DYNAMIC FLASHING YELLOW FOR EMERGENCY EVACUATION SIGNAL

TIMING PLAN IN A CORRIDOR

by

Charles Amoateng Asamoah
May 8th, 2014

A thesis submitted to the
Faculty of the Graduate School of
the University at Buffalo, State University of New York
in partial fulfillment of the requirements for the degree of

Master of Science

Department of Civil, Structural, and Environmental Engineering
ACKNOWLEDGEMENTS

I would like to express my gratitude to my adviser Dr. Qing He for the useful comments, remarks and engagement through the learning process of this master thesis. Without his guidance and persistent help this dissertation would not have been possible.

Furthermore I would like to thank my committee member Dr. Adel Sadek for serving as my committee member despite his busy schedule and offering me invaluable guidance in writing this thesis. I would also like to thank Dr. Qian Wang and Dr. Panagiotis Anastasopoulos for their advice and support throughout my master’s studies. I would also thank my colleagues in the Transportation Systems Engineering program whose association inspired me to strive for excellence.

Special thanks to my parents, Janet and Edward Asamoah, whose financial sacrifices have kept me in school. At the end I would like express appreciation to my beloved wife Pamela who has been supportive throughout my studies.
# TABLE OF CONTENTS

ACKNOWLEDGEMENTS ........................................................................................................... ii

LIST OF TABLES ................................................................................................................... vi

LIST OF FIGURES .................................................................................................................. vii

ABSTRACT .............................................................................................................................. viii

CHAPTER 1: INTRODUCTION .................................................................................................. 1

1.1 Background ...................................................................................................................... 1

1.2 Research Objectives ....................................................................................................... 3

1.3 Thesis Organization ......................................................................................................... 4

CHAPTER 2: LITERATURE REVIEW ....................................................................................... 5

2.1 Evacuation Plans and Policies ......................................................................................... 5

2.2 Intersection Traffic Control Strategies and Routing ....................................................... 6

2.3 Traffic Simulation Models for Evacuation modeling ....................................................... 8

2.4 Traffic Signal Timing for Evacuation ............................................................................. 10

CHAPTER 3: MODELING TECHNIQUE .................................................................................. 12

3.1 Introduction to Dynamic Flashing Yellow Plan ............................................................... 12

3.2 Potential Capacity of Through Traffic at Side Streets .................................................. 14

3.3 Dynamic Flashing Yellow with Fixed Splits (DFY-F) ................................................... 16

3.4 Dynamic Flashing Yellow with Actuations (DFY-A) .................................................... 17

3.5 Dynamic Flashing Yellow with Actuations and Coordination (DFY-AC) ...................... 18
3.6 Multiple Criteria Optimization ............................................................................................................. 21

CHAPTER 4: NETWORK MODELING AND SIMULATION .............................................................................. 23

4.1 Study Network ..................................................................................................................................... 23

4.2 Simulated Emergency Signal Timing Scenarios .................................................................................. 25

4.3 VISSIM Model ..................................................................................................................................... 28

4.4 Calibration of the VISSIM Model ......................................................................................................... 29

4.5 Performance Measures ....................................................................................................................... 30

CHAPTER 5: SIMULATION RESULTS AND ANALYSIS ............................................................................. 32

5.1 Network Throughput ............................................................................................................................ 32

5.2 Number of Evacuated Vehicles ........................................................................................................... 35

5.3 Average Delay .................................................................................................................................... 37

5.3.1 Average Network Delay .................................................................................................................. 37

5.3.2 Average Delay on Main Street ......................................................................................................... 39

5.3 Average Speed ..................................................................................................................................... 41

5.4 Signalized Intersections Delay ............................................................................................................ 42

5.5 Signalized Intersections Average Queue Length .................................................................................. 47

5.6 Selection of Best Emergency Signal Plan ............................................................................................. 47

CHAPTER 6: CONCLUSIONS ..................................................................................................................... 51

6.1 Summary of Findings ............................................................................................................................ 51

6.2 Recommendations ............................................................................................................................... 53
6.3 Future Research .............................................................................................................. 54

BIBLIOGRAPHY ...................................................................................................................... 56
LIST OF TABLES

Table 1. VISSIM Network calibration................................................................. 30
Table 2. Summary of network performance measures for emergency evacuation plans. .......... 34
Table 3. LOS at signalized intersections.................................................................. 43
Table 4. Average Intersection Delay (seconds)......................................................... 45
Table 5. Average Intersection Queue Length (feet)................................................... 46
LIST OF FIGURES

Figure 1(a) DFY signal timing plan    (b) DFY phase transition .................................................. 13

Figure 2. Potential capacities of through traffic at side streets for a one-lane four-leg intersection
controlled by flashing yellow .................................................................................................................. 15

Figure 3(a) Pre-defined splits; (b) Floating force-offs implementation ............................................. 19

Figure 4. Time-Space Diagram of Signalized Intersections ................................................................. 21

Figure 5. Layout of South Park Avenue, Buffalo, NY ....................................................................... 24

Figure 6. Comparison of network throughput ..................................................................................... 33

Figure 7. Comparison of number of evacuated vehicles ..................................................................... 36

Figure 8. Comparison of average network delay ............................................................................... 38

Figure 9. Comparison of average delay on main street ..................................................................... 40

Figure 10. Comparison of average delay on side streets ................................................................. 41

Figure 11. Comparison of network average speed ........................................................................... 42

Figure 12. Average network delay (PM1) against the Inverse of Evacuated Vehicles (PM2) ....... 49
ABSTRACT

An effective and efficient signal timing plan for emergency evacuation is very crucial for public safety. Two main objectives of emergency evacuations are to increase throughput on the main street and decrease delay on the side streets. Some studies have proved the effectiveness of the static flashing yellow (SFY) signal timing plan in evacuating high number of vehicles (Chen et al. 2007). However, one disadvantage of the static flashing yellow signal timing plan is the high delay that side street traffic experiences. This thesis investigates a variant of the static flashing yellow signal timing plan called dynamic flashing yellow (DFY) signal plan. The dynamic flashing yellow signal timing plan has two main phases of operation for every signal controller. Phase 1 is flashing yellow on the main street and flashing red on the side street, whereas phase 2 is red signal on main street and green signal on the side street. Three different types of DFY signal timing plan are proposed- Fixed DFY, Actuated DFY and Actuated and Coordinated DFY. This thesis demonstrates that the dynamic flashing yellow provides a high volume of evacuated vehicles with relatively low delay to side street traffic. Also the proposed DFY is adjustable to favor different weights between throughput and delay.

A microscopic traffic simulation tool, VISSIM, is used to model and compare several emergency signal timing plans for a real network in Buffalo, NY which is a 4.1 mile corridor. The DFY signal timing plan is compared to PM peak plans and the SFY signal plan. The DFY signal timing plan is further analyzed under different minimal cycle lengths. It is realized that a minimal cycle length of 60s gives the best results (Pareto non-dominated solutions) for the DFY plan.
CHAPTER 1: INTRODUCTION

1.1 Background

Evacuation is defined as the immediate, urgent and collective movement of people and the mode of transport used from a hazard or potential hazard (Alsnih and Stopher 2004). The National Response Plan (NRP) defines an evacuation as an organized, phased, and supervised withdrawal, dispersal, or removal of civilians from dangerous or potentially dangerous areas, and includes their reception and care in safe areas (FHWA 2014). In the US, there is at least one warning for natural and man-made hazardous event every day (Xie 2008). Several times each year, transportation and industrial accidents release harmful substances that forces people to leave their homes (RIEMA 2014). The type of hazardous event determines the amount of time available for the evacuation. Weather conditions such as a hurricane can be monitored and there is likely to be a day or more to get ready. However, some disasters, including terrorist attacks, serious accidents that cause road closures, release of a biological or chemical substance and others, do not allow any time for people to gather even the most basic necessities. The impromptu nature of these events underscores the need for advance planning (RIEMA 2014). A network’s ability to handle evacuation demand depends on the rate at which the demand can be exerted and the capacity of the network (Alsnih and Stopher 2004).

Emergency evacuations result in a sharp increase in traffic demand within a short time on the main streets. Emergency service vehicles will also have to move towards the emergency situation zones. There is likely to be massive congestions, driver frustration and possible accidents on the main streets due to the high influx of vehicles on the main streets. Fully utilizing existing road capacity for traffic can improve the efficiency of the emergency evacuation process. One of the ways of increasing the capacity of a road network involves changing the signal timing by giving t
majority of the green time to the main street (Jahangiri et al. 2011). Due to the no-notice nature of emergency evacuations, it is desirable to have emergency signal timing plans that can be quickly and easily implemented. Emergency signal timing plans are necessary since intersections are the reason for most traffic delays in regional evacuations (Cova et al. 2002). Reducing intersection delay and maximizing network throughput is the main goal of emergency evacuations. It is expected that optimizing traffic signals for evacuation demand will increase the number of evacuated vehicles and also reduce the delay on side street traffic.

As indicated by Chen et al (2007), flashing yellow (FY) is a very effective way to evacuate vehicles out of an area where emergency events occur. Flashing yellow mode usually allows larger intersection throughputs than traditional green and red signals. FY flashes yellow on main evacuation approach, and flashes red on the side street. In this approach, priority is given to traffic on the evacuation arterial to achieve a continuous flow, allowing the roadway capacity to be used more efficiently. A drawback of this approach, indicated as static flashing yellow (SFY) in the rest of paper, is that extremely long delays may result for vehicles on the side streets. If delays are extremely long, drivers may not be willing to obey the traffic rules. Therefore SFY is not a desirable signal timing plan for practical evacuation. This thesis proposes the dynamic flashing yellow (DFY) signal timing plan, which is a variant of the SFY signal plan and compares it to the PM peak hour signal plan and SFY plan. The PM Peak and Evacuation plan modeled in this thesis is similar to the 240 seconds cycle length plan used by Chen et al. 2007. The main street used for this thesis is the South Park Avenue, Buffalo, NY. It is expected that the DFY for emergency signal timing will be suitable for urban areas during emergency situations in ensuring high number of evacuated vehicles and acceptable vehicle delay for side streets.
South Park Avenue in Buffalo is an integral route because of its closeness and parallel location to some of the major highways like Buffalo Skyway (Route 5) and Niagara Thruway (I-190). It is approximately 4.1 miles. Its strategic location makes it an alternative route in case of emergencies such as accidents, release of dangerous substances or terrorist attacks that prevent the use of Buffalo Skyway (Route 5) or Niagara Thruway (I-190). This emergency signal timing plan is also expected to be useful when there is a need to quickly evacuate people from downtown to suburban areas.

1.2 Research Objectives

The objective of this thesis is to demonstrate the effectiveness and flexibility of the DFY signal timing plan for emergency evacuations. The DFY will be compared to other emergency signal timing plans and its advantages will be identified.

This thesis will contribute towards research in developing emergency evacuation signal timing plans for urban areas. This research can assist transportation engineers in making decisions about the most appropriate emergency signal timing plan based upon their preferences among different objectives such as increasing network throughput, minimizing average delay or attaining a weighted balance between the throughput and delay.
1.3 Thesis Organization

The remainder of this thesis is organized as follows. In Chapter 2, a literature review is conducted to summarize previous work related to emergency evacuations and signal timing under emergency evacuation. Chapter 3 introduces the DFY plan, describes the model for computing the potential capacities of through traffic at side streets for a one-lane four-leg intersection controlled by flashing yellow, derive equations for determining the green split on side streets, and present the underlying principles of multiple criteria optimization. Chapter 4 describes the study network, alternative emergency signal timing plans, and the major steps in creating and validating of the simulation network. Chapter 5 focuses on analysis of the simulation results and the selection of the best model. Finally, a summary of findings and recommendations is given in Chapter 6.
CHAPTER 2: LITERATURE REVIEW

This chapter presents a literature review of research related to emergency evacuations. It includes a discussion of available evacuation plans and policies, intersection traffic control and traffic routing, traffic simulation models for emergency evacuation, and traffic signal timing for emergency evacuation. Even though this thesis is about traffic signal timing for emergency evacuations, technical information about emergency evacuations have also been provided in this chapter.

2.1 Evacuation Plans and Policies

This section reviews the emergency evacuation plans and policies that are used by the Federal, State and Local Governments. The first line of emergency response in disasters is the State and Local Governments. State and Local Governments have fire, police, emergency medical services (EMS) and emergency management agencies dedicated to disaster response (FHWA 2014). The Federal government comes in when State and Local Governments are overwhelmed beyond their ability to satisfy their traditional roles in the system (FHWA 2014). A recent example of such disaster is the Hurricane Katrina where FEMA had to intervene. All States are required by the Federal Government through the Federal Emergency Management Agency (FEMA) to have a comprehensive emergency operation plan (Wolson et al 2005). According to Federal Highway Administration (FHWA), evacuations can be classified as spontaneous, voluntary, mandatory or directed, notice versus no-notice evacuation, and shelter in place evacuation. A survey was conducted by Wolson et al. (2005) to gather information about the general practices for evacuation in each state and to examine the use of newer technologies such as reverse flow and ITS. They emphasized on authority and command structure, advance warning times required to implement evacuations, policies that govern enforcement and management of evacuations,
planning and management of contraflow operations, and communication strategies for the exchange of data and information. Miller–Hooks and Tarnoff (2005) also conducted nationwide interviews with experts and agents in Federal, State and Local Agencies in the United States between September 2004 and February 2005 about their approach to signal timing for emergency situations. These interviews illustrated that there were four approaches to setting signal timing, which include setting signals on flash, controlling signals by police at critical intersections, setting signals on PM-peak plan, and setting signal timing plans on maximum cycle length by giving the majority of green time to the major directions. The use of traffic control agencies (TCAs), which includes police officers, firefighters or other traffic law enforcement officers, to control traffic during planned and unplanned was researched by Ding et al. 2014. They found that manual traffic control can significantly improve the control performance of intersections.

Triche et al (2005) reviewed current emergency evacuation plans and procedures for Alabama Gulf Coast and made recommendations for advanced technologies such as Global Positioning System (GPS), Geographic Information System (GIS) and Intelligent Transportation Systems (ITS). They simulated traffic flows for major arterials by using the Oakridge Evacuation Modeling System (OREMS). They also considered reverse-laning of Interstate highways for hurricane evacuations.

2.2 Intersection Traffic Control Strategies and Routing

Jahangiri et al. (2014) developed a bi-level model to evaluate crossing elimination as an evacuation traffic management strategy for no-notice events. They found that elimination and/or reduction of conflicting maneuvers at intersections could significantly reduce travel delay and evacuation clearance times during emergencies. Another bi-level network optimization model
was developed by Liu and Luo (2012) for the optimal location planning of signalized and uninterrupted flow intersections in an urban network for emergency evacuation. They studied a number of intersections that should have signals and uninterrupted flow strategies. The goal of their research was to find the most appropriate locations, and how turning restriction plans are to be properly designed for the uninterrupted flow intersections.

Cova et al (2002) applied lane-based routing to reduce delay at traffic intersections during emergency evacuations. Their proposed model was an integer extension of the minimum-cost flow problem. A mixed-integer linear programming solver was used to derive optimal routing plans for a sample network. Their results showed that channeling flows at intersections to remove crossing conflicts can significantly decrease network clearing time over no routing plan. Stepanov et al. (2009) suggested an optimal egress route assignment for evacuation demand. An integer programming formulation for optimal route assignment was presented. They evaluated the performance measures for the generated evacuation policy such as clearance time, total traveled distance and congestion level. The evaluation was done with the MGCCSimul simulation software. Osman et al. (2011) proposed a capacity-constrained evacuation scheduling problem over a discrete time as an integer optimization. Yamada (1996) modelled a city as an undirected graph, and solved a shortest path problem on this graph. Franzese and Han (2001) developed a microcomputer-based system to analyze and evaluate the impacts of different factors affecting large-scale emergency evacuations from a traffic operation’s perspective. The methodology was used to simulate traffic flow during emergency vehicle evacuations that are caused by natural disasters or man-made catastrophes. Liu et al (2008) studied terrorist attack emergency evacuation system for Washington, D.C. They accounted for critical issues associated with planning and real-time operations, including the integration of data from multiple
sources, network decomposition, network-level traffic routing, contraflow design, staged evacuation and optimal signal timing. Further, they found that GIS models allow operators to assess the impact of the emergency incident, specify preliminary control plans, identify TAZ (Traffic Analysis Zone)-based evacuation demands, allocate main streets, and revise the evacuation plans that have been implemented.

2.3 Traffic Simulation Models for Evacuation modeling

Microscopic traffic simulation (or micro-simulation) is the most detailed level of transportation simulation modeling (Cova and Johnson, 2002). Shiwakoti et al. (2013) summarized many of these micro-simulation traffic simulation models. Chen and Zhan (2008) used Paramics (Paramics, 2009) to solve the inability to model individual vehicle movements by network flow models dynamically through Agent Based Modelling (ABM) to build group behavior. They employed agent-based simulations to show, for conditions employed, that staged evacuation had no advantage over simultaneous evacuation except for a theoretical high-density population grid network. Elmitiny et al. (2007) used VISSIM (PTV 2009) to simulate the surrounding traffic network, traffic diversion, bus signal optimization, access restriction and multi-destinations. They found that the number of buses used had equal clearance time, despite affecting overall network. They also concluded that ITS technologies may greatly support traffic management in an emergency situation. Williams et al. (2007) used CORSIM (Federal Highway Administration 1996) to implement lane reversal plan for Interstate 40 to facilitate hurricane evacuation of residents and tourists in south-eastern North Carolina. They quantified the utility of simulation modelling in examining the viability of transportation systems using I-40 lane reversal. The Oak Ridge Evacuation Modeling System (OREMS) is another micro-simulation too that was
developed by the Oak Ridge National Laboratories Center for Transportation Analysis. It can be used to estimate evacuation time, develop traffic management and control strategies, and to identify evacuation routes, traffic control points, and traffic operational characteristics for different scenarios (Moriarty et al. 2007)

Macroscopic and Mesoscopic models have also been used to model evacuations. Abdelgawad et al (2010) developed optimal spatiotemporal evacuation (OSTE) formulation. The OSTE formulation was proposed for auto evacuees while a multiple-depot, time-constrained, pickup and delivery vehicle routing problem (MDTCPD-VRP) was proposed for transit vehicles. They found that mass transit can provide latent transportation capacity that is needed in evacuation situations. Chan (2010) applied a model based on single source capacitated facility location problem for carless evacuation. The model includes a location problem that aims at congregating the carless at specific locations, and a routing problem with the objective to pick up the carless. That study found that giving priority to idle buses to visit evacuation sites over other buses performed better than sending idle buses directly to the closest available safe locations. A macroscopic evacuation simulation model, NETVACI, was used by Sheffi et al. (1982) to model traffic flow patterns and estimate clearance times during nuclear power plant accidents. NETVACI models queue formation and route choice at an aggregate level. IDYNEV (Interactive DYNamic EVacuation) developed by KLD Associates for the Federal Emergency Management Agency (FEMA), has different evacuation models with functions for estimating evacuation travel times and assessing evacuation plans (Xie 2008).
2.4 Traffic Signal Timing for Evacuation

There are a number of studies on optimizing signal times for an effective emergency evacuation. McHale and Collura (2003) modeled emergency vehicles with CORSIM and used optimum signal timing plans that were concluded from TRANSYT-7F (Wallace et al, 1984) to evaluate the impacts of emergency vehicle preemption (EVP) on all passengers. Chen et al. (2007) used the simulation tool CORSIM to test different signal timing plans and offsets. They concluded that with regards to the number of vehicles evacuated, the flash mode plan is the most effective plan to evacuate people from emergency zones. However, they realized a significant increase in delay for vehicles traveling on the side roadways. This might lead to drivers on the side roads not willing to comply with the traffic rules anymore that might result in incidents. Sisiopiku et al. (2007) also applied CORSIM to analyze some evacuation plans and response actions.

They focused on a small region in Birmingham, Alabama to evaluate the effect of signal timing optimization as a traffic management strategy. They also used SYNCHRO to optimize signal timing plans. Liu et al. (2008) proposed a corridor-based emergency evacuation system for Washington D.C metropolitan area. They optimized the signal timings during the evacuation process by using the signal optimization software (e.g., SYNCHRO and TRANSYT-7F) to generate the optimal signal-timing plan and used the CORSIM simulator to evaluate the resulting performance and impacts. They suggested that the optimization of signal timing considerably reduced delays. Zhang et al. (2010) reviewed simulation-based and optimization-based models for network emergency evaluation modeling. Jahangiri et al. (2011) developed a simulated annealing algorithm to optimize signal timing for emergency evacuations. They found cycle length of 120 seconds to be the best, and concluded that when travel demand is heavy, higher cycle length is more suitable and vice versa.
Although many studies have proposed signal optimization methods for evacuation plan, none of the above studies provides a flexible timing plan which can adjust the weights between network throughput and side street average delay for different evacuation scenarios.
CHAPTER 3: MODELING TECHNIQUE

This chapter will first introduce the concept of DFY signal timing plan. It will then proceed with the models to calculate the intersection capacities associated with the DFY plan, DFY actuated plan, DFY actuated-coordinated, and finally a description of the optimization technique used in this thesis. This thesis makes the following assumptions with regards to traffic demand, turning movements, and driver behavior in the presence of flashing yellow or flashing red signal:

- **Assumption 1.** Traffic demand and turning ratios are known.
- **Assumption 2.** Left turn is prohibited, and left turn vehicles are rerouted to take three consecutive right turns.
- **Assumption 3.** Drivers understand what flashing yellow and flashing red signals signify.
  
  Flashing yellow implies that drivers can proceed with caution, whereas flashing red signal operates like a stop sign.

3.1 Introduction to Dynamic Flashing Yellow Plan

The proposed DFY signal timing plan consists of two phases in its operation, shown as Figure 1(a). In the first phase (flashing yellow/flashing red, short as FY/FR) the traffic signals on the main street flash yellow whereas the side street signals flash red. In the second phase (green/red, short as G/R), the main street signal will stay in red and the side street signal turn green.

The goal of using green/red phase is to quickly clear waiting vehicles on the side streets. This is necessary especially for side streets with significant traffic demand. Even though the side streets have flashing red which allows vehicles to move within gaps in the main street traffic, vehicles on the side street might not be able to find enough gaps to pass the intersection due to high
evacuation demand. When side street traffic is very light, we can skip green/red phase and keep flashing yellow on main street and flashing red on side street. The green/red phase also improves intersection safety by virtue of the fact that drivers on main streets might panic during evacuation and they might not be used to stopping and waiting for gaps in side street traffic. Therefore, the use of the green and red in the second phase instead of the flashing yellow and flashing red eliminates this ambiguity.

The duration of each phase is determined based on three different DFY strategies: fixed DFY, actuated DFY and actuated-coordinated DFY, which will be presented later in this chapter. The different settings of DFY plan are tested on a real network in Buffalo, NY through the micro-simulation tool VISSIM.

To ensure safety, it is very essential to add yellow and all red as transition phases for alternative flashing yellow plan, shown as Figure 1(b). In this paper, we set yellow time as 4 seconds, all red as 2 seconds, and assume the lost time is 6 seconds in each phase switch.

Figure 1(a) DFY signal timing plan      (b) DFY phase transition
3.2 Potential Capacity of Through Traffic at Side Streets

Since a junction with flashing yellow can be treated as a two-way stop controlled intersection (TWSC), the Highway Capacity Manual (HCM) 2010 is used to calculate the capacity of turning flows. HCM provides an exponential function to compute the potential capacity of each turn at a TWSC. The exponential function is given as (HCM 2010):

\[ Q_p = V_c \frac{e^{-V_c t_c/3600}}{1-e^{-V_c t_f/3600}} \]  \hspace{1cm} (1)

Where

- \( Q_p \) = potential capacity of side movement (veh/hr)
- \( V_c \) = conflicting flow rate for side movement (veh/hr)
- \( t_c \) = critical gap (i.e. the minimum time that allows intersection entry for one side stream vehicle) for side movement (s), and
- \( t_f \) = follow up time (i.e. The time between the departure of one vehicle from the side street and the departure of the next under a continuous queue condition) for side movement (s).

The potential capacity of a side movement is denoted \( Q_p \) and is defined as the capacity for a specific side movement, assuming the following base conditions:

- Traffic from nearby intersections does not back up into the subject intersection.
- A separate lane is provided for the exclusive use of each side-street movement.
- An upstream signal does not affect the arrival pattern of the major-street traffic.
- No other movements of Rank 2, 3, or 4 impede the subject movement.
Considering the potential capacity of side streets for a one-lane four-leg intersection controlled by flashing yellow, the following parameters are applied: $t_c=6.5$ sec, and $t_f=4$ sec. A plot of potential capacities of through traffic at side streets for a one-lane four-leg intersection controlled by flashing yellow is shown in Figure 2 below.

![Potential capacities of through traffic at side streets for a one-lane four-leg intersection controlled by flashing yellow](image)

Figure 2. Potential capacities of through traffic at side streets for a one-lane four-leg intersection controlled by flashing yellow

It can be seen from Figure 2, that when the main street demand or conflict flow is very high (approximately greater than 1600), the potential capacity of through traffic at the side streets is almost zero. This limitation can be overcome by the green/red phase introduced in DFY.
3.3 Dynamic Flashing Yellow with Fixed Splits (DFY-F)

We first introduce fixed DFY, in which the phase splits are pre-defined and constant through the simulation. We proposed a model to decide the green split for side streets under DFY. The green split can be determined through the following equations.

\[
\delta \lambda_s C \leq Q_p. (C - G_s) + G_s. Q_s
\]

\[0 \leq \delta \leq 1\]

where the notations are listed as follows:

- \(Q_p\) is the capacity of side street when flashing red (veh/sec).
- \(\lambda_s\) is the arrival rate of the side street (veh/sec).
- \(\delta\) is a weighting factor for side street traffic.
- \(C\) is the cycle length (seconds)
- \(G_s\) is the green split on side street (seconds).
- \(Q_s\) is the capacity of side street when it is green (veh/sec).

Equation (2), \(\delta \lambda_s C\), represents the total number of vehicles on the side street that can be served in a cycle. The weighting factor \(\delta \in [0, 1]\), is used to determine the proportion of side street traffic that should be served in a cycle. It gives an indication of the level of priority that is given to the side street. If \(\delta\) is equal to 1, the full demand of side street traffic is being served. If \(\delta\) is equal to 0, the fixed DFY is equivalent to SFY, which does not provide any green split for side streets. The first term on the right side of Equation (2), \(Q_p. (C - G_s)\), estimates the number of side street vehicles that can be served when the main street is flashing yellow and the side street
is flashing red. The second term, $G_s, Q_s$, calculates the number of side street vehicles that can be served when the side street is given the green signal. This thesis used 1 as the weighting factor for side street traffic ($\delta$).

Equation (2) is solved in terms of the side street green split as shown in Equation (3) below:

$$G_s \geq (\delta \lambda_s C - Q_p, C)/(Q_s - Q_p)$$

The following conditions were used for setting the green time on the side streets:

i. If $G_s < 0$, then the intersection should be set as SFY.

ii. If $0 \leq G_s \leq$ minimal green, then minimal green should be used.

iii. If $G_s >$ minimal green, $G_s$ should be used as obtained.

iv. If $G_s >$ maximal green, the maximal allowable green should be applied.

3.4 Dynamic Flashing Yellow with Actuations (DFY-A)

Traditional actuated signal control utilizes traffic detectors to observe real-time traffic arrivals to adjust the phase durations (timing) between pre-specified minimum and maximum phase time (Sen and Head 1997). Typically actuated signal control employs vehicle detection to identify real-time traffic arrivals. As opposed to traditional actuated signal controls, DFY-A, however, does not rely on vehicle detection for signal actuations since the detected vehicle may stop and pass the intersection given sufficient gap on main approach. Unlike DFY-F which uses pre-defined splits constant throughout the simulation, DFY-A switches based on side street occupancy time (or detection delay time), which is defined as the time in seconds since the last time the detector is occupied. Therefore, the proposed DFY-A uses the side street detector’s
occupancy time to recognize signal actuations, and decide whether to stop flashing yellow on the main street. It will be reset to zero if there is no longer any vehicle detected.

In this thesis, the side street occupancy time of 10 seconds is used in deciding whether to switch or not. This means that FY/FR phase is terminated only if the FY/FR phase has reached its green time split and a vehicle has waited on the side street for more than 10 seconds. The duration is used because it is expected that within 10 seconds, a vehicle on the side street should be able to find gaps in the main street if there was any gaps.

3.5 Dynamic Flashing Yellow with Actuations and Coordination (DFY-AC)

Traffic signal coordination is defined as the ability to synchronize multiple intersections to enhance the operation of one or more directional movements (FHWA 2013). It is mostly needed when traffic signals are in close proximity. According to FHWA (2013), traffic signal coordination is needed when traffic signals are within 0.75 mile of each other and traffic volume between adjacent intersections is large. Traffic signal coordination can help to reduce delay, maximize capacity, minimize queue length, minimize fuel consumption, and many others.

In view of these advantages, the DFY plan should be also coordinated to measure improvements in the number of evacuated vehicles and the reduction in the average delay. A description of the parameters of traffic signal coordination that were used in thesis has been explained below:

- Cycle Length: In DFY-AC, the cycle is defined as a sequence of phase FY/FR and phase G/R. The cycle length includes the total time spent on these two phases. However, we allow the flashing yellow (FY) rests on main approach, if there is no actuation received
on side street. Therefore, the given cycle length is actually the minimal cycle for implementation.

- Splits: The phase splits assigned to each phase were determined based on Equations (1), (2) and (3). Equation (3) gives the side street green time which is used to determine FY/FR splits. Figure 3 (a) and 3(b) below gives an example of a pre-defined split and floating force-off split implementation.

![Figure 3(a) Pre-defined splits; (b) Floating force-offs implementation](image-url)
• Offsets: In emergency evacuation, we assume the traffic is oversaturated on main street and FY will often allow vehicles to fill the main street between two adjacent signals. Therefore, the offset is defined as the time when the discharging shockwave reaches the last vehicle in the queue, shown as Figure 4. The offset is then determined by the ratio of the distance between the adjacent intersections and the shockwave speed, depicted in Equation (4). In this thesis, we set the discharging shockwave speed as 12 mph.

\[ O = \frac{L}{w} \]  

where \( O \) is the ideal offset under DFY, \( L \) represents the distance between adjacent intersections, and \( w \) denotes the shockwave speed for queue discharging. Real-time queue length should be used to calculate the offsets if they are available.

• Force-offs: Typical force-offs include fixed floating-offs and floating force-offs. Floating force-offs are used in DFY-AC to favor evacuation route traffic on main street. The force-off maintains the non-coordinated maximum times for each non-coordinated phase (G/R phase in DFY) in isolation of one another. This is used because of the need return to the FY/FR phase if there are no more vehicle actuations on the side street or G/R phase has reached its maximal green time.
3.6 Multiple Criteria Optimization

Emergency evacuations can be considered as a multiple criteria optimization problem due to the number of different objectives. Multicriteria objective optimization chooses a “good” or “best” among alternatives by assuming the existence of a certain criteria according to which the quality of the alternatives is measured (Ehrgott 2005). The multicriteria optimization problem can be presented in the form of a minimization problem as given below (Ehrgott 2005).

\[
\min (f_1(x), \ldots, f_p(x))
\]

subject to \( x \in X \)
In this thesis, the criteria $f_i(x) \forall i = 1, \ldots, p$ represent performance measures like the inverse of the number of evacuated vehicles, average number of stops, intersection queue length, inverse of average speed and others. The constraints include flow conservation constraints in the network and signal timing constraints. The two main objectives of evacuation planning are to determine the shortest possible evacuation time and to evacuate as many people as possible (Yusoff et al 2008). This thesis considers both objectives: maximizing the number of evacuated vehicles and minimizing the average network delay. We seek to find a Pareto frontier between the numbers of evacuated vehicles and average network delay.

There are several approaches to solve the multiple criteria optimization problem. These include the $\varepsilon$-constraint method, hybrid method, elastic constraint method, Benson’s method and others. In this thesis, the concept of $\varepsilon$-constraint method is applied to treat the emergency evacuation signal timing problem under multicriteria optimization. In this method, there is no aggregation of criteria, instead only one of the original objectives is minimized or maximized, while the others are transformed to constraints (Ehrgott 2005).

The $\varepsilon$-constraint method is given as:

$$\max_{x \in X} f_j(x)$$

subject to $f_k(x) \leq \varepsilon_k, k = 1, \ldots, p \ k \neq j$

where $\varepsilon \in \mathbb{R}_p$

In this thesis, the $f_j(x)$ in the formulation above represents the network throughput, whereas the $f_k(x)$ represents the average network delay (suppose $p = 1$). The $\varepsilon$ used in this thesis is 250 seconds to address waiting time equity for side street traffic. Therefore, the mathematic program aims to maximize throughput and keep average delay less than 250 seconds.
CHAPTER 4: NETWORK MODELING AND SIMULATION

This chapter describes the details of selected study network and simulation configurations. Popular traffic signal optimization tool SYNCHRO is applied to develop baseline signal timing plan. The entire simulation is modeled with VISSIM, and the DFY control algorithms are built through VISSIM COM (Component Object Model) technologies and Java. We also present the entire process of calibrating the simulation network. Finally, this chapter summarizes different emergency signal timing plans to be tested, and concludes with a description of the performance measures that are used to compare the emergency signal timing plans.

4.1 Study Network

South Park Avenue, around 4.1 miles long, lies within the Southern area of the City of Buffalo, NY. South Park Avenue in Buffalo is an integral and critical route because it is treated as an alternative route to some of the major highways like Buffalo Skyway (Route 5) and Niagara Thruway (I-190). South Park Ave carries most of traffic from downtown to south suburban area when Route 5 would be blocked during evacuation for other reasons (e.g., flood, inclement weather, construction, accidents, etc.).
South Park Avenue contains 15 signalized intersections and 48 un-signalized intersections, shown as Figure 5. The signalized intersections are located where South Park avenue intersects with Michigan Ave, Louisiana St, Alabama St, Hamburg St, Elk St, Smith St, New Abby St, Hopkins St, Bailey Ave, Southside Pkwy, Tifft St, Choate Ave, Marilla St, McKinley Pkwy and Ridge Road. Figure 5 depicts the layout of the study network. PM peak traffic volume data are collected either from manual traffic counts or turning movement counts from Greater Buffalo-Niagara Regional Transportation Council (GBNRTC), also shown on Figure 5.
It can also be seen from Figure 5 that some of the signalized intersections are within close proximity of other intersections. This implies that coordination of traffic signals may be beneficial for network efficiency.

4.2 Simulated Emergency Signal Timing Scenarios

This section gives a brief description of the various signal timing plans that are evaluated through the VISSIM simulations. The VISSIM simulations are run through Java and COM (Component Object Model) technology (PTV 2006). We assume that evacuation traffic demand, 1940 veh/hr, from Route 5, is imputed into South Park Avenue on top of the daily PM peak traffic volume during emergency evacuation. The simulation duration is 4500 seconds with 900 second warm-up period. The data is collected after the warm-up period to the end of the simulation. The warm-up period is used to avoid capturing network data when the effects of the emergency evacuation have not set in. Different timing plans have been implemented and compared, shown as below:

1. **PM-peak (PME):** This approach implements the signal timing settings obtained through the SYNCHRO optimization of the existing PM peak traffic demand. The simulation is run under this setting to test the effectiveness of the existing PM peak signal setting in handling the evacuation vehicle traffic. It thereby gives an indication of the performance of the network when the need for evacuation happens and no changes are made in the signal timing plan.

2. **PM-peak Optimized for Evacuation Demand (PPED):** This plan also uses the signal timing splits obtained through the SYNCHRO optimization. However, this one takes both
the existing PM traffic and the evacuation demand into account. The SYNCHRO optimization resulted in a 240s cycle length for all the intersections. This plan is similar to the 240s plan used by the District Department of Transportation (DDOT) in Washington D.C. to facilitate the outbound flow of traffic along the arterials as an evacuation plan after the 9/11 terror attack (Chen et al. 2007).

3. **Static flashing yellow (SFY):** SFY applies yellow flash on the main street direction, and red flash on the side street direction. In this state, high priority is given to traffic on the main directions. A drawback of this approach is that extremely long delays may occur for vehicles on the side street directions and so drivers may not be willing to obey traffic rules.

4. **Dynamic flashing yellow (DFY):** This is the proposed signal timing plan for emergency evacuation to increase throughput and reduce delay on side street traffic. Different types of the DFY are developed and tested as mentioned before:

   **i.** Dynamic Flashing Yellow with Fixed Splits (DFY-F): This emergency signal timing plan operated basically like a fixed time signal with no coordination. This is tested because of the ease of its implementation. The test is carried out under different main street green time and cycle lengths. Each intersection (signal controller) had its own fixed dynamic flashing yellow plan, calculated by Equation (3).

   **ii.** Dynamic Flashing Yellow with Actuations (DFY-A): This emergency signal timing plan uses vehicle occupancy time on the side streets to allow them to time to their full green splits or switch back to flashing yellow on the main street when
the phase gaps out. They are tested under different cycle lengths to obtain the optimal cycle length that gives the best results. The cycle is actually the minimal cycle for implementation. If there is no actuations on side street, the flashing yellow (FY) rests on main approach.

iii. Dynamic Flashing Yellow with Actuations and Coordination (DFY-AC): This emergency signal timing plan is similar to the DFY-A with the only exception being that this plan coordinates the signalized intersections. Intersection offsets are obtained by Equation (4) to achieve the coordination. The cycle is also actually minimal cycle for implementation. If there is no actuations on side street, the flashing yellow (FY) rests on main approach. Different cycle lengths are evaluated for the DFY-AC plans.

Results are presented for cycle lengths 60, 90, 120, 180, and 240 seconds. Cycle lengths less than 60 seconds were tested but it was realized that they offered very low throughput but low network average delay. DFY plans with cycle lengths greater than 240 seconds were also tested but their throughput were low and their average delays were very high. As intersection cycle length is increased, longer queues are formed at the intersection approaches. In discharging these longer queues there is an increase in average discharge headways or reduction in saturation flow rates. This reduction in actual saturation flow rate reduces vehicle throughput and thus makes longer cycle lengths ineffective (TRB, 2008). Moreover, Chen et al. 2005 states that most signal traffic controllers cannot handle cycle lengths greater than 240 seconds and vehicles on side street may run the red light if they wait too long. Therefore, cycle lengths greater than 240 seconds are not considered further.
4.3 VISSIM Model

The South Park Avenue corridor model is developed with VISSIM 5.40 (PTV, 2009), a popular microscopic traffic simulation tool. Some of the turning movement data and traffic count data are obtained from the Transportation Data Management Systems (TDMS) of GBNRTC. Manual traffic counts are also conducted to collect traffic volume and turning movement counts for intersections without readily available data.

Network elements, including lanes, lane widths, signal controllers, vehicle inputs, routing decisions, priority rules, detectors, stop signs and many others are built based on Google Earth images. The free flow speed is set to 35mph according to existing speed limits.

The VISSIM Ring Barrier Controller (RBC) is used to set the signal timing and phasing plans for the PME and PPED plans. The timing and phasing plans for the SFY and DFY plans are coded through the Java and VISSIM COM.

VISSIM offers users the opportunity to dynamically access and manipulate VISSIM objects during the simulation (Tettamanti et al 2012). This is provided through the COM interface. The VISSIM COM object model is structured based on a strict object hierarchy. “Vissim” is the highest object in the hierarchy and all the objects belong to “Vissim”. To access an object like “Nodes”, you need to first build the “Vissim” and “Net” objects. The VISSIM COM allows the simulator to manipulate graphical user interface (GUI) and the attributes of most of the internal objects through programming languages like C++, Visual Basic, Java and others (Tettamanti et al 2012). Java is selected as the programming language in this thesis. Through Java and VISSIM COM, we are able to access and control the attributes of most of the internal objects (e.g., “Signal Controllers”, “Detectors”, “Signal Groups”, etc.). The simulation results are also exported through Java.
4.4 Calibration of the VISSIM Model

The calibration of the simulation model is conducted to determine if the VISSIM model is able to reproduce existing traffic conditions with sufficient accuracy. The TDMS data provide traffic counts for several locations on South Park Avenue. Since not all the data locations are used in the model, the calibration procedure first places detectors in the VISSIM network at these locations whose traffic counts are not input in the VISISM model. The traffic count locations that are used for the simulation calibration are indicated as “VP” in Figure 5.

The traffic data obtained from the VISSIM detector are then compared to the field TDMS data. The differences in these two measurements are computed as errors in percentage. The error at location “i” is determined by the following equation:

\[
    Error_i(\%) = \frac{TC - VSC}{TC} \times 100\%
\]

where TC is the TDMS traffic count data, and VSC is the VISSIM simulation count.

The error (%) obtained at the various location IDs have been tabulated below in Table 1. It can be realized from Table 1 that the errors in reproducing the existing traffic conditions are all less than 10% and within acceptable ranges.
Table 1. VISSIM Network calibration

<table>
<thead>
<tr>
<th>Location ID*</th>
<th>VISSIM</th>
<th>Field</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>530192N</td>
<td>856</td>
<td>800</td>
<td>-7.00</td>
</tr>
<tr>
<td>530192S</td>
<td>985</td>
<td>1057</td>
<td>6.81</td>
</tr>
<tr>
<td>530137N</td>
<td>709</td>
<td>675</td>
<td>-5.04</td>
</tr>
<tr>
<td>530137S</td>
<td>744</td>
<td>815</td>
<td>8.71</td>
</tr>
<tr>
<td>530133N</td>
<td>780</td>
<td>809</td>
<td>3.58</td>
</tr>
<tr>
<td>530133S</td>
<td>590</td>
<td>557</td>
<td>-5.92</td>
</tr>
<tr>
<td>536093N</td>
<td>450</td>
<td>423</td>
<td>-6.38</td>
</tr>
<tr>
<td>536093S</td>
<td>644</td>
<td>690</td>
<td>6.67</td>
</tr>
<tr>
<td>534753N</td>
<td>571</td>
<td>619</td>
<td>7.75</td>
</tr>
<tr>
<td>534753S</td>
<td>488</td>
<td>452</td>
<td>-7.96</td>
</tr>
<tr>
<td>536489S</td>
<td>555</td>
<td>540</td>
<td>-2.78</td>
</tr>
<tr>
<td>536489N</td>
<td>274</td>
<td>250</td>
<td>-9.6</td>
</tr>
<tr>
<td>534755E</td>
<td>532</td>
<td>543</td>
<td>2.03</td>
</tr>
<tr>
<td>534755W</td>
<td>512</td>
<td>520</td>
<td>1.54</td>
</tr>
<tr>
<td>536442E</td>
<td>778</td>
<td>719</td>
<td>-8.21</td>
</tr>
<tr>
<td>536442W</td>
<td>643</td>
<td>655</td>
<td>1.83</td>
</tr>
</tbody>
</table>

4.5 Performance Measures

Two main performance measures are used to compare the proposed signal timing plans. These are the total number of vehicles evacuated within an hour and the network average delay. During the evacuation, the goal is to quickly move people out of the affected area in order to avoid fatalities or other discomfort. The time the last vehicle escapes the affected area is therefore an important criteria in measuring the performance of an evacuation. Due to the nature of this thesis, a vehicle is considered to be evacuated only when it reaches the end of South Park Ave which is right after the intersection of South Park Ave and Ridge Road. This is location where South Park Avenue in Buffalo ends.
There is also a need to consider all other vehicles that use South Park Ave during normal periods. The average network delay is therefore used to measure the impact imposed on all drivers as a result of the evacuation and to determine if the delay is acceptable. The delay experienced by vehicles on the main route (South Park Avenue) and by vehicles on the side streets are also recorded to aid in comparing the evacuation plans. In addition, network throughput and the network average speed are considered as network performance measures.

At the individual signalized intersection level, performance measures collected include average queue length and average delay.
CHAPTER 5: SIMULATION RESULTS AND ANALYSIS

This chapter presents the results obtained for the different emergency evacuation signal timing plans. The two main emergency evacuation performance measures, number of evacuated vehicles and the average network delay, will be discussed first. Then this chapter will elaborate the other performance measures, including average delay on main street, average delay on side streets, network average speed, intersection average delay and intersection average queue length. Table 2 summarizes the results for the different evacuation plans and the existing PM peak traffic condition without evacuation traffic. The existing PM peak performance measures are included for the purpose of comparing emergency evacuation situations to no emergency evacuation situations.

5.1 Network Throughput

The network throughput represents the total number of vehicles in the network that are able to leave the network at the end of the simulation period. DFY–A (60 seconds cycle) gives the highest network throughput (7832) whilst SFY gives the lowest network throughput (6461) as can be seen in Table 2. In our evacuation settings, the side street traffic demand dominates in the total network traffic demand. DFY-A (60 seconds cycle) with its relatively short cycle length allows more vehicles on the side streets to leave the network. This is because side street vehicles do not wait for too long before they are given the green signal to proceed. This thereby increases the entire network throughput. SFY has the lowest network throughput because vehicles on the side street are only given the flashing red which inhibits their ability to leave the network which consequently results in a lower network throughput. With the exception of DFY-AC (60 seconds cycle), all the DFY plans give a higher network throughput than the SFY, PME and PPED plans.
DFY-AC (60 seconds cycle) gives a lower network throughput as compared to the other DFY plans because of its relatively high number of evacuated vehicles. In most of the plans, higher network throughput comes with a relatively lower number of evacuated vehicles. Figure 6 below shows how the best three DFY plans perform against the PME, PPED and SFY plans in terms on network throughput.

![Figure 6. Comparison of network throughput](image-url)
Table 2. Summary of network performance measures for emergency evacuation plans.

<table>
<thead>
<tr>
<th>Emergency Evacuation Plans</th>
<th>Signal Timing Plans</th>
<th>Network Throughput</th>
<th>Number of Evacuated Vehicles</th>
<th>Average network delay (Sec)</th>
<th>Network Average Speed (mph)</th>
<th>Average Delay on Evac. Rte (Sec)</th>
<th>Average Delay on Side Sts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchro Optimized Timing Plans</td>
<td>PME</td>
<td>7215</td>
<td>989</td>
<td>303.42</td>
<td>9.02</td>
<td>992.57</td>
<td>25.63</td>
</tr>
<tr>
<td></td>
<td>PPED</td>
<td>6773</td>
<td>1278</td>
<td>463.9</td>
<td>6.91</td>
<td>1185.70</td>
<td>231.72</td>
</tr>
<tr>
<td>Static Flashing Yellow</td>
<td>SFY</td>
<td>6461</td>
<td>1922</td>
<td>421.75</td>
<td>10.15</td>
<td>276.27</td>
<td>329.24</td>
</tr>
<tr>
<td>Dynamic Flashing Yellow (Fixed)</td>
<td>60s Cycle</td>
<td>7776</td>
<td>1565</td>
<td>219.16</td>
<td>12.40</td>
<td>690.60</td>
<td>30.42</td>
</tr>
<tr>
<td></td>
<td>90s Cycle</td>
<td>7746</td>
<td>1520</td>
<td>265.63</td>
<td>11.74</td>
<td>874.00</td>
<td>50.39</td>
</tr>
<tr>
<td></td>
<td>120s Cycle</td>
<td>7575</td>
<td>1500</td>
<td>307.44</td>
<td>11.83</td>
<td>892.33</td>
<td>69.29</td>
</tr>
<tr>
<td></td>
<td>180s Cycle</td>
<td>7525</td>
<td>1442</td>
<td>315.3</td>
<td>10.68</td>
<td>959.53</td>
<td>78.57</td>
</tr>
<tr>
<td></td>
<td>240s Cycle</td>
<td>7441</td>
<td>1498</td>
<td>348.63</td>
<td>10.07</td>
<td>1048.17</td>
<td>96.49</td>
</tr>
<tr>
<td>Dynamic Flashing Yellow (Actuated)</td>
<td>60s Cycle*</td>
<td>7832</td>
<td>1653</td>
<td>245.9</td>
<td>12.79</td>
<td>682.93</td>
<td>49.40</td>
</tr>
<tr>
<td></td>
<td>90s Cycle</td>
<td>7813</td>
<td>1673</td>
<td>267.52</td>
<td>11.88</td>
<td>685.73</td>
<td>63.60</td>
</tr>
<tr>
<td></td>
<td>120s Cycle</td>
<td>7333</td>
<td>1764</td>
<td>303.75</td>
<td>10.92</td>
<td>397.47</td>
<td>85.14</td>
</tr>
<tr>
<td></td>
<td>180s Cycle</td>
<td>7478</td>
<td>1611</td>
<td>310.89</td>
<td>10.71</td>
<td>699.30</td>
<td>93.42</td>
</tr>
<tr>
<td></td>
<td>240s Cycle</td>
<td>7572</td>
<td>1596</td>
<td>327.99</td>
<td>10.15</td>
<td>588.71</td>
<td>105.36</td>
</tr>
<tr>
<td>Dynamic Flashing Yellow (Actuated &amp; Coordinated)</td>
<td>60s Cycle</td>
<td>7669</td>
<td>1755</td>
<td>249.8</td>
<td>13.24</td>
<td>486.13</td>
<td>65.31</td>
</tr>
<tr>
<td></td>
<td>90s Cycle</td>
<td>7755</td>
<td>1697</td>
<td>269.71</td>
<td>11.38</td>
<td>584.40</td>
<td>73.92</td>
</tr>
<tr>
<td></td>
<td>120s Cycle</td>
<td>7059</td>
<td>1811</td>
<td>275.99</td>
<td>10.29</td>
<td>417.17</td>
<td>91.21</td>
</tr>
<tr>
<td></td>
<td>180s Cycle</td>
<td>7647</td>
<td>1653</td>
<td>296.63</td>
<td>9.94</td>
<td>690.13</td>
<td>98.13</td>
</tr>
<tr>
<td></td>
<td>240s Cycle</td>
<td>7575</td>
<td>1631</td>
<td>327.5</td>
<td>9.09</td>
<td>733.50</td>
<td>106.12</td>
</tr>
</tbody>
</table>

*The cycle is not implemented in DFY-A. It is only used to calculates DFY-A parameters (e.g., maximal FY time on main street, maximal green time on side street), according to Equation (3)
5.2 Number of Evacuated Vehicles

The number of vehicles that are evacuated is a critical measure of the effectiveness of an emergency evacuation plan. Table 2 shows that SFY yields the highest number of evacuated vehicles of 1922. It performs better in this performance measure than all the PM-Peak plans and the DFY plans. This is intuitive since the main street flashes yellow and the side streets flash red for the entire evacuation duration. This gives the highest priority to the main street traffic and it is the best signal timing plan if evacuating a high number of vehicles is the only objective.

The DFY-AC (120 second cycle) is the second best plan in this performance measure with 1811 evacuated vehicles. This is mainly due to the fact that the main street signals will keep on flashing yellow until the condition for terminating them is met. The condition for terminating them is that they reach their split limit for flashing yellow and the occupancy on the side streets is greater than 10 seconds. The number of vehicles evacuated by this plan is the peak number of evacuated vehicles for the DFY plans. DFY plans with cycle lengths more than 120 seconds give much lower number of evacuated vehicles. As intersection cycle length is increased, longer queues are formed at the intersection approaches. In discharging these longer queues there is an increase in average discharge headways or reduction in saturation flow rates. This reduction in actual saturation flow rate reduces vehicle throughput and thus makes longer cycle lengths ineffective (TRB, 2008).

The DFY-AC (120 second cycle) is followed by the DFY-A (120 second cycle) with 1764 vehicles and the DFY-AC (60 seconds cycle) with 1755 vehicles. The relatively high number of vehicles evacuated through the DFY-A (120 second cycle) plan is also due to the fact that that the main street signals will keep on flashing yellow until the condition for terminating them is
met. The condition for terminating them is the same as the condition for terminating the DFY-AC plans.

The DFY-AC (60 second cycle) is able to evacuate a relatively high number of vehicles due to the fact that this plan is able to increase throughput by reducing demand and by breaking up platoons of cars. Moreover, DFY-AC (60 second cycle) provides much less average delay compared with other high throughput plans.

PME produces 989 evacuated vehicles which is the lowest number of evacuated vehicles. This is reasonable since this emergency signal timing plan represents the situation where the existing time-of-day signal timing plan is not changed in the event of an emergency evacuation. The number of evacuated vehicles for the major emergency signal timing plans is presented in Figure 6. The Comparison shows how the best three DFY plans perform against the PME, PPED and SFY plans. It is evident from the plot that SFY is the best in terms of number of evacuated vehicles and PME is the worst performing plan.

![Comparison of number of evacuated vehicles](image)

Figure 7. Comparison of number of evacuated vehicles
5.3 Average Delay

Average delay is also an important measure of the effectiveness of signal timing for emergency evacuation. The network average delay, the delay on the main street and the delay on the side streets will be discussed.

5.3.1 Average Network Delay

The average network delay gives a broad view of the delay experienced by each vehicle in the entire network. DFY-F (60 second cycle) gives the lowest average network delay of 219.15 seconds as can be seen in Table 2. This is due to the fact that vehicles on all approaches do not have to wait for a long time before they are given the green light or the flashing yellow. Since a majority of the network’s delay during an emergency evacuation is experienced by side street vehicles, reducing delay for side street vehicles is the key to reduce the network average delay. It can be realized from Table 2 that shorter cycle lengths in all the emergency signal timing plans resulted in lower average network delay.

SFY has average network delay of 421.75 seconds which is higher than the average network delay of all the DFY plans. A high proportion of this delay comes from the delay on side street traffic. This is because SFY keeps side street traffic flashing red for the entire duration of the emergency evacuation which makes side street traffic wait longer periods. This demonstrates that DFY plans are better than the SFY plan when considering average network delay as another main performance measure.

The PPED plan which is similar to the 240 second cycle plan used by Chen et al (2007) generates the highest network average delay. This is due to the fact that a majority of the cycle time is allocated to vehicles on the main street, whereas little green is given to vehicles on the
side streets. Vehicles on the side streets therefore have to wait for a long time before they are given the opportunity to move unrestricted.

It can be seen in Table 2 for all the DFY plans that the average network delay increases as the cycle length increases. This is due to the fact that longer cycle lengths imply longer flashing red time for side street vehicles. It can also be realized in terms of average network delay from Table 2 that the existing time of day PM peak plan performs better than the PPED plan. This means that in terms of average network delay, leaving the PM peak signal timing just as it is will give better results than applying the PPED plan. The average network delay for major emergency signal timing plans is shown in Figure 7 below.

![Figure 8. Comparison of average network delay](image)

The plot makes clear the relative magnitude of average network delay for the major emergency signal timing plans.
5.3.2 Average Delay on Main Street

The average delay experienced by vehicles on the main street is also used to compare the evacuation plans. SFY gives the lowest average delay (276.27 seconds) to vehicles on the main street. The average delay of this plan is approximately 50% less the amount of main street average delay for all the other signal timing plans. This is mainly due to the fact this plan gives highest priority to vehicles on the main street.

PPED plan has the highest average delay on the main street of 1185.70 seconds. This is mainly due to the effect of long cycle length that results in an increased delay at intersections.

Benefiting from signal actuations, the DFY-AC (120 second cycle) and the DFY-A (120 second cycle) have relatively low average delay on the main street of 397.47 seconds and 417.17 seconds, respectively. This may be due to their ability to reduce congestions by breaking platoons.

Benefiting from actuations and coordination, the DFY-AC plan outperforms all the other DFY plans and the PM-Peak plans. With regards to DFY-F plans, increasing the cycle length increases the average delay to vehicles on the main street. The average delay on the main street for some of the major emergency signal timing plans is shown in Figure 8 below.
Figure 9. Comparison of average delay on main street

5.2.3 Average Delay on Side Streets

One of the disadvantages of the SFY plan is the high average delay that it imposes on the side street traffic. This has been clearly demonstrated in Table 2 that SFY gives an average side streets delay of 329.24 seconds which is approximately more than three times the average side street delay in the other emergency evacuation plans. This high side street delay is due to the fact that side street traffic is given only the flashing red signal for the entire evacuation period. The PPED plan also gives a high average side street delay of 231.72 seconds which is due to similar reasons as the SFY plan. The PPED plan has longer cycle lengths with a majority of the green time allocated to vehicles on the main street. This implies that vehicles on the side street wait for long periods before they are given the green.

The PME plan gives the lowest side street delay of 25.63 seconds as it can be seen from Table 2. This is due to its low cycle length for the various signalized intersections. Shorter cycle lengths imply that side street traffic experiences the green light more frequently and this consequently reduces the average side street delay.
In general, it can be observed from Table 2 that the average side street delay increases as the cycle length increases. This is due to the fact that longer cycle lengths imply longer flashing yellow time on the main street. The average delay on the side streets for some of the major emergency signal timing plans is illustrated in Figure 9 below.

![Figure 9. Comparison of average delay on side streets](image_url)

### 5.3 Average Speed

The average network speed can also be used as a performance measure in selecting the best emergency signal timing plan. Networks with higher average speeds are normally assumed to perform better than networks with lower average speeds. The DFY-AC (60 second cycle) has the highest average speed of 13.24 mph as can be seen from Table 2. This is because of its ability to regulate the number of vehicles on the main street. This plan is able to increase speed by responsive traffic signal control and signal coordination.
The PPED plan yields the lowest average speed of 6.91 mph as can be seen from Table 2. This plan allocates a high proportion of the cycle time to the green signal on the main street which increases the number of vehicles on the main street, and ends up creating more congestions and reducing speed for side street traffic. It can also be seen from Table 2 that increasing cycle length causes a decrease in the average network speed for all the emergency signal timing plans. The network average speed for some of the selected emergency signal timing plans are depicted in Figure 10 below.

![Figure 11. Comparison of network average speed](image)

5.4 Signalized Intersections Delay

The average delay experienced by vehicles at each individual intersection is also measured to compare the emergency signal timing plans. This performance measure shows how each emergency signal timing plan performs at the intersection level. The average delay at the
intersections is compared using the level of service (LOS). HCM 2010 gives the corresponding LOS for average delay ranges as shown below in Table 3.

**Table 3. LOS at signalized intersections**

<table>
<thead>
<tr>
<th>LOS</th>
<th>Average Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>( \leq 10 )</td>
</tr>
<tr>
<td>B</td>
<td>&gt; 10-20</td>
</tr>
<tr>
<td>C</td>
<td>&gt;20-35</td>
</tr>
<tr>
<td>D</td>
<td>&gt;35-55</td>
</tr>
<tr>
<td>E</td>
<td>&gt;55-80</td>
</tr>
</tbody>
</table>

Tables 4 summarize the average delay at each intersection for the emergency evacuation signal timing plans respectively. It can be seen from Table 4 that the PPED plan and the SFY plan give higher delay at most of the intersections than the DFY plans. For instance, at the Ridge Rd intersection, which is the busiest intersection along the evacuation corridor, SFY gives an average delay of 227.88 seconds which is approximately more than 200% of the delay caused by the other emergency signal timing plans. This corresponds possibly to a Level of Service (LOS) F. This is due to the high delay that side street vehicles experience in the SFY plan. The PPED plan also gives an average intersection delay of 65.5 seconds which is much higher than the average intersection delay for all the DFY plans. The average intersection delay of the PPED corresponds to a LOS E.
In general, the average delay at each of the intersections increases when the cycle length increases in all the DFY plans. This means that the LOS gets worse as the cycle length increases. This is due to the fact that longer cycle lengths imply more flashing yellow time for the main street which causes the side street traffic to wait for longer periods. In general, the DFY plans present better LOS than the SFY and PPED plans.
Table 4. Average Intersection Delay (seconds)

<table>
<thead>
<tr>
<th>Intersection</th>
<th>Synchro Optimized Timing Plans</th>
<th>Static Flashing Yellow (Fixed)</th>
<th>Dynamic Flashing Yellow (Actuated)</th>
<th>Dynamic Flashing Yellow (Actuated &amp; Coordinated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PME</td>
<td>PPED</td>
<td>SFY 60s 90s 120s 180s 240s</td>
<td>60s 90s 120s 180s 240s</td>
<td>60s 90s 120s 180s 240s</td>
</tr>
<tr>
<td>Ridge</td>
<td>25.8</td>
<td>65.5</td>
<td>227.9</td>
<td>13.1 16.3 20.2 36.4 35.3</td>
</tr>
<tr>
<td>McKinley</td>
<td>13.9</td>
<td>25.3</td>
<td>92.9</td>
<td>8.1 10.9 14.3 19.4 26.9</td>
</tr>
<tr>
<td>Marilla</td>
<td>14.2</td>
<td>37.5</td>
<td>40.6</td>
<td>8.8 8.9 10.7 8.7 9.2</td>
</tr>
<tr>
<td>Choate</td>
<td>12.0</td>
<td>12.8</td>
<td>2.2</td>
<td>3.8 3.7 5.0 5.3 8.1</td>
</tr>
<tr>
<td>Tift</td>
<td>16.0</td>
<td>80.9</td>
<td>443.9</td>
<td>17.5 54.4 75.5 72.2 68.3</td>
</tr>
<tr>
<td>Southside Pkwy</td>
<td>57.6</td>
<td>73.3</td>
<td>68.0</td>
<td>35.3 18.1 20.6 31.7 35.4</td>
</tr>
<tr>
<td>Bailey</td>
<td>18.0</td>
<td>198.3</td>
<td>9.8</td>
<td>9.7 11.5 14.7 16.0 17.6</td>
</tr>
<tr>
<td>Hopkins</td>
<td>15.1</td>
<td>25.8</td>
<td>71.3</td>
<td>8.7 11.0 13.8 14.2 16.3</td>
</tr>
<tr>
<td>New Abby</td>
<td>31.7</td>
<td>112.2</td>
<td>93.4</td>
<td>21.4 26.0 30.3 21.8 39.5</td>
</tr>
<tr>
<td>Smith</td>
<td>11.5</td>
<td>48.0</td>
<td>242.5</td>
<td>17.8 17.3 37.9 81.4 62.5</td>
</tr>
<tr>
<td>Elk</td>
<td>10.3</td>
<td>30.9</td>
<td>9.4</td>
<td>12.1 14.3 15.2 10.9 12.4</td>
</tr>
<tr>
<td>Hamburg</td>
<td>11.5</td>
<td>149.6</td>
<td>131.9</td>
<td>15.3 38.0 39.8 57.8 57.8</td>
</tr>
<tr>
<td>Alabama</td>
<td>14.4</td>
<td>125.6</td>
<td>80.0</td>
<td>9.5 15.0 15.8 15.7 20.1</td>
</tr>
<tr>
<td>Louisiana</td>
<td>17.0</td>
<td>187.5</td>
<td>295.3</td>
<td>18.5 26.3 39.6 38.6 68.4</td>
</tr>
<tr>
<td>Michigan</td>
<td>16.9</td>
<td>39.3</td>
<td>86.1</td>
<td>26.6 28.9 32.7 41.5 43.3</td>
</tr>
</tbody>
</table>

45
Table 5. Average Intersection Queue Length (feet)

<table>
<thead>
<tr>
<th>Inter.</th>
<th>Synchro Optimized Timing Plans</th>
<th>Static Flashing Yellow</th>
<th>Dynamic Flashing Yellow (Fixed)</th>
<th>Dynamic Flashing Yellow (Actuated)</th>
<th>Dynamic Flashing Yellow (Actuated Coordinated)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PME</td>
<td>PPPED</td>
<td>SFY</td>
<td>60s</td>
<td>90s</td>
</tr>
<tr>
<td>Ridge</td>
<td>65.8</td>
<td>315.5</td>
<td>468.0</td>
<td>44.8</td>
<td>70.6</td>
</tr>
<tr>
<td>McKinley</td>
<td>88.3</td>
<td>79.1</td>
<td>158.2</td>
<td>12.7</td>
<td>30.8</td>
</tr>
<tr>
<td>Marilla</td>
<td>322.8</td>
<td>69.4</td>
<td>54.7</td>
<td>6.1</td>
<td>25.5</td>
</tr>
<tr>
<td>Choate</td>
<td>380.7</td>
<td>28.3</td>
<td>13.2</td>
<td>15.9</td>
<td>64.4</td>
</tr>
<tr>
<td>Tift</td>
<td>106.2</td>
<td>105.0</td>
<td>599.2</td>
<td>38.6</td>
<td>108.8</td>
</tr>
<tr>
<td>Southside Pkwy</td>
<td>579.3</td>
<td>421.2</td>
<td>296.6</td>
<td>354.8</td>
<td>371.3</td>
</tr>
<tr>
<td>Bailey</td>
<td>89.8</td>
<td>546.5</td>
<td>55.1</td>
<td>61.8</td>
<td>79.5</td>
</tr>
<tr>
<td>Hopkins</td>
<td>202.2</td>
<td>59.5</td>
<td>134.3</td>
<td>13.4</td>
<td>38.4</td>
</tr>
<tr>
<td>New Abby</td>
<td>156.0</td>
<td>472.1</td>
<td>212.4</td>
<td>270.9</td>
<td>383.8</td>
</tr>
<tr>
<td>Smith</td>
<td>120.4</td>
<td>221.5</td>
<td>161.9</td>
<td>150.6</td>
<td>181.6</td>
</tr>
<tr>
<td>Elk</td>
<td>169.0</td>
<td>366.8</td>
<td>78.4</td>
<td>198.4</td>
<td>234.1</td>
</tr>
<tr>
<td>Hamburg</td>
<td>116.4</td>
<td>479.8</td>
<td>388.5</td>
<td>87.1</td>
<td>232.6</td>
</tr>
<tr>
<td>Alabama</td>
<td>179.3</td>
<td>432.3</td>
<td>241.8</td>
<td>67.7</td>
<td>133.9</td>
</tr>
<tr>
<td>Louisiana</td>
<td>299.9</td>
<td>497.1</td>
<td>620.2</td>
<td>194.9</td>
<td>258.3</td>
</tr>
<tr>
<td>Michigan</td>
<td>334.1</td>
<td>450.6</td>
<td>467.0</td>
<td>435.2</td>
<td>520.1</td>
</tr>
</tbody>
</table>
5.5 Signalized Intersections Average Queue Length

Table 5 summarizes the average queue length for each intersection with different emergency signal timing plans. It can be seen from Table 5 that the PPED plan and the SFY plan give longer queue lengths at most of the intersections than the DFY plans. For instance, at the Ridge Rd intersection, it can be realized that SFY plan gives an average queue length of 468 feet which is higher than the average queue length of all the other emergency signal timing plans. The PPED plan also gives an average intersection queue length of 315.5 feet which is higher than the average intersection queue length for all the DFY plans. These higher average queue lengths under these two emergency signal timing plans is due to the long wait experienced by side street vehicles under these plans.

It also can be observed from Table 5 that the average queue length at each of the intersections increases when the cycle length increases in all the DFY plans. This is due to the fact that longer cycle lengths imply more flashing yellow time for the main street which causes the side street traffic to wait for longer periods and consequently more vehicles to join the queue.

5.6 Selection of Best Emergency Signal Plan

The goal of this thesis is to develop an emergency signal timing plan that can evacuate a high number of vehicles and also overcome the high delay experienced by side street traffic in the SFY and the PM-Peak plans. This goal should bear in mind when selecting the best emergency signal timing plan. It can be realized through the simulation results in Tables 2, 4, and 5 that the DFY-AC with cycle lengths 60 seconds and 120 seconds are the two potential best models. There are only minor differences observed between these models in terms of number of evacuated vehicles and average network delay.
DFY-AC (120 second cycle) generates 1811 evacuated vehicles and an average network delay of 275.99 seconds whereas DFY-AC (60 second cycle) produces 1755 evacuated vehicles and an average network delay of 249.81 seconds.

The DFY-AC (60 seconds cycle) is able to evacuate a high number of vehicles and give low average network delay because of its short cycle length. The short cycle length (60 seconds) prevents side street vehicles from waiting for too long. This keeps average delay to a low level. The relative high number of evacuated vehicles is generated because of its ability in signal actuations and coordination. The shorter cycle can potentially reduce the average discharging headways and increase the saturation flow rate due to shorter queue length. However, when considering both throughput and average delay, we need to compromise between these objectives and search for the best (non-dominated) solutions, which are located on Pareto frontier.

In order to assist in decision making on plan selection, Figure 11 is created to compare all the signal timing plans, with regard to both average network delay (PM1) and the inverse of the number of evacuated vehicles (PM2).
Figure 12. Average network delay (PM1) against the Inverse of Evacuated Vehicles (PM2).
Note: Inverse of the evacuated is scaled by multiplying by 10,000. Average network delay is scaled by dividing by 100.

To make it consistent with PM1, we take the inverse transformation of the number of evacuated vehicles to change the objective from maximization to minimization. The dominant and non-dominant points are displayed in Figure 11 as blue dots and red diamonds, respectively. The non-dominant points represent feasible choices, and smaller values are preferred to larger ones. Any blue dot in the plot is not a good choice because it is dominated by both other non-dominated points along the Pareto frontier. In the context of this thesis, for any dominated plan, a non-dominated plan can always be found with larger throughput or less delay. Points A and B are not strictly dominated by any other, and hence do lie on the frontier. As it can be seen on Figure 11,
emergency evacuation signal timing plans that are located on Pareto frontier include SFY, DFY-AC (120 second cycle), DFY-A (60 second cycle), and DFY-F (60 second cycle). It can be inferred from Figure 11 that SFY has a high average network delay (PM1) but the highest throughput (lowest PM2). Below the SFY point is the DFY-AC (120 second cycle) which has a much lower average network delay and a good number of evacuated vehicles. It is then followed by the DFY-AC- (60 second cycle) which also gives the good compromise between number of evacuated vehicles and network average delay. At lower end of the boundary is the DFY-F (60 second cycle) which produces the lowest average network delay and a relatively good number of evacuated vehicles. Therefore, the traffic operators are allowed to choose the appropriate signal timing plan for emergency evacuation with different preferences.
CHAPTER 6: CONCLUSIONS

The objective of this thesis is to show the effectiveness of the Dynamic Flashing Yellow (DFY) for emergency evacuations. The Dynamic Flashing Yellow (DFY), a variant of the static flashing yellow (SFY), is proposed to address the issue of unacceptable excessive delay to side street vehicles associated with the SFY plan. This chapter will briefly summarize the findings, provide recommendations, and suggest directions for future research. However, it must be noted that simulations are not perfect and therefore further analysis needs to be carried out before they are implemented on a real-world emergency evacuation.

6.1 Summary of Findings

It is found in the previous chapters that the Dynamic Flashing Yellow with Actuations and Coordination (DFY-AC) with 60 second cycle plan is the best emergency signal timing plan since it gives relatively high number of evacuated vehicles (1755) with a lower average network delay (249.8 seconds). The average network delay of the DFY-AC with 60 second plan is 40.7% lower than the average network delay of the static flashing yellow (SFY). However, the number of vehicles evacuated by the SFY is only 8.68% higher than the number of vehicles evacuated by the DFY-AC with 60 seconds cycle plan. There is more equity with this emergency signal timing plan than the others. This plan is able to keep average network delay below 250 seconds (approximately 4.17 minutes) which is very significant in making all the travelers to obey the traffic rules during an emergency evacuation event.

The DFY-AC with 120 second cycle also performed very well in terms of the number of evacuated vehicles (1811) and the average network delay (275.99 seconds). Even though SFY
gives a 5.78% higher number of evacuated vehicles than DFY-AC with 120 seconds cycle, its average network delay was 34.56% higher than the DFY-AC with 120 seconds cycle.

Even though the DFY-AC with 120 second cycle gives a 3.1% higher number of evacuated than the DFY-AC with 60 seconds cycle, its average network delay is 10% higher than the average network delay of the DFY-AC with 60 seconds cycle plan.

It is realized that the Dynamic Flashing Yellow with Actuation and Coordination (DFY-AC) plans performed better than the Dynamic Flashing Yellow- Actuated (DFY-A) and the Dynamic Flashing Yellow- Fixed (DFY-F) plans in terms of average network delay and number of evacuated vehicles. Furthermore, the Dynamic Flashing Yellow (DFY) plans perform better than the static flashing yellow and PM-Peak plans in terms of network average delay.

The Static Flashing Yellow (SFY) plan gives the highest number of evacuated vehicles (1922) but it has the disadvantage of having high average delays on the side streets (329.24 seconds). If drivers on the side streets wait for too long, they might get frustrated and decide to move when they are not supposed to. This may result in accidents and more congestion.

The PM-peak Optimized for Evacuation Demand (PPED) plan gave a relatively high number of evacuated vehicles (1278) but it has the highest average network delay (463.9 seconds) and a high side street delay (329.24 seconds). This plan uses a 240 seconds cycle length with a majority of the green given to the main street.
The PM-Peak plan which represents the situation where the existing time-of-day PM signal plan is not changed in the event of an emergency evacuation gives the lowest number of evacuated vehicles (989). The number of vehicles evacuated by this plan is approximately 50% less the number of vehicles evacuated by all the other emergency evacuation plans.

Furthermore, it is observed that longer cycle length does not guarantee higher number of evacuated vehicles and lower side street delays especially for the dynamic flashing yellow plans. This is evident in the result for emergency evacuation plans where 240 seconds cycle lengths had lower number of evacuated vehicles than the 60 seconds cycle lengths.

6.2 Recommendations

This thesis makes recommendations on the best emergency evacuation signal timing plan based on multiple objectives. Evacuating a high number of vehicles is the main purpose of emergency evacuations and is therefore the first and most important objective. This objective of increasing the number of evacuated vehicles can be best served by the static flashing yellow plan. However, the only drawback of this plan is the high delay it imposes on side street traffic. This is the reason why other objectives like minimizing side street delay must be considered.

The results and discussions have demonstrated that the Dynamic Flashing Yellow-Fixed (60 second cycle) gives the lowest average network delay but its number of evacuated vehicles is not very high. This plan can be implemented when reducing delay on the side streets takes a high priority.
Furthermore, it has been demonstrated that the Dynamic Flashing Yellow with Actuations and Coordination (60 second cycle and 120 second cycle) give the best compromise between average network delay and number of evacuated vehicles. This thesis recommends these plans for emergency evacuations in a corridor evacuation setting.

6.3 Future Research

Future research will examine how emergency evacuations can be improved through the use of an Adaptive Dynamic Flashing Yellow signal timing plan. This plan is expected to adjust the cycle length, and splits for flashing yellow/flashing red and green/red phases to accommodate dynamic traffic patterns. The weighting factor for side street traffic ($\delta$) in Equation (3) can also be adjusted to change the level of service in side street traffic as well as its capacity for emergency evacuations. This provides flexibility to address different preferences between the number of evacuated vehicles and average network delay.

Additionally, the dynamic flashing yellow plan can be tested in the presence of Connected Vehicle technology (USDOT 2014), commonly referred to as Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), or more generally V2X communications. Wen et al. (2012) conducted a study on the coordination of IVI (IntelliDrive) and transit signal priority on transit evacuations. They found out that the implementation of TSP and IntelliDrive can substantially reduce the bus travel time of 12.8% without seriously interrupting conflicting vehicles. It is expected that implementing the dynamic flashing yellow plan in the presence of connected vehicle technology can increase throughput, reduce delay and improve safety.
This thesis assumes that the event that causes the need for the emergency evacuation is in downtown Buffalo. As a result, they are evacuated along the South Park Avenue corridor with no evacuation on the side streets. Future research can look at realistic demand for evacuations that considers evacuation of side street traffic.

Moreover, peoples’ driving behavior when they encounter a flashing yellow or flashing red signal has not been fully studied. Lenne et al (2011) studied driver behavior at two railway level crossings with active controls, flashing red lights and traffic signals through a driving simulator experiment. They found that the mean vehicle speed on approach to the level crossings decreased more rapidly in response to flashing lights than to traffic signals. Future research can leverage a driving simulator to study peoples’ driving behavior in the presence of dynamic flashing yellow. However, one drawback of the driving simulator study is that participants may not feel the real life panic that is associated with emergency evacuations. Therefore, it is essential to perform the field implementation of dynamic flashing yellow.
BIBLIOGRAPHY


Sisiopiku, V.P., 2007 "Application of traffic simulation modeling for improved emergency preparedness planning." Journal of urban planning and development 133.1 : 51-60.


