Using Dynamic Flashing Yellow for Traffic Signal Control under Emergency Evacuation

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Abstract

Effective signal timing plan for emergency evacuation is very crucial for public safety. Two conflicting objectives of emergency evacuation in a corridor are to increase throughput on the main street (evacuation route) and decrease delay on side streets. Some studies have proven the effectiveness of the static flashing yellow (SFY) signal timing plan in evacuating high number of vehicles [1]. However, SFY plan also yields extremely high delay on side streets. This paper investigates a variant of the SFY plan called dynamic flashing yellow (DFY) signal timing plan under a few reasonable assumptions. DFY plan basically consists of two signal phases. Phase 1 is flashing yellow on the main street and flashing red on the side street, whereas phase 2 is red signal on the main street and green signal on the side street. Three different types of the DFY plan are proposed, including Fixed DFY (DFY-F), Actuated DFY (DFY-A) and Actuated and Coordinated DFY (DFY-AC). This paper demonstrates that DFY provides a high volume of evacuated vehicles with relatively low delay to side street traffic. Moreover, the proposed DFY is adjustable to favor different weights between network throughput and average delay. To compare DFY with SFY and PM peak plan, VISSIM is implemented to model a 4.1 mile corridor in Buffalo, NY. The DFY plan is further analyzed under different methods and minimal cycle lengths. According to Pareto frontier, it is realized that DFY-AC with minimal cycle length of 60 seconds and 120 seconds produces more desirable results (Pareto non-dominated solutions) than others.
1. Introduction

Evacuation is defined as the immediate, urgent and collective movement of people and their mode of transport used from a hazard or potential hazard [2]. Emergency evacuations lead to a sharp increase in traffic demand within a short time on the main streets. There are likely to be massive congestions, driver frustration and possible accidents on the main streets due to the high influx of vehicles on them. Fully utilizing existing road capacity for traffic can improve the efficiency of the emergency evacuation process. One way of increasing the capacity of the main street is changing the signal timing by giving majority of the green time to the main street [3]. Due to the no-notice nature of some 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 cause of most traffic delays in regional evacuations [4]. 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.

Flashing yellow (FY), which flashes yellow on the main evacuation approach, and flashes red on the side street, is a very effective way to evacuate vehicles out of the area where emergency events occur [1]. FY usually allows larger intersection throughputs than traditional green and red signals. In this approach, priority is given to traffic on the evacuation arterial to achieve a continuous flow, allowing the majority of roadway capacity to be assigned to the main street. A drawback of this approach, indicated as static flashing yellow (SFY) in the rest of the paper, is that extremely long delays may result for vehicles on the side streets. If delays are too long, drivers may not be willing to obey the traffic rules. Therefore, SFY is not the ideal signal timing plan for practical evacuation. This paper 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 and SFY signal plan. They are implemented with micro-simulation on South Park Avenue, Buffalo, NY. 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.

The objective of this paper is to demonstrate the effectiveness and flexibility of the DFY signal timing plan for emergency evacuations. 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 network throughput and delay.

2. Literature Review
Nationwide interviews with experts and agents in Federal, State and Local Agencies in the United States were conducted about their approach to signal timing for emergency situations [5-7]. 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 events was also investigated [8]. They found that manual traffic control can significantly improve the control performance of intersections. A bi-level model was developed to evaluate crossing elimination as an evacuation traffic management strategy for no-notice events [9, 10]. They found that elimination and reduction of conflicting maneuvers at intersections could significantly reduce travel delay and evacuation clearance times during emergencies. Mathematical formulations with mixed-integer linear programming have also been implemented to derive optimal routing plans [11, 12].

There are a number of studies on choosing signal times for effective emergency evacuation with microscopic simulation tools. CORSIM was used to test different signal timing plans and offsets [1, 13]. 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.

A corridor-based emergency evacuation system was proposed for Washington D.C. metropolitan area [14]. Signal timings were optimized during the evacuation process by using signal optimization software (SYNCHRO and TRANSYT-7F) and CORSIM to evaluate the resulting performance and impact. They suggested that optimization of signal timing considerably reduced delays. A cycle length of 120 seconds was found to be the best, and a conclusion was made that when travel demand is heavy, higher cycle length is more suitable and vice versa [3].

However, there exist some limitations for previous studies: (1) 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; (2) the popular signal optimization tools, such as SYNCHRO and TRANSYT-7F, are not designed for evacuation traffic.

3. Modeling Dynamic Flashing Yellow
This paper makes the following assumptions with regards to traffic demand, turning movements, and driver behavior:

- **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.

Assumption 1 is valid since this plan is implemented with only one corridor. Assumption 2 is needed to reduce lost time through a reduction in signal phases. Assumption 3 is essential since lack of knowledge of the operation of flashing red and flashing yellow can be inimical to the success of the DFY signal plan. It is necessary that motorists are educated about this operation.

### 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 Phase 1 (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 Phase 2 (green/red, short as G/R), the main street signal will stay in red and the side street signal will 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. FY/FR was not used in Phase 2 because drivers on main streets might be panic during evacuation, and they might not be used to stopping and waiting for gaps in side street traffic. Therefore, the use of the G/R in Phase 2 instead of FY/FR 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 section. 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 period for DFY plans, 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.
3.2 Potential Capacity of Through Traffic at Side Streets for Flashing Red

Since a junction with flashing yellow can be treated as a two-way stop controlled intersection (TWSC), the Highway Capacity Manual (HCM) 2010 gives an exponential function which is used to compute the potential capacity of each turn at a TWSC [15]. The exponential function is given as:

\[ Q_p = V_c \frac{e^{-v_c t_c / 3600}}{1 - e^{-v_c t_f / 3600}} \]  

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).

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 this exponential function shows 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 [16]. 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. A model is proposed to decide the green split for side streets under DFY. The green split can be determined through the following equations.

\[ \delta \lambda_s C \leq Q_p \cdot (C - G_s) + G_s \cdot Q_s \]
\[ 0 \leq \delta \leq 1 \]  

where the notations are explained 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 saturation flow rate of side street (veh/sec).

\( \delta \lambda_s C \) represents the total number of vehicles on the side street that can be served in a cycle. The weighting factor \( \delta \) is used to determine the proportion of side street traffic that can 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 (deterministic) 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. It’s worth mentioning that \( \delta \) can be set larger than 1 in order to accommodate the stochastic nature of arrivals. In this paper, \( \delta \) is set to 1 for fixed DFY. The first term on the right side of Equation (2), \( Q_p \cdot (C - G_s) \), estimates the number of side street vehicles that can be served during FY/FR phase. The second term, \( G_s \cdot Q_s \), calculates the number of side street vehicles that can be served when the side street is given the green signal. Therefore, the side street green split can be derived in Equation (3) below:

\[ G_s \geq \frac{\delta \lambda_s C - Q_p \cdot C}{Q_s - Q_p} \]  

The following conditions are 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 \( 0 \leq G_s \leq G_L \) (lower bound of green), \( G_L \) should be used.
iii. If \( G_s > G_L \) (lower bound of green), \( G_s \) should be used as obtained.
iv. If \( G_s > G_U \) (upper bound of green), \( G_U \) should be applied.

In this paper \( G_L \) and \( G_U \) are set to 10 seconds and 60 seconds, respectively.
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 [17]. 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 the main approach. Unlike DFY-F which uses pre-defined splits constant throughout the simulation, DFY-A operates 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 leverage the side street detector’s occupancy time to recognize signal actuations, and decide whether to stop flashing yellow on the main street. 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 the predefined occupancy time. It will be reset to zero if there is no longer any vehicle detected. The following parameters are defined for side street traffic in DFY-A:

- Occupancy time (detection delay time) of 10 seconds.
- Minimum green of 10 seconds [18].
- Maximum green determined by Equation (2), with $\delta=1.2$.
- Vehicle extension of 3 seconds.

With main street traffic, the following parameters are defined:

- Minimum flashing yellow time is the difference between designated “cycle time” (which is not actual cycle time) and maximum side street green time.

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 [19]. It is mostly needed when traffic signals are within 0.75 mile of each other and traffic volume between adjacent intersections is large [19]. 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 should take into account coordination to measure improvements in the number of evacuated vehicles and the reduction in the average delay. The parameters of traffic signal coordination are defined 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) to rest on the 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 are determined based on Equations (1), (2) and (3). Equation (3) gives the side street green time that is used to determine FY/FR splits.

- Offsets: In emergency evacuation, we assume the traffic is oversaturated on the 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 paper, we set the discharging shockwave speed as 12 mph.

\[
O = \frac{L}{w} \tag{4}
\]

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: Floating force-offs are used in DFY-AC to favor evacuation route traffic on the main street [20]. The force-off maintains the non-coordinated maximum split for each non-coordinated phase (G/R phase in DFY) in isolation of one another. This allocate extra flashing yellow time for main street because it returns 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.

![Figure 2. Time-Space Diagram of Signalized Intersections](image-url)
4. Network Modeling and Simulation

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 freeways 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 is blocked during evacuation for reasons such as flood, inclement weather, construction, accidents, and others.

![Figure 3. Layout of South Park Avenue, Buffalo, NY](image)

South Park Avenue contains 15 signalized intersections and 48 unsignalized intersections, shown as Figure 3. The signalized intersections have been shown by their names in Figure 3. It is a two lane road with side street parking in some sections. 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 3.

### 4.2 Simulated Emergency Signal Timing Scenarios

This section gives a brief description of the signal timing plans that are compared with the DFY plans through the VISSIM simulations. The VISSIM simulations are run through Java and COM (Component Object Model) technology [21]. We assume that evacuation traffic demand, 1940 veh/hr, from Route 5, is imputed into South Park Avenue in addition to 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. Five simulation runs are conducted with different random seeds. These emergency signal timing plans are listed as follows:

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 evacuation happens and no changes are made in the signal timing plan.

2. **PM-peak Optimized for Evacuation Demand (PPED):** This plan also adapts the signal timing splits obtained through the SYNCHRO optimization. However, PPED 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.

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.

### 4.3 Performance Measures

Two major performance measures are used to compare the proposed signal timing plans. These are the total number of vehicles evacuated within an hour and the average network delay. 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. Other performance measures used are average delay on the main street, average delay on the side streets, and network throughput.
5. Simulation Results and Analysis

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. As one can see from Table 1, DFY –A (60 seconds cycle) gives the highest network throughput within one hour (7832) whilst SFY gives the lowest network throughput within one hour (6461) as can be seen in Table 1. The side street traffic demand dominates in the total network traffic demand in the absence of evacuation. DFY-A (60 seconds cycle) with its relatively short cycle length allows more vehicles on the side streets to leave the network 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. The network throughput for the major emergency signal timing plans is presented in Figure 4(a).

5.2 Number of Evacuated Vehicles

Table 1 shows that SFY yields the highest number of evacuated vehicles (1922) within one hour. It 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 seconds cycle) is the second best plan in this performance measure with 1811 evacuated vehicles within one hour. 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 number of vehicles evacuated by this plan is the peak number of evacuated vehicles for the DFY plans. In addition, it is observed that longer cycle lengths do not always guarantee higher number of evacuated vehicles. This is because 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 [22].
Figure 4 (a) Comparison of network throughput (b) Comparison of number of evacuated vehicles (c) Comparison of average network delay (seconds) (d) Comparison of average delay (seconds) on main street (e) Comparison of average delay (seconds) on side streets.
Table 1 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 the main st. (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>542.81</td>
</tr>
<tr>
<td>Dynamic Flashing Yellow</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>
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<tr>
<td>(Fixed)</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>
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<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>
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<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>
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<td>Dynamic Flashing Yellow</td>
<td>60s Cycle*</td>
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<td>1653</td>
<td>245.9</td>
<td>12.79</td>
<td>682.93</td>
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<tr>
<td>(Actuated)</td>
<td>90s Cycle</td>
<td>7813</td>
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<td>11.88</td>
<td>685.73</td>
<td>63.60</td>
</tr>
<tr>
<td></td>
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<td>10.15</td>
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<td>(Actuated &amp; Coordinated)</td>
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<td>11.38</td>
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<td></td>
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<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)
## Table 2. Average Intersection Delay (seconds)

<table>
<thead>
<tr>
<th>Intersection</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 &amp; Coordinated)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PME</td>
<td>PPED</td>
<td>SFY</td>
<td>60s</td>
<td>90s</td>
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<tr>
<td>Ridge</td>
<td>25.8</td>
<td>65.5</td>
<td>227.9</td>
<td>13.1</td>
<td>16.3</td>
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<tr>
<td>McKinley</td>
<td>13.9</td>
<td>25.3</td>
<td>92.9</td>
<td>8.1</td>
<td>10.9</td>
</tr>
<tr>
<td>Marilla</td>
<td>14.2</td>
<td>37.5</td>
<td>40.6</td>
<td>8.8</td>
<td>8.9</td>
</tr>
<tr>
<td>Choate</td>
<td>12.0</td>
<td>12.8</td>
<td>2.2</td>
<td>3.8</td>
<td>3.7</td>
</tr>
<tr>
<td>Tiff</td>
<td>16.0</td>
<td>80.9</td>
<td>443.9</td>
<td>17.5</td>
<td>54.4</td>
</tr>
<tr>
<td>Southside Pkwy</td>
<td>57.6</td>
<td>73.3</td>
<td>68.0</td>
<td>35.3</td>
<td>18.1</td>
</tr>
<tr>
<td>Bailey</td>
<td>18.0</td>
<td>198.3</td>
<td>9.8</td>
<td>9.7</td>
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</table>
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1. PME gives the lowest number of evacuated vehicles (989). This is reasonable since this 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 4(b).

5.3 Average Delay

5.3.1 Average Network Delay

DFY-F (60 seconds cycle) gives the lowest average network delay of 219.15 seconds as can be seen in Table 1. This is due to the fact that vehicles on all approaches do not 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 average network delay. It can be realized from Table 1 that shorter cycle lengths in all the emergency signal timing plans result in lower average network delay.

The PPED plan which is similar to the 240 seconds cycle plan used by [1] generates the highest average network 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 wait for a long time before they are given the opportunity to move unrestricted. SFY also has average network delay of 421.75 seconds which is higher than the average network delay of all the DFY plans. This is due to similar reasons as the PPED plans average network delay.

Comparing Figure 4(b) and 4(c), it can be seen that all the DFY plans achieve much less average delay than SFY (as much as 40%), with similar number of evacuated vehicles. Therefore, DFY plans provide more equity for side street traffic and solve the excessively long delay during emergency evacuation.

5.3.2 Average Delay on the Main Street

SFY gives the lowest average delay (276.27 seconds) to vehicles on the main street as can be seen from Table 1, which seems very reasonable. PPED plan produces 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 seconds cycle) and the DFY-A (120 seconds cycle) have relatively low average delay on the main street of 397.47 seconds and 417.17 seconds, respectively, shown as Figure 4(d). Benefiting from actuations and coordination, the DFY-AC plan outperforms all the other DFY plans and the PM-Peak plans.
5.3.3 Average Delay on Side Streets

It can be seen from Table 1 that SFY yields an average side streets delay of 542.81 seconds which is approximately more than five times the average side street delay in the other emergency evacuation plans. On the contrary, the PME plan gives the lowest side street delay of 25.63 seconds 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. DFY-AC (60 seconds) and DFY-F (60 seconds) also have relatively low average delay of 65.31s and 30.42s respectively with the similar reason, shown as Figure 4(e).

5.3.4 Average Intersection Delay

Tables 2 summarizes the average delay at each intersection for the emergency evacuation signal timing plans respectively. It can be seen from Table 2 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 produces an average delay of 227.9 seconds which is approximately 5~10 times more than the delay caused by the DFY plans.

5.4 Selection of Best Emergency Signal Plan

The objectives of this paper should be considered when selecting the best emergency signal timing plan. When considering both the number of evacuated vehicles (in a limited time period) and average delay, we need to compromise between these objectives and search for the best (non-dominated) solutions, which are located on Pareto frontier [23].

In order to assist in decision making on plan selection, Figure 5 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 5 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 5 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 paper, 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 5, four signal timing plans that are located on Pareto frontier include SFY, DFY-AC (120 seconds cycle), DFY-A (60 seconds cycle), and DFY-F (60 seconds cycle). It can be inferred from Figure 5 that SFY has a high average network delay (PM1) but the highest throughput (lowest PM2). Below the SFY point is the DFY-AC (120 seconds 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 seconds cycle) which also gives a good compromise between the number of evacuated vehicles and average network delay. At lower end of the boundary is the DFY-F (60 seconds 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.
6. CONCLUSIONS

6.1 Summary of Findings

This paper develops a flashing yellow based signal timing plan, called Dynamic Flashing Yellow and applies it for corridor emergency evacuation. It is found that the Dynamic Flashing Yellow with Actuations and Coordination (DFY-AC) with 60 or 120 seconds cycle plan shows the best performance results since it gives relatively high number of evacuated vehicles with a relatively lower average network delay. The SFY plan produces the highest number of evacuated vehicles, but it has the disadvantage of having high average delays on the side streets. DFY-AC with 60 seconds cycle (120 seconds cycle) reduces the average network delay of SFY by 40.7% (34.6%), whilst the number of vehicles evacuated by the SFY is only 8.68% (5.8%) higher than the number of vehicles evacuated by the DFY-AC plan. Therefore, there is more equity to implement the DFY-AC emergency signal timing plan than the others. Moreover, 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. Moreover, Dynamic Flashing Yellow- Fixed (DFY-F) with 60 seconds cycle gives the lowest average network delay whilst Dynamic Flashing Yellow- Actuated (DFY –A) with 60 seconds cycle generates the highest network throughput. However, DFY-AC with 60 or 120 seconds cycle provides a good balance between network throughput and average delay.

Among all three types of DFY plans, it is realized that the DFY-AC plans mostly outperform the (DFY-A) and the (DFY-F) plans in terms of average network delay and number of evacuated vehicles.

Furthermore, it is observed that longer cycle length of DFY plans does not always guarantee higher number of evacuated vehicles and lower side street delays. This is evident in the results for emergency evacuation plans in which 240 seconds cycle lengths yield lower number of evacuated vehicles than the 120 seconds cycle lengths.

6.2 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.

Additionally, the dynamic flashing yellow plan can be tested in the presence of Connected Vehicle technology [24], commonly referred to as Vehicle-to-Vehicle (V2V), Vehicle-to-
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Infrastructure (V2I), or more generally V2X communications. Moreover, multi-modal traffic evacuation can also be taken into account for signal optimization [25, 26].

Moreover, peoples’ driving behavior when they encounter a flashing yellow or flashing red signal has not been fully investigated. 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 pilot test of dynamic flashing yellow signal timing plans in the near future.

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