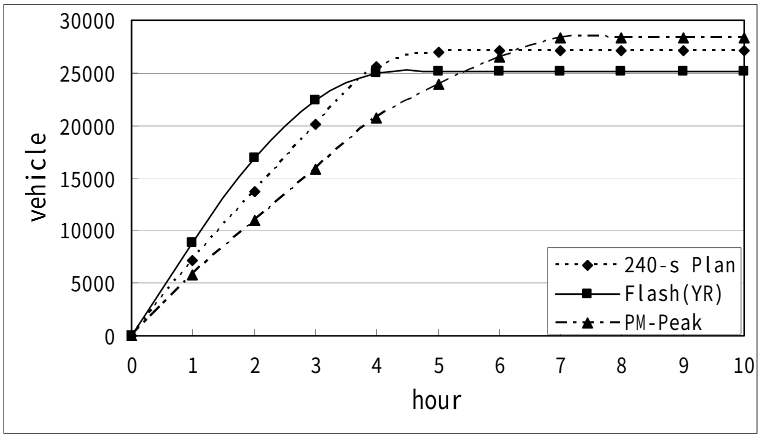


Figure 5-14 Total number of vehicles evacuated over 10 hours for the worst demand case of sub-scenario 6

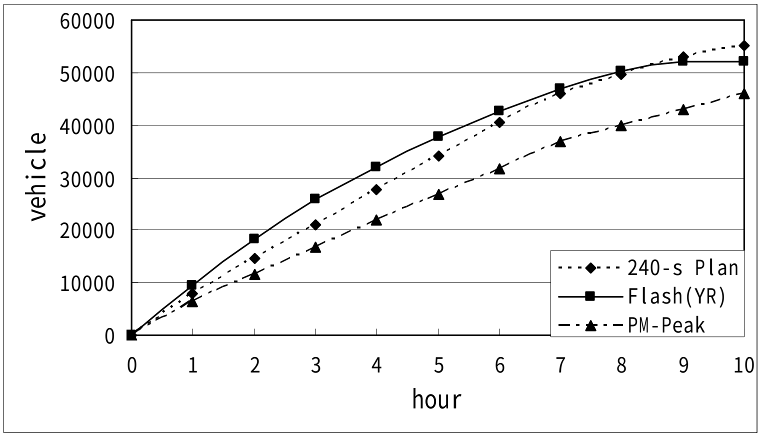


Figure 5-15 Total number of vehicles evacuated over 10 hours for the average demand case of sub-scenario 7

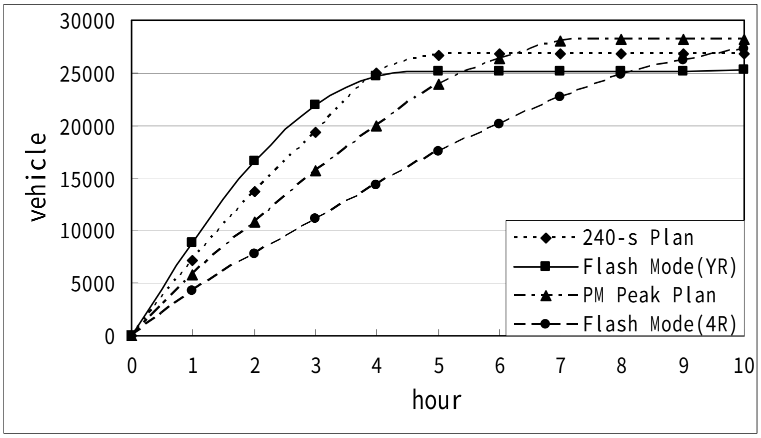


Figure 5-16 Total number of vehicles evacuated over 10 hours for the worst demand case of sub-scenario 7

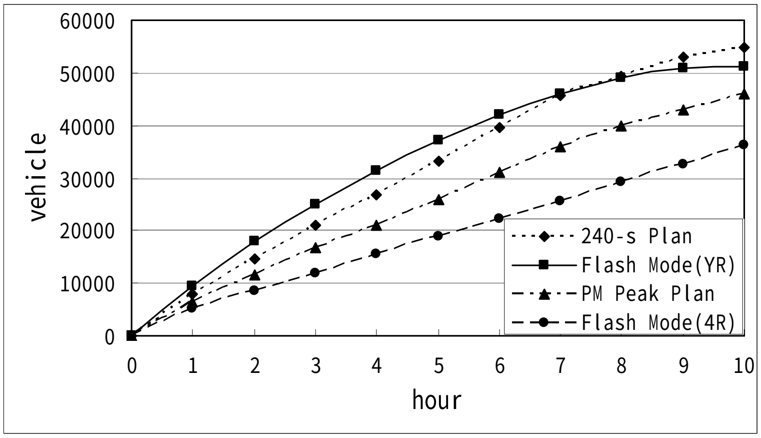


Figure 5-17 Total number of vehicles evacuated over 10 hours for the average demand case of sub-scenario 8

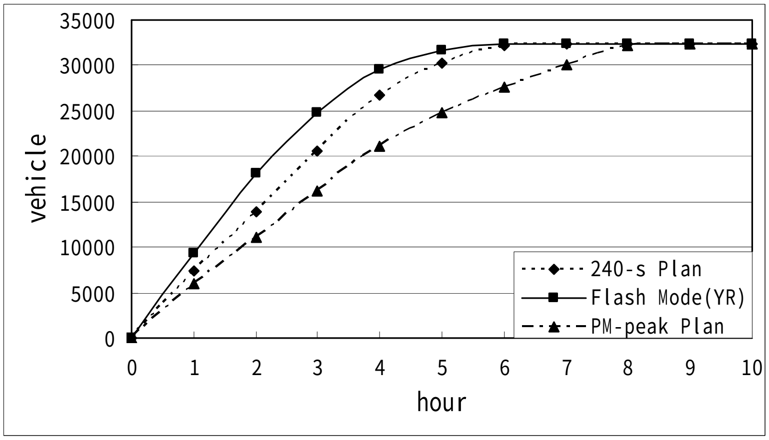


Figure 5-18 Total number of vehicles evacuated over 10 hours for the worst demand case of sub-scenario 8

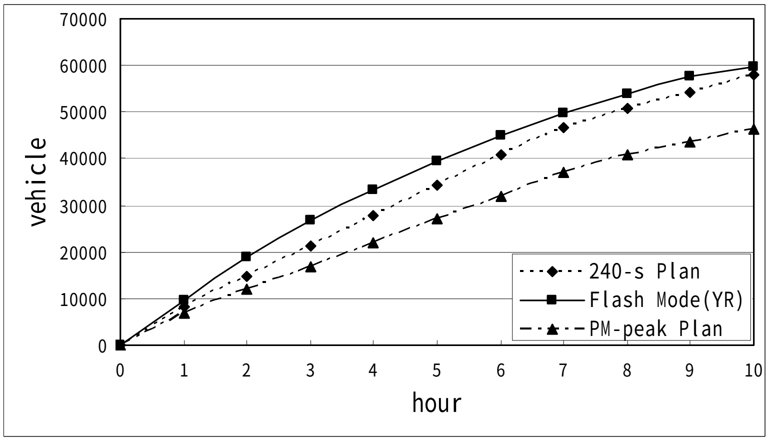


Figure 5-19 Total number of vehicles evacuated over 10 hours for the average demand case of sub-scenario 9

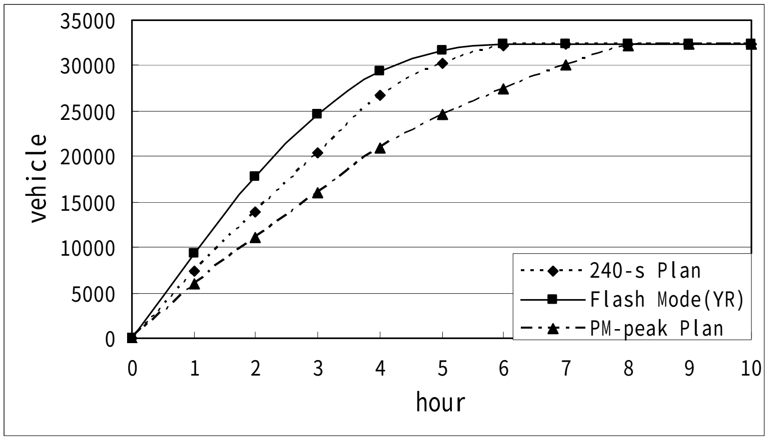


Figure 5-20 Total number of vehicles evacuated over 10 hours for the worst demand case of sub-scenario 9

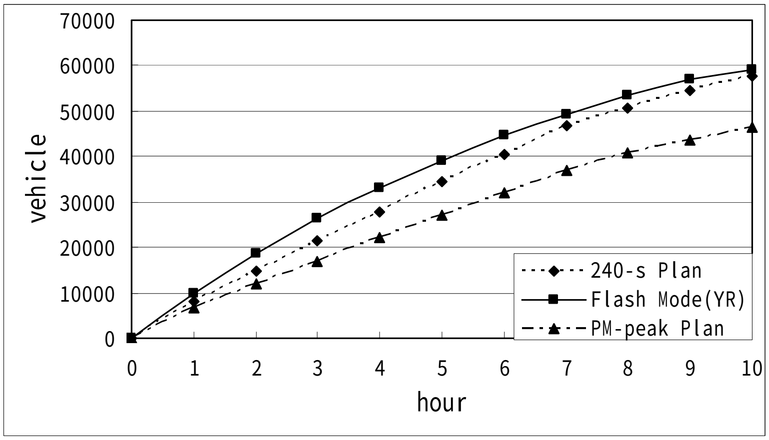


Figure 5-21 Total number of vehicles evacuated over 10 hours for the average demand case of sub-scenario 10

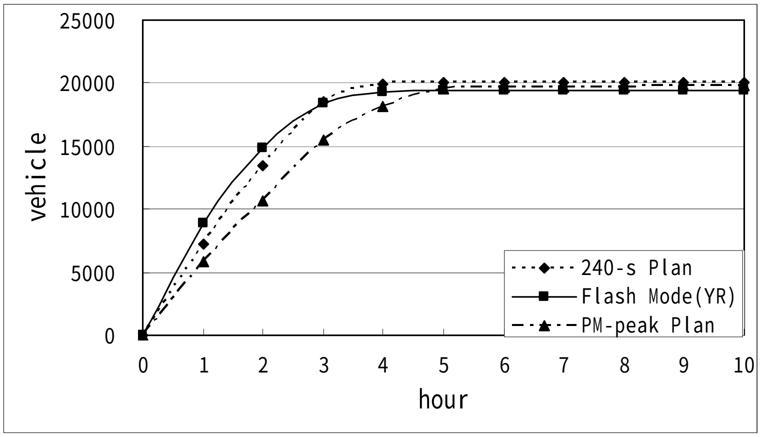


Figure 5-22 Total number of vehicles evacuated over 10 hours for the worst demand case of sub-scenario 10

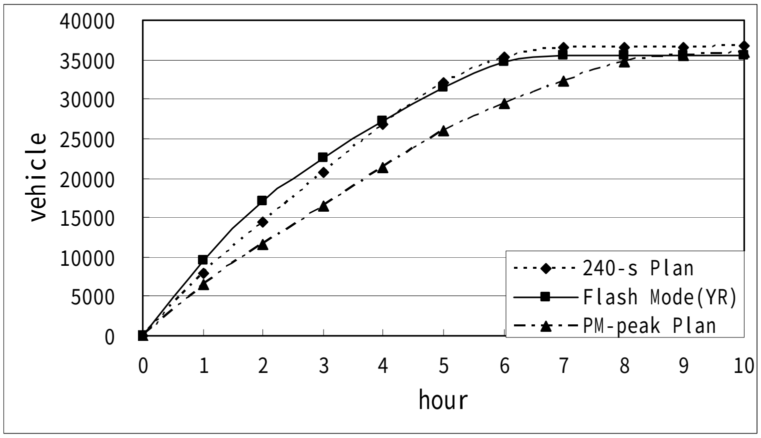


Figure 5-23 Total number of vehicles evacuated over 10 hours for the average demand case of sub-scenario 11

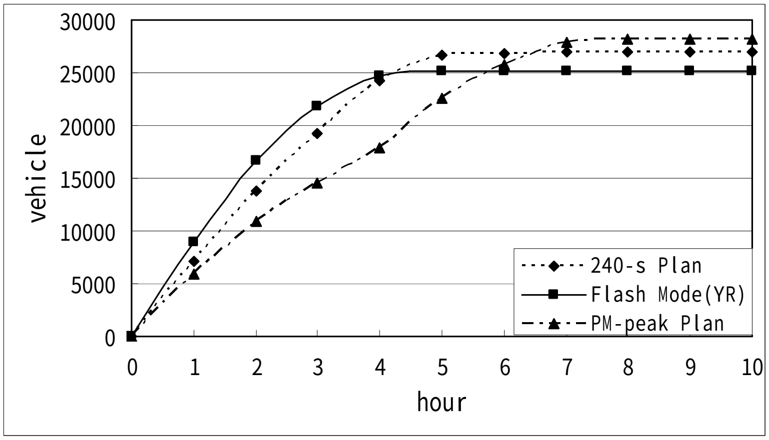


Figure 5-24 Total number of vehicles evacuated over 10 hours for the worst demand case of sub-scenario 11

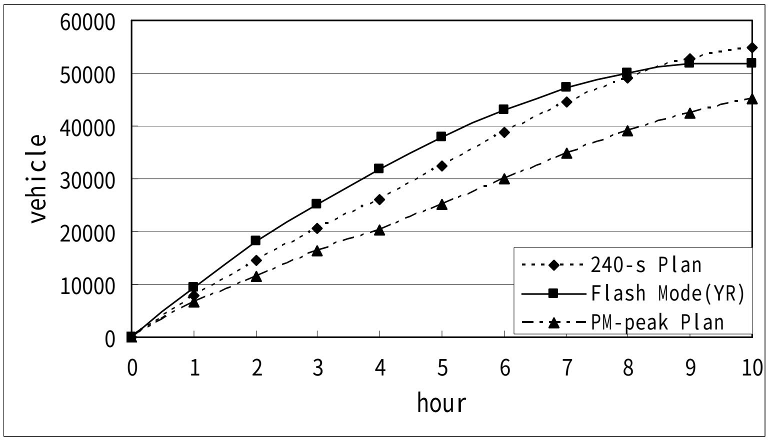


Figure 5-25 Total number of vehicles evacuated over 10 hours for the average demand case of sub-scenario 12

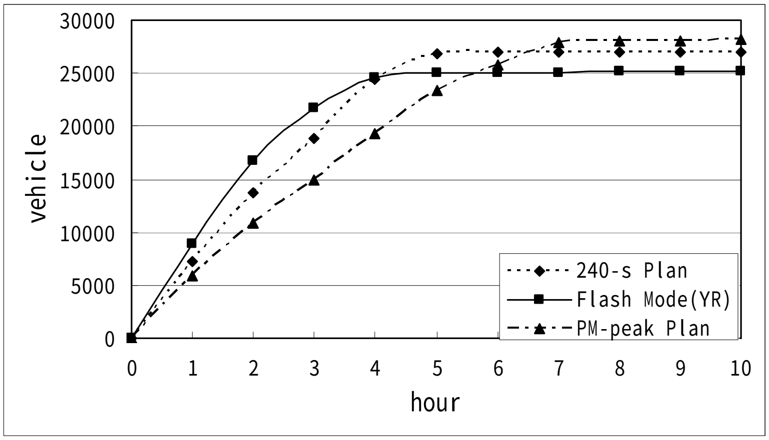


Figure 5-26 Total number of vehicles evacuated over 10 hours for the worst demand case of sub-scenario 12

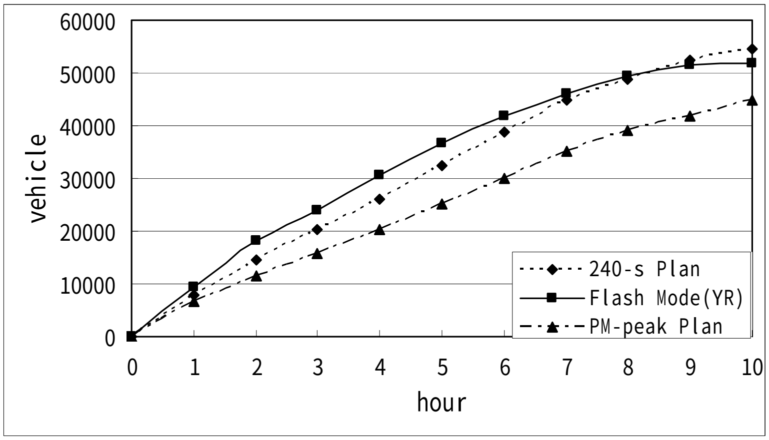


Table 5-2 Total number of vehicles evacuated over 10 hours when employing five different settings for traffic incident

	time	setting(1)	setting(2)	setting(3)	setting(4)	setting(5)
240-s plan	1	7158	7170	7148	7188	7192
	2	13700	13705	13692	13766	13721
	3	20283	20078	19335	19207	18790
	4	25643	25545	25015	24186	24405
	5	26764	26721	26725	26728	26835
	6	26875	26831	26819	26839	26922
	7	26898	26865	26833	26952	26934
	8	26911	26877	26845	26968	26946
	9	26925	26889	26857	26980	26958
	10	26939	26901	26869	26992	26970
flash mode (YR)	1	8890	8885	8886	8907	8890
	2	17123	16954	16612	16651	16673
	3	22591	22444	21862	21807	21720
	4	25116	25056	24700	24681	24597
	5	25200	25165	25151	25093	25076
	6	25212	25177	25163	25105	25088
	7	25224	25189	25175	25117	25100
	8	25236	25201	25187	25129	25112
	9	25248	25213	25199	25141	25124
	10	25260	25225	25211	25153	25136
PM-peak plan	1	5782	5777	5777	5834	5810
	2	10882	10871	10887	10883	10884
	3	15885	15786	15657	14581	14951
	4	20811	20710	19968	17830	19269
	5	23876	23852	23844	22514	23308
	6	26359	26340	26336	25685	25771
	7	28059	28042	28091	27849	27894
	8	28073	28058	28105	28131	28096
	9	28085	28070	28117	28143	28108
	10	28097	28082	28129	28155	28120
flash mode (4R)	1	4267	4267	4268		
	2	7740	7738	7751		
	3	11176	11055	11060		
	4	14617	14345	14269		
	5	18048	17642	17450		
	6	21344	20803	20174		
	7	24024	23332	22712		
	8	25736	24881	24824		
	9	27216	26187	26139		
	10	28376	27283	27275		

Table 5-3 Total number of vehicles evacuated over 10 hours when employing different settings for contraflow operations

	240-s plan		Flash mode(YR)		PM-peak plan	
time	contraflow	no	contraflow	no	contraflow	no
1	7158	7181	8890	8882	5782	5783
2	13700	13714	17123	17104	10882	10892
3	20283	20318	22591	22463	15885	15911
4	25643	25639	25116	24984	20811	20863
5	26764	26964	25200	25126	23876	24002
6	26875	27071	25212	25138	26359	26501
7	26898	27093	25224	25150	28059	28307
8	26911	27105	25236	25162	28073	28326
9	26925	27117	25248	25174	28085	28338
10	26939	27129	25260	25186	28097	28350

Table 5-4 Total number of vehicles evacuated over 10 hours when employing different settings for roadside parking

	240-s plan		Flash mode(YR)		PM-peak plan	
time	parking	no-parking	parking	no-parking	parking	no-parking
1	6274	7158	7636	8890	5656	5782
2	11746	13700	14847	17123	10505	10882
3	17322	20283	19941	22591	15233	15885
4	21676	25643	24082	25116	19928	20811
5	24004	26764	25579	25200	22777	23876
6	26549	26875	25591	25212	25059	26359
7	27422	26898	25603	25224	27205	28059
8	27436	26911	25615	25236	28268	28073
9	27450	26925	25627	25248	28280	28085
10	27464	26939	25639	25260	28292	28097

5.2.1.2 Master Scenario 1 (off-peak hour case)

Figures 5-27 through 5-30 show the results of runs for the off-peak hour case of master scenario 1. A list of the off-peak hour sub-scenarios and the corresponding figures in which the results are presented is provided in Table 5-5. The demand for evacuation in this case is the highest among all the cases. As indicated in these figures, no portion of network in all of the sub-scenarios for this case is cleared as a result of the high demand level. The results consistently show that the PM-peak plan performs poorly in terms of the total number of vehicles evacuated in the ten hour time period as compared with the other plans under such high demand level. While the performance of the flash mode plan (YR) is the best in all these sub-scenarios, it performs nearly equivalently to the 240-s plan especially in the last a few hours.

Similar results regarding the influence of traffic incidents on the performance of the proposed traffic signal timing plans as discussed in the midnight case of master 1 (see section 5.2.1.1) were found in this case. No assessment was conducted in sub-scenarios considering roadside parking or without employing contraflow operations in this case.

Table 5-5 List of sub –scenarios and the corresponding figures for off-peak hour demand case of master scenario 1

Sub-scenairo	Turning Movement	Traffic Incident	Contraflow Operation	Roadside-parking	average case	Worst case
13	1	1	Yes	No	5-27	5-28
14	1	2	Yes	No	5-29	5-30

Figure 5-27 Total number of vehicles evacuated over 10 hours for the average demand case of sub-scenario 13

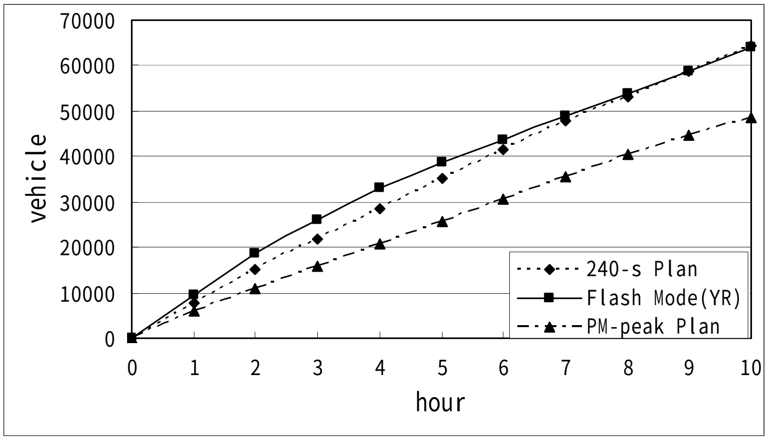


Figure 5-28 Total number of vehicles evacuated over 10 hours for the worst demand case of sub-scenario 13

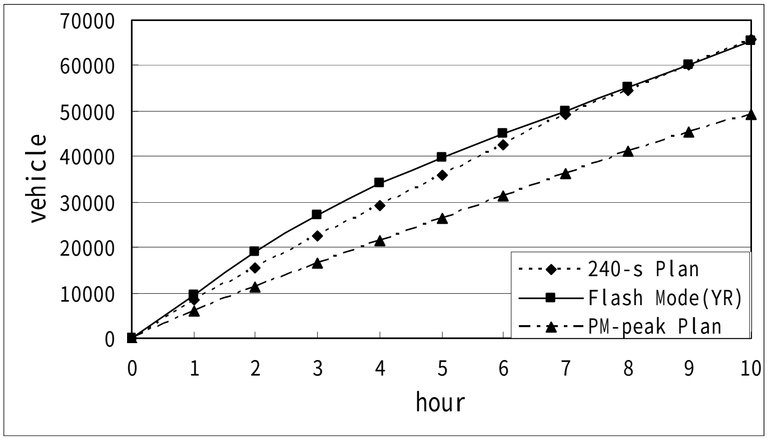


Figure 5-29 Total number of vehicles evacuated over 10 hours for the average demand case of sub-scenario 14

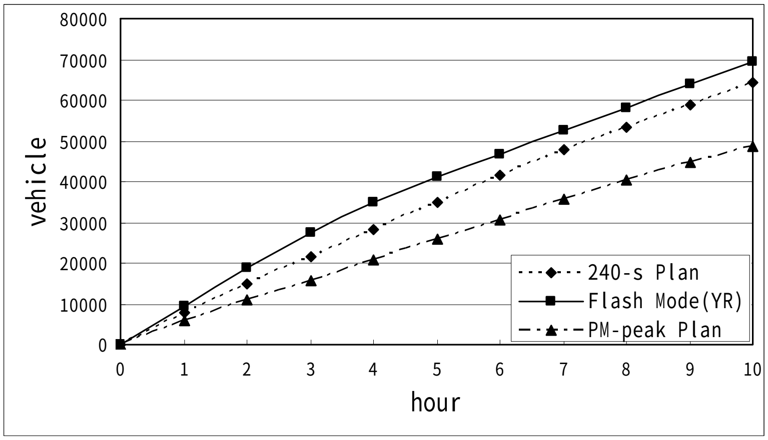
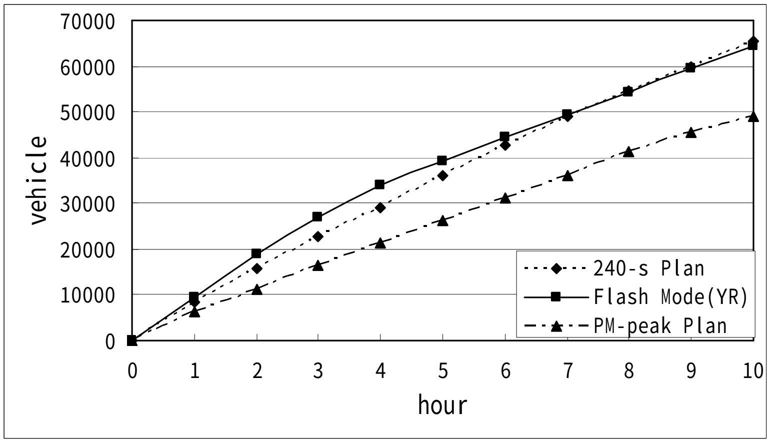


Figure 5-30 Total number of vehicles evacuated over 10 hours for the worst demand case of sub-scenario 14



5.2.1.3 Master Scenario 1 (AM-peak Hour Case)

Figures 5-31 through 5-36 show the results of runs for the AM-peak hour case of master scenario 1. A list of the AM-peak hour sub-scenarios and the corresponding figures in which the results are presented is provided in Table 5-6. As indicated in the figures, similar to the off-peak hour case, no portion of network in the all of the sub-scenarios for this case is cleared as a result of the high demand level. Results consistently show that the flash mode plan (YR) performs the best and the PM-peak plan performs the worst.

Similar results regarding the influence of traffic incidents on the performance of the proposed traffic signal timing plans as discussed in the midnight case of master 1 (see section 5.2.1.1) were found in this case. No assessment was conducted in sub-scenarios considering roadside parking or without employing contraflow plans in this case.

Table 5-6 List of sub –scenarios and the corresponding figures for AM-peak hour demand case of master scenario 1

Sub-scenairo	Turning Movement	Traffic Incident	Contraflow Operation	Roadside-parking	average case	Worst case
15	1	1	Yes	No	5-31	5-32
16	1	2	Yes	No	5-33	5-34
17	3	1	Yes	No	5-35	5-36

Figure 5-31 Total number of vehicles evacuated over 10 hours for the average demand case of sub-scenario 15

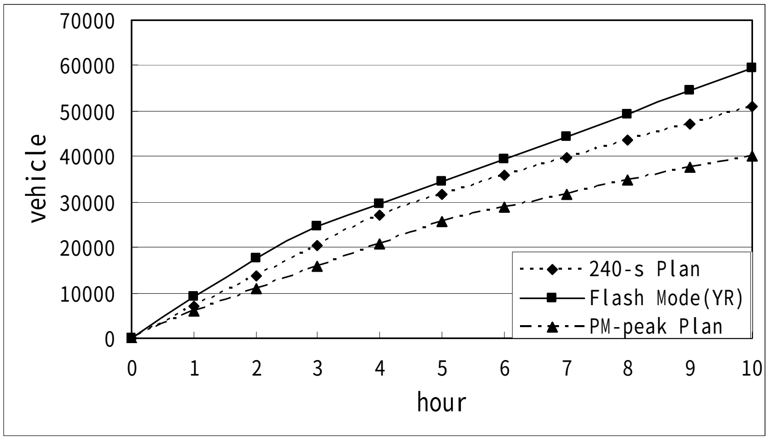


Figure 5-32 Total number of vehicles evacuated over 10 hours for the worst demand case of sub-scenario 15

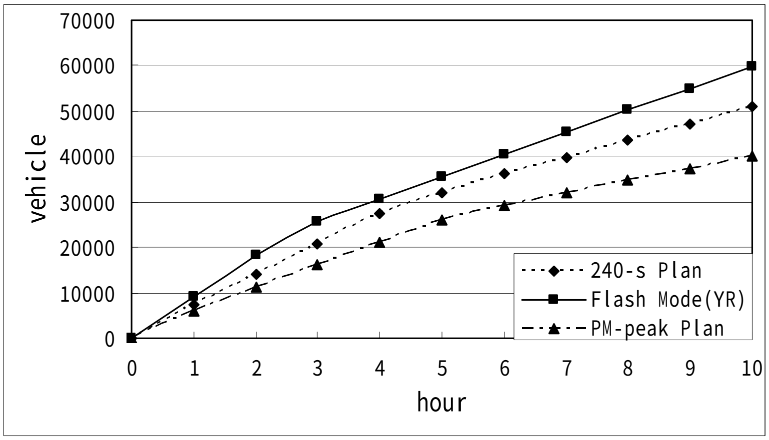


Figure 5-33 Total number of vehicles evacuated over 10 hours for the average demand case of sub-scenario 16

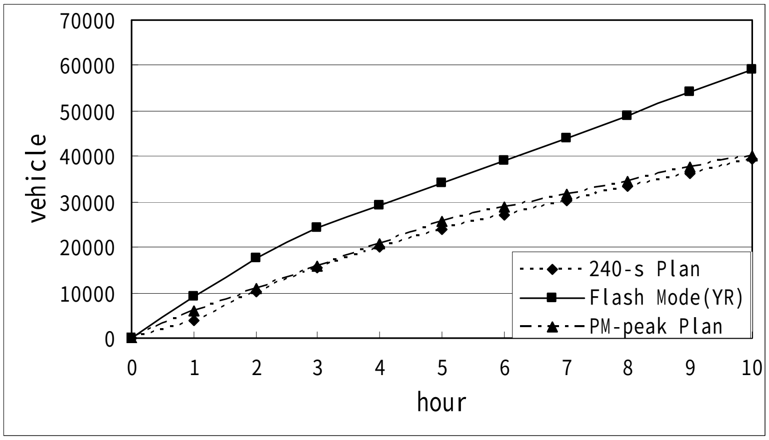


Figure 5-34 Total number of vehicles evacuated over 10 hours for the worst demand case of sub-scenario 16

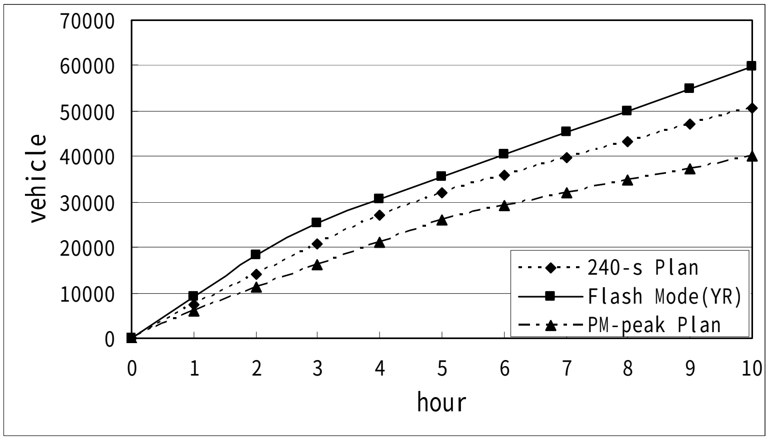


Figure 5-35 Total number of vehicles evacuated over 10 hours for the average demand case of sub-scenario 17

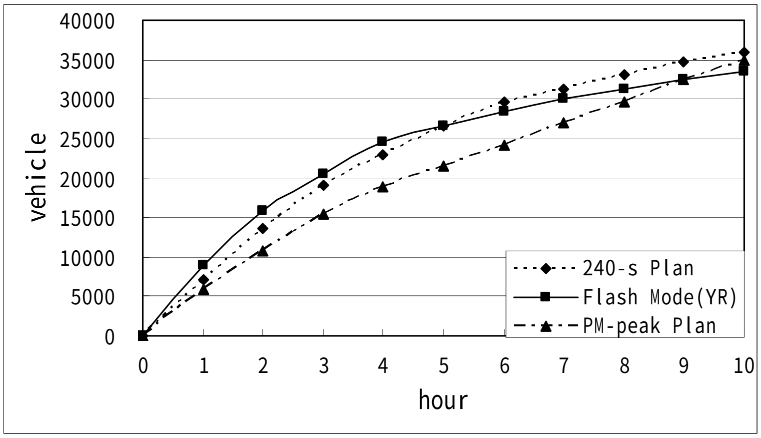
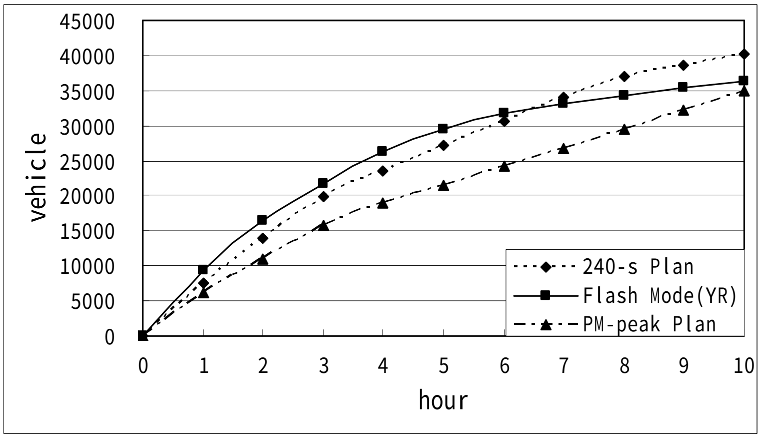


Figure 5-36 Total number of vehicles evacuated over 10 hours for the worst demand case of sub-scenario 17



5.2.1.4 Master Scenario 2 (Federal shutdown)

Master scenario 2 involving a Federal shutdown is a selective evacuation. That is, a selective evacuation affects only a subset of the people in the area. As a result, the expected traffic demand will be much lower than would be expected for a full evacuation. Since the demand is relatively low in this scenario and the network clearance time can be obtained in reasonable simulation time, network clearance time was employed to assess the performance of the various plans under this second master scenario. For these runs, the network clearance time is defined as the hour at which fewer than 20 vehicles remain to be evacuated.

Tables 5-8 through 5-10 show the results of runs for master scenario 2. A list of sub-scenarios and the corresponding tables in which the results are shown is provided in Table 5-7. An asterisk is used in the tables to indicate the hour at which the network is considered to be cleared. In all succeeding hours, only a small number (at most 20) of vehicles exit the network. These vehicles are present as a result of the CORSIM methodology. That is, CORSIM does not allow the modeler to assign destinations to the vehicles and thus, some vehicle may travel aimlessly through the network. Additionally, transit was modeled such that transit vehicles continue to operate even after the network is complete.

Results given in the tables indicate that, in terms of the network clearance time, the flash mode (RY) and PM-peak plans perform similarly, but both perform better than the 240-s plan for sub-scenario 20 and the average demand case of sub-scenarios 18 and 19. In the worst case in sub-scenarios 18 and 19, the flash mode plan (YR) performs the best and the PM-peak and 240-s plans perform equally well.

Similar results regarding the influence of traffic incidents on the performance of the proposed traffic signal timing plans as discussed in the midnight case of master 1 (see section 5.2.1.1) were found in this case. No assessment was conducted in sub-scenarios considering roadside parking or without employing contraflow operations in this case.

Table 5-7 List of sub –scenarios and the corresponding tables for master scenario 2

Sub-scenairo	Turning Movement	Traffic Incident	Contraflow Operation	Roadside-parking	Table
18	1	1	Yes	No	5-8
19	1	2	Yes	No	5-9
20	3	1	Yes	No	5-10

Table 5-8 Total number of vehicles evacuated over 10 hours for sub-scenario 18

	average case demand			worst case demand		
Time	240-s Plan	Flash Mode(YR)	PM-peak Plan	240-s Plan	Flash Mode(YR)	PM-peak Plan
1	3379	3613	3324	4158	4463	3981
2	7147	8138	6916	8098	9362	7647
3	9823	10652	9800	11551	13428	10697
4	11015	11298(*)	11441(*)	14955	15724	13449
5	11406(*)	11310	11452	16767	17129	15825
6	11418	11322	11465	17871	17462(*)	18108
7	11430	11334	11476	18078(*)	17474	18154(*)
8	11442	11346	11489	18090	17486	18166
9	11454	11358	11501	18102	17498	18178
10	11466	11370	11513	18114	17510	18190

Table 5-9 Total number of vehicles evacuated over 10 hours for sub-scenario 19

	average case demand			worst case demand		
Time	240-s Plan	Flash Mode(YR)	PM-peak Plan	240-s Plan	Flash Mode(YR)	PM-peak Plan
1	3362	3617	3315	4163	4436	3976
2	7138	8158	6877	8094	9353	7613
3	9911	10654	9764	11520	13449	10623
4	11088	11276(*)	11478(*)	14930	15800	13361
5	11453(*)	11288	11489	16744	17141	15775
6	11465	11300	11501	17831	17437(*)	18097
7	11477	11312	11513	18065(*)	17449	18152(*)
8	11489	11324	11525	18077	17461	18164
9	11501	11336	11538	18089	17473	18177
10	11513	11348	11549	18101	17485	18188

Table 5-10 Total number of vehicles evacuated over 10 hours for sub-scenario 20

	average case demand			worst case demand		
time	240-s Plan	Flash Mode(YR)	PM-peak Plan	240-s Plan	Flash Mode(YR)	PM-peak Plan
1	3248	3083	3174	3946	3709	3827
2	4932	4768	5067	5794	5540	5827
3	5498	5676	6102	7160	6954	7332
4	6028	5808(*)	6173(*)	7845	7930	8457
5	6197(*)	5820	6185	8309	8405(*)	8741(*)
6	6209	5832	6196	8738	8417	8752
7	6221	5844	6208	8827(*)	8429	8764
8	6233	5856	6221	8839	8441	8777
9	6245	5868	6233	8851	8453	8789
10	6257	5880	6245	8863	8465	8801

5.2.2 Results in Terms of Average Vehicle Delay

The average vehicle delay for each link was collected from the simulation output. Two average values representing the vehicle delay experienced on the corridor and on the minor roadways were computed via equation 5-1.

$$\overline{D} = \sum_i (n_i \cdot \overline{d}_i) \Big/ \sum_i n_i \ , \tag{5-1}$$

where

$\overline{D}$ represents the average vehicle delay over a set of links;

n_i represents the total vehicle trips on link i; and

$\overline{d}_i$ represents the average vehicle delay on link i;

Note that in the analyses herein, average vehicle delay is computed over all links in the network.

The analysis was conducted on three sub-scenarios, sub-scenarios 1, 15 and 18. For the off-peak hour case of master scenario 1, the study corridor was far from cleared within the preset simulation time of 10 hours. Thus, the delay data obtained from the corresponding simulation runs may be underestimated. Consequently, results from this scenario were not analyzed in this section. The average vehicle delay for each signal timing plan, including the distribution of delay by time into elapsed from the beginning of the simulation, is given in tables 5-11 through 5-16.

5.2.2.1 Master Scenario 1

Tables 5-11 through 5-14 show the results obtained from simulation runs of sub-scenarios 1and 15. As indicated in these tables, the 240-s plan achieves shorter delays on the primary evacuation routes compared with the PM-peak plan in the midnight case of master scenario 1 (shown in Tables 5-11 and 5-12). One can also find the 240-s plan simultaneously increases the delays on the minor roadways. The average vehicle delays on the minor roadways when employing this plan are approximately 6 minutes and 10 minutes for the average demand and worst demand cases respectively, as compared with 5 minutes and 9 minutes when employing the PM-peak plan. In the AM-peak hour case, the 240-s plan achieves shorter delays on both the evacuation routes and the minor roadways, as shown in Tables 5-13 and 5-14. Results also show that the flash mode (YR) achieves the shortest delay on the primary evacuation routes, but leads to significantly longer delay on the minor roadways compared with other plans, as shown in Tables 5-11 through 5-14. The average vehicle delay on the minor roadways when employing the flash mode plan (YR) exceeds 20 minutes in the AM-peak hour case of master scenario 1, more than twice as long as in other plans. Note that, the delay obtained from simulation runs for the peak-hour case may be underestimated, because the network is not cleared within the preset 10 hour time period. The flash mode plan (4R) leads to long delays on not only the minor roadways, but also along the main evacuation routes.

Table5-11 Average vehicle delay for the average demand case of sub-scenario 1

Delay	240-s		Flash(YR)		PM-peak		Flash(4R)	
	Corridor	Minor	Corridor	Minor	Corridor	Minor	Corridor	Minor
Average Delay(s)	34	356	5	817	89	295	167	714
0-1 min	84.89%	11.23%	99.98%	17.75%	41.38%	28.62%	16.78%	19.94%
1-5 min	15.10%	49.35%	0.01%	13.08%	57.78%	30.62%	71.46%	11.66%
5-15 min	0.01%	27.63%	0.01%	31.05%	0.84%	38.71%	11.38%	30.69%
15-30 min	0.00%	9.47%	0.00%	28.58%	0.01%	0.80%	0.33%	33.03%
30-60 min	0.00%	1.97%	0.00%	8.11%	0.00%	1.25%	0.06%	4.32%
1-2 hr	0.00%	0.36%	0.00%	1.27%	0.00%	0.00%	0.00%	0.36%
>2 hr	0.00%	0.00%	0.00%	0.15%	0.00%	0.00%	0.00%	0.00%
sum	100%	100%	100%	100%	100%	100%	100%	100%

Table5-12 Average vehicle delay for the worst demand case of sub-scenario 1

Delay	240-s		Flash(YR)		PM-peak		Flash(4R)	
	Corridor	Minor	Corridor	Minor	Corridor	Minor	Corridor	Minor
Average Delay(s)	70	592	18	1156	122	539	209	929
0-1 min	53.67%	6.49%	92.40%	9.17%	30.97%	17.63%	18.13%	14.72%
1-5 min	45.75%	23.99%	7.59%	20.24%	64.83%	13.11%	64.47%	10.47%
5-15 min	0.58%	53.20%	0.01%	29.66%	3.69%	57.25%	14.70%	38.73%
15-30 min	0.00%	11.05%	0.00%	23.24%	0.43%	8.04%	1.92%	25.73%
30-60 min	0.00%	4.62%	0.00%	13.29%	0.08%	3.98%	0.60%	6.62%
1-2 hr	0.00%	0.27%	0.00%	3.15%	0.00%	0.00%	0.18%	2.47%
>2 hr	0.00%	0.37%	0.00%	1.25%	0.00%	0.00%	0.00%	1.25%
sum	100%	100%	100%	100%	100%	100%	100%	100%

Table5-13 Average vehicle delay for the average demand case of sub-scenario 15

Delay	240-s		Flash(YR)		PM-peak	
	Corridor	Minor	Corridor	Minor	Corridor	Minor
Average delay(s)	70	473	29	1286	114	534
0-1 min	58.76%	4.18%	87.65%	3.91%	41.89%	17.76%
1-5 min	39.41%	50.95%	12.33%	26.66%	51.26%	36.19%
5-15 min	1.49%	34.50%	0.01%	45.61%	6.34%	22.40%
15-30 min	0.23%	8.91%	0.00%	9.17%	0.51%	15.48%
30-60 min	0.11%	0.95%	0.01%	3.42%	0.00%	7.32%
1-2 hr	0.00%	0.33%	0.00%	6.78%	0.00%	0.85%
>2 hr	0.00%	0.18%	0.00%	4.45%	0.00%	0.00%
sum	100%	100%	100%	100%	100%	100%

Table5-14 Average vehicle delay for the worst demand case of sub-scenario 15

Delay	240-s		Flash(YR)		PM-peak	
	Corridor	Minor	Corridor	Minor	Corridor	Minor
Average delay(s)	80	533	33	1395	131	596
0-1 min	54.69%	4.19%	89.89%	4.88%	37.95%	15.36%
1-5 min	41.74%	40.80%	10.07%	29.67%	54.46%	42.39%
5-15 min	3.57%	41.64%	0.00%	20.55%	6.83%	22.92%
15-30 min	0.00%	7.69%	0.02%	28.24%	0.48%	13.28%
30-60 min	0.00%	4.95%	0.01%	8.01%	0.29%	5.17%
1-2 hr	0.00%	0.57%	0.00%	5.76%	0.00%	0.89%
>2 hr	0.00%	0.15%	0.00%	2.90%	0.00%	0.00%

5.2.2.2 Master Scenario 2

As shown in Tables 5-15 and 5-16, the PM-peak plan produces significantly shorter delay on the minor roadways compared with the 240-s plan. This shorter delay is a result of employing a shorter cycle length and allocating less green time to the primary evacuation routes than is allocated in the 240-s plan. As a result, the PM-peak plan leads to slightly increased delays on the main evacuation routes. The results also show that the flash mode plan (YR) will produce slightly shorter delays on the main evacuation routes, but significantly longer delays on the minor roadways as compared with results of runs employing the other two plans.

Table5-15 Average vehicle delay for the average demand case of sub-scenario 18

Delay	240-s		Flash(YR)		PM-peak	
	Corridor	Minor	Corridor	Minor	Corridor	Minor
Average delay(s)	14	293	3	422	24	154
0-1 min	94.89%	22.79%	99.92%	12.31%	92.70%	31.64%
1-5 min	5.11%	43.26%	0.08%	36.96%	7.30%	55.97%
5-15 min	0.00%	33.01%	0.00%	45.97%	0.00%	12.33%
15-30 min	0.00%	0.00%	0.00%	3.58%	0.00%	0.06%
30-60 min	0.00%	0.00%	0.00%	1.18%	0.00%	0.00%
1-2 hr	0.00%	0.94%	0.00%	0.00%	0.00%	0.00%
>2 hr	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
sum	100%	100%	100%	100%	100%	100%

Table5-16 Average vehicle delay for the worst demand case of sub-scenario 18

Delay	240-s		Flash(YR)		PM-peak	
	Corridor	Minor	Corridor	Minor	Corridor	Minor
Average delay(s)	17	308	5	479	38	170
0-1 min	94.45%	22.44%	99.93%	8.06%	82.45%	28.38%
1-5 min	5.55%	43.20%	0.01%	39.21%	17.55%	59.16%
5-15 min	0.00%	33.42%	0.06%	46.49%	0.00%	12.39%
15-30 min	0.00%	0.00%	0.00%	2.51%	0.00%	0.00%
30-60 min	0.00%	0.00%	0.00%	3.73%	0.00%	0.00%
1-2 hr	0.00%	0.94%	0.00%	0.00%	0.00%	0.07%
>2 hr	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
sum	100%	100%	100%	100%	100%	100%

5.3 Discussion and Findings

The performance of each proposed signal timing plan in each sub-scenario is synopsized in section 5.2. One can see that the network is cleared within the preset simulation time of ten hours in master scenario 2 (Federal shutdown) and in the midnight case of master scenario 1(average demand level). In all other sub-scenarios, the network is not cleared due to the high demand level. The network clearance time for master scenario 2 is between three and four hours for the average demand level and is between five and seven hours for the worst demand level. The network clearance time in the midnight case of master scenario 1(average demand level) is between five and eight hours.

Results from simulation runs on sub-scenarios are identical in terms of the relative benefits of the signal timing plans in terms of number of vehicles evacuated in the given time period. For the majority of sub-scenarios tested, the results in terms of the total number of vehicles evacuated indicate that the flash mode plan (YR) is the best, the 240-s plan is second best and the PM-peak plan is the worst. Results from several sub-scenarios in which the flash mode plan (4R) was tested indicate that this plan performs much worse than the other three. It is found in several sub-scenarios of master scenario 2 in which the demand level is relatively low compared with other cases that the performance of the PM-peak plan is on par with that of the flash mode (YR) plan and is better than the 240-s plan in terms of the network clearance time.

Results in terms of the average vehicle delay indicate that increasing the cycle length while allocating the majority of the green time to the primary evacuation routes can lead to a reduction in delay along the primary evacuation routes. However, this method of allocating green time can simultaneously lead to an increase in delay on the minor roadways. While the flash mode plan (YR) achieves very short delay for vehicles traveling along the main evacuation routes, significantly longer delay is incurred by vehicles on the minor roadways compared with other plans. The flash mode plan (4R) leads to significantly long delays for those on both the evacuation routes and the minor roadways.

One can see from the results given in this chapter that increasing the cycle length of the PM-peak plan while giving the majority of the green time to the major roadways, as in the 240-s plan, can increase the number of vehicles that are successfully evacuated when demand is high. This implies that an approach that gives more green time to the main evacuation routes is effective in evacuating more people in a given time period. However, when the traffic demand for evacuation is more comparable with the demand of an ordinary peak period, such as the case in master scenario 2, employing a long cycle length does not necessarily increase the number of vehicles evacuated in a given time period. On the contrary, it can lead to a reduction in the number of vehicles that escape, as found in this study.

Increasing the cycle length of the peak-hour signal timing plans while allocating the majority of the green time to the major evacuation routes may increase the delay on the minor roadways. The flash mode plan (YR) is an extreme case, equivalent to giving infinite green time to the main evacuation routes. This plan achieves the best efficiency in evacuating people by always giving priority to vehicles traveling on the primary evacuation routes and, as consequently, obtains a continuous flow. However, it also simultaneously and significantly increases the vehicle delay for those vehicles on the minor roadways. Significant delays on minor roadways may not be tolerated by the drivers on these roadways. On the contrary, the flash mode plan (4R) facilitates equal opportunity for vehicles approaching from all directions to escape in an evacuation. However, it leads to long delays on both the evacuation routes and the minor roadways.

Contrary to expectations, results of this study indicate that there is no significant difference in terms of the total number of vehicles evacuated in the presence of traffic incidents in the sub-scenarios tested when only one lane is blocked due to the occurrence of a traffic incident. However, significant effects were noted when two lanes are blocked, which may be more realistic. It was also found that the occurrence of a traffic incident at the bottleneck of an evacuation route can significantly affect the number of vehicles that are successfully evacuated. It was observed, however, that the occurrence of traffic incidents during an evacuation does not affect the relative benefit of the proposed signal timing plans. That is, the sequence of the proposed signal timing plans ranked according to their performance does not change.

In sub-scenarios where contraflow operations are employed, one might expect improved performance for the outbound traffic. However, in this study, no significant difference in terms of the total number of vehicles evacuated was found when employing contraflow operations in the simulation model as compared to operations where no contraflow operations are employed. One should not, however, conclude that contraflow operations have no effect in facilitating an evacuation. Possible reasons lie in the varying capacity of roadway sections along Connecticut Ave. That is, contraflow is only employed along a short segment of Connecticut Ave. The total number of vehicle travel lanes in both directions varies from four to six lanes and, as a results, a bottleneck exists at the Northern-most end of this route. One might study whether or not maintaining a constant number of lanes along the entire route in the outbound direction will more favorably impact the evacuation.

Results from the simulation runs show that roadside parking, which is permitted along the entire length of the main evacuation corridors in some of the sub-scenarios, greatly impacts the performance of the evacuation by decreasing the overall capacity of the network. However, whether or not roadside parking is permitted does not affect the sequence of the proposed signal timing plans when ranked according to their performance.

Chapter 6. Simulation Results and Analysis of Alternative Plans

As observed in chapter 5, cycle length can significantly affect the performance (total number of vehicles evacuated and average vehicle delay) of signal timing plans. The extent to which the performance is affected depends on the demand level. To examine the effects of setting different cycle lengths in an evacuation, four additional signal timing plans were developed and tested. These plans employ cycle lengths of 180 seconds and 300 seconds. The plans were assessed under three sub-scenarios discussed in chapter 4. The results obtained from the simulation runs for these plans were compared with the results for the PM-peak plan and the 240-s plan as given in chapter 5 to examine the relationship between the cycle length and network performance in terms of two measures, the total number of vehicles evacuated and the average vehicle delay.

6.1 The Alternative Signal Timing Plans

In this section, four additional signal timing plans were developed based on the PM-peak and 240-s plans described in Chapter 3. These four plans were assessed under three sub-scenarios that were chosen from the sub-scenarios constructed in chapter 4. Details are provided in section 6.2.

In chapter 5, the PM-peak and 240-s plans were assessed. The PM-peak plan employs a cycle length of 100 seconds. The additional four plans employ two different cycle lengths, 180 seconds and 300 seconds. The two plans with the cycle length of

180 seconds were developed based on the PM-peak plan by employing two approaches: (1) increasing the cycle length while allocating the same number of seconds of green time to the minor roadways and keeping the offsets unchanged; and (2) increasing the cycle length while allocating the same percent of green time to the minor roadways and keeping the offsets unchanged. The other two plans with the cycle length of 300 seconds were similarly developed based on the 240-s plan. Note that the split and offsets employed in the 240-s plan differ from those employed in the PM-peak plan. The newly-developed plans by employing the first approach are referred to herein as the 180(1)-s and 300(1)-s plans. The newly-developed plans by employing the second approach are referred to as the 180(2)-s and 300(2)-s plans.

6.2 Experimental Design

As shown in chapter 5, the optimal cycle length may depend on the level of traffic demand. To assess the additional four plans, three sub-scenarios were chosen for testing: sub-scenarios 1, 15 and 18 (descriptions of these sub-scenarios are given in chapter 4, section 4.1.2). These three sub-scenarios involve six different levels of traffic demand for evacuation, i.e. each one involves an average case demand and a worst case demand. Thus, a systematic assessment of these signal timing plans under different levels of traffic demand can be undertaken. Factors, such as traffic incidents and roadside parking, were not considered in these experiments.

6.3 Results and Analyses

The results from simulation runs were analyzed in terms of the same two performance measures employed in the analyses of Chapter 5. Ten runs were made for each plan and each sub-scenario. The results given in the following subsections are average values obtained from each set of ten runs. A portion of the results for the PM-peak plan and the 240-s plan from the same sub-scenarios tested here are included in this section for comparison.

6.3.1 Results In Terms of Total Number of Vehicles Evacuated

Results from simulation runs of sub-scenarios 1 and 15 for the 180(1)-s and 300(1)-s plans as well as the PM-peak and 240-s plans are provided in Figures 6-1 through 6-4. Results from simulation runs of the same two sub-scenarios for the 180(2)-s and 300(2)-s plans as well as the PM-peak and 240-s plans are provided in Figures 6-5 through 6-8. Tables 6-1 and 6-2 provide the total number of vehicles evacuated in a ten hour time period for sub-scenario 18.

Results show that increasing the cycle length while allocating the same number of seconds of green time to the minor roadways can significantly increase the number of vehicles that are successfully evacuated, as shown in Figures 6-1 through 6-4. However, increasing the cycle length while allocating the same percent of green time to the minor roadways has considerably less impact, as shown in Figures 6-5 through 6-8.

It was observed that when the traffic demand for evacuation is relatively low, as is the case in master scenario 2 when compared with a full-scale evacuation of master scenario 1, the PM-peak plan performs the best in terms of the network clearance time. One can see that under the average demand level, the network is cleared within 4 hours when employing the PM-peak plan and within 5 hours when employing the 180(1)-s and 240-s plans (shown in Table 6-1). Under the worst demand level, the network is cleared within 7 hours when employing any one of these three plans (shown in Table 6-2).

Figure 6-1 Total number of vehicles evacuated over 10 hours for the average demand case of sub-scenario 1 for plans employing the first approach

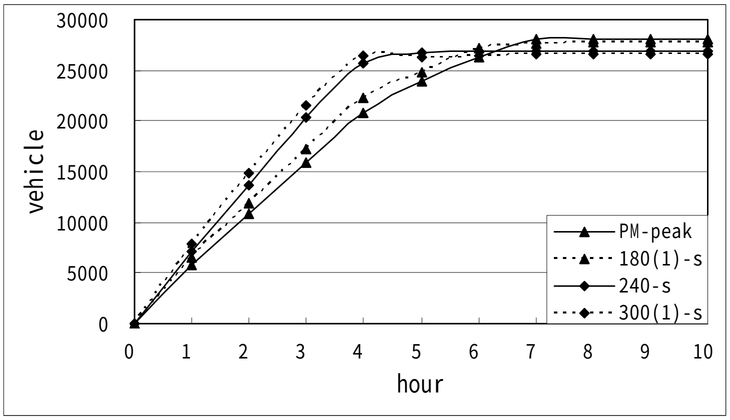


Figure 6-2 Total number of vehicles evacuated over 10 hours for the worst demand case of sub-scenario 1 for plans employing the first approach

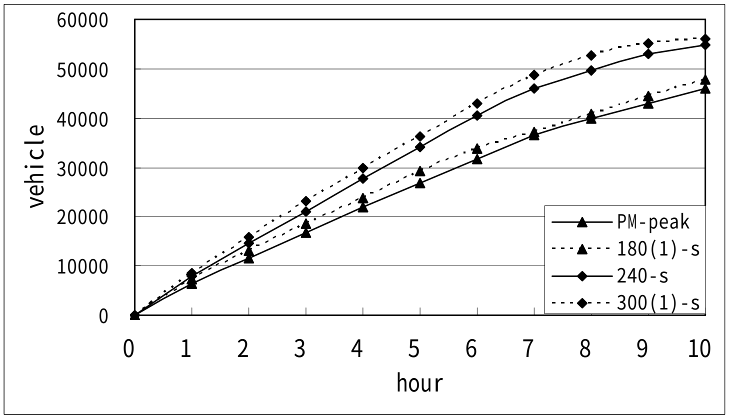


Figure 6-3 Total number of vehicles evacuated over 10 hours for the average demand case of sub-scenario 15 for plans employing the first approach

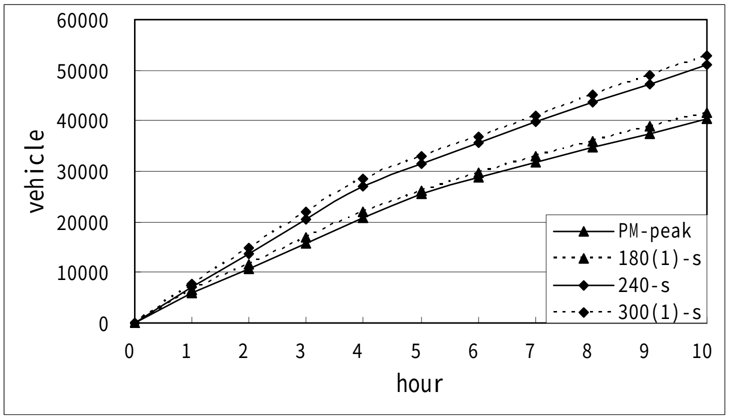


Figure 6-4 Total number of vehicles evacuated over 10 hours for the worst demand case of sub-scenario 15 for plans employing the first approach

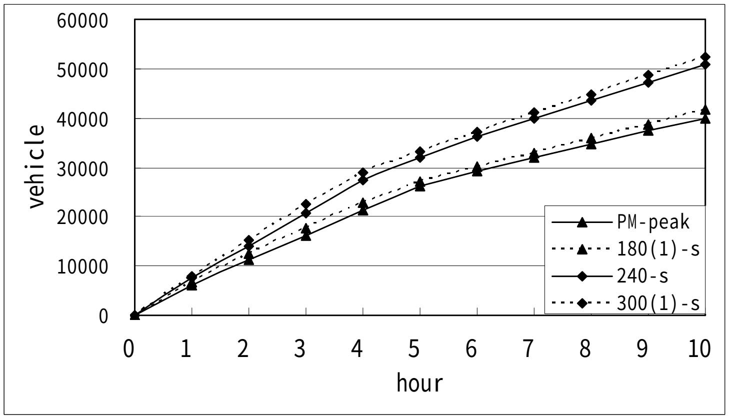


Figure 6-5 Total number of vehicles evacuated over 10 hours for the average demand case of sub-scenario 1 for plans employing the second approach

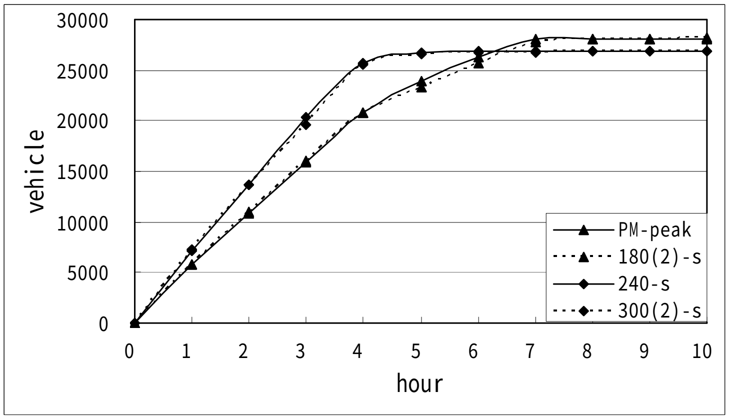


Figure 6-6 Total number of vehicles evacuated over 10 hours for the worst demand case of sub-scenario 1, for plans employing the second approach

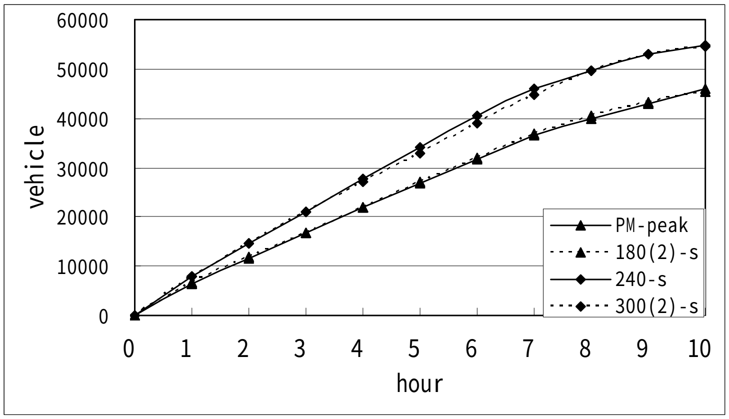


Figure 6-7 Total number of vehicles evacuated over 10 hours for the average demand case of sub-scenario 15, for plans employing the second approach

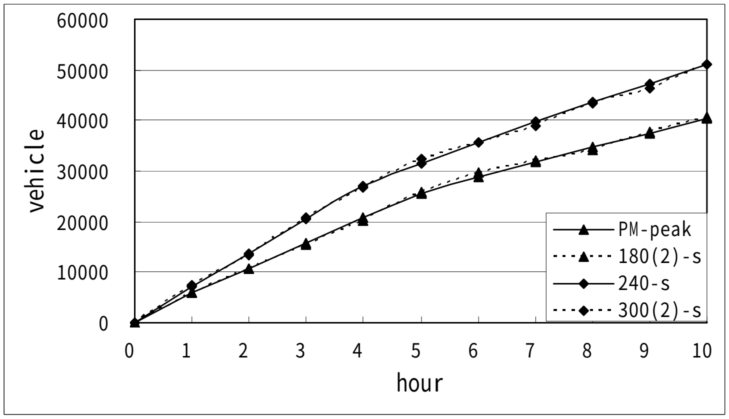


Figure 6-8 Total number of vehicles evacuated over 10 hours for the worst demand case of sub-scenario 15, for plans employing the second approach

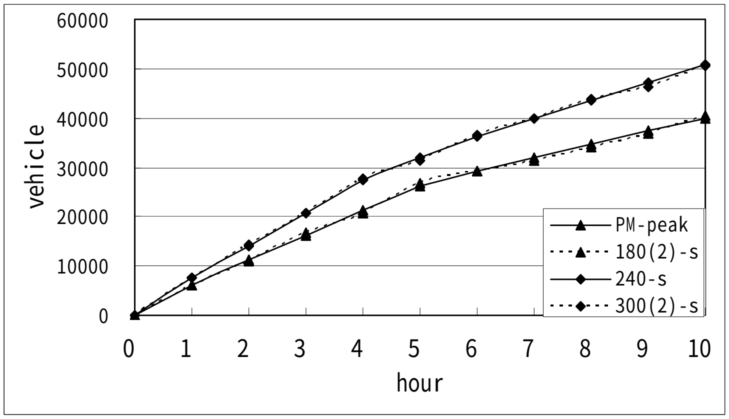


Table 6-1 Total number of vehicles evacuated over 10 hours for the average demand case of sub-scenario 18

Time	100-s	180(1)-s	240-s
1	3324	3432	3379
2	6916	7110	7147
3	9800	9735	9823
4	11441 (*)	11374	11015
5	11452	11549 (*)	11406 (*)
6	11465	11560	11418
7	11476	11573	11430
8	11489	11585	11442
9	11501	11597	11454
10	11513	11609	11466

Table 6-2 Total number of vehicles evacuated over 10 hours for the worst demand case of sub-scenario 18

Time	100-s	180(1)-s	240-s
1	3981	4156	4158
2	7647	8402	8098
3	10697	11325	11551
4	13449	13831	14955
5	15825	16323	16767
6	18108	17883	17871
7	18154(*)	18289(*)	18078(*)
8	18166	18302	18090
9	18178	18314	18102
10	18190	18326	18114

6.3.2 Results In Terms of Average Vehicle Delay

Results from simulation runs of the 180(1)-s and 300(1)-s plans as well as the PM-peak and 240-s plans are provided in this section. Results for sub-scenario 1, 15, 18 are given in Tables 6-3 and 6-4, Tables 6-5 and 6-6, Tables 6-7 and 6-8, respectively.

The results show that in sub-scenarios 1 and 15, when the cycle length increases, the average vehicle delay on the minor roadways increases and the average vehicle delay on the evacuation corridor decreases. In sub-scenario 15, no consistent change in terms of average vehicle delay on the minor roadways across the four plans (180(1)-s, 300(1)-s, PM-peak and the 240-s plans) was noted. One can note, however, that the 300(1)-s plan produces shorter delay on the primary evacuation routes and longer delay on the minor roadways as compared with the 240-s plan. Similarly, the 180(1)-s plan produces shorter delay on the evacuation routes and longer delay on the minor roadways as compared with the PM-peak plan.

In sub-scenario 1 a significantly higher percentage of vehicles on the minor roadways with delay exceeding 15 minutes were found when the cycle length reaches or exceeds 180 seconds for both average and worst demand cases. In sub-scenario 15, the same result was found when the cycle length exceeds 240 seconds. In sub-scenario 18, a significantly higher percentage of vehicles on the minor roadways with delay exceeding 5 minutes was noted when employing signal timing plans other than the PM-peak plan.

Table 6-3 average vehicle delay for the average demand case of sub-scenario 1

Delay	PM-peak		180(1)-s		240-s		300(1)-s	
	Corridor	Minor	Corridor	Minor	Corridor	Minor	Corridor	Minor
Average Delay (s)	89	295	70	333	34	356	36	373
0-1 min	41.38%	28.62%	47.91%	13.94%	84.89%	11.23%	80.96%	8.54%
1-5 min	57.78%	30.62%	52.08%	49.34%	15.10%	49.35%	19.04%	46.05%
5-15 min	0.84%	38.71%	0.00%	25.64%	0.01%	27.63%	0.01%	35.98%
15-30 min	0.01%	0.80%	0.01%	11.07%	0.00%	9.47%	0.00%	7.59%
30-60 min	0.00%	1.25%	0.00%	0.00%	0.00%	1.97%	0.00%	1.85%
1-2 hr	0.00%	0.00%	0.00%	0.00%	0.00%	0.36%	0.00%	0.00%
>2 hr	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
sum	100%	100%	100%	100%	100%	100%	100%	100%

Table 6-4 average vehicle delay for the worst demand case of sub-scenario 1

Delay	PM-peak		180(1)-s		240-s		300(1)-s	
	Corridor	Minor	Corridor	Minor	Corridor	Minor	Corridor	Minor
Average Delay (s)	122	539	104	556	70	592	61	607
0-1 min	30.97%	17.63%	31.97%	7.97%	53.67%	6.49%	59.41%	5.44%
1-5 min	64.83%	13.11%	65.96%	20.37%	45.75%	23.99%	40.00%	25.58%
5-15 min	3.69%	57.25%	2.07%	54.55%	0.58%	53.20%	0.58%	50.38%
15-30 min	0.43%	8.04%	0.00%	15.11%	0.00%	11.05%	0.01%	14.63%
30-60 min	0.08%	3.98%	0.00%	1.99%	0.00%	4.62%	0.00%	3.97%
1-2 hr	0.00%	0.00%	0.00%	0.00%	0.00%	0.27%	0.00%	0.00%
>2 hr	0.00%	0.00%	0.00%	0.00%	0.00%	0.37%	0.00%	0.00%
sum	100%	100%	100%	100%	100%	100%	100%	100%

Table 6-5 average vehicle delay for the average demand case of sub-scenario 15

Delay	PM-peak		180(1)-s		240-s		300(1)-s	
	Corridor	Minor	Corridor	Minor	Corridor	Minor	Corridor	Minor
Average Delay (s)	114	534	106	673	70	473	65	520
0-1 min	41.89%	17.76%	39.06%	7.09%	58.76%	4.18%	59.28%	3.36%
1-5 min	51.26%	36.19%	57.76%	31.75%	39.41%	50.95%	39.29%	54.25%
5-15 min	6.34%	22.40%	3.18%	41.09%	1.49%	34.50%	1.43%	17.56%
15-30 min	0.51%	15.48%	0.00%	16.46%	0.23%	8.91%	0.00%	17.93%
30-60 min	0.00%	7.32%	0.00%	0.68%	0.11%	0.95%	0.00%	6.90%
1-2 hr	0.00%	0.85%	0.00%	2.09%	0.00%	0.33%	0.00%	0.00%
>2 hr	0.00%	0.00%	0.00%	0.84%	0.00%	0.18%	0.00%	0.00%
sum	100%	100%	100%	100%	100%	100%	100%	100%

Table 6-6 average vehicle delay for the worst demand case of sub-scenario 15

Delay	PM-peak		180(1)-s		240-s		300(1)-s	
	Corridor	Minor	Corridor	Minor	Corridor	Minor	Corridor	Minor
Average Delay (s)	131	596	117	750	80	533	75	617
0-1 min	37.95%	15.36%	37.21%	7.35%	54.69%	4.19%	57.09%	3.36%
1-5 min	54.46%	42.39%	56.77%	17.93%	41.74%	40.80%	40.42%	51.15%
5-15 min	6.83%	22.92%	6.02%	52.85%	3.57%	41.64%	2.48%	24.69%
15-30 min	0.48%	13.28%	0.00%	13.40%	0.00%	7.69%	0.01%	13.94%
30-60 min	0.29%	5.17%	0.00%	5.68%	0.00%	4.95%	0.00%	6.86%
1-2 hr	0.00%	0.89%	0.00%	1.93%	0.00%	0.57%	0.00%	0.00%
>2 hr	0.00%	0.00%	0.00%	0.85%	0.00%	0.15%	0.00%	0.00%
sum	100%	100%	100%	100%	100%	100%	100%	100%

Table 6-7 average vehicle delay for the average demand case of sub-scenario 18

Delay	PM-peak		180(1)-s		240-s		300(1)-s	
	Corridor	Minor	Corridor	Minor	Corridor	Minor	Corridor	Minor
Average Delay (s)	24	154	19	210	14	293	10	305
0-1 min	92.70%	31.64%	91.93%	10.67%	94.89%	22.79%	97.40%	11.92%
1-5 min	7.30%	55.97%	8.06%	56.00%	5.11%	43.26%	2.60%	54.76%
5-15 min	0.00%	12.33%	0.00%	33.33%	0.00%	33.01%	0.00%	21.02%
15-30 min	0.00%	0.06%	0.00%	0.00%	0.00%	0.00%	0.00%	12.30%
30-60 min	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
1-2 hr	0.00%	0.00%	0.00%	0.00%	0.00%	0.94%	0.00%	0.00%
>2 hr	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
sum	100%	100%	100%	100%	100%	100%	100%	100%

Table 6-8 average vehicle delay for the worst demand case of sub-scenario 18

Delay	PM-peak		180(1)-s		240-s		300(1)-s	
	Corridor	Minor	Corridor	Minor	Corridor	Minor	Corridor	Minor
Average delay	38	170	27	223	17	308	15	340
0-1 min	82.45%	28.38%	89.66%	10.20%	94.45%	22.44%	97.97%	8.29%
1-5 min	17.55%	59.16%	10.34%	56.50%	5.55%	43.20%	2.03%	45.53%
5-15 min	0.00%	12.39%	0.00%	33.30%	0.00%	33.42%	0.00%	33.70%
15-30 min	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	12.40%
30-60 min	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.07%
1-2 hr	0.00%	0.07%	0.00%	0.00%	0.00%	0.94%	0.00%	0.00%
>2 hr	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
sum	100%	100%	100%	100%	100%	100%	100%	100%

6.4 Findings

Results from simulation runs show that under a high level of traffic demand for evacuation, the 300(1)-s plan performs better than the 240-s plan and the 180(1)-s plan performs better than the PM-peak plan in terms of the total number of vehicles evacuated in a given period of time. The performance of the 300(2)-s plan in terms of the same measure is similar with the 240-s plan, and the performance of the 180(2)-s plan is similar with the PM-peak plan. This implies that increasing the cycle length of signal timing plans while allocating the same number of seconds of green time to the minor roadways can significantly increase the number of vehicles that are successfully evacuated. Increasing the cycle length while allocating the same percent of green time to the minor roadways, however, does not produce significant change in the performance of signal timing plans in terms of the same measure. Results also show that the 240-s plan performs better than the 180(1)-s plan. One can conclude from these results that longer cycle length with the majority of green time allocated to the primary evacuation routes in most cases will lead to a greater number of vehicles that escape when the level of traffic demand for evacuation is high.

It was also noted that under a relatively low level of traffic demand for evacuation, the PM-peak plan performs the best in terms of the network clearance time. The result indicates that the optimal cycle length in terms of the number of vehicles to escape depends on the traffic demand level. For a selective evacuation such as the case in master scenario 2, employing the peak-hour plan can reduce the evacuation time, while for a full-scale evacuation, employing a longer cycle length can be beneficial in evacuating a larger number of vehicles in a given period of time.

Results in terms of the average vehicle delay show that longer cycle length with the majority of green time allocated to the primary evacuation routes will likely lead to shorter delay on the primary evacuation routes and longer delay on the minor roadways. While the difference in average vehicle delay on the minor roadways for the four tested signal timing plans (i.e. the PM-peak, 180(1)-s, 240-s, 300(1)-s plans) is not exceptionally large, in master scenario 1, a large percentage of vehicles on the minor roadways with delays exceeding 15 minutes occurs in the midnight case when the cycle length is equal to or longer than 180 seconds and in the peak hour case when the cycle length is longer than 240 seconds. One can also note that in master scenario 2, a significantly higher percentage of vehicles on the minor roadways with delays exceeding 5 minutes exists.

It was found that the PM-peak plan employing a cycle length of 100 seconds performs the best (i.e. leads to shorter network clearance times and simultaneously achieves relatively shorter delay on the minor roadways) when the traffic demand for evacuation is comparable with the demand that arises in ordinary peak-hour conditions.

It appears that when the traffic demand is high, tradeoffs exist between the total number of vehicles evacuated over a time period and average vehicle delay incurred by vehicles traveling on the major and minor roadways. Employing a longer cycle length in an evacuation can lead to a larger number of vehicles that evacuate in a given period of time when the traffic demand for evacuation is high. However, it can simultaneously lead to longer delay on the minor roadways. It seems that there is no single “best” plan that dominates others in terms of both performance measures. Which plan to use depends on the level of preference for one criterion over the other.

If the only objective is to maximize throughput, the ideal solution is to provide infinite green time to the evacuation routes and leave the vehicles on the minor roadways waiting until they find a gap to turn onto the evacuation routes or until the evacuation routes are cleared. The flash mode plan (RY) would, perhaps, be chosen for this instance. On the other hand, if the only objective is to maintain fairness in average delay for vehicles from all directions, the ideal solution is probably the flash mode (4R) or the peak hour plan. When trade-offs between both of these objectives are preferred, which plan will be the best will depend on the level of preference for one objective over the other. Perhaps the best compromise plan is the evacuation plan proposed by DDOT or one that is similar but with longer or shorter cycle length depending on the actual level of demand for evacuation and the decision-maker’s preference for one objective over the other.

Chapter 7. Conclusions

In this chapter, conclusions developed from the analyses of the simulation runs given in chapters 5 and 6 are provided. Recommendations are made based on results of experiments conducted in a simulated environment for developing signal timing plans for evacuation. It is pertinent to note that simulation has its limitations and the recommendations given here will require further testing to judge their suitability for an actual evacuation.

7.1 Summary of Findings

As discussed in chapter 5, the flash mode plan (YR) achieves the best efficiency in evacuating people from an effected area when an emergency event occurs, i.e. it can permit more vehicles to escape in a given time period as compared with other tested signal timing plans. However, a significant increase in delay for those vehicles traveling on the minor roadways was noted as compared with delay observed under other tested plans. It is very likely that drivers on these minor roadways might not be willing to abide by the traffic rules in an evacuation if delays of the magnitude noted in the simulation runs exist. Consequently, this plan may be difficult to implement in a real evacuation.

The flash mode plan (4R) is most equitable in terms of the delay incurred by vehicles from all directions as compared with the other three proposed signal timing plans. As a consequence, however, this plan leads to inefficient use of roadway capacity and causes significantly fewer vehicles to escape in a given time period.

The peak-hour plan is not a suitable signal timing plan for a full-scale evacuation, particularly if the traffic demand is very high. Results show that the number of vehicles evacuated when employing this plan is much lower than for the flash mode plan (YR) or 240-s plan in master scenario 1. However, when the traffic demand for evacuation is comparable with the demand of an ordinary peak period, such as the case in master scenario 2 (a selective evacuation), the peak-hour plan performs best among the plans tested in terms of network clearance time and delay incurred on both the evacuation routes and the minor roadways. Results of Chapters 5 and 6 indicate that plans with longer cycle length and more continuous green time for the main evacuation routes are warranted, as is discussed next.

It was observed that increasing the cycle length of the peak-hour plan can improve the performance of signal timing plans in terms of the total number vehicles evacuated in a given time period when the traffic demand for evacuation is high. However, one must note that if the percent of green time allocated to the minor roadways remains unchanged, i.e. the green time is proportionately increased on both the evacuation routes and the minor roadways, the performance might not be significantly improved. Alternatively, the cycle length can be increased while the same amount of or slightly more green time is allocated to the minor roadways as in the peak-hour plan. By doing this, it was observed that more vehicles were able to escape and the delays incurred by vehicles on the evacuation routes were greatly reduced. However, the delays incurred by vehicles on the minor roadways were significantly increased. The results obtained in this study show that when the cycle length exceeds 180 seconds in the midnight case of a full-scale evacuation, the percent of vehicles with delays on the minor roadways exceeding 15 minutes can significantly increase. Similar results were found when the cycle length exceeds 240 seconds in the peak-hour case of a full-scale evacuation. In both cases, drivers are unlikely to bear with the long delays.

As observed in this study, traffic incidents (particularly those incidents that affect more than one lane or that arise at bottlenecks (so-called choking points) along a main evacuation route) and roadside parking can significantly affect the performance of the proposed signal timing plans. However, the influence is consistent across plans, i.e. the occurrence of traffic incidents and roadside parking do not change the relative ranking of these signal timing plans.

No significant difference in terms of the total number of vehicles evacuated was found in this study when employing contraflow operations over a portion of one of the evacuation routes in the simulation model as compared to operations where no contraflow operations were employed. Whether or not maintaining a constant number of lanes along the entire route in the outbound direction will more favorably impact the evacuation requires further study.

7.2 Recommendations

As can be seen from the results of simulation runs obtained in this study, there are significant trade-offs between efficiency (i.e. network clearance time) and fairness (i.e. relative delays incurred) in choosing an appropriate signal timing plan for evacuation. Among the signal timing plans tested in this research, there is no single plan that dominates all others in terms of the total number of vehicles evacuated in a given time period and average delays incurred by vehicles on both evacuation routes and minor roadways. Which plan is the “best” depends on the severity of the emergency event and the magnitude of the delays on the minor roadways that the decision-makers are willing to accept. As described previously, if the only objective is to maximize throughput, the ideal solution is to provide infinite green time to the evacuation routes until they are cleared, leaving the vehicles on the minor roadways waiting until the evacuation routes are cleared. The flash mode plan (RY) would, perhaps, be chosen for this instance. On the other hand, if the only objective is to maintain fairness in average delay for vehicles along both major and minor roadways, the ideal solution is the flash mode (4R) or peak hour plans. When trade-offs between both of these objectives are preferred, which plan will be best will depend on the level of preference for one objective over the other. Perhaps the best compromise plan is the evacuation plan proposed by DDOT or one that is similar but with longer or shorter cycle length depending on the level of demand for evacuation.

From the analysis of results obtained in this study, employing a flash mode plan, i.e. either yellow on main and red on minor or red in all directions, is not recommended for use in an evacuation. While flash mode (YR) is recommended if the only objective is to maximize throughput, the significantly longer delay incurred by vehicles on the minor roadways may cause great difficulty in implementing this plan in a real evacuation. Similarly, while the flash mode (4R) is suggested if the only objective is to maintain fairness in delay for vehicles from all directions, the roadway capacity would be seriously underutilized and the evacuation time would be unnecessarily long if such a plan were used. This is unacceptable for a no-notice evacuation in which the network clearance time can be extremely important. When demand for evacuation is comparable with the demand of an ordinary peak period, such as might be the case in a selective evacuation, one should consider the use of the proposed peak-hour plans. When the demand is significantly higher than is present in ordinary peak-hour conditions, as is the case in most full-scale evacuations, increasing the cycle length of the peak-hour plan while allocating the same amount of or slightly more green time to the minor roadways as in the peak-hour plan could provide the best outcome. The longer the cycle length used, the better the performance in terms of the number of vehicles to escape in a given time period, but the worse the performance in terms of delay to vehicles on the minor roadways. Thus, the cycle length chosen should correspond with the trade-offs that the decision-maker is willing to make in terms of network clearance time and equity in delay incurred by individual vehicles.

Results of this study in a particular region of Washington D.C. indicate that if the preference is to control the delay incurred by vehicles on the minor roadways such that fewer vehicles incur delays greater than 15 minutes, then a plan with cycle length shorter than 180 seconds for the midnight case of a full-scale evacuation and of or near 240 seconds for the peak hour case of a full-scale evacuation might be considered.

Other approaches that one might consider include, for example, a hybrid of flash mode (Y/R) with fixed timing plans at key intersections, such as those modeled in the study network that connect Connecticut Ave with 16th Street. Further study is needed to test the performance of such plans.

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