TRAFFIC ADAPTIVE OFFSET-BASED PREEMPTION
FOR EMERGENCY VEHICLES

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Abstract

This research analyzed and evaluated a new strategy for preemption of emergency vehicles along a corridor, which is route-based and adaptive to real-time traffic conditions. The method uses dynamic offsets which are adjusted using congestion-levels to provide uninterrupted preempted green signal for the emergency vehicle throughout its route. By achieving a higher average emergency vehicle speed, this method promises faster emergency response which results in saving life and property as well as larger emergency service radius for the dispatch stations. The research evaluated the effectiveness of two possible algorithms for offset adjustment using measured vehicle queues. It is showed to reduce the emergency vehicle travel-time by 31 percent when compared to cases without preemption and 13 percent when compared to traditional method of individual-intersection preemption.

Dedication

To my parents.

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1. Introduction

Emergency Vehicle Preemption (EVP) is a form of preferential treatment given to emergency vehicles at intersections to reduce their travel-time by reserving the right of way for their movement [1]. Traditionally, preemption worked on the principle that the emergency vehicle is detected by a controller and is then given a green signal which is held until it exits the intersection. Most preemption systems in the United States operate on an intersection-by-intersection basis [2]. An emergency vehicle is detected by sensors at each controller and each individual controller switches to a predefined preemptive phase. This result in preemption of each intersection only after the emergency vehicle reaches it. This also potentially results in the emergency vehicle to stopping at each intersection as it waits for vehicles to clear. This can also result in confusion for drivers of other vehicles about whether to pull over or proceed in the presence of an emergency vehicle at a preempted green. Local detection of an emergency vehicle is further complicated by peak hour traffic or after-event traffic when the corridor is congested. In such conditions, preemption can create increased delays at local intersections due to lack of clearance at downstream intersections [2].

Limited research has been done in developing route clearance strategies for emergency vehicle preemption in congested corridors, where congestion levels are used to modify signal patterns to clear downstream intersections along the path of the emergency vehicle to improve emergency service in this situation.

1.1. Background

Emergency vehicles, such as, fire trucks, ambulances and police vehicles, should be able to respond to emergency calls for an incident with a minimum delay. The level of emergency service is determined by how rapidly the responder arrives at the incident location. Although signalized vehicle preemption is a relatively recent development resulting from advancements in Intelligent Transportation Systems (ITS), the concept of prioritizing emergency vehicle movement is not. The American Engineering Council indicated in its 1929 publication Street Traffic Signs, Signals and Markings that “In any coordinated system, supplemental arrangements may be provided for breaking the system into smaller units for emergency operation, such as the runs of fire apparatus" [3]. Emergency vehicles were and are still prioritized on streets using sirens and strobe lights. But intersections remained to hinder it from moving uninterruptedly. In the 1960s, hardware technology to detect vehicles using vehicle-based emitters and signal-based detectors emerged.

Advancements in ITS have changed the technology used in emergency vehicle preemption. Automatic Vehicle Location (AVL) systems using Global Positioning Systems (GPS) and Vehicle to Roadside Communication (VRC) systems using encrypted infrared and radio waves are hardware advancements in the preemption industry. However, little change has been made to preemption logic. Currently, the majority of systems in the United States are structured as detection, preemption and transition systems, which involve detection of emergency vehicles which invoke preemption of an intersection and controller switches to a predefined preemptive phase. In 2007, the Research and Innovative Technology Administration (RITA) surveyed major metropolitan areas about ITS deployment including emergency vehicle preemption systems. These surveys indicated the use of some type of EVP system in almost 93 metropolitan areas. Over 33,000 intersections, or 24% of the total number of signalized intersections, are found to have some sort of EVP mechanism in place. Survey results also show that nearly 4,800 emergency vehicles are equipped with Vehicle-to-Roadside Communication (VRC) devices and 4,650 emergency vehicles use Automatic Vehicle Location (AVL) Systems [4].

The major preemption technologies currently used are light and infrared based systems, sound-based systems and radio-based systems [5]. Each of these systems has its own advantages and disadvantages as shown in Table 1.

Table 1 - Comparison of preemption technologies currently in use

Comparison / Technology	Dedicated vehicle emitter required	Susceptible to electronic noise interference	Clear line of sight required	Affected by weather	Preemption possible on other approaches
Light/Infrared Systems	Yes	No	Yes	Yes	No
Sound-based Systems	No	No	No	No	Yes
Radio-based Systems	Yes	Yes	No	No	Yes

The goal of preemption at both coordinated and non-coordinated signalized intersections is to reduce travel time of emergency vehicles [5]. However, current vehicle preemption techniques do not perform well along congested corridors where spillbacks and gridlock can occur [2]. In such conditions, even when the emergency vehicle preempts a signal controller, the queued vehicles from the next intersection delays movement because the emergency vehicle cannot preempt that controller until it is within range of the VRC. In such situations, the preemption needs advanced clearing of downstream approaches so that the emergency vehicle can move with minimal delay or stops. Without such a preemption technique, the traditional intersection-by-intersection preemption results in longer travel times for both the emergency vehicle and other traffic, degrading the corridor and intersection levels of service.

Research has shown that methods of preemption which are route-wide can reduce emergency response times [2]. Technology for communicating between the controller and emergency vehicles are now available and can aid implementation of systems which involve real-time congestion monitoring. Also, more corridors are being monitored for traffic conditions using vehicle detection and traffic flow measurement systems. These improvements, along with increasing congestion, have provided the tools and motivation for the development of a traffic adaptive offset-based preemption method for emergency vehicles.

1.2. Research Objective

The goal of this research was to develop and evaluate a preemption method for emergency vehicles which utilizes the available technology in corridor monitoring and real-time computations to adjust controllers along a corridor to minimize the travel-time of emergency vehicles and thereby improve emergency level of service. Objectives of this research were to:

1. Develop a preemption method which utilizes information from real-time traffic monitoring to provide a faster emergency response without compromising safety.
2. Evaluate the method using a case study for its effectiveness in providing faster emergency response and minimizing its impact on overall traffic

1.3. Research Tasks

The following tasks were involved in the development of the offset-based preemption method for emergency vehicles.

1. A comprehensive review of the available literature was performed covering the research done in the field of emergency vehicle preemption.
2. The guidelines for EVP in the Manual on Uniform Traffic Control Devices (MUTCD) [6] were reviewed so that safe transition to preemption can be considered in this research.
3. Traffic flow characteristics pertaining to movement of vehicles at a signalized intersection and queue accumulation were studied.
4. Equations were developed for the dynamic offset-based preemption using real-time traffic variables..
5. A simulation model was built for a case study using available data to execute the proposed method.
6. Two possible algorithms for the new method were developed, coded and simulated, and comparisons were made between the using delay, stops, stop-time and travel-time as performance measures.

1.4. Thesis Outline

This thesis is organized using the accepted manuscript format. Chapter 1 provides an introduction to the research followed by the motivations, research objectives and tasks. Chapter 2 presents a comprehensive review of available literature which provided the basis for this research. Chapter 3 is the manuscript providing details on background and model formulation for the suggested preemption method. It also includes a preliminary evaluation using a small micro-simulation case-study. Chapter 4 presents the manuscript on the evaluation of the suggested preemption method using a micro-simulation case-study of Arlington, Virginia. Finally, Chapter 5 presents a descriptive analysis of the evaluation results along with conclusions and recommendations made in this research.

Supplemental information is provided in the appendices. Appendix A gives the script used in running the micro-simulation model for the two algorithms tested. It also gives a briefing of most macros. Appendix B gives a discussion on the comparative study of traffic simulation software VISSIM, CORSIM, AIMSUN and TransModeler™. Appendix C shows a sample Universal Traffic Data Format (UTDF) metadata file received from Arlington County Division of Transportation which helped in programming controllers of the simulation model. Finally appendix D provides the categorized results obtained from microscopic simulation.

2. Literature Review

Emergency Vehicle Preemption has been an important consideration because of its potential to save lives. However, emergency vehicle preemption adversely affects overall traffic flow [7]. Giving priority to emergency responders has been a tradition even before current ITS preemption technologies came in to existence. Vehicles moved out of the way to provide space to the emergency vehicle. Safety concerns and increasing traffic volumes, combined with improved technologies, encouraged the implementation of ITS strategies to provide a special green interval to the emergency vehicle while ensuring red intervals to conflicting approaches [5].

A review of the state of the practice on vehicle preemption is provided. Its usefulness, benefits and consequences are highlighted followed by a discussion of the different techniques currently in use. Finally, a summary of research into advanced applications is provided.

2.1. Current State of Practice

The history of preemption started in 1929 when the American Engineering Council publication described the need for supplemental arrangements for emergency vehicle operation in a coordinated system [3]. Technology for incorporating preemption in signal systems started developing in the 1960s [5]. This resulted in the first of its kind preemption system devised by 3M in the early 1970s [8]. These early systems had a detector attached to the signal heads to detect pulses of strobe lights from emergency vehicles to transition the signal phase to a special mode as shown in figure 1 [8]. St. Paul, Minnesota was one of the first to adopt EVP in its signal system where almost 100 percent of the traffic controllers had preemption control [9].

In 1979, 3M built a new system which could prioritize preemption requests [8]. This marked the beginning of Transit Signal Priority with the system allowing two priorities, a higher for emergency vehicles and a lower for transit vehicles. The brand name Opticom was given to these preemption products which included a separate emitter unit required for emergency vehicles and transit vehicles. Soon, infrared emitters and detectors replaced strobes because of the public use of strobe lights to fool traffic signals [10]. In 1992, 3M added encryption codes to its infrared transmitters to avoid false preemption calls made by hackers [8].

Figure 1 - Emergency vehicle detection and preemption [1]

Recently, technological advancements, such as use of GPS to calculate the latitude, longitude, speed and heading of emergency vehicles, came into common use [11]. Today, the 3M Opticom Preemption System is the most commonly used in the United States [12]. Ninety-eight metropolitan areas have installed it in more than 30,000 intersections which represents one-fifth of all signalized intersections in the United States [5]. Cities like Bellingham (WA), Boise City (ID) and Syracuse (NY) have recently implemented preemption systems in more than 90% of their signalized intersections [8].

2.2. Benefits and Consequences

The rapid growth in populated areas has resulted in increased congestion which has resulted in multiple impacts to the emergency operations community. It has increased the risk of emergency vehicle crashes as well as the response time of emergency teams [13]. Emergency Vehicle Preemption has helped to mitigate these impacts but often at the cost of higher travel time for cross-street traffic and, in some cases, traffic gridlock [14].

2.2.1. Benefits

Emergency Vehicle Preemption has many advantages. These include faster response by the emergency team, improved safety for emergency vehicles as well as other vehicles, cost savings to the public because of reduced property loss which is enabled by quicker emergency response and cost savings to the authorities because of a larger service area for each emergency dispatch station [5].

a) Faster Response

Studies done by FHWA showed that providing green to emergency vehicles improves response times by reducing driver confusion and conflicts and increasing the average speed maintained by an emergency vehicle [5]. In an analysis of the implementation of emergency vehicle preemption in Fairfax County, Virginia, it was shown that, on average, 30 to 45 seconds are saved per intersection for emergency vehicle movement along the US 1 corridor. Studies done by the City of Denver Department of Safety in 1978 [15], also verified an improvement in the level of service. This study, which was done over a 90-day period in an area with three fire stations and 75 signalized intersections, showed a 14 to 25 percentage reduction in response time. An emergency vehicle movement involving three to six signalized intersections showed average savings of 70 seconds.

Such savings can be of critical importance in case of an emergency. The American Heart Association stated that the survival chances for a cardiac arrest patient are reduced by 7 to 10 percentage for every minute lost until defibrillation [5]. A small fire doubles every 17 seconds and can reach flashover in 7 minutes [16]. Hence, fire and rescue operations have set the operational standard response time to be less than 7 minutes. Emergency Vehicle Preemption can help achieve this goal.

b) Improved Safety

The Fatality Analysis and Reporting System (FARS), a web-based encyclopedia of crash fatality statistics in the United States maintained by the National Highway Traffic Safety Administration, shows that approximately one-fourth of the crashes involving emergency vehicles in the last ten years are intersection crashes [17]. Such emergency vehicle crashes have larger impacts than ordinary vehicle crashes. On one hand, it delays emergency service to 9-1-1 calls. On the other hand, it results in increased injury and possible death to emergency care personnel. It also forms a financial liability for emergency care units. Studies have shown that implementation of Emergency Vehicle Preemption can help in reducing intersection related crashes of emergency vehicles. In the city of Plano, Texas, the intersection crash rate of emergency vehicles was reduced from 2.3 crashes per year to less than one in five years after the implementation of Emergency Vehicle Preemption [5]. In St. Paul, Minnesota, where the preemption systems were deployed as early as 1976, emergency vehicle crashes were reduced by 50% despite the considerable increase in population [8]. St. Paul showed a decline of emergency vehicle crashes from 8 to an average of 3.3 post-installation [5].

c) Savings to the Public

The implementation of Emergency Vehicle Preemption can save the public money. A faster response can save lives which are priceless. Property losses are also minimized. Apart from the savings yielded from lower property loss and fatalities, it also enhances the insurance industry rating for the community's fire suppression service; thereby reducing insurance costs [5]. The Town of Blacksburg, Virginia, has reported an improvement in its Insurance Service Organization (ISO) class due to faster responses after preemption installations [18].

d) Savings to the Authorities

Emergency Vehicle Preemption has helped to increase the service area of each fire and rescue station because of its potential higher level of service. The city of Plano, Texas was able to serve an average of 7.5 square miles per fire station after the installation of preemption systems whereas the target service area per fire station without preemption was 5.6 square miles [5]. This has helped them save $9 million in construction costs and $7.5 million in annual operating costs [8].

2.2.2. Consequences

Although the implementation of Emergency Vehicle Preemption can help reduce the travel time of emergency vehicles, it can affect overall traffic negatively [19]. Studies were conducted in New York City to evaluate the impact and benefits of Emergency Vehicle Preemption [20]. This study showed an improved emergency vehicle operation at all the six locations, but also showed a disruption in the coordination of the signal systems. Recovery required not less than four cycle lengths. Also, it showed an average increase in traffic delay of 4 to 58 percent.

A hardware-in-the-loop simulation using CORSIM with Leesburg, Virginia as the study area and Route 7 as the study corridor, was conducted at Federal Highway Administration's Traffic Research Laboratory (TReL) in 1999 [7]. This showed an increase in overall travel time to be one to two percent. The study also stated that the effect depended on upstream preemption distance, corridor volumes and baseline timing plan. Coordination of signals was not considered in this study. A year later, in 2000, preemption was tested in a closely spaced arterial with various preemption paths and transition algorithm [14]. As stated in the previous research, a single preemption had negligible effects on the overall traffic, whereas, multiple preemptions caused severe delays to the overall traffic.

2.3. Current Techniques

Several advancements took place in preemptive techniques over the last four decades. These advancements mainly occurred in the technology of transmission and reception of calls. From detection of strobe lights for placing calls to the latest GPS enabled Automatic Vehicle Location system, almost all the advancements were concentrated on placing preemptive calls. Another concentration of research has focused on the transition of preemption or how to transition into and out of the preemptive operation. Since normal signal timing and logic is different from the signal timing and logic used during preemption, a transition is required between the two timing plans [1]. Guidelines for this transition are given in the Manual on Uniform Traffic Control Devices [21] and include:

Transition into Preemptive Phase:

i. Yellow and All-red intervals should be served before transitioning to preemptive phase.

ii. Pedestrian wall interval or clearance interval may be shortened according to the priority received.

iii. Returning to a previously served steady green interval is permitted following a steady yellow interval in the same approach and omitting all-red interval.

Transition out of Preemptive Phase:

i. Yellow and All-red intervals must not be shortened.

ii. Returning from a yellow interval to green is not permitted during transitioning out without an all-red interval.

Figure 2 shows the logical operation of a controller during normal emergency vehicle preemption from the moment that the preemption call is received until the operation switches back to normal logic.

Studies also showed that the transition strategy has impacts on the safety and efficiency of the general traffic at an intersection and hence the right strategy must be used to exit preemption control [22]. This occurs because transitioning involves reallocation of green time. Some of the transition strategies in use are summarized in Table 2.

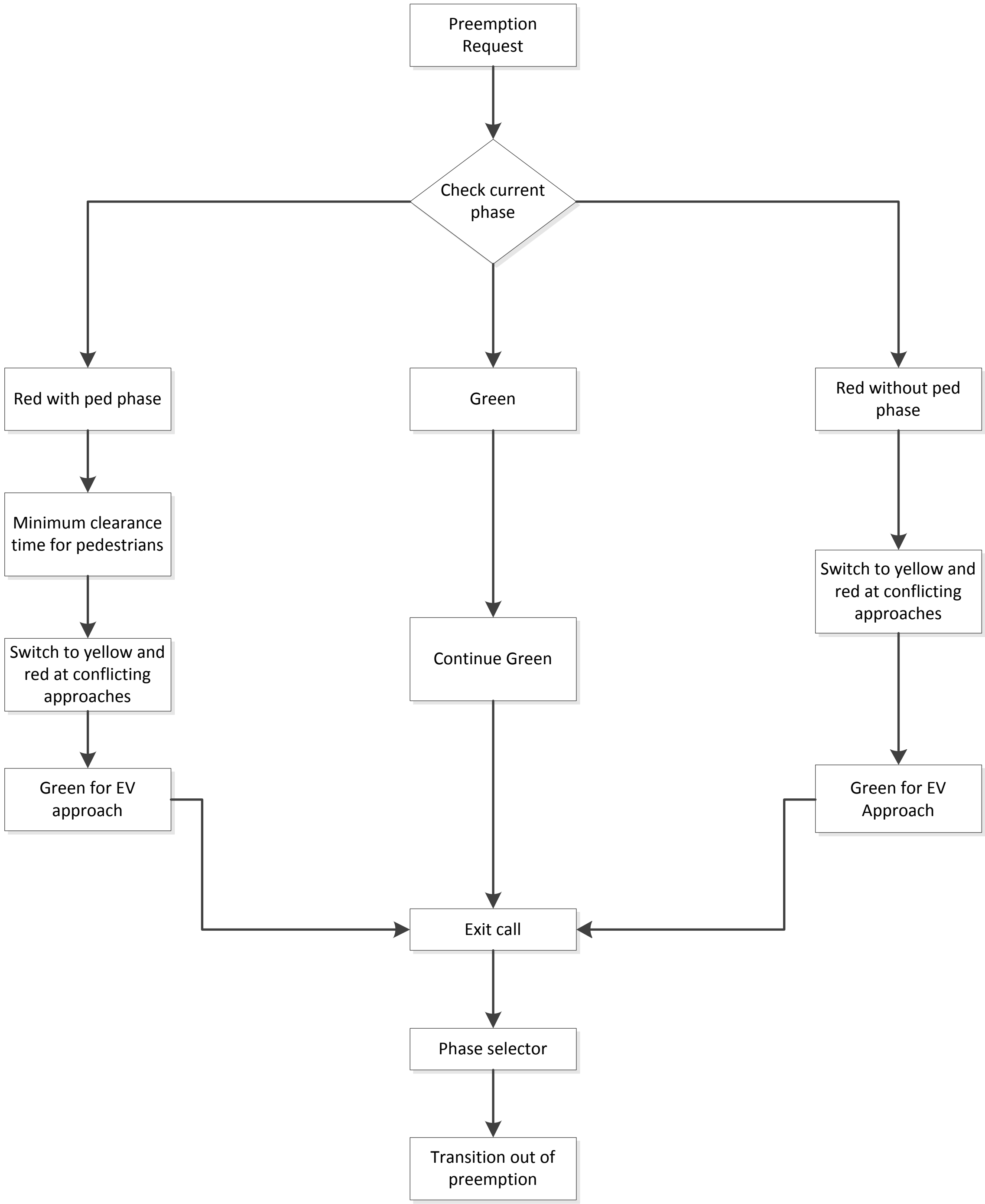

Figure 2 - Controller operation during traditional preemption

Table 2 - Various types of transitions used in EVP [22]

Controller Type	Transition Type	Description
Free or uncoor-dinated signal controller	Return to preempted phase	The controller shifts to the phase when preemption was started.
	Return to designated phase	The controller shifts to a previously designat-ed phase irrespective of when preemption was started.
Coordinated signal controller	Hold or dwell	The controller returns to the interval contain-ing the coordination point and then increases the length of that interval till a desired coor-dination point is reached.
	Maximum dwell	The controller returns to a specified interval which serves for a preset maximum time (by which any interval may be extended) till the coordination point is reached
	Long Way or Add	The controller serves the same phase for a maximum preset time before it advances and reaches the coordination point.
	Short Way	The controller serves phases for a minimum preset time till it reaches the coordination point
	Best Way or Smooth	The controller selects long-way or short-way method depending on which one takes least time and number of cycles.

2.4 Advancements

ITS is growing rapidly and with the latest generation of GPS equipped systems which can pinpoint the emergency vehicle's location and speed, Emergency Vehicle Preemption is receiv-ing greater acceptance among communities. The system in one part of the world helps emer-gency vehicles to reach incident locations in a shorter time, whereas in traffic-strangled Middle Eastern cities like Dubai, it is being implemented to allow diplomats and sheikhs to quickly move through traffic [8]. Current EVP systems can work with vehicle circuitry to clear side-street traffic if the turn indicator is operated. It can also cancel preemption requests when the vehicle switches to the parking gear if the incident location is near an intersection [11]. In many places, traffic lights are equipped with floodlights which can show the path of emergency ve-hicle movement and, thereby, let commuters know that it is in a preemptive phase [12].

In spite of these advancements, limited research has been done in optimizing emergency vehicle movement along a congested corridor with preemption. Literature shows that most of the preemption systems are still working on an intersection-to-intersection basis [2]. Although there are preemption systems which can invoke preemption at the next intersection, they still require local detection of the emergency vehicle [11]. In the research done for the Office of Research Services, Minnesota Department of Transportation, a dynamic sequential preemption method showed a 10-16 percent reduction in travel time of emergency vehicles, even with long and complicated routes [2]. It dealt with a sequential preemption approach in which signals are preempted automatically in a selected route for emergency vehicle movement.

In this research, the sequential preemption will be aided by offsets similar to a signal progression pattern. These offsets will be set either by real-time congestion levels or pre-set time-of-day congestion levels. Such a system should be effective and inexpensive to implement.

3. Traffic Adaptive Offset-Based Preemption for Emergency Vehicles: Model Development

Raj Kishore, Kathleen Hancock

This paper presents a strategy for Emergency Vehicle Preemption along a busy arterial corridor. The approach adapts to real-time traffic conditions to minimize the delay to emergency vehicles and optimize overall traffic. The approach uses sequential progression for the preemption logic along the route of the emergency vehicle. Back-up queue lengths at intersections are used to compute offsets to be used for preemption timing at subsequent intersections. Because the queue lengths depend on traffic conditions, the resulting logic is the basis for a dynamic preemption strategy.

3.1 Introduction

Emergency Vehicle Preemption (EVP) is a preferential strategy to allow emergency vehicles to pass a signalized intersection with minimum delay and maximum safety [1]. It interrupts the normal operation of a signal and transfers the right of way to the direction of an approaching emergency vehicle [2]. Most preemption systems used in the United States operate on an intersection-by-intersection basis [3]. These systems work on the principle of the emergency vehicle being detected as it approaches an intersection and the controller switching its operation to a predefined preemptive logic as shown in Figure 3 [1, 2]. This operation is local to the intersection being traversed and may result in time-loss due to accumulated delay from each intersection. Peak-hour congestion and after-event traffic can worsen the situation by preventing the emergency vehicle from reaching the point of local detection causing significant delays to the vehicle.

Recent developments in Intelligent Transportation Systems (ITS) have enhanced reliability of travel-time predictions and traffic monitoring using real-time traffic feeds [4, 5]. Loop detectors and video detection units are becoming popular on freeways and arterials because of increased transmission capabilities and reduced costs. Advancements in artificial intelligence and use of artificial neural networks in smart signal control have provided the foundation for real-time traffic adaptive signal control systems using feedback agents [6]. These developments in conjunction with the importance of preemption in saving lives and property provide the necessary infrastructure and motivation for an adaptive emergency vehicle preemption system.

Figure 3 - Emergency vehicle detection and preemption at an intersection [2]

3.2 Background

The history of emergency vehicle preemption dates back to 1929 when the American Engineering Council proposed splitting cycles to allow emergency vehicle to move through traffic easily [7]. In the 1960s and 1970s, preemption systems which can detect strobe lights or radio waves emitted by the emergency vehicles became available [1, 8]. St. Paul, Minnesota was one of the first cities to adopt EVP in its signal system and included it in almost all controllers [9]. As technologies evolved, they included the use of strobe lights, sirens, loop detectors, radio waves and push-buttons to request preemptive green [2]. Developments in preemption technology include the addition of encryption codes to infrared transmitters and use of Global Positioning Systems (GPS) to locate emergency vehicles [8, 10, 11]. Today, over one-fifth of signalized intersections in the United States have preemption capability [1].

Several studies have documented the benefits and consequences of emergency vehicle preemption. Faster response and improved safety due to the exclusive right of way received by emergency vehicles and reduced driver confusion and conflicts are the primary benefits [1, 8, 12]. Communities also save money because of reduced property damage and fatalities resulting from faster response times, as well as having improved emergency service radii for each dispatch station [1, 8, 13]. A consequence is that as roads become congested, preemption has been found to adversely affect overall traffic. Studies show that these impacts include higher overall traffic delay, a negative impact on signal progression and coordination, and increased delays due to multiple preemptions [14-16].

Most EVP systems currently operate on an intersection-by-intersection basis. Although studies have shown that dynamic sequential preemption methods can reduce emergency vehicle travel time by 10-16 percent, no dynamic preemption systems are currently operational nor have methodologies that incorporate real time queue accumulations at intersections been developed [3]. This paper proposes such a preemption strategy at a corridor level.

3.3 Model Formulation

In the proposed preemption strategy, the preemption of intersections along a corridor is structured to optimize the movement of an emergency vehicle such that local detection is not needed at each intersection. This avoids the accumulated time loss at each intersection resulting from local detection of an approaching emergency vehicle and transition to preemption logic. As the emergency vehicle enters the corridor, it is detected and preemption is requested to the first intersection controller which then transmits the request to downstream controllers. As the emergency vehicle moves through the corridor, it progressively receives ‘preemption green’. Alternatively, a centralized control center receives the preemption request and propagates the request to intersection controllers along the response route.

The principle behind this preemption progression is analogous to traffic signal pattern progression along a coordinated signal system using offsets. As each intersection controller receives the preemption call, it calculates the time required to initiate the preemptive phase to ensure uninterrupted movement of the emergency vehicle. This time is called the preemption offset and is a function of its distance from the emergency vehicle’s entry point into the corridor, desired average speed of the emergency vehicle, and the congestion level at each intersection at the time when the emergency vehicle enters the corridor. A logical diagram explaining the proposed method is given in Figure 4.

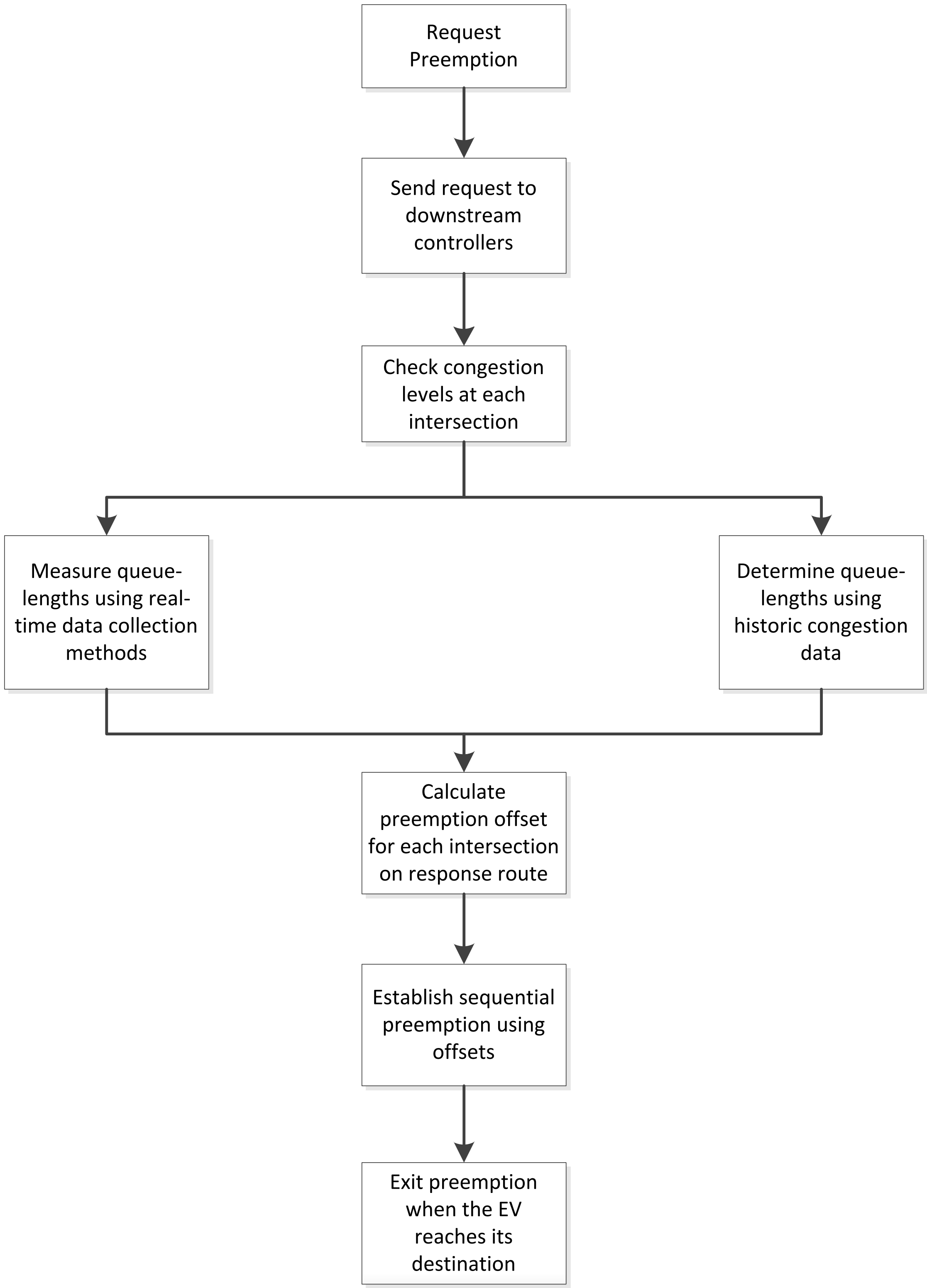

Figure 4- Logic for congestion-based preemption

3.3.1 Measuring Congestion

If the system is to provide uninterrupted emergency vehicle movement, controllers must be programmed to adjust the preemption offsets according to the level of congestion in the corridor. This congestion is quantified as the length of queue waiting to be cleared at each intersection which is used to adjust preemption offsets. Under normal circumstances, such a back-up will be the result of the red phase of the signal. Back-up from the downstream intersections can also inhibit vehicle movement at an intersection and cause queues. Length of queue can be determined in real-time using detectors or can be extracted from historic congestion data.

a. Queue Lengths Using Real-Time Congestion Data

Each intersection may have queued vehicles which must be cleared to enable free movement of the emergency vehicle. The length of the queue to be cleared plays a significant role in modifying the preemption offset. This length can be measured in real-time using road-side sensors or inductive loop-detectors. Active or Passive Infrared, Radar, Doppler Microwave, Pulse Ultrasonic and Video Image Detection System (VIDS) are some of the available technologies for road-side vehicle detection [17]. These methods, being non-invasive, will be preferred over invasive methods such as loop-detectors.

VIDS technology involves placing cameras over the corridor to determine the extent of queues at each intersection. Image processing is used to compute the length of queues at each intersection. Most presence monitors which connect cameras to the controller have built-in queue length measurement capabilities [18]. VIDS has the advantages of having a longer range and of serving multiple objectives. However, it will be constrained by the geometry of the corridor as shown in Figure 5 [18, 19].

Figure 5 - VIDS' range limited by road geometry [18]

Sensors, other than VIDS, use step-wise data collection methods for determining length of queues. This involves mounting sensors at predetermined intervals of length near the intersection and measuring the occupancy at each. Length of queue is then measured as the distance to the last occupied sensor. Unlike VIDS, these methods are not constrained by road geometry, but the resulting measured lengths will be in increments of the sensor intervals. Sensor selection depends on available mounting methods, physical conditions, desired level of accuracy, and installation and maintenance costs.

b. Queue Lengths Using Historic Data

In situations where sensor placement is expensive or not feasible, congestion-based emergency vehicle preemption can use historic data for approximate measurements of preemption offset. However, this method is not as accurate as using real-time data. This approach may be appropriate for corridors which display a more uniform traffic behavior. Data from data collection devices can be converted to an average estimated queue length by time for the approaches of intersections on a corridor. Once preemption is requested, the controller retrieves the historic queue lengths for each approach, time of day and day of week for the signals along the response route. For reliable performance, these archived queue lengths would need to be regularly updated.

3.3.2 Calculation of Offsets

Offsetting preemptive green is the principle behind offset-based preemption technique for emergency vehicles along a corridor. As the emergency vehicle moves along the corridor, preemptive green is given to it in a way that it will incur minimum delay. The offset of preemptive green, hence, has to be measured using the queue lengths formed at each intersection for efficient operation of this system. From these queue-lengths, offset adjustments are done to compute the effective offset needed for proper operation of the system. The equations or logic governing the computation depends on the level of congestion over the path of emergency vehicle movement.

Consider an intersection '*D*' ft away from the point of entry of the emergency vehicle in the downstream of a corridor. Assume that the corridor is devoid of any traffic and we desire a maximum emergency vehicle speed of 'v_{ev}' ft/s. The preemption offset 'Δ_p' at which that particular intersection should turn preemptive green on for the emergency vehicle to move uninterruptedly is given by:

$$\Delta_{p1} = \frac{D}{v_{ev}} \tag{1}$$

Hence, knowing the distance of the intersection stop-line from the point of entry of the emergency vehicle into the corridor and its desired average speed, the time after which it should give a preemptive green to the emergency vehicle can be precisely measured using Equation 1. But in real situations, there will be vehicles queued at the intersections which need to be cleared for the emergency vehicle to move. Hence this offset should be adjusted to account for queue clearance time.

Consider the case where a queue of vehicles is already waiting at the intersection for green. If an emergency vehicle has to pass that intersection, these vehicles have to be cleared for minimizing its delay. Hence this queue clearance time should be subtracted from Equation 1 to get the adjusted preemption offset. Assume that the intersection accumulated vehicles queuing '*L*' ft from the stop-line. As the approach receives green, vehicles will start moving following a shockwave principle for departure. If 'k_j' is the jam density in vehicles per mile and '*s*' is the saturation flow rate in vehicles per hour, then the time in seconds until the last vehicle departs is given by [20]:

$$t_{sw} = \frac{Lk_j}{2.94s} \tag{2}$$

If '*v*' is the speed achieved by the last vehicle in the queue in ft/s and '*a*' is it's acceleration in ft/s^2, then the distance in feet covered when it is accelerating is given by:

$$L_a = \frac{v^2}{2a} \tag{3}$$

If '*L*' is less than or equal to 'L_a', then the last vehicle will be accelerating when it passes the stop-line. In this case, the time required to clear the link will be the sum of time needed for the last vehicle to start moving (given by equation 2) and the time it takes to reach the stop-line. This is given by:

$$t_2 = \frac{Lk_j}{2.94s} + \sqrt{\frac{2L}{a}} \tag{4}$$

Therefore, the modified preemption offset for this intersection will be

$$\Delta_{p2} = \frac{D}{v_{ev}} - \left\{ \frac{Lk_j}{2.94s} + \sqrt{\frac{2L}{a}} \right\} \tag{5}$$

The jam density and saturation flow-rate can be assumed, given the corridor characteristics. Acceleration of the last vehicle can also be assumed. Hence the only variable in Equation 5 for a particular intersection will be the queue length which can be measured using detectors as described earlier.

Now assume '*L*' to be greater than 'L_a'. Therefore, the last vehicle in the queue will accelerate to '*v*' before it reaches the stop-line. The total time required to clear the link, in this case, will be the sum of time needed for the last vehicle to start moving (t_{sw}), time of acceleration till '*v*' (t_a) and the time of constant motion for the remaining distance L_{cm} (t_{cm}).

$$t_a = \frac{v}{a} \tag{6}$$

For this time, the vehicle will be accelerating and then it will move at constant speed of '*v*'. During this time, it will cover the remaining distance till the stop-line at the constant speed. The remaining distance is given by the following equation.

$$L_{cm} = L - \frac{v^2}{2a} \tag{7}$$

The time for which it moves at '*v*' before passing the stop-line is given by:

$$t_{cm} = \frac{2aL}{v} - \frac{v}{2a} \tag{8}$$

Hence, the total time taken by the last queued vehicle to leave the link from the moment, its approach gets green is given by:

$$t_3 = \frac{Lk_j}{2.94s} + \frac{2aL}{v} + \frac{v}{2a} \tag{9}$$

Therefore, the modified preemption offset for this intersection will be

$$\varDelta_{p3} = \frac{D}{v_{ev}} - \left\{\frac{Lk_j}{2.94s} + \frac{2aL}{v} + \frac{v}{2a}\right\} \tag{10}$$

Just as in Equation 5, the only variable in this equation from a particular intersection is the queue length. The Highway Capacity Manual can be used to estimate saturation flow rates and jam densities according to corridor characteristics [21]. Alternatively, a jam density of 240 vehicles per mile and saturation flow rates of 1600 vehicles per hour for through lanes and 1400 vehicles per hour for turn lanes can be assumed [20]. Generally, the trade-off between the queue-length and acceleration distance will be of the order of fourth or fifth vehicle in the queue when the saturation headway is achieved at the stop-line [22].

3.3.3 Assumptions

Equations 1, 5 and 10 give offsets to start preemptive green for various levels of congestion. These offsets are computed such that the links will be clear of waiting vehicles at an intersection. While moving on a link, the emergency vehicle is assumed to pass other vehicles and lead the platoon over a link. This assumption is valid since, in reality, drivers of other vehicles will yield to the emergency vehicle. Since micro-simulation tools cannot simulate driver behavior when a normal vehicle is being followed by an emergency vehicle, a higher desired average speed for the emergency vehicle can represent the situation.

The equations for preemption offset give an exact measurement of time after which preemption should be sequentially initiated at each intersection to just clear the link as the emergency vehicle reaches that intersection. Hence, it is advisable to subtract a suitable safety interval to account for any deviation from the assumed empirical shock-wave equation. In case of rail-road preemption, the safety interval used to clear the track is 4 to 8 seconds which considers the speed of a train and its inability to alter its path [20]. For this research, the safety interval is assumed to be 2 to 4 seconds depending on the desired average speed of the emergency vehicle. This assumption is valid because, unlike trains, emergency vehicles have better maneuverability and can adjust its speed to supplement any shortcomings in queue calculation.

The proposed model assumes no penalty for turns. If the route traversed by the emergency vehicle involves turn, a turn penalty should be added to all preemption offsets at intersections that would be traversed after the turn. This turn penalty is the additional time in seconds that the emergency vehicle requires to make a turn and involves time to decelerate to a safe turning speed, time to make the turn and time to accelerate to the desired speed.

3.3.4 Sample Calculations

Figure 6 shows a simplified network used to evaluate the proposed method. The shaded links represents the path traversed by the emergency vehicle as it passes the signalized intersections numbered 1 through 6. The origin and destination of the emergency vehicle are marked as O and D respectively. The estimated values for calculating offsets are:

Desired average speed of emergency vehicle, v_{ev} = 30 mph
Maximum speed of a moving platoon of vehicle, v = 25 mph
Acceleration of a standard queued vehicle, a = 4 ft/sec/sec
Jam density, k_j = 240 vehicles/mile
Saturation flow rate, s = 1600 vehicles per hour

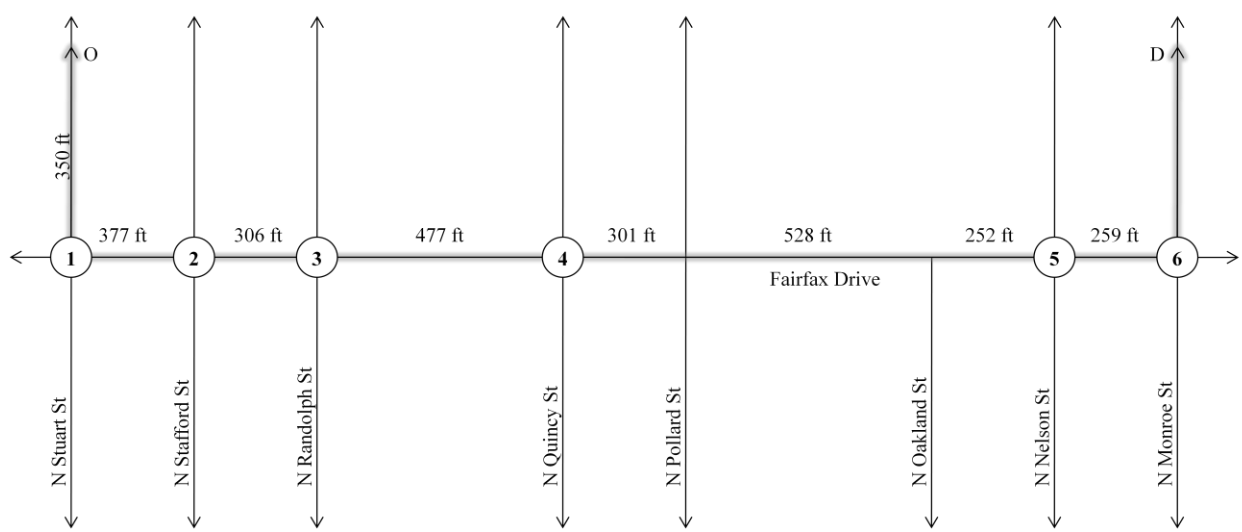

Figure 6 – Preliminary testing simulation network

Table 3 shows calculated preemption offsets using equations 1, 5 and 10 for a set of assumed queue lengths for each intersection. For uninterrupted movement of an emergency vehicle, the offsets at intersections 1 through 6 should be 2, 15, 22, 33, 52 and 66 seconds respectively for the given set of queue-lengths.

Table 3 - Calculation of Preemption Offsets

Intersection ID	1	2	3	4	5	6
Upstream link length (ft)	350	377	306	477	1081	259
Distance from entry point (ft)	350	727	1033	1510	2591	2850
Initial Offset, $\frac{D}{v_{ev}}$ (s)	8	17	23	34	59	65
Assumed queue-length, L (ft)	22	66	66	66	110	44
$L > L_a$	No	No	No	No	No	No
$\frac{Lk_j}{2.94s}$ (s)	1	3	3	3	6	2
$\sqrt{\frac{2L}{a}}$ (s)	3	6	6	6	7	5
$\frac{2aL}{v}$ (s)	5	14	14	14	24	10
$\frac{v}{2a}$ (s)	5	5	5	5	5	5
Safety Interval (s)	2	2	2	2	2	2
Turn penalty (s)	0	10	10	10	10	10
Preemption Offset (s)	2	15	22	33	51	66

3.4 Preliminary Results

Microscopic simulation was used to evaluate the behavior of this preemption method using the network shown in Figure 6 with simulated commuter traffic and actual signal phasing. TransModeler™ and its corresponding script language were used to model the proposed preemption. Simulations were done for a one-hour duration for three cases,

1. No preemption
2. Localized preemption
3. Proposed offset preemption

The measures of effectiveness used for comparison of the three cases included average travel time, average delay and average number of stops for the emergency vehicle movements, traffic moving along the corridor, traffic crossing the corridor and total traffic in the simulation.

Table 4 - Simulation Results Summary

Performance Measure	Vehicle Trip Classification	No Preemption	Local Preemption	Proposed offset preemption
Average Travel Time (s)	Emergency Vehicle	170.09	151.68	103.86
	Along Corridor	135.65	123.03	141.21
	Across Corridor	91.73	98.76	103.27
	Overall	128.87	122.31	132.10
Average Delay (%)	Emergency Vehicle	1.80	1.49	0.69
	Along Corridor	1.41	1.19	1.49
	Across Corridor	0.80	0.78	0.85
	Overall	1.27	1.11	1.27
Average Number of Stops	Emergency Vehicle	3.00	6.00	0.00
	Along Corridor	2.65	2.11	2.88
	Across Corridor	1.00	0.93	0.96
	Overall	1.85	1.64	1.99

Table 4 shows the summary of simulation results. The proposed offset-based preemption technique showed a 39% reduction in travel time of the emergency vehicle compared to the case where no preemption was used, whereas, local preemption was able to reduce the travel time of emergency vehicle by only 11%. A similar trend was found in the delay experienced by the emergency vehicle during its movement. The proposed method was able to reduce the delay by 62%, whereas, local preemption was able to reduce the delay by only 17%. However, it should be noted that the proposed method caused a minor 2.5% increase in the average of travel times of all the vehicles in the simulation.

Figure 7 shows a comparison of average travel times for the emergency vehicle when compared to the overall traffic. As shown, the average travel time of emergency vehicle reduces for each case while the overall traffic travel time increases for the proposed offset preemption which is expected given the additional red time to cross traffic.

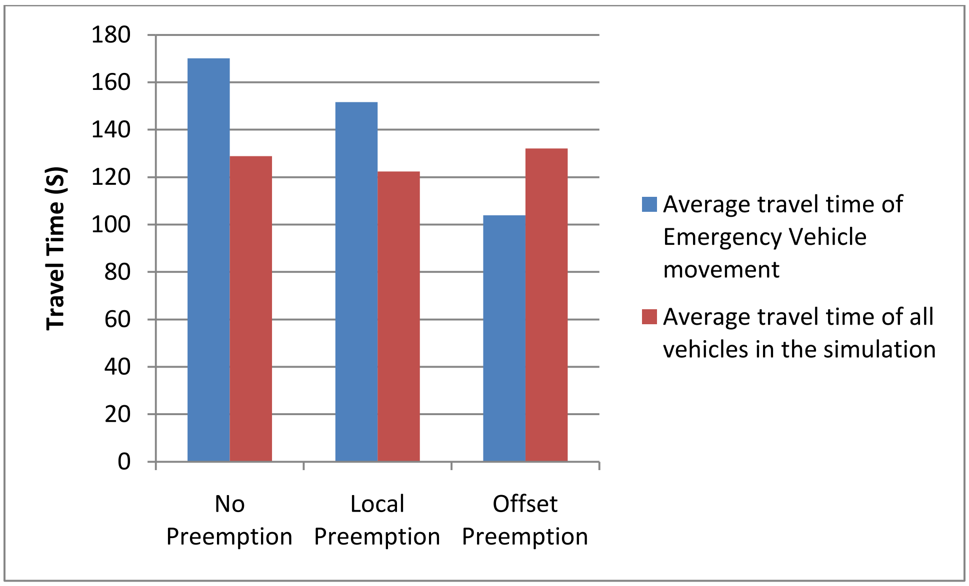

Figure 7 – Comparison of average travel times of emergency vehicles to overall traffic

Figure 8 shows a comparison of average delay experienced by the emergency vehicle when compared to the overall traffic. The delay experienced by emergency vehicle is far less in the case of offset preemption when compared to no preemption and local preemption. The average delay of all vehicles in the simulation is almost the same as that of the case where no preemption was used.

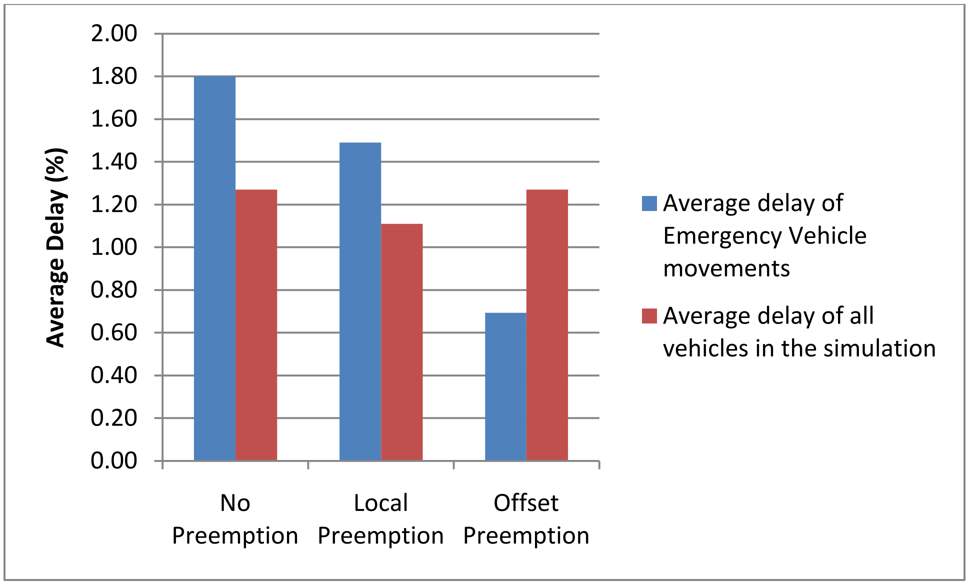

Figure 8 - Comparison of average delay of emergency vehicles to overall traffic

3.5 Conclusion

From the results of preliminary studies, the offset-based preemption technique improves the movement of emergency vehicle, and hence, the performance of emergency service with limited impact on the overall traffic performance. As a result, a more comprehensive evaluation of the strategy is warranted.

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4. Evaluation of Offset-Based Preemption for Emergency Vehicles

Raj Kishore, Kathleen Hancock

This paper presents an evaluation of the effectiveness of a traffic adaptive offset-based preemption technique for emergency vehicles. The system works on the principle of progression of a preemption wave along the emergency response route using offsets which are calculated using real time traffic conditions. In this paper, two possible algorithms are evaluated using microscopic simulation in TransModeler™. Simulations are performed using a network of a large arterial corridor along the Wilson Boulevard in Arlington, Virginia with several randomly chosen incident locations. Measures of Effectiveness include number of stops, stop-times, delays and travel-time of the emergency vehicle as well as other vehicles in the network. Preliminary studies using the proposed offset-based preemption methodology showed up to a 39 percent reduction in the travel-time of an emergency vehicle when compared to a corridor without any preemption system, whereas the reduction due to the standard intersection-by-intersection preemption method was 11 percent.

4.1 Introduction

Since its inception in 1992, the Intelligent Transportation Systems (ITS) Program under Research and Innovative Technology Administration (RITA) has been working to bring intelligent infrastructure and intelligent vehicles together to create a safer and more effective transportation system in the United States [1]. The Emergency Transportation Operations initiative focuses on the development of tools including emergency management, faster emergency vehicle movements and safer hazardous material transportation [2]. The Integrated Corridor Management Systems initiative focuses on reducing congestion on key corridors by providing real-time traveler information on incidents, Variable Message Signs (VMS), congestion monitoring etc. [4]. These initiatives have helped to bring the necessary intelligent infrastructure and intelligent vehicles to the streets so that innovation like adaptive preemption can be readily implemented.

This paper presents an evaluation of a new approach to adaptive emergency response preemption along a route called traffic adaptive offset-based preemption. The offset-based preemption offers a route-based clearance mechanism and is designed to operate over the entire response route with a single activation followed by a series of adapted timed preemptions. Preemption at each intersection is timed using offsets calculated from intersection spacing and average emergency vehicle speed. Adjustments are then made in real time using prevailing congestion on each link to provide uninterrupted movement for the emergency vehicle over the response route.

This evaluation is done using microscopic simulation and focuses on the underlying concepts and algorithms of the method. It does not address actual implementation of offset preemption. The physical network of an arterial corridor in Arlington, VA was simulated for the evaluation. It was built to replicate actual field conditions as closely as possible using current signal timing and logic and simulated morning peak volumes obtained from Arlington County Division of Transportation. Two algorithms for the new approach are evaluated and compared against cases without preemption and with the widely prevailing form of intersection-by-intersection preemption.

4.2 Background

Since the 1960s, several developments have occurred in incorporating technology and computing power into the control of traffic signals [4]. Emergency Vehicle Preemption (EVP) remains one of the focuses of technological advancements in the field of traffic engineering primarily due to its effectiveness in reducing consequences on lives and property [5]. EVP is a system associated with the traffic controller which transfers the right-of-way at an intersection to the direction of movement of an emergency vehicle [6]. Nearly a quarter of the signal controllers in place in the United States incorporate some form of preemption [7]. EVP works on the simple principle of the emergency vehicle being detected either from its strobe lights or radio waves or more recently, using a GPS-enabled Automatic Vehicle Location system, and the controller switching to a pre-programmed preemptive phase. This detection and preemption mechanism is local to each intersection and, hence, is associated with an inherent delay as well as problems such as loss of signal coordination and transition delays [8].

Most studies on preemption have focused on evaluating the benefits and consequences of preemption and on ways to minimize these consequences. Research has also been done in new implementations of detection and transition mechanisms. Preemption is known to reduce the travel time of emergency vehicles by 14 to 25 percent and to reduce intersection crashes by over 50 percent [5, 9]. Conversely, an increase in overall traffic delays of 4 to 58 percent have been identified when traditional preemption is used [10, 11]. Delays at multiple signals and off-peak directional preemption during congested hours are the most adversely affected [12].

Limited research has considered a dynamic approach to preemption. In a recent study by the Minnesota Department of Transportation, a dynamic sequential preemption method was proposed that uses traffic conditions to optimize emergency vehicle movement [8]. It suggested using travel-time information for congestion-monitoring and used an operator to choose the least-congested route. Dynamic preemption was then performed by identifying "safe-pass phases" at each intersection. Results from the research showed a reduction in travel time of the emergency vehicles to be 10 to 16 percent.

This paper proposes an approach to preemption of emergency vehicles which is offset-based and traffic adaptive. Contrary to the MNDOT method, the proposed approach uses offsets which are measured from real-time congestion levels for route-wide preemption. It uses vehicle-detection for congestion monitoring and does not require human selection of a least-congested route. An extensive arterial network was used in the evaluation of the method discussed in this paper.

4.3 Basic Principles

Offset-based preemption is a form of route-based dynamic clearance for an emergency vehicle to move uninterruptedly over its response route. This method requires an initial activation call to start preemption. This is followed by a progression of preemption calls to each subsequent intersection along the response route which is timed such that the emergency vehicle will incur minimal stops and maintain a higher average speed. Offsets for the preemption to progress along the response route are calculated in two steps:

1. Calculation of the initial offsets for each controller along the route based on intersection spacing and average speed of emergency vehicles, and
2. Calculation of an offset-adjustment for each controller along the route based on the prevailing traffic.

Consider free-flow movement of the emergency vehicle over a corridor. The time after which a particular intersection should give green to the emergency vehicle, referred to as the preemption offset for that intersection, is given by [13]:

$$\Delta_{initial} = \frac{D}{v_{ev}} \quad (1)$$

where:

$\Delta_{initial}$ = initial preemption offset of the intersection (s).

v_{ev} = desired average speed of the emergency vehicle (ft/s).

D = distance of the intersection stop-bar from the entry point (ft).

Length of queues (L) at each intersection, measured by loop detectors, wayside sensors or video detection, is the index used for adjusting offsets. The adjusted offset is calculated from the initial offset by subtracting the time required to clear the link of queued vehicles. From the Marshall and Berg equation for the calculation of a clearance interval, there are two cases [13, 14]. When length of queue is less than or equal to the average distance it takes for a passenger car to accelerate to its free-flow speed along the corridor, the equation is:

$$\Delta_{adjusted} = \frac{D}{v_{ev}} - \left\{\frac{Lk_j}{2.94s} + \sqrt{\frac{2L}{a}}\right\} \quad (2)$$

where:

$\Delta_{adjusted}$ = adjusted preemption offset for a particular intersection (s).

L = length of queue at that intersection on the emergency vehicle approach (ft).

k_j = average jam density of the corridor (vehicles/mile).

s = saturation flow rate for the corridor (vehicles/hour).

a = maximum acceleration of a passenger car (ft/s^2).

When the length of queue exceeds the average distance it takes for a passenger car to accelerate to its free-flow speed along the corridor, the equation becomes:

$$\Delta_{adjusted} = \frac{D}{v_{ev}} - \left\{\frac{Lk_j}{2.94s} + \frac{2aL}{v} + \frac{v}{2a}\right\} \qquad (3)$$

where:

v = average flow speed of a passenger car on the corridor.

These basic equations are adjusted for turn-penalties and suitable safety intervals to yield the equations governing the principle of offset preemption.

$$\Delta_{final} = \Delta_{adjusted} + \Delta_{turns} - \Delta_{safety\ interval} \qquad (4)$$

The turn-penalty represents the time lost due to turns on the response route and are primarily characterized by the turn-geometry and emergency vehicle characteristics. Larger emergency vehicles would have a larger turn-penalty. The safety interval is a 2 to 4 second interval given to handle any contingencies in predicted traffic.

4.4 Methodology

Microscopic simulation is used for evaluating the effectiveness of the proposed offset-based preemption for emergency vehicles. TransModeler™, a traffic simulation software from Caliper® Corporation, is used for simulating a major urban arterial corridor network of Arlington, Virginia.

4.4.1 Algorithms

The principle of offset-based preemption is based on determining the number of queued vehicles at an intersection and adjusting the offset based on that value. Depending on the order and time at which these measurements and adjustments are done, many algorithms can be derived from the basic principles because the emergency vehicle movement occurs over time and queue lengths continuously change on a link during this interval.

Two possible algorithms to implement the proposed method were tested in the simulation and compared against cases without the use of any preemption method and using intersection-by-intersection preemption. The cases used in simulation and a short description are summarized in Table 5.

Table 5 - Cases simulated in TransModeler™

No.	Case Name	Description
1	Base Case – No Preemption	No preemption system in use in the network. Emergency vehicle is modeled with no special capabilities and hence behaves as a normal vehicle. It also follows the same lane-changing and car-following models as other vehicles.
2	Individual-Intersection Preemption	Each intersection is programmed to have preemption privileges with an EV detection range of 500ft. The emergency vehicle invokes preemption at each intersection individually.
3	Simultaneous offset adjustment algorithm	Offset-based preemption is performed for the entire response route with a single initial activation. Offsets are measured for all intersections simultaneously using the prevailing congestion at the time of the initial activation. Figure 9 shows this logic.
4	Progressive offset-adjustment algorithm	Offset-based preemption is performed using offsets calculated initially and adjusted for each intersection in a progressive manner using real-time congestion levels. Adjusted offset for the next intersection is calculated when the previous intersection is preempted. Figure 10 shows this logic.

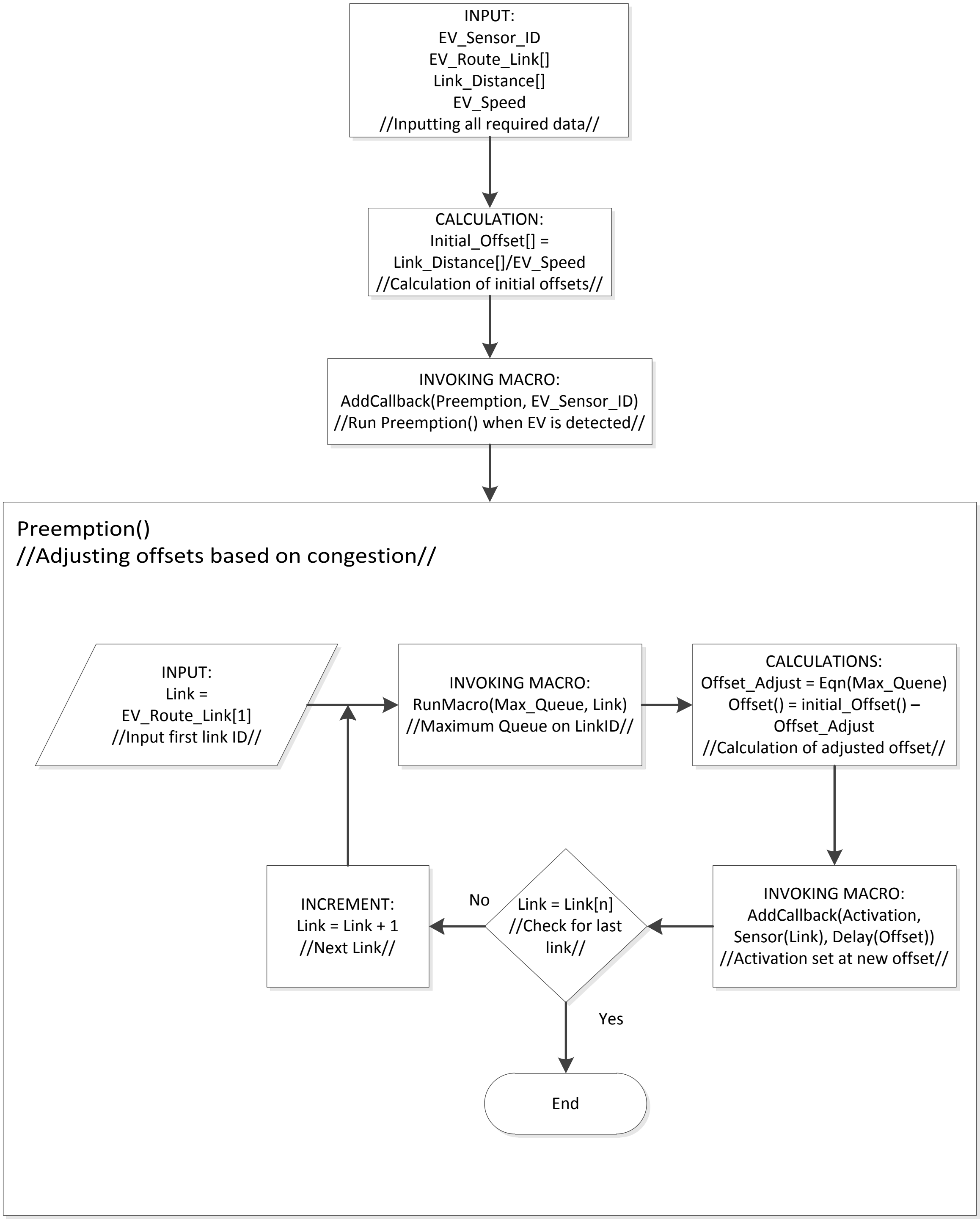

Figure 9- Logic for simultaneous offset adjustment algorithm

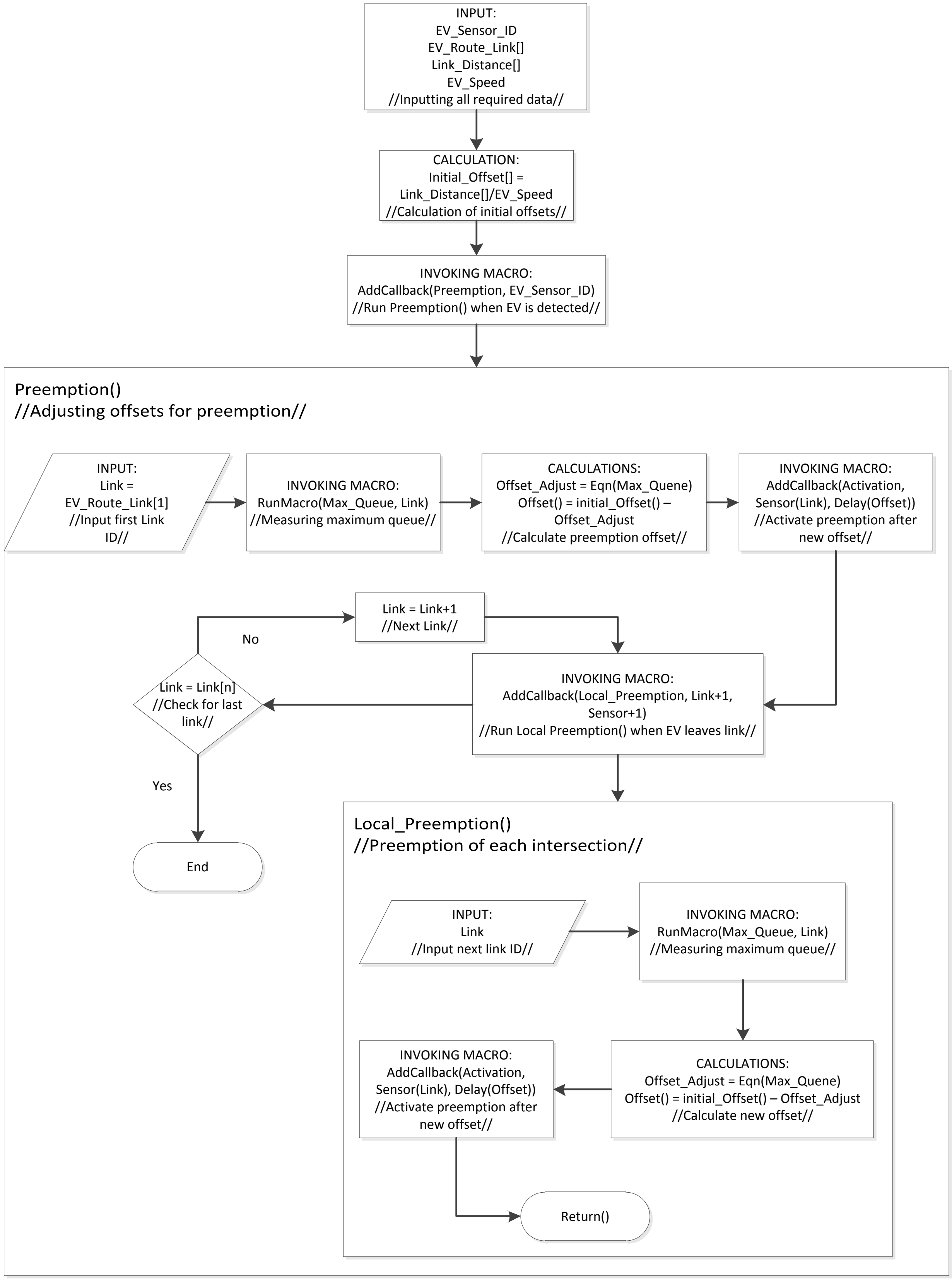

Figure 10 - Logic for progressive offset-adjustment algorithm

4.4.2 Performance Measures

To compare the results of the simulation, performance of the emergency vehicle and of overall traffic were evaluated using the measures of effectiveness in Table 6.

Table 6 - Performance measures on which evaluation is done

Performance Measures	Emergency Vehicle	Overall Traffic
Number of stops	X	X
Stop-times	X	X
Average delay	X	X
Average travel-time	X	-
Average speed of travel	X	-

4.4.3 Case Study

The study area used to evaluate the offset-based preemption method consisted of a five-mile section of the Wilson Boulevard corridor in Arlington County, Virginia, shown in Figure 11. This corridor serves Rosslyn to the east and Seven Corners to the west and runs through residential areas, commercial areas and school zones and is one of the major commuter feeders to the Nation's Capital. To consider the effect of alternate route choice behavior by vehicles, adjacent streets and major connecting corridors such as North Glebe Road, Washington Boulevard and Fairfax Drive are included in the simulation network.

The network consists of 976 links and 699 nodes representing multiple types of road segments and signal systems. It has 92 signalized and 359 non-signalized intersections with some dual-intersection controllers and midblock crossings and includes 3 fire/paramedic stations. Arlington County Division of Transportation, the agency responsible for the timing and logic for the operation of these signal controllers, provided the data used to develop the micro-simulation model. Additional information such as non-signalized traffic control devices, turnbay geometries, lane geometries, turn permissions etc. was obtained using Google Earth and Google Street View along with data collected from field visits.

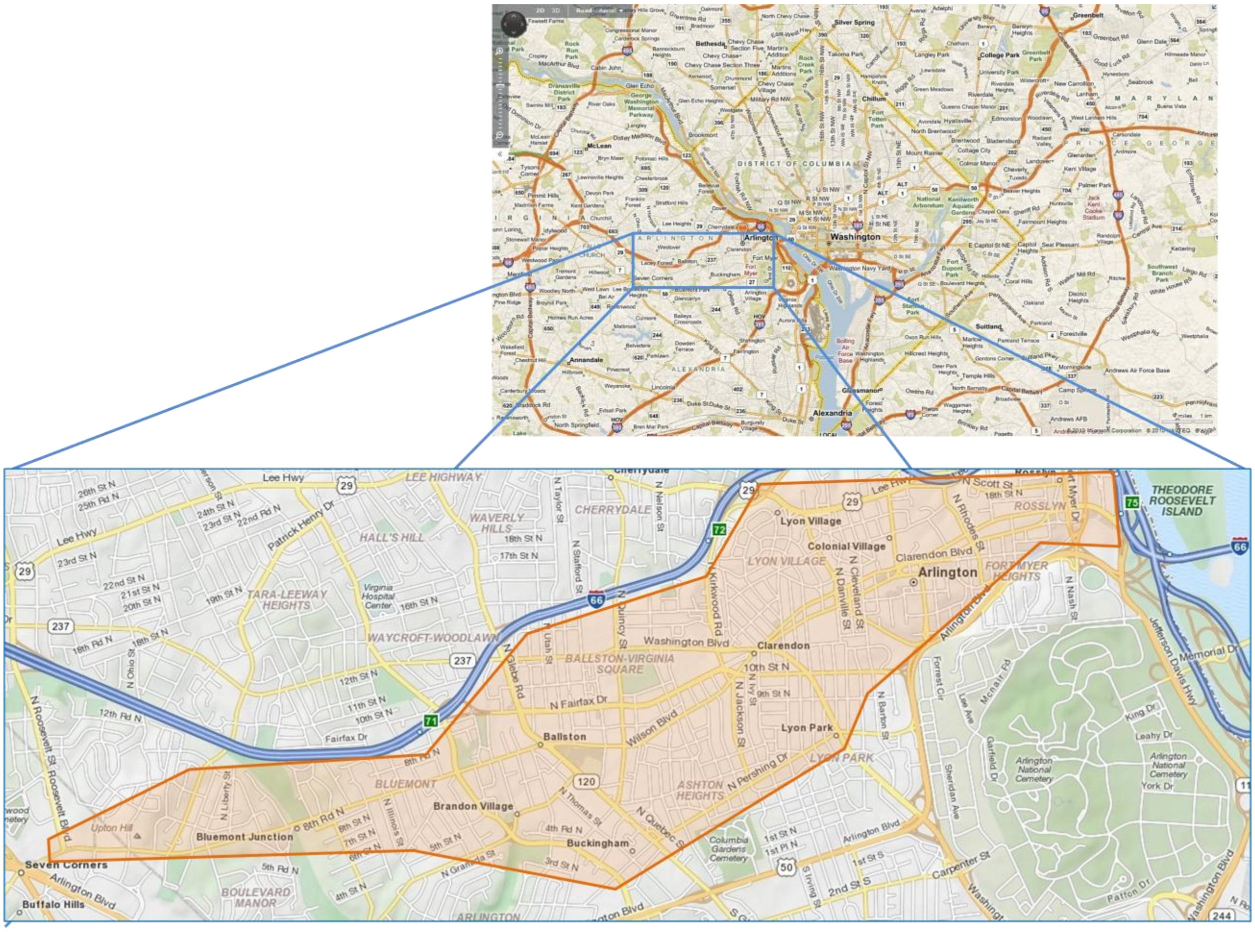

Figure 11 - Study corridor in Arlington, VA

The simulations were performed using Caliper® Corporation's TransModeler™, a traffic simulation software package with an underlying GIS structure. It allows easy network building because of its GIS capabilities. Links, nodes, vehicles, signals, sensors etc. are saved as layers and hence, can be managed and edited easily. It also allows multiple controller types and implementation of advanced ITS logic due to its Caliper Script™ enabled API. It does not model modified driver behavior for yielding to an emergency vehicle and the ability of an emergency vehicle to run a red signal at an intersection.

The network was built by importing Arlington's GIS street layer [15] and a dataset of number of lanes. Turn permissions and turn-bays were added manually and cross-checked with Google Maps. Signalized controller timings and logic provided by the Arlington County in Universal Traffic Data Format (UTDF) and turn-volumes and non-signalized control were added for each intersection. Calibration of the model was done using traffic counts available from the County. Sensors for emergency vehicle detection and preemption capabilities were then added.

Incidents

Simulations were performed for 12 randomly-chosen incident locations during a one-hour AM peak period for the four different cases given in Table 5. For each incident simulation, two EV were dispatched during the simulation time window according to a stochastic distribution and each simulation was performed five times to represent ten variations in traffic conditions. Table 7 gives the locations of the Fire/Medic Stations and Table 8 summarizes the twelve incident locations and emergency vehicle route characteristics. Figure 12 shows the network routes, dispatch stations and incident locations. A total of 360 emergency responses were simulated representing the 4 cases for 12 incidents with 2 emergency vehicle dispatches each run 5 times with random seeds.

Table 7 - Locations of emergency vehicle dispatch stations

Station No.	Location
A	Wilson Boulevard and North Pierce Street
B	10th Street North and North Hudson Street
C	Wilson Boulevard and North Buchanan Street

Table 8 - Details of simulated incident locations in the network

Incident No.	Incident Location	Dispatch Station	Length (mi)	No. of Signalized Intersections on EV Route	Peak flow direction	Comments
1	N Livingston St & Wilson Blvd	C	1.324	3	Against peak traffic	Along Wilson Blvd corridor
2	N Barton St & Wilson Blvd	A	0.796	7	One- way (against peak traffic)	
3	N Randolph St & Wilson Blvd	C	0.699	5	With peak traffic	
4	N Edgewood St & Clarendon Blvd	B	0.492	6	One- way (with peak traffic)	
5	N Glebe Rd & N Pershing St	C	1.034	6	Against peak traffic	Along other major corri- dors
6	10th St N and N Barton St	B	0.500	3	With peak traffic	
7	N Glebe Rd and Washington Blvd	C	0.846	5	Against peak traffic	
8	Fairfax Dr and N Quincy St	B	0.754	5	With peak traffic	
9	13th St N and N Courthouse Rd	A	0.835	7	One- way (with peak traffic)	Across major corridors
10	19th St N and N Kent St	A	0.704	7	Against peak traffic	
11	N Pershing St and N Jackson St	B	0.703	2	With peak traffic	
12	N Veitch St and Key Blvd	A	0.814	7	One- way (against peak traffic)	

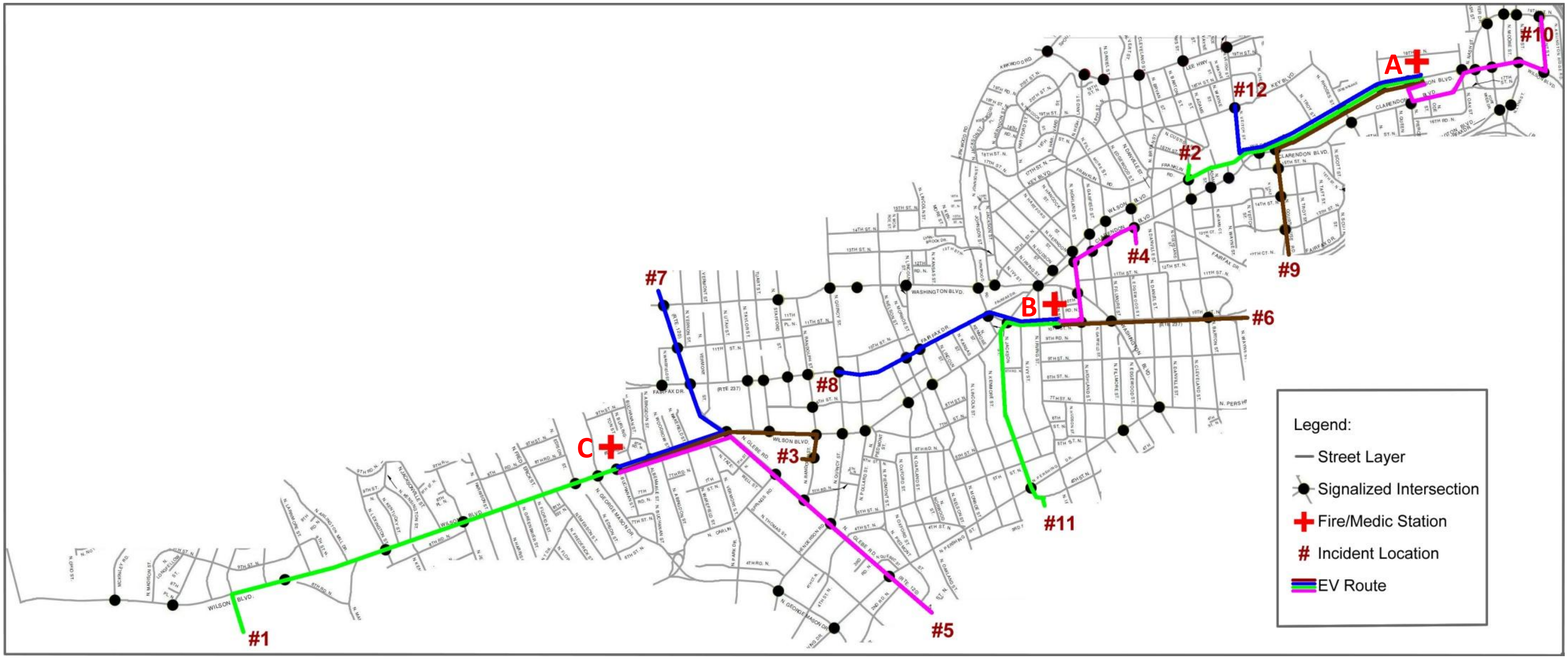

Figure 12 - Simulation network showing incident locations and emergency vehicle routes

4.5 Results

Percentage difference in delay, stop-time, stops and travel-time of emergency vehicles for each preemption case and the base case were the primary measures of effectiveness used in studying the performance of the offset-based preemption method. To effectively study and understand the impact of offset-based preemption method on overall traffic, results generated from the simulations were converted to percentage difference between the three preemption options and the base case for delay, stop-time and number of stops of all vehicles as described below.

Each simulation run reported approximately 21,000 vehicle trips. The results from each simulation included characteristics of each trip such as delay, stop-time, stops, time at origin, time at destination and length of trip. Time at origin and destination were used to compute the travel-time (including stop-time) of each vehicle. Emergency vehicle travel speed was computed using its travel-time and length of trip. Emergency vehicle trip results were isolated and values of delay, stop-time, stops and travel-time were averaged for all runs of each incident and each case. Average values of the four performance measures represented the emergency vehicle characteristic for a particular incident and a particular case. Values for all incidents for each of the four cases were then averaged to obtain percentage difference between the average of emergency vehicle delay, stop-time, stops and travel-time for each of the three preemption cases as they related to the base case.

A similar approach was used to find the percentage difference in average delay, stop-time, stops and travel-time for all vehicles in the simulation between the three preemption cases and the base case. The delay, stop-time, stops and travel-time of all vehicles were averaged for the five random seed runs for each incident and each preemption case. These values were used to compute the overall average delay, stop-time, stops and travel-time of vehicles for each case. Percentage differences for the performance measures from the base case for the three preemption cases were then computed.

It should be noted that since the simulation tool does not consider the effect of driver behavior when an emergency vehicle is in the traffic mix or the ability of the emergency vehicle to run through a red signal, the measures for the base-case are over-represented.

Performance measures for emergency vehicles are summarized in Figure 13.

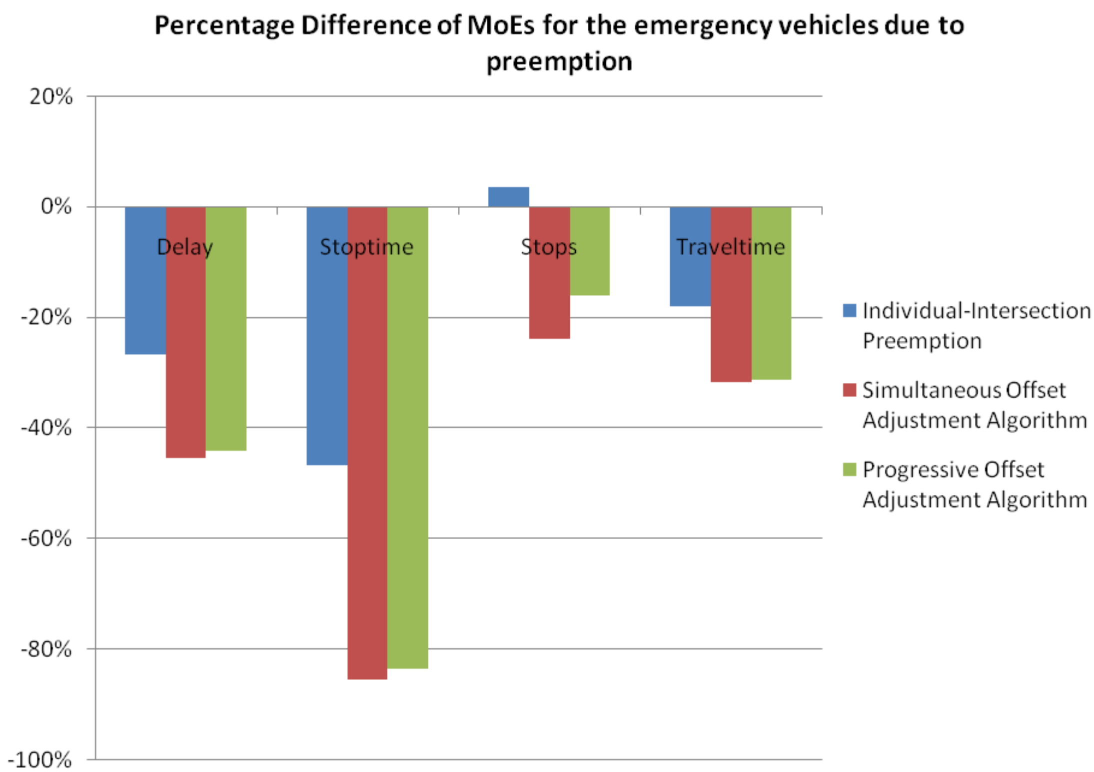

Figure 13 - Comparison of performance measures for the emergency vehicle with the case without preemption

Findings include:

- Delay: On average the delay for emergency vehicles when offset-based preemption was used was 45 percent less than the base case of no-preemption and 18 percent less than the case with individual-intersection preemption. The simultaneous offset-adjustment performs slightly better than the progressive offset-adjustment algorithm.
- Stop-time: There was an 85 percent reduction in average stop-time of emergency vehicles with offset-based preemption than the base case. It showed a 38 percent reduc-

tion in stop-time over individual-intersection preemption. Simultaneous offset adjustment showed a 2 percent better performance than progressive offset-adjustment.

- Number of stops: Offset-based preemption resulted in 20 percent fewer stops for emergency vehicles when compared to the base case and 23 percent fewer stops when compared to the individual-intersection preemption. Simultaneous offset-adjustment was found to reduce the number of stops by 8 percent more than progressive offset-adjustment.
- Travel-time: Average travel-time of emergency vehicles was reduced by 31 percent when compared to the base case when offset-based preemption was used and 13 percent lower than the reduction caused by individual-intersection preemption. Both algorithms resulted in nearly the same travel-time.
- Figure 14 shows a comparison of average travel-speed achieved by the emergency vehicle throughout its response route. Offset-based preemption methods showed a faster emergency vehicle movement compared to other cases. Average emergency vehicle travel speed was 16 percent higher than the individual intersection case.

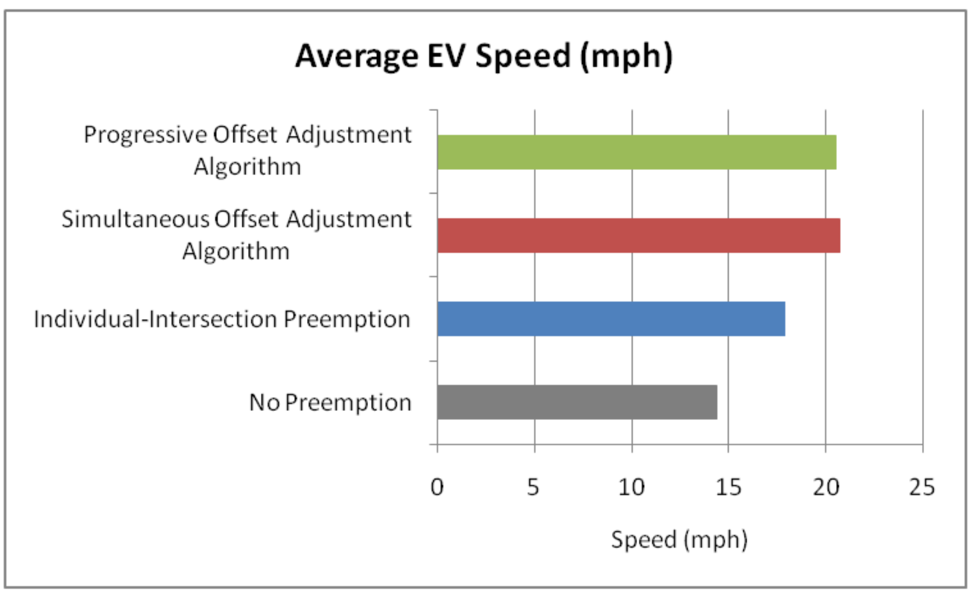

Figure 14 - Comparison of average speed of the emergency vehicle

Impact to overall traffic is important to the evaluation of the proposed preemption strategy. Figure 15 shows the percentage difference of the average delay, stop-time, stops and travel-time of the overall traffic.

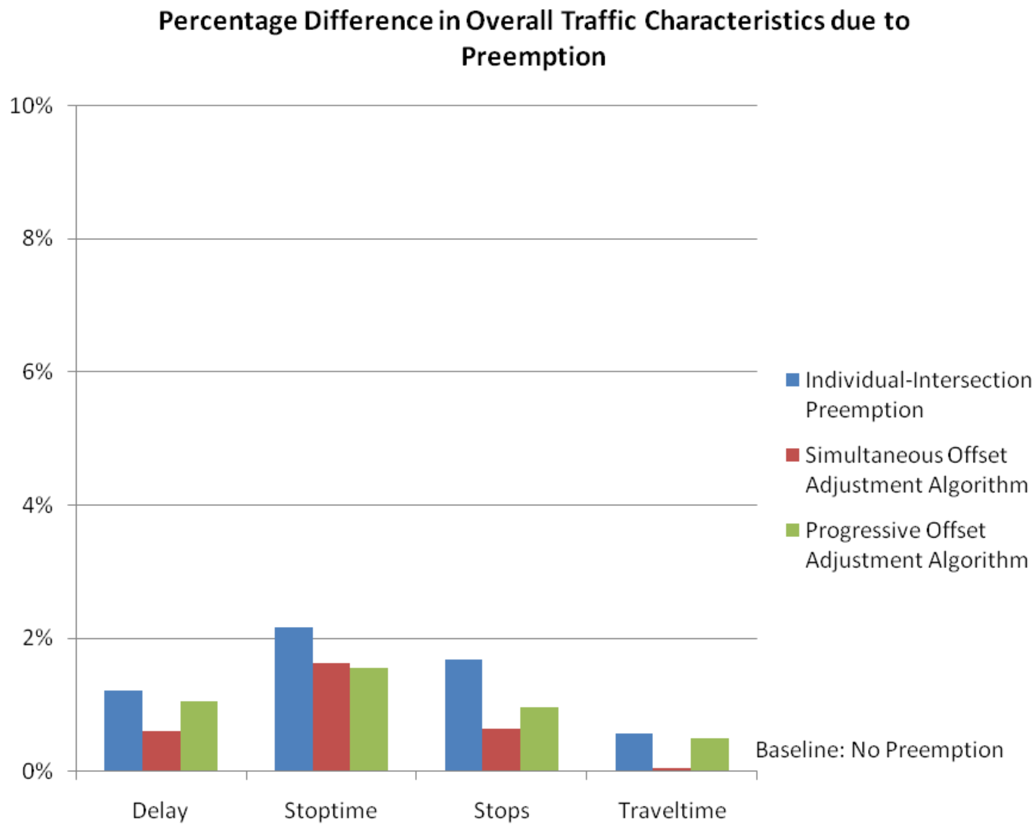

Figure 15 - Comparison of measures of effectiveness for all trips in each case with no-preemption case

Major findings include:

- Delay: Offset-based preemption had a reduced impact of 0.4 percent on overall traffic delay when compared to individual-intersection preemption. Simultaneous offset-adjustment had nearly half the impact on overall delay than progressive offset-adjustment.

- Stop-time: Average stop time of overall traffic was reduced by 0.3 percent over individual-intersection preemption. Progressive offset-adjustment was slightly better in reducing the impact on overall stop-time than simultaneous offset-adjustment.
- Stops: Offset-based preemption had 0.4 percent less impact on overall stops than progressive offset-adjustment.
- Travel-time: Preemption caused an increase in the average travel-time of vehicles in the simulation. Individual-intersection preemption increased this by 0.6 percent, whereas offset-based preemption, on an average, caused 0.3 percent increase in average travel-time of vehicles. Simultaneous offset-adjustment had 0.45 percent less impact on average vehicle travel-time than progressive offset adjustment.

Between the two algorithms, the simultaneous offset adjustment algorithm performed better than the progressive offset adjustment algorithm in most cases. This may be due to the heavy peak-hour volumes on the corridor and close spacing of intersections. Heavy volumes on the corridor can cause higher clearance times, and hence, larger adjustments to initial offsets which simply depend on route geometry and desired emergency vehicle speed. In progressive offset adjustment, adjustments are made for subsequent intersections only when the emergency vehicle reaches an intersection. When intersections are closely spaced, this may not provide enough clearance time. Simultaneous offset-adjustment causes adjustments to be made at the dispatch time, thereby giving enough time to clear the links.

4.6 Conclusion

Congestion-based offset preemption was evaluated to be an effective method for improving emergency vehicle movement through congested urban arterials. It is shown to perform better than traditional preemption of individual intersections for all performance measures tested. This indicates its ability to improve emergency response level of service and widen service radii of emergency dispatch stations without sacrificing safety. The results also indicate a lesser impact on overall traffic than with traditional preemption methods.

This study shows that offset-based preemption methods are effective in achieving route-wide preemption by incorporating real-time congestion conditions. The two algorithms tested in this research are shown to have improved performance over the traditional individual-intersection approach. Between the two algorithms, simultaneous offset-adjustment algorithm performed better.

4.7 Acknowledgements

The research presented in this paper was supported by the Mid Atlantic Universities Transportation Center (MAUTC). Mr. Amit Sidhaye, Project Manager – Signal Systems and ITS, Arlington County Division of Transportation, provided the traffic-controller data and the traffic counts for the network used in this research.

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5. Results, Conclusions and Recommendations

This chapter provides a more detailed evaluation of the results obtained from the simulation case study so that conclusions regarding the effectiveness of the proposed offset-based preemption method can be drawn. This is followed by a discussion of major findings and recommendations for future research in the area of offset-based preemption.

5.1 Evaluation of Results

Chapter 3 evaluated the concept of offset-based preemption using a small limited network. Chapter 4 evaluated the proposed method using two different algorithms to implement preemption offsets on a wide network simulation case study. Both results showed promising outcomes on the effectiveness of the proposed method. Benefits of emergency vehicle movement are shown to include reduced delays and higher average travel-speeds when compared to traditional intersection-by-intersection preemption. This section gives a more detailed summary of the simulation results for different conditions. It also gives a comparison of the two algorithms.

The results from the case study are categorized on the basis of the direction of emergency vehicle movement with respect to the peak flow direction in each simulated case. Appendix D gives tables of detailed simulation results for each incident.

5.1.1 Comprehensive Results

Values for delay, stop-time, stops and travel-time of emergency vehicles show that the proposed method performs better for emergency vehicles than individual intersection preemption. The average travel-time for emergency vehicles was 31 percent lower when compared to the case without preemption and 13 percent lower when compared to the case with traditional preemption (Figure 16). Among the two algorithms simulated, simultaneous offset-adjustment algorithm was found to perform better than progressive offset adjustment algorithm.

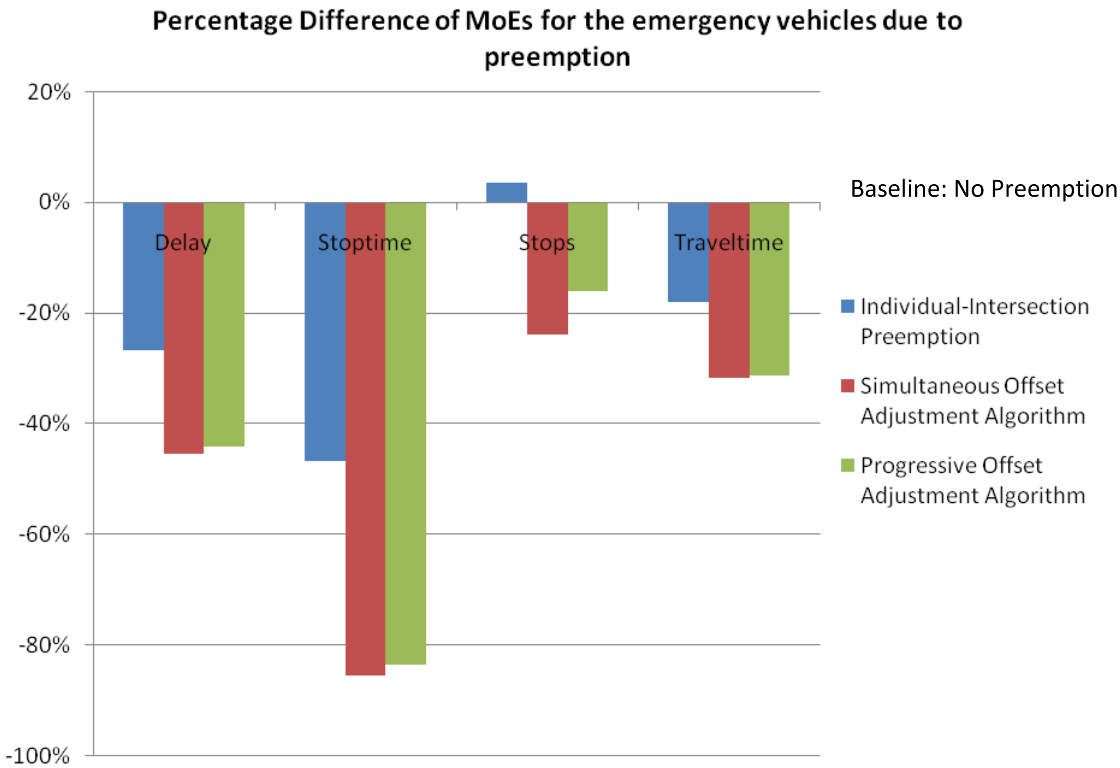

Figure 16 - Percentage difference in delay, stop-time, stops and travel time of emergency vehicles due to preemption

Figure 17 compares types of preemption for average delay, stop-time, stops and travel time for all vehicle trips in the simulation. Prioritizing emergency vehicles, clearly, impacts overall traffic movement. But the results show that individual-intersection preemption causes a greater impact on overall traffic than the offset-based algorithms. When overall delay, stops and travel-time are considered, simultaneous offset adjustment is found to perform better than progressive offset adjustment. This is because simultaneously adjusting the offsets at the start of preemption helps in clearing intersections which are closely spaced. The method of progressively adjusting offsets is unable to give enough clearance time for subsequent offsets when intersection spacing is small. Individual-intersection preemption increased travel-time of all vehicles on average by 0.6 percent whereas the impact due to simultaneous offset-adjustment was just 0.1 percent.

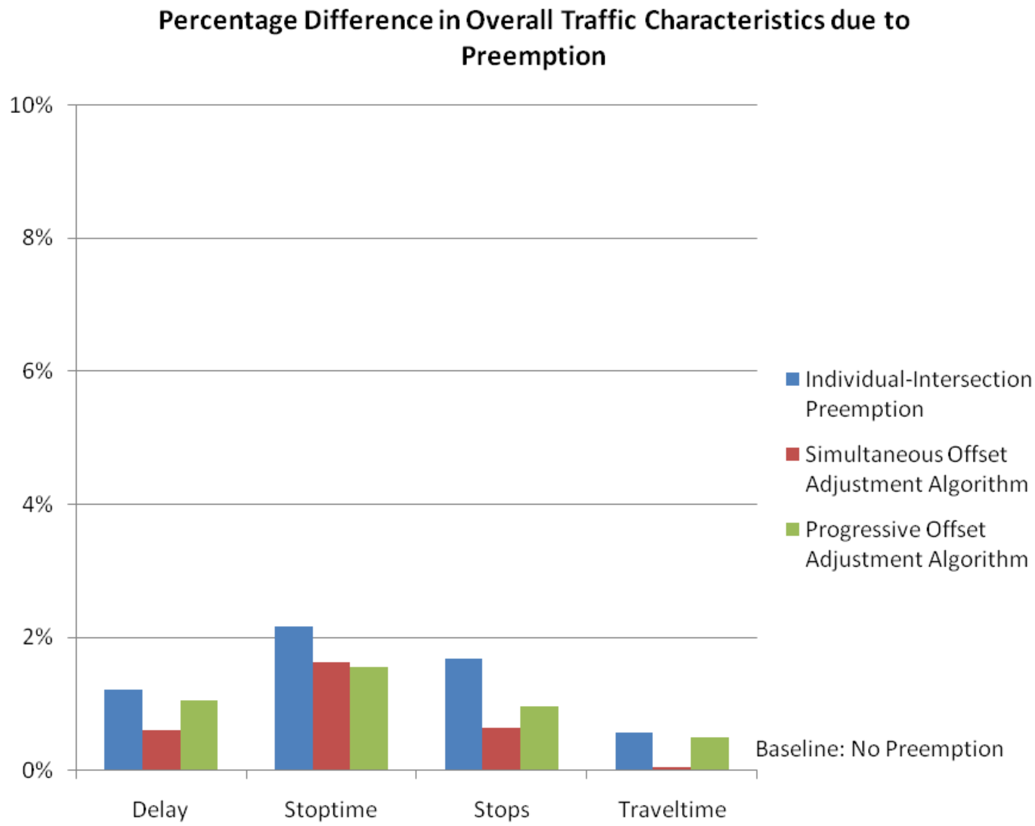

Figure 17 - Percentage difference of average traffic delay, stop-time, stops and travel-time of all trips

5.1.2 Cases with emergency vehicle moving with peak traffic flow

The results of simulation cases in which the emergency vehicle response routes were in the direction of peak traffic flow were studied. Figure 18 shows the percentage difference from no-preemption case for the delay, stop-time, stops and travel-time of the emergency vehicle. Offset-based preemption shows a 33 percent reduction in the travel-time of emergency vehicles. Both algorithms performed in a similar manner with simultaneous offset-adjustment being a little better than progressive offset adjustment algorithm.

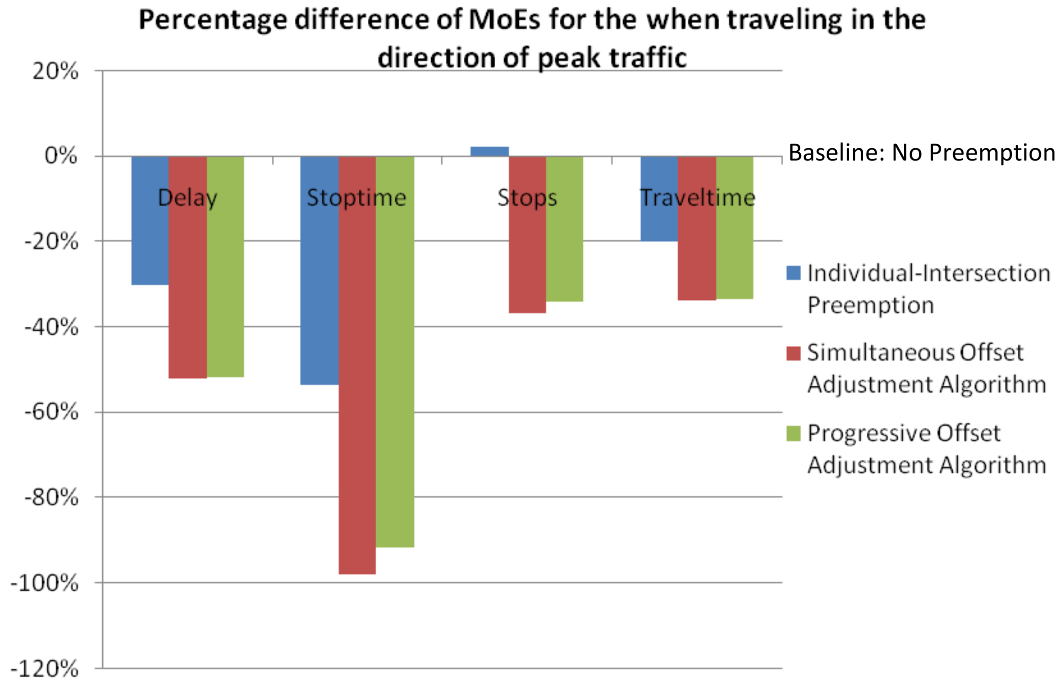

Figure 18 - Percentage difference in delay, stop-time, stops and travel-time of the emergency vehicle when traveling in the direction of peak traffic

Figure 19 shows the results for overall traffic delay, stops, stop-time and travel-time when the emergency vehicle is moving in the direction of peak traffic. In contrast to all cases of EV movement shown in Figure 17, offset-based preemption indicated improved performance to overall traffic as opposed to having a negative impact. Offset-based preemption, on average, could reduce the overall delay by 0.4 percent and simultaneous offset-adjustment algorithm could reduce overall travel-time by 0.3 percent. For all measures of effectiveness, simultaneous offset-adjustment performed better than progressive offset algorithm. Figure 20 shows a comparison of average speed attained by the emergency vehicle in each case with average EV speed during offset preemption being 13 percent more than traditional preemption.

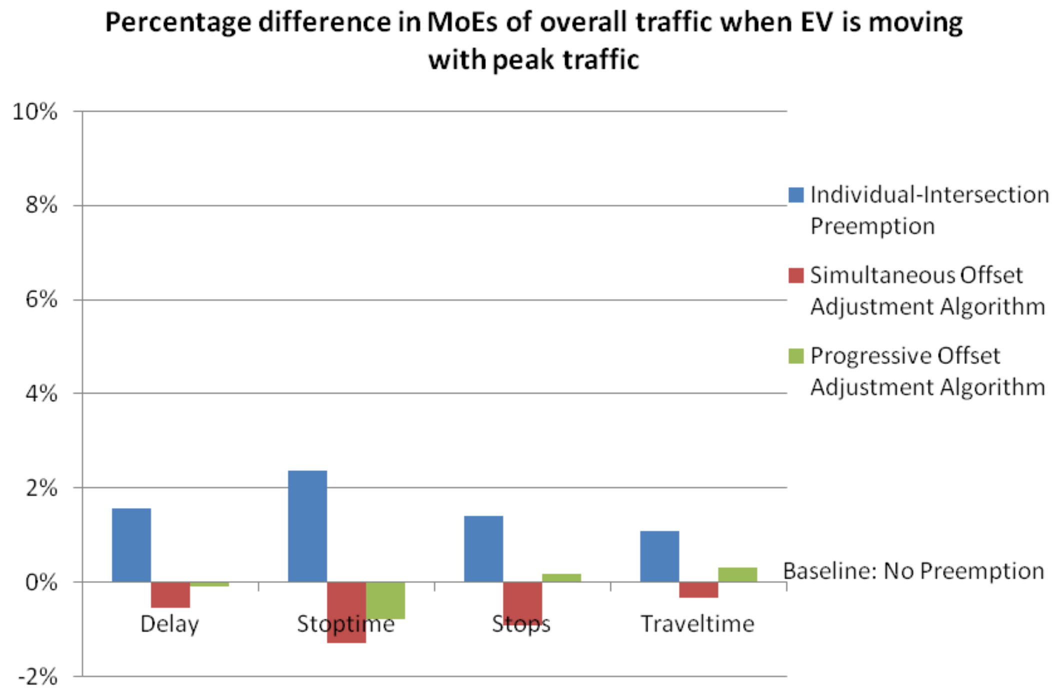

Figure 19 - Percentage difference in average delay, stop-time, stops and travel-time of all vehicle trips when the emergency response route is in the direction of peak traffic

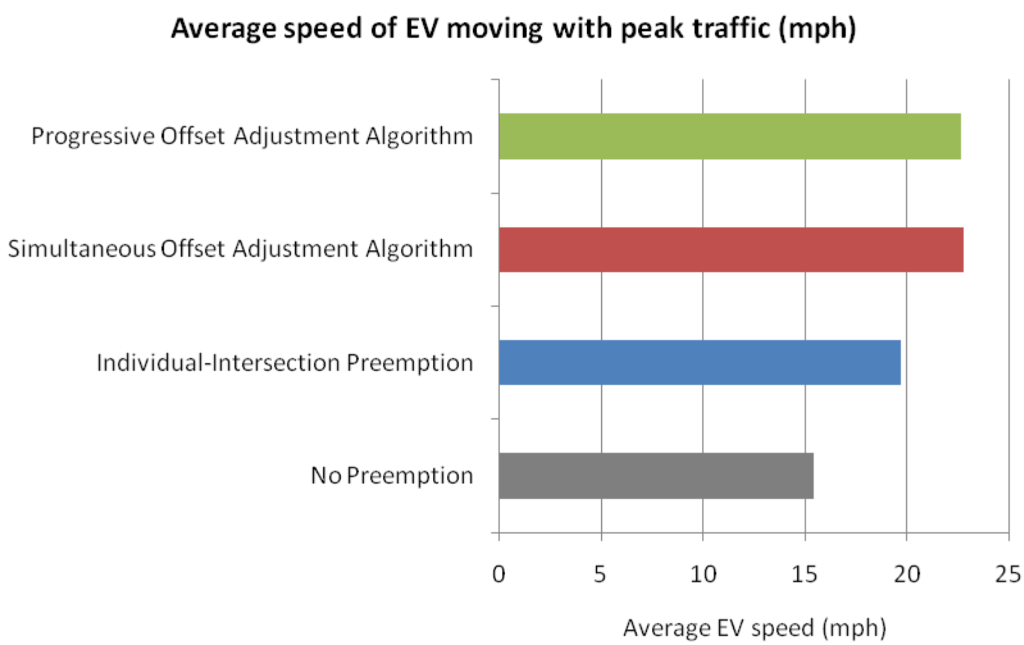

Figure 20 - Comparison of average speed of travel of the emergency vehicle in cases where the response route is parallel to peak traffic

5.1.3 Cases with emergency vehicle moving against peak traffic flow

Figure 21 shows the comparison of change in delay, stop-time, stops and travel-time for the cases in which emergency vehicle movement is against the direction of peak traffic. The performance of offset-based preemption, with respect to delay and travel-time, is better than when intersections are preempted individually. Unlike in the cases in which emergency vehicle moved in the direction of peak traffic, the progressive offset-adjustment algorithm performs better than simultaneous offset-adjustment algorithm. The number of stops was higher than individual-intersection preemption for progressive offset-adjustment. This may be the effect of the extra clearance time required due to the movement against peak traffic coupled with the comparatively smaller time the EV receives till the offset of subsequent intersection is adjusted.

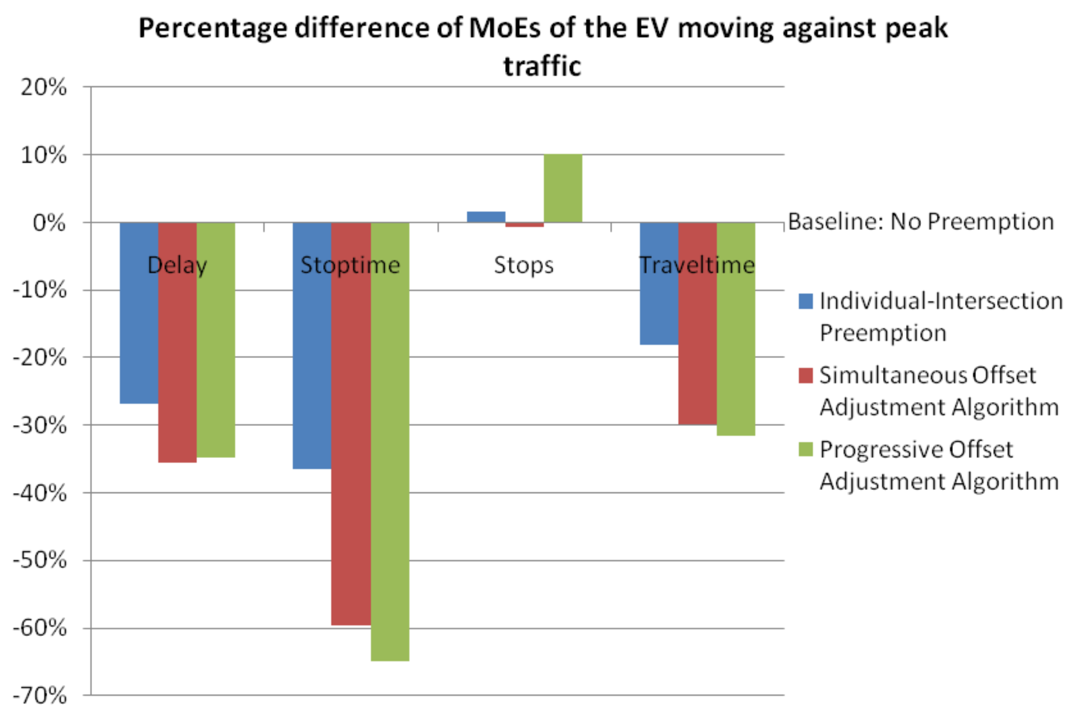

Figure 21 - Percentage difference in delay, stop-time, stops and travel time of emergency vehicle when it is moving against peak traffic direction

Figure 22 shows the comparison of all vehicle trips for response route against peak traffic direction. The impact on overall traffic parameters is higher for individual-intersection preemption. Simultaneous offset adjustment algorithm caused a reduction in the average travel-time of overall traffic. Progressive offset-adjustment algorithm caused a negligible increase in the average travel-time of overall traffic.

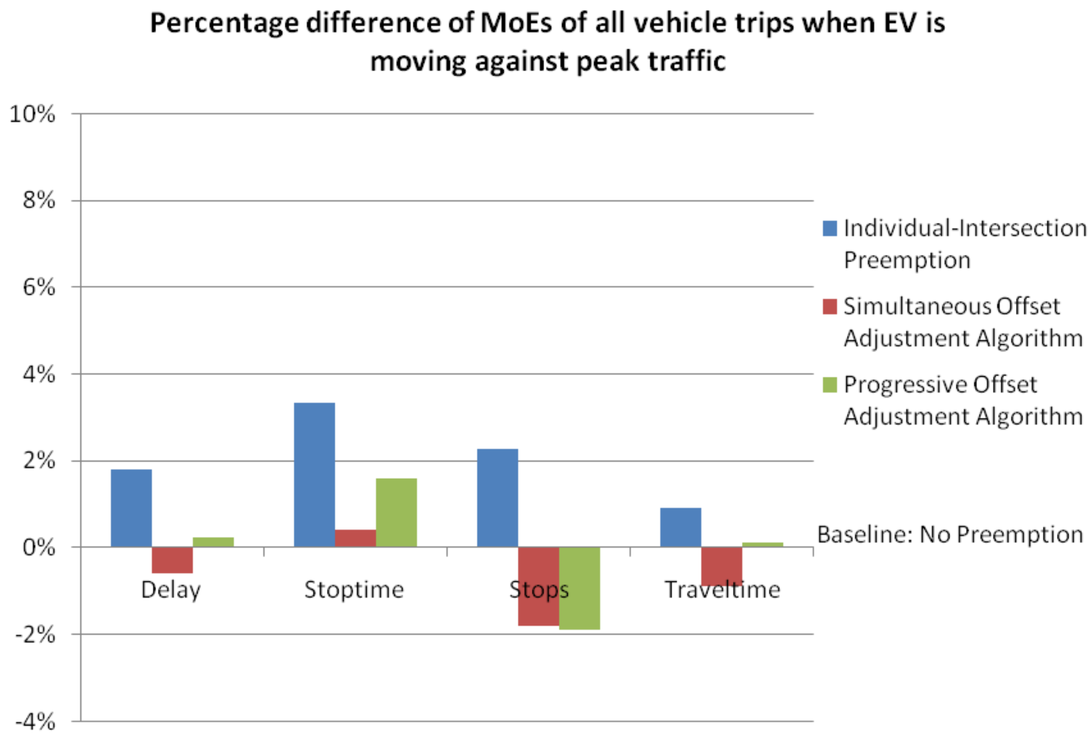

Figure 22 - Percentage deviation in average delay, stop-time, stops and travel time of all vehicle trips when EV route is against peak traffic

5.1.4 Response routes along one-way streets

Block-separated one-way streets formed by Wilson Boulevard running west and Clarendon Boulevard running east were a part of the corridor analyzed. There were four incident cases where emergency vehicle movement was along one-way streets. These cases have fewer conflicting approaches at intersections than the cases with two-way streets. Figure 23 shows the percentage difference in delay, stop-time, stops and travel-time of emergency vehicles for the three preemption cases from no-preemption case for these incident cases. Offset-based preemption, in particular, the simultaneous offset adjustment algorithm, caused a greater reduction in the performance measures of emergency vehicles than other cases.

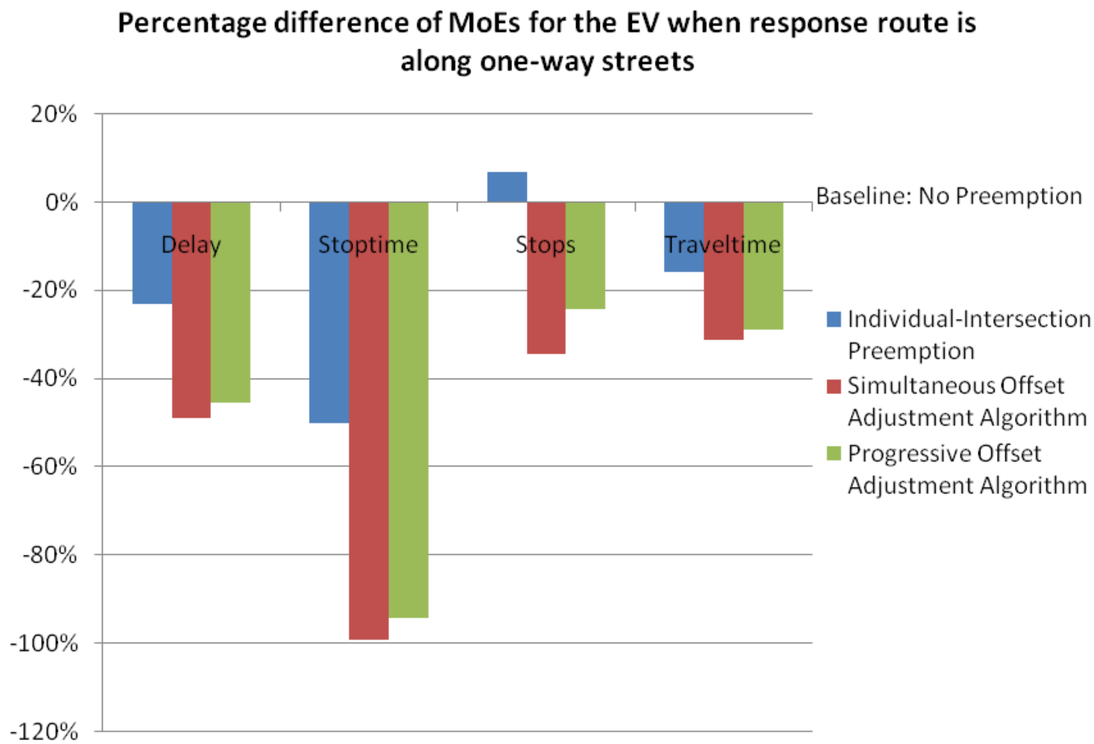

Figure 23 - Percentage difference in delay, stop-time, stops and travel-time of emergency vehicle when the response route uses one-way streets

Figure 24 shows the percentage change in delay, stop-time, stops and travel-time of all vehicles in the simulation for cases in which the emergency vehicle uses one-way streets. The overall performance measures are higher for offset-based preemption than individual intersection preemption case. This is due to the inability to preempt intersections with dual-intersection controllers independently, causing unintended preemption. Three of the major intersections along the one-way streets are controlled by dual-intersection controllers. Transition out of preemption for dual-intersection controllers after offset-based preemption is also causing delays to overall traffic.

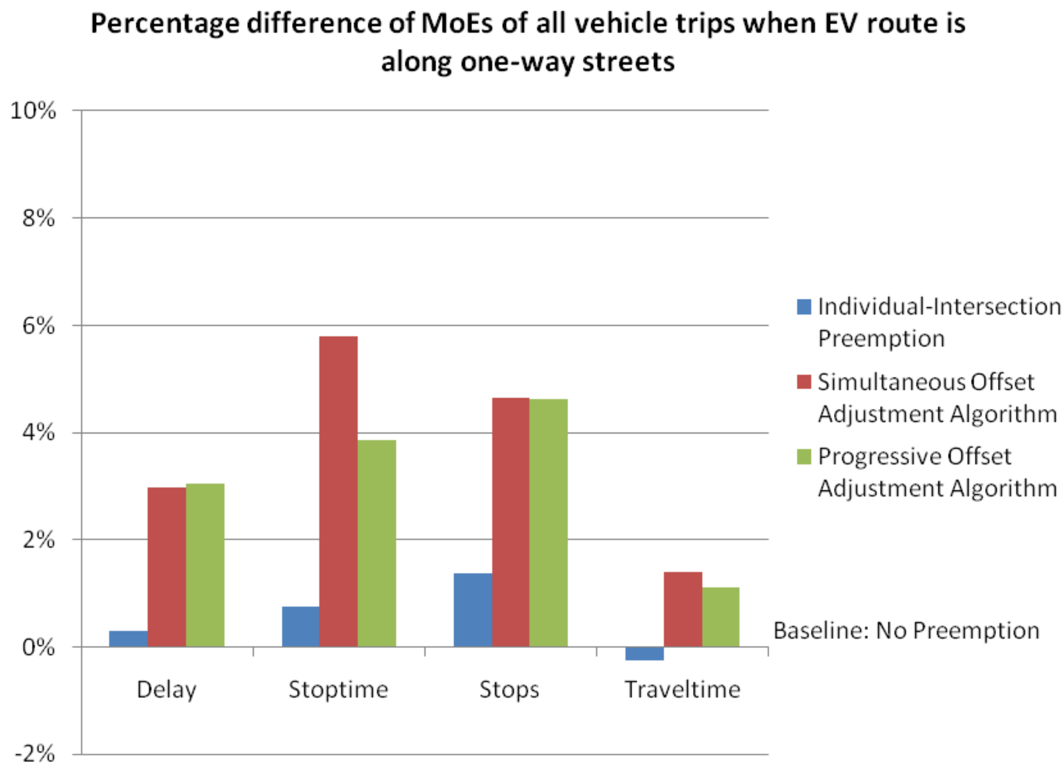

Figure 24 - Percentage difference in the average delay, stop-time, stops and travel-time of all vehicle trips when emergency vehicle route uses one-way streets

5.1.5 Analysis of Throughput

For each simulation run, the percentage of trips completed among the total number of trips generated was identified to be the throughput. Average of throughputs of each of the four simulation cases is shown in Figure 25. Even though the value falls within a small range, it should be noted that the average throughput of cases with preemption is less than the case without preemption. Among the two offset-based preemption cases simulated, the average throughput of progressive offset-adjustment was better than simultaneous preemption offset. Both the offset-based methods showed reduced throughput to traditional preemption.

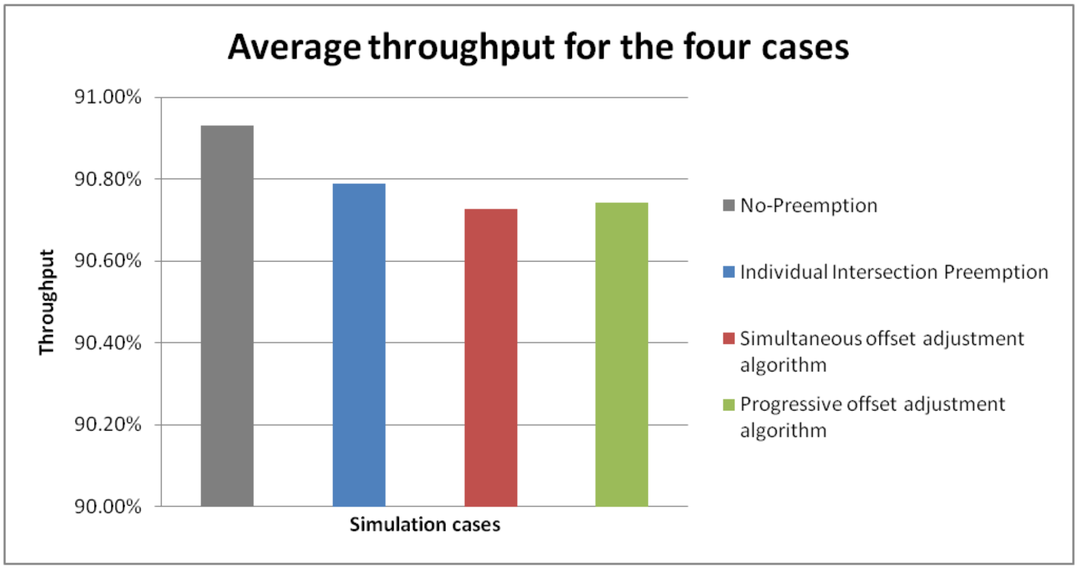

Figure 25 - Average of percentage of completed trips in each simulated preemption case.

5.2 Conclusions

The research presented in this thesis provides an application of integrating vehicle detection, congestion monitoring and controller communication for emergency vehicle preemption. The new strategy, called traffic-adaptive offset-based emergency vehicle preemption technique, is route-based and adaptive to real-time traffic conditions. It uses dynamic offsets for preemption over the entire response route. The case study was performed using microscopic simulation and shows that offset-based preemption improves emergency vehicle performance by reducing its delay, travel-time and number and duration of stops. The impact on overall traffic delay, stops, stop-time and travel-time is found to be lower than when intersection-by-intersection preemption is used. The reduction in number of stops for the emergency vehicle is due to the underlying offset calculation rule which is based on the promise that an emergency vehicle moves uninterruptedly throughout its response route. This has the potential to improve emergency vehicle safety by reducing the probability of intersection crashes. The following conclusions are made from this research:

- The offset-based preemption method caused 13 percent reduction in emergency vehicle delay and emergency vehicle travel time even for complicated routes over individual-intersection preemption.

- The offset-based preemption method makes emergency vehicle movement more consistent and uninterrupted with 23 percent fewer stops than individual-intersection preemption.
- The overall traffic delay and travel-time due to offset-based preemption was 0.4 percent and 0.3 percent, respectively less than individual-intersection preemption. It also caused 0.8 percent fewer overall traffic stops than traditional preemption methods.
- Offset-based preemption increased the average emergency vehicle speed over the response route by 16 percent with respect to individual-intersection preemption.
- For cases with response routes in the opposite direction of peak traffic, offset-based preemption was able to reduce the overall stops and travel-time by 1.8 percent and 0.5 percent respectively over the values for individual-intersection preemption.
- For cases with response route in the direction of peak traffic, offset-based preemption was able to reduce the overall stops and delays by 0.4 percent and 0.3 percent respectively over the values for individual-intersection preemption.
- When a response route involved one-way streets, offset-based preemption increased overall traffic delay and travel-time by 3 percent and 1.1 percent respectively over traditional preemption. However, the delay, stop-time, stops and travel-time of emergency vehicles were lower than individual-intersection preemption.
- The simultaneous offset-adjustment algorithm resulted in a 0.4 percent lower impact on overall traffic delay and travel-time than the progressive offset adjustment.
- Both algorithms showed almost same performance when the travel-time and average emergency vehicle speed over the route is compared.
- In most cases, progressive offset adjustment showed higher delays and stops to overall traffic than simultaneous offset adjustment.

These conclusions indicate that offset-based preemption has the potential to improve performance of emergency vehicles in congested arterial corridors. The reduction in emergency response times has the potential to allow jurisdictions to provide a larger emergency service radius for dispatch stations and to provide faster response times to save lives and property. Reducing the number of stops and having uninterrupted movement of emergency vehicles could reduce intersection crashes and thereby improve safety.

5.3 Recommendations

The findings in this study support further research on offset-based preemption methods given that congestion is increasing and emergency vehicles need to move with minimum delay to incident locations. This research focused on the theoretical feasibility of an emergency vehicle preemption method which uses dynamic offsets to enable preemption along a response route using real-time congestion levels to adjust preemption offsets. However, practical implementation requires in-depth research on available congestion monitoring methods, vehicle-infrastructure integration (VII) capabilities, and use of advanced methods for traffic predictions. Recommendations for expanding this research and additional research required on this topic are provided in this section.

5.3.1 Expanding this research:

Assumptions on Case-study: Even though the case study included in this thesis uses micro-simulation of a large network using actual signal timing, controller logic, network geometry and vehicle volumes, there are factors such as driveway access, parking lanes and pedestrian calls which were excluded due to non-availability of data. Incorporating pedestrian calls is important in studies pertaining to preemption and priority because of the need for a minimum pedestrian clearance interval.

New Transition Methods: The impact that a preemption method will have on overall traffic is primarily due to the transition logic used to switch from the preemptive phase to an operating phase [22]. The transition logic used in this thesis uses “in-step” phase transition which is similar to hold/dwell from Table 2. Alternate phase transitions need to be tested to evaluate possible reduction to the impact of offset-based preemption on overall traffic delays and stops.

Alternative Algorithms: Alternative algorithms for offset-based preemption should be tested to refine the preemption logic. In this study, the simultaneous offset adjustment method which adjusted all the offsets simultaneously performed better than progressive adjustment method in most cases because progressive adjustment waits for each link to clear prior to adjusting the next offset. An algorithm which optimizes the time of adjustment could help in refining the method. This would require additional dynamic logic in offset adjustment.

Negative Offsets: Studies which include “negative offsets” are also warranted. Negative offsets occur when a later intersection needs to be preempted before a former one. This situation occurs during heavy congestion or after-event traffic conditions when a downstream intersection has a longer queue than the upstream intersection.

Field Implementation: Future research should also consider studies of field implementation of such a system after comprehensive research and refinement of offset-based preemption logic and factors affecting its performance under various traffic conditions. Hardware-in-the-loop (HITL) simulations can provide precursors on understanding the challenges of field implementation and can provide vital statistics regarding controller behavior related to various traffic conditions.

ITS Implementation: Studies could include evaluating queue measurement, controller capabilities including inter-controller communications, and methods of formatting dynamic queue data so that offsets are adjusted in real-time for effective performance. Probe vehicles, which can communicate with controllers and collect data, can be used during testing phases. IntelliDrive^{SM} by the US Department of Transportation could be used with ordinary vehicles as probe vehicles, thereby, helping in a comprehensive statistical study using field data.

5.3.2 Additional Research

Additional research is warranted on signal priority for different applications including transit (TSP) which uses similar concept. TSP is a form of preemption which enables transit vehicles to get priority at intersections and reduce delay. The concept of offset-based preemption for emergency vehicles could be extended to be used in TSP. But this will require including additional parameters of bus-stop location and bus-stopping duration. Also, such systems may require bus-users to pre-ticket at their origin so that the system can effectively calculate the number of persons boarding and alighting the bus. This is required in precise calculation of bus stop time. Offset-based preemption may also be used in railroad preemption if several rail-road crossings need to be preempted in a short stretch. Railroad preemption might also be associated with preempting nearby intersections for clearing tracks. Logic for offset-based preemption in such cases depends on the geometry of the network.

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APPENDIX A – Algorithms Tested

The evaluation of offset-based preemption method presented in this thesis is done using microsimulation in TransModeler™. Caliper Script™ is the programming script associated with the software. It uses a macro structure to code the necessary algorithms in to the simulation network. The advantage of using a macro structure includes reusability of codes and easier debugging using GISDK Debugger™ available with TransModeler™.

Two algorithms for the proposed preemption strategy was tested separately and the codes used for these algorithms are given in the following pages of this appendix. First algorithm or the simultaneous offset adjustment algorithm uses the principle of calculating adjustments to initial offsets simultaneously over the response route at the moment of preemption using the level of queues at intersections measured at that time. Second algorithm or the progressive offset adjustment algorithm calculates initial offsets simultaneously. Adjustments are then made in a progressive manner for each intersection as the emergency vehicle traverses its response route thereby using a more recent congestion estimate.

A.1 Caliper Script™ for Simultaneous Offset Adjustment Algorithm

<table>
<tr><th>Code</th><th>Explanation</th></tr>
<tr><td><pre>Macro "Add Callback"
   // Register the macro to be called when the simulation begins
   specs = null
   specs.Name = "Set Up"
   specs.Ui   = "Final.dbd"
   specs.Type = "start"
   RegisterCallback(specs,)

   // Register the macro to be called when the simulation ends
   specs = null
   specs.Name = "Quit"
   specs.Ui = "Final.dbd"
   specs.Type = "stop"
   RegisterCallback(specs,)
endMacro</pre></td><td>Add Callback runs when simulation is started. Macros Set Up and Quit are registered then.</td></tr>
<tr><td><pre>Macro "Remove Callback"
   macro_names = {
      "Process",
      "Queue",
      "Preemption",
      "Activation",
      "Deactivation",
      "Quit",
      "Set Up",
      "Maximum Queue"
   }
   on error, notfound goto skip
   for i = 1 to macro_names.length do
      UnregisterCallback(macro_names[i])
   skip:
      end
   on error, notfound default
endMacro</pre></td><td>Remove Callback runs when simulation ends. All macros are unregistered then.</td></tr>
<tr><td><pre>Macro "Reload Callback"
   RunMacro("Remove Callback")
   RunMacro("Add Callback")
endMacro</pre></td><td>Macro for unregistering all callbacks and registering new callbacks.</td></tr>
</table>

`` Macro "Set Up" (args) data = null //ID of sensor invoking adaptive preemption data.Evsensor = 420 //Array of IDs of lanes on EV route data.LaneIds = {33603218, 33565340, 33564175, 33575750, 33564286, 33609469, 33564273} //Array of IDs of segments on EV route data.SegmentIds = {7942, 2893, 366, 7705, 2935, 7712, 2938} //Array of turn penalties in seconds data.Turnpenalties = {3, 3, 3, 3 ,3 ,3 ,12} //Array of distances of intersections traversed by the EV in feet data.Lanelengths = {180, 604, 1274, 2481, 2753, 3062, 3800} //Desired average emergency vehicle speed in ft/s data.Evspeed = 37 ```	Macro to set up input parameters
`` //Array of seconds of delay for each queued vehicle data.Queuedelays = {4, 7, 9, 11, 13, 15, 17, 52, 58, 64} ```	Calculated from arterial characteristics.
`` //Measuring initial offsets offset_num = data.LaneIds.length dim initial_offset[offset_num] for i = 1 to offset_num do initial_offset[i] = data.Lanelengths[i] / data.Evspeed end data.Offset = initial_offset ```	Computing initial offsets from distance between intersections and emergency vehicle speed
`` //Fetching sensor Ids dim first_sensor[offset_num] for i = 1 to offset_num do segment_id = data.SegmentIds[i] opts = null opts.Priority = "2" station_ids = GetSegmentSensorStations(segment_id, opts) station_id = station_ids[1][1] sensor_ids = GetStationSensors(station_id) first_sensor[i] = sensor_ids[1] end data.FirstSensor = first_sensor ```	Getting IDs of sensors on the network for activating and deactivating preemption. Sensors act as VRC in the simulation. Advanced command option *Priority* is used to filter out VRC from detection sensors.
`` dim second_sensor[offset_num] for i = 1 to offset_num do segment_id = data.SegmentIds[i] opts = null ```	Second set of sensors are used to

opts.Priority = "2" station_ids = GetSegmentSensorStations(segment_id, opts) station_id = station_ids[1][2] sensor_ids = GetStationSensors(station_id) second_sensor[i] = sensor_ids[1] end data.SecondSensor = second_sensor	detect passage of EV through intersections so that preemption can be exited.
//Registering "Process" Macro specs = null specs.Ui = "Final.dbd" specs.Name = "Process" specs.Type = "Detector" specs.IDs = {data.Evsensor} RegisterCallback(specs, data) //Registering "Preemption" Macro specs = null specs.Ui = "Final.dbd" specs.Name = "Preemption" specs.Type = "Runtime" specs.[Register Only] = "True" RegisterCallback(specs,) //Registering "Queue" Macro specs = null specs.Ui = "Final.dbd" specs.Name = "Queue" specs.Type = "runtime" specs.[Register Only] = "True" RegisterCallback(specs,) //Registering "Activation" Macro specs = null specs.Ui = "Final.dbd" specs.Name = "Activation" specs.Type = "runtime" specs.[Register Only] = "True" RegisterCallback(specs,) //Registering "Deactivation" Macro specs = null specs.Ui = "Final.dbd"	Registering macros for queue detection, offset adjustment and adaptive preemption.

specs.Name = "Deactivation" specs.Type = "runtime" specs.[Register Only] = "True" RegisterCallback(specs,) //Registering "Maximum Queue" Macro specs = null specs.Ui = "Final.dbd" specs.Name = "Maximum Queue" specs.Type = "runtime" specs.[Register Only] = "True" RegisterCallback(specs,) endMacro //Macro for the entire process - invoked when EV hits evsensor	
Macro "Process" (args) process_data = args.Data first_sensor = process_data.FirstSensor second_sensor = process_data.SecondSensor offsets = process_data.Offset lane_ids = process_data.LaneIds turn_penalties = process_data.Turnpenalties lane_lengths = process_data.Lanelengths queue_delays = process_data.Queuedelays segment_ids = process_data.SegmentIds lane_num = lane_ids.length data.Lanes = lane_ids	When EV starts from the dispatch station, this macro is run.
queued_vehicles = RunMacro("Maximum Queue", data) //Maximum queue should return an array of number of vehicles queued at each intersection for i = 1 to lane_num do if queued_vehicles[i] = 0 then clearing_time = 0 else do if queued_vehicles[i] < 10 then clearing_time =	Simultaneously, macro for counting queued vehicles at intersections on the response route is run.
queue_delays[queued_vehicles[i]] else clearing_time = queue_delays[10] end preemption_offset = offsets[i] - clearing_time + turn_penalties[i] specs = null	Preemption offsets are adjusted using those values.
data = null	Macro *preemption* is

specs.Name = "Preemption" specs.Delay = preemption_offset data.FirstSensor = first_sensor[i] data.SecondSensor = second_sensor[i] AddCallback(specs, data) end endMacro	set to run in those intervals at each intersection.
Macro "Preemption" (args) preemption_data = args.Data first_sensor = preemption_data.FirstSensor second_sensor = preemption_data.SecondSensor data = null data.Sensor = second_sensor RunMacro("Activation", data) specs = null data = null specs.Name = "Deactivation" specs.Delay = 5 data.Sensor = second_sensor AddCallback(specs, data) endMacro	*Preemption* macro involves activating preemption and deactivating preemption when EV passes the intersection. This operation is done using *Activation* and *Deactivation* macros.
//Macro for making an array of maximum queues on each link Macro "Maximum Queue" (args) queue_lanes = args.Lanes dim queue[queue_lanes.length] for i = 1 to queue_lanes.length do data.Lane = queue_lanes[i] queue[i] = RunMacro("Queue", data) end Return(queue) endMacro	This is the macro to create an array of number of queued vehicles at each intersection using *Queue* macro.
//Macro for finding queue of a lane Macro "Queue" (args) queue_lane = args.Lane vehicle_info = GetVehicles("lane", queue_lane, {{"Attributes", "True"}}) vehicle_attributes = vehicle_info.Attributes	This macro filters out the number of queued vehicles (characterized by vehicles with instan-

vehicle_ids = vehicle_info.IDs vehicle_number = vehicle_ids.length num = 0 for i = 1 to vehicle_ids.length do if vehicle_attributes[i][3] < 10 then do num = num + 1 end end queue_length = num Return(queue_length) endMacro	taneous speed below 10ft/s) at each intersection.
//Macro for deativating the activation sensor Macro "Deactivation" (args) deactivation_data = args.Data sensor_id = deactivation_data.Sensor SetSensorState(sensor_id, "Deactivate") endMacro	This macro initiates deactivation of preemption at each intersection on detecting a passing emergency vehicle.
//Macro for activating a sensor Macro "Activation" (args) sensor_id = args.Sensor SetSensorState(sensor_id, "Activate") endMacro	This macro activates VRC sensor to invoke advanced preemption even in the absence of emergency vehicle so that the link is cleared.
Macro "Quit" // Remove "Process" runtime callback on error, notfound goto skip UnregisterCallback("Process") skip: on error, notfound default endMacro	This macro unregisters *Process* macro when simulation ends.

A.2 Caliper Script™ for Progressive Offset Adjustment Algorithm

Code	Explanation
Macro "Add Callback" // Register the macro to be called when the simulation begins specs = null specs.Name = "Set Up" specs.Ui = "RTUpdate.dbd" specs.Type = "Start" RegisterCallback(specs,) // Register the macro to be called when the simulation ends specs = null specs.Name = "Quit" specs.Ui = "RTUpdate.dbd" specs.Type = "Stop" RegisterCallback(specs,) endMacro	Registers *Set Up* and *Quit* macros to be run when the simulation begins and ends.
Macro "Remove Callback" macro_names = { "Process", "Queue", "Preemption", "Activation", "Deactivation", "Quit", "Set Up", "Actdeact" } on error, notfound goto skip for i = 1 to macro_names.length do UnregisterCallback(macro_names[i]) skip: end on error, notfound default endMacro	Macro for unregistering all callbacks.
Macro "Reload Callback" RunMacro("Remove Callback") RunMacro("Add Callback") endMacro	Macro for unregistering callbacks and again registering callbacks.

Macro "Set Up" (args) data = null //ID of sensor invoking adaptive preemption data.EvSensor = 10 //Array of IDs of lanes on EV route for which queues are measured data.LaneId = {33554450, 33554439} //Array of turn penalties in seconds (turn penalties are ignored at signalized intersections) data.TurnPenalty = {0, 0} //Array of distances between signalized intersections on EV route in feet data.LinkLength = {326, 446} //Desired average emergency vehicle speed in ft/s data.EvSpeed = 37	Macro to specify input parameters.
//Array of delay caused by queued vehicle (to be calculated using basic equations) data.QueueDelay = {4, 7, 9, 11, 13, 15, 17, 52, 58, 64} //Array of preemption invoking sensor (first sensor) data.FirstSensor = {16, 18} //Array of preemption activation sensor (last sensor)	Calculated using arterial characteristics.
data.SecondSensor = {15, 17} //Measuring initial offsets purely from distances offset_num = data.LaneId.length dim initial_offset[offset_num] for i = 1 to offset_num do initial_offset[i] = data.LinkLength[i] / data.EvSpeed end data.InitialOffset = initial_offset	Computation of initial offsets from intersection spacing and emergency vehicle speed.
//Registering "Process" Macro specs = null specs.Ui = "RTUpdate.dbd" specs.Name = "Process" specs.Type = "Detector" specs.IDs = {data.EvSensor} RegisterCallback(specs, data) //Registering "Preemption" Macro specs = null specs.Ui = "RTUpdate.dbd" specs.Name = "Preemption" specs.Type = "Detector"	Registering all macros which needed to be called back later.

```
        specs.[Register Only] = "True"
        RegisterCallback(specs, )

        //Registering "Queue" Macro
        specs = null
        specs.Ui   = "RTUpdate.dbd"
        specs.Name = "Queue"
        specs.Type = "Runtime"
        specs.[Register Only] = "True"
        RegisterCallback(specs, )

        //Registering "Activation" Macro
        specs = null
        specs.Ui   = "RTUpdate.dbd"
        specs.Name = "Activation"
        specs.Type = "Runtime"
        specs.[Register Only] = "True"
        RegisterCallback(specs, )

        //Registering "Deactivation" Macro
        specs = null
        specs.Ui   = "RTUpdate.dbd"
        specs.Name = "Deactivation"
        specs.Type = "Runtime"
        specs.[Register Only] = "True"
        RegisterCallback(specs, )

        //Registering "Actdeact" Macro
        specs = null
        specs.Ui   = "RTUpdate.dbd"
        specs.Name = "Actdeact"
        specs.Type = "Runtime"
        specs.[Register Only] = "True"
        RegisterCallback(specs, )

endMacro

//Macro for the entire process - invoked when EV hits evsensor.
//This macro adds callbacks to preemption macros associated with all
invoking detectors.
Macro "Process" (args)
        process_data = args.Data
        first_sensor = process_data.FirstSensor
        second_sensor = process_data.SecondSensor
```

Process macro is invoked when EV starts from the dispatch station. It invokes of *preemption* macro.

```
        initial_offset = process_data.InitialOffset
        lane_id = process_data.LaneId
        turn_penalty = process_data.TurnPenalty
        queue_delay = process_data.QueueDelay
        lane_num = lane_id.length

        for i = 1 to lane_num do
                specs = null
                data = null
                specs.Name = "Preemption"
                specs.IDs = {first_sensor[i]}
                data.Offset = initial_offset[i]
                data.LaneId = lane_id[i]
                data.TurnPenalty = turn_penalty[i]
                data.FirstSensor = first_sensor[i]
                data.SecondSensor = second_sensor[i]
                data.QueueDelay = queue_delay
                AddCallback(specs, data)
        end
endMacro
```

This sets callbacks to preemption for each deactivation sensor for the next intersection

```
Macro "Preemption" (args)
        //Importing required data
        preemption_data = args.Data
        offset = preemption_data.Offset
        lane_id = preemption_data.LaneId
        turn_penalty = preemption_data.TurnPenalty
        first_sensor = preemption_data.FirstSensor
        second_sensor = preemption_data.SecondSensor
        queue_delay = preemption_data.QueueDelay

        //fetching queue data
        data.Lane = lane_id
        queued_vehicles = RunMacro("Queue", data)

        //recalculating offsets
        if queued_vehicles = 0 then clearing_time = 0
                else do
                        if queued_vehicles < 10 then clearing_time =
queue_delay[queued_vehicles]
                        else clearing_time = queue_delays[10]
                end
        preemption_offset = offset - clearing_time + turn_penalty - 2
```

This computes the queue for next link and calculates adjusted preemption offset. It then sets a call back for activation of preemption of that intersection.

<pre> //setting callbacks for preemption activation and deactivation specs = null data = null specs.Name = "Actdeact" specs.Delay = preemption_offset data.Sensor = second_sensor AddCallback(specs, data) endMacro</pre>	
<pre>Macro "Queue" (args) queue_lane = args.Lane vehicle_info = GetVehicles("lane", queue_lane, {{"Attributes", "True"}}) vehicle_attributes = vehicle_info.Attributes vehicle_ids = vehicle_info.IDs vehicle_number = vehicle_ids.length num = 0 for i = 1 to vehicle_ids.length do if vehicle_attributes[i][3] < 10 then do num = num + 1 end end queue_length = num Return(queue_length) endMacro</pre>	This macro finds out the number of queued vehicles in a lane (vehicles with instantaneous speed less than 10 ft/s).
<pre>//Macro for running activation and deactivation of a sensor Macro "Actdeact" (args) actdeact_data = args.Data sensor_id = actdeact_data.Sensor data = null data.Sensor = sensor_id RunMacro("Activation", data) specs = null data = null specs.Name = "Deactivation" specs.Delay = 1 data.Sensor = sensor_id AddCallback(specs, data) endMacro</pre>	This macro activates the VRC sensor for preempting the intersection even in the absence of emergency vehicles and deactivates it so that the emergency vehicle can hold preemption till it exits the intersection.

```
//Macro for activating a sensor
Macro "Activation" (args)
	sensor_id = args.Sensor
	SetSensorState(sensor_id, "Activate")
endMacro

//Macro for deativating the activation sensor
Macro "Deactivation" (args)
	deactivation_data = args.Data
	sensor_id = deactivation_data.Sensor
	SetSensorState(sensor_id, "Deactivate")
endMacro

//macro to exit the entire process
Macro "Quit"
   // Remove "Process" runtime callback
   on error, notfound goto skip
   UnregisterCallback("Process")
skip:
   on error, notfound default
endMacro
```

APPENDIX B – About Micro-simulation

Microscopic simulation provides the necessary capabilities to evaluate signal-vehicle behavioral strategies. Effective evaluation of the proposed congestion-based preemption techniques requires that the micro-simulation should realistically model the dynamics of vehicle movements and the interaction between drivers, vehicles and control systems. Other requirements include the capability of modeling vehicle sensing strategies, preemption strategies and emergency vehicle behaviors. Microscopic simulation also provides detailed measures of traffic such as travel times, instantaneous speeds, trajectories of vehicles, speeds, delays and queuing. Several micro-simulation tools are available and each of them has its own characteristics.

VISSIM is a microscopic simulation package developed by Planung Transport Verkehr (PTV) in Germany and has been in use for over 15 years [23]. It is a multi-modal simulation package which can simulate modes such as general traffic, buses, HOV, light rail, heavy rail, pedestrians and bicycles. ITS components such as variable message signs, ramp metering, lane control signs, incident diversion, priority control etc. can also be modeled in VISSIM. The latest versions come with 3D visualization capabilities and virtually no limit on the numbers of nodes and links [24]. It also provides an Application Programming Interface (API) for more customized simulation modeling. VISSIM also has capabilities for interfacing with major firmware. Limitations include difficulty in modeling large networks due to the need to input too many parameters.

CORSIM, developed by FHWA, is the most widely used simulation tool in the United States [25]. Along with TRAFED, TRAFVU and tools such as TShell, it forms a package TSIS (Traffic Software Integrated Systems). CORSIM consists of NETSIM for network simulation and FRESIM for freeway simulation. CORSIM is suitable for microsimulation studies of a single intersection or a small network [26]. Large networks are labor-intensive to build. Some of the limitations of CORSIM include inability to model two-way left turn lanes, roundabouts, U-turns, transit signal priority, emergency vehicle preemption systems and variable message signs.

AIMSUN (Advanced Interactive Microscopic Simulator for Urban and Non-urban Networks) is a micro-simulation tool developed by the Department of Statistics and Operational Research, Universitat Poletecnica de Catalunya, Barcelona, Spain [27]. It has been in use for over 20 years and is now maintained by Transport Simulation Systems (TSS). AIMSUN includes four modules, a traffic network editor, a network database, a simulator module and an API. Version 6 of AIMSUN features 3D visualization and the ability to interface with applications such as EMME 2/3, VISSIM, SYNCHRO etc. It cannot, however, model various parking behaviors and lacks programmability in vehicle behaviors such as car-following or gap acceptance.

TransModeler is a powerful and versatile traffic simulation tool developed by the Caliper Corporation with 3D visualization and simulation capabilities [28]. Version 2.5 has capabilities to call C or C++ functions into its GISDK based API. It can simulate any transportation network with a comprehensive and flexible user interface based on its GIS architecture and database structure. Some of the key features of TransModeler include dynamic trip routing, trip modeling using Origin-Destination matrix or turn movement volumes. TransModeler can efficiently simulate public transportation as well as special vehicles such as emergency vehicles. TransModeler uses multiple classes of vehicles with varying physical properties and performance parameters for simulation. It also allows users to custom-define their own vehicle fleet or use predefined fleets. Acceleration, deceleration, car-following, lane-changing, merging, yielding and intersection movements are simulated with precision and users are allowed to change settings for these models. Driver aggressiveness, vehicle characteristics and road geometry can also be customized. Other capabilities of TransModeler includes dynamic traffic assignment, mesoscopic, microscopic, macroscopic and hybrid simulation, advanced signal controller configurations, ITS and public transportation. ITS applications such as lane-use signs, flexible variable message signs, variable speed limit signs, ramp metering and real-time traffic rerouting can be modeled. HOV lanes, HOT lanes and lane usage restrictions can also be configured in TransModeler.

Appendix C – Sample UTDF File

Data for controllers at intersections, lane properties, turn volumes and intersection properties for this research were taken from Arlington County Division of Transportation in Universal Traffic Data Format generated by Synchro™. Excerpts from the data are given in the modules below.

Lane Group Data

```
RECORDNAME,INTID,NBL,NBT,NBR,SBL,SBT,SBR,EBL,EBT,EBR,WBL,WBT,WBR
Lanes,46,0,1,1,1,1,1,1,2,0,1,2,0
Shared,46,0,1,,0,0,,0,2,,0,2,
Width,46,12,12,12,12,12,12,12,12,12,12,12,12
Storage,46,,,50,105,,200,400,,,110,,
StLanes,46,,,1,1,,1,1,,,1,,
Grade,46,,-4,,,0,,,3,,,2,
Speed,46,,25,,,25,,,30,,,30,
FirstDetect,46,5,46,5,46,46,46,5,5,,46,5,
LastDetect,46,0,0,0,0,0,0,0,0,,0,0,
Phase1,46,,2,,,2,,,1,,3,1,
Phase2,46,,,,,,,,,,3,
PermPhase1,46,2,,2,2,,2,1,,,,,
DetectPhase1,46,2,2,2,2,2,2,0,0,,3,0,
IdealFlow,46,1900,1900,1900,1900,1900,1900,1900,1900,1900,1900,1900,1900
LostTime,46,4,4,4,4,4,4,4,4,4,4,4,4
SatFlow,46,0,1834,1615,1770,1863,1583,1743,3462,0,1752,3451,0
SatFlowPerm,46,0,1402,1615,738,1863,1583,198,3462,0,1752,3451,0
SatFlowRTOR,46,0,0,71,0,0,24,0,7,0,0,22,0
HeadwayFact,46,0.97,0.97,0.97,1.00,1.00,1.00,1.02,1.02,1.02,1.01,1.01,1.01
Volume,46,218,84,118,76,70,22,40,854,44,72,410,46
Peds,46,0,0,0,0,0,0,0,0,0,0,0,0
Bicycles,46,0,0,0,0,0,0,0,0,0,0,0,0
PHF,46,0.92,0.92,0.92,0.92,0.92,0.92,0.92,0.92,0.92,0.92,0.92,0.92
Growth,46,100,100,100,100,100,100,100,100,100,100,100,100
HeavyVehicles,46,2,2,2,2,2,2,2,2,2,2,2,2
BusStops,46,0,0,0,0,0,0,0,0,0,0,0,0
Midblock,46,,0,,,0,,,0,,,0,
Distance,46,,315,,,593,,,926,,,926,
TravelTime,46,,8.6,,,16.2,,,21.0,,,21.0,
```

Layout Data

```
IN-
TID,INTNAME,TYPE,X,Y,NID,SID,EID,WID,NEID,NWID,NNAME,SNAME,ENAME,WNAME,NENAME,NWNA
ME
46,Wilson Blvd. & McKinley Rd.,0,11868066,7003943,12,67,47,43,,,McKinley Rd.,McKinley Rd.,Wilson
Blvd.,Wilson Blvd.,,
47,Wilson Blvd. & Patrick Henry Dr.,0,11868989,7003868,33,65,490,46,,,Patrick Henry Dr.,Patrick Henry
Dr.,Wilson Blvd.,Wilson Blvd.,,
49,Wilson Blvd. & Larrimore Midblk Xing,0,11870715,7004257,,85,40,490,,,,Larrimore Midblk
Xing,Wilson Blvd.,Wilson Blvd.,,
51,Wilson Blvd. & N. Jefferson St.,0,11873424,7005137,29,30,53,40,,,N. Jefferson St.,N. Jefferson
St.,Wilson Blvd.,Wilson Blvd.,,
53,Wilson Blvd. & N. Edison St.,0,11875170,7005720,25,,54,51,,,N. Edison St.,,Wilson Blvd.,Wilson Blvd.,,
54,Wilson Blvd. & N. George Mason Dr.,0,11875489,7005822,20,1,55,53,,,N. George Mason Dr.,N.
George Mason Dr.,Wilson Blvd.,Wilson Blvd.,,
55,Wilson Blvd. & N. Abington St.,0,11876470,7006151,,21,88,54,,,,N. Abington St.,Wilson Blvd.,Wilson
Blvd.,,
56,Wilson Blvd. & N. Glebe Rd.,0,11877494,7006513,93,6,100,88,,,N. Glebe Rd.,N. Glebe Rd.,Wilson
Blvd.,Wilson Blvd.,,
```

Controller Phasing Data

```
RECORDNAME,INTID,D1,D2,D3,D4,D5,D6,D7,D8,D9,D10,D11,D12,D13,D14,D15,D16
BRP,46,111,112,113,,,,,,311,312,411,412,321,322,421,422
MinGreen,46,5,5,5,,,,,,,,,,,,,
MaxGreen,46,35,28,8,,,,,,,,,,,,,
VehExt,46,0.2,2,2,,,,,,,,,,,,,
TimeBeforeReduce,46,0,0,0,,,,,,,,,,,,,
TimeToReduce,46,0,0,0,,,,,,,,,,,,,
MinGap,46,0.2,2,2,,,,,,,,,,,,,
Yellow,46,4,4,4,,,,,,,,,,,,,
AllRed,46,2,3,2,,,,,,,,,,,,,
Recall,46,0,0,0,,,,,,,,,,,,,
Walk,46,7,7,,,,,,,,,,,,,,
DontWalk,46,17,20,,,,,,,,,,,,,,
PedCalls,46,12,4,,,,,,,,,,,,,,
MinSplit,46,31,35,12,,,,,,,,,,,,,
DualEntry,46,1,0,0,,,,,,,,,,,,,
InhibitMax,46,1,0,0,,,,,,,,,,,,,
Start,46,28,69,14,,,,,,,,,,,,,
End,46,69,14,28,,,,,,,,,,,,,
Yield,46,63,7,22,,,,,,,,,,,,,
Yield170,46,46,7,22,,,,,,,,,,,,,
LocalStart,46,0,41,76,,,,,,,,,,,,,
LocalYield,46,35,69,84,,,,,,,,,,,,,
LocalYield170,46,18,69,84,,,,,,,,,,,,,
```

Timing Plans for Intersections

```
PLANID,INTID,S1,S2,S3,S4,S5,S6,S7,S8,CL,OFF,LD,REF,CLR
DEFAULT,46,41,35,14,,,,,,90,28,1,1,
DEFAULT,47,52,38,,,,,,,90,36,1,1,
DEFAULT,49,,59,,31,,,,,90,70,,2,
DEFAULT,51,63,27,,,,,,,90,50,1,1,
DEFAULT,53,61,29,,,,,,,90,10,1,1,
DEFAULT,54,,43,15,32,,43,,47,90,10,3,26,
DEFAULT,55,65,25,,,,,,,90,11,1,1,
DEFAULT,56,15,66,,54,23,58,,,135,29,15,26,
DEFAULT,93,35,42,14,44,35,42,14,44,135,90,1357,26,
DEFAULT,100,,57,,33,18,39,,,90,65,5,26+,
DEFAULT,232,101,34,,,,,,,135,11,1,1,
```

60 Minute Turn-Volume Data

```
DATE,TIME,INTID,NBL,NBT,NBR,SBL,SBT,SBR,EBL,EBT,EBR,WBL,WBT,WBR
2/4/2004,1700,46,218,84,118,76,70,22,40,854,44,72,410,46
2/4/2004,1700,47,,,2,76,,42,88,1004,,2,492,32
2/4/2004,1700,49,,,,,,,,1000,,,525,
2/4/2004,1700,51,32,8,116,12,14,12,16,1084,4,44,486,2
2/4/2004,1700,53,,,,104,,22,28,1228,,,499,54
2/4/2004,1700,54,192,918,106,74,636,68,224,928,164,34,294,32
2/4/2004,1700,55,14,,66,,,,,1064,4,28,367,
2/4/2004,1700,56,32,1152,78,194,800,122,184,860,38,58,294,196
2/4/2004,1700,93,694,664,132,446,770,194,92,302,268,108,832,202
2/4/2004,1700,100,,,,70,,72,210,818,,,440,102
2/4/2004,1700,232,4,2,,38,4,50,30,592,,16,1626,66
2/4/2004,1700,328,102,88,106,22,4,22,80,498,104,60,902,98
2/4/2004,1700,490,,,,,,,,1000,,,525,
```

Appendix D – Categorized Simulation Results

This section gives a compilation of simulation results. Each table provides average value of measures of effectiveness from the five simulation runs per case. Sections D-1 to D-12 give the average values of delay, stop-time, stops and travel-time for each of the four cases for four vehicle-trip classes: all vehicle trips in the simulation, emergency vehicle trips, non-emergency vehicle trips along the response route and non-emergency vehicle trips in the opposite direction to the response route. These sections also give the average emergency vehicle speed achieved in each case and the length of emergency route. Values from these sections were used to calculate the percentage differences in Chapters 4 and 5.

D-1 Average Values of Performance Measures for Incident 1

Response Route Length = 1.324 miles

Performance Measure	Vehicle Trip Class	No Preemption	Traditional Preemption	Simultaneous Offset Adjustment Algorithm	Progressive Offset Adjustment Algorithm
Average Delay (%)	All Vehicle Trips	2.866	2.937	2.622	2.741
	Emergency Vehicle Trips*	2.686	1.175	2.131	2.128
	Trips along EV Route	3.009	2.510	2.481	2.413
	Trips opposing EV route	4.326	4.523	3.662	3.898
Average Stop-time (s)	All Vehicle Trips	1.464	1.524	1.362	1.491
	Emergency Vehicle Trips*	0.732	0.305	0.772	0.682
	Trips along EV Route	1.370	1.050	1.039	1.008
	Trips opposing EV route	1.607	1.756	1.308	1.334
Average Stops (no.)	All Vehicle Trips	3.749	3.854	3.349	3.361
	Emergency Vehicle Trips*	2.500	1.500	3.500	4.000
	Trips along EV Route	3.095	2.743	2.682	2.602
	Trips opposing EV route	4.378	4.614	3.541	4.006
Average Travel-time (s)	All Vehicle Trips	273.727	277.079	250.419	263.512
	Emergency Vehicle Trips*	275.941	185.277	242.631	212.326
	Trips along EV Route	332.758	294.671	290.705	291.881
	Trips opposing EV route	462.807	478.261	400.121	421.686
Average Speed (mph)	Emergency Vehicle*	17.273	25.726	19.645	22.448

*This incident case represents a response route with numerous non-signalized intersections and widely spaced signalized intersections. Moreover, the response route is against peak traffic flow. Here, the individual-intersection preemption performed better than offset-based preemption. This is due to the change in traffic conditions and the discrepancies in offset prediction when spacing between signalized intersections is more.

D-2 Average Values of Performance Measures for Incident 2

Response Route Length = 0.796 miles

Performance Measure	Vehicle Trip Class	No Preemption	Traditional Preemption	Simultaneous Offset Adjustment Algorithm	Progressive Offset Adjustment Algorithm
Average Delay (%)	All Vehicle Trips	2.803	2.816	2.925	2.922
	Emergency Vehicle Trips	2.122	1.611	1.004	0.953
	Trips along EV Route	3.046	3.025	3.006	3.011
	Trips opposing EV route*	-	-	-	-
Average Stop-time (s)	All Vehicle Trips	1.414	1.436	1.537	1.452
	Emergency Vehicle Trips	1.033	0.292	0.157	0.152
	Trips along EV Route	1.605	1.583	1.619	1.599
	Trips opposing EV route*	-	-	-	-
Average Stops (no.)	All Vehicle Trips	3.615	3.687	3.862	3.874
	Emergency Vehicle Trips	3.500	4.000	2.000	2.500
	Trips along EV Route	4.263	4.173	4.257	4.183
	Trips opposing EV route*	-	-	-	-
Average Travel-time (s)	All Vehicle Trips	271.528	268.512	274.086	273.587
	Emergency Vehicle Trips	195.310	164.698	127.002	132.612
	Trips along EV Route	272.753	272.499	269.267	270.122
	Trips opposing EV route*	-	-	-	-
Average Speed (mph)	Emergency Vehicle	14.672	17.399	22.563	21.609

*Since the response route is along one-way streets, there are no trips opposite to it.

D-3 Average Values of Performance Measures for Incident 3

Response Route Length = 0.699 miles

Performance Measure	Vehicle Trip Class	No Preemption	Traditional Preemption	Simultaneous Offset Adjustment Algorithm	Progressive Offset Adjustment Algorithm
Average Delay (%)	All Vehicle Trips	2.816	2.875	2.829	2.855
	Emergency Vehicle Trips	2.396	1.816	1.211	1.225
	Trips along EV Route	4.049	4.199	4.231	4.214
	Trips opposing EV route	2.566	2.327	2.206	2.203
Average Stop-time(s)	All Vehicle Trips	1.441	1.485	1.445	1.454
	Emergency Vehicle Trips	1.135	0.721	0.277	0.351
	Trips along EV Route	1.511	1.578	1.573	1.552
	Trips opposing EV route	1.076	0.950	0.872	0.899
Average Stops (no.)	All Vehicle Trips	3.669	3.742	3.697	3.703
	Emergency Vehicle Trips	3.500	3.500	2.000	2.500
	Trips along EV Route	4.009	4.242	4.121	4.201
	Trips opposing EV route	2.734	2.369	2.433	2.392
Average Travel-time (s)	All Vehicle Trips	268.246	275.007	272.530	271.025
	Emergency Vehicle Trips	198.376	163.661	127.317	131.200
	Trips along EV Route	435.413	448.501	454.088	450.234
	Trips opposing EV route	309.197	277.857	269.055	271.624
Average Speed (mph)	Emergency Vehicle	12.685	15.376	19.765	19.180

D-4 Average Values of Performance Measures for Incident 4

Response Route Length = 0.492 miles

Performance Measure	Vehicle Trip Class	No Preemption	Traditional Preemption	Simultaneous Offset Adjustment Algorithm	Progressive Offset Adjustment Algorithm
Average Delay (%)	All Vehicle Trips	2.869	2.932	2.907	2.915
	Emergency Vehicle Trips	1.995	1.100	0.884	0.921
	Trips along EV Route	3.849	4.391	3.981	3.995
	Trips opposing EV route*	-	-	-	-
Average Stop-time(s)	All Vehicle Trips	1.472	1.540	1.516	1.525
	Emergency Vehicle Trips	1.052	0.234	0.165	0.171
	Trips along EV Route	1.800	2.149	1.926	1.985
	Trips opposing EV route*	-	-	-	-
Average Stops (no.)	All Vehicle Trips	3.705	3.810	3.828	3.825
	Emergency Vehicle Trips	4.000	4.500	3.000	3.500
	Trips along EV Route	5.240	5.778	5.295	5.441
	Trips opposing EV route*	-	-	-	-
Average Travel-time (s)	All Vehicle Trips	274.071	277.419	275.898	276.114
	Emergency Vehicle Trips	159.457	105.803	92.768	95.386
	Trips along EV Route	365.149	409.975	376.928	377.233
	Trips opposing EV route*	-	-	-	-
Average Speed (mph)	Emergency Vehicle	11.108	16.741	19.093	18.569

*Since the response route is along one-way streets, there are no trips opposite to it.

D-5 Average Values of Performance Measures for Incident 5

Response Route Length = 1.034 miles

Performance Measure	Vehicle Trip Class	No Preemption	Traditional Preemption	Simultaneous Offset Adjustment Algorithm	Progressive Offset Adjustment Algorithm
Average Delay (%)	All Vehicle Trips	2.748	2.896	2.893	2.889
	Emergency Vehicle Trips	2.098	2.227	1.593	1.621
	Trips along EV Route	3.681	3.410	3.687	3.652
	Trips opposing EV route	3.168	3.163	3.247	3.256
Average Stop-time(s)	All Vehicle Trips	1.376	1.507	1.491	1.454
	Emergency Vehicle Trips	0.795	0.963	0.052	0.112
	Trips along EV Route	2.163	2.009	2.155	2.223
	Trips opposing EV route	1.582	1.596	1.628	1.629
Average Stops (no.)	All Vehicle Trips	3.620	3.841	3.774	3.751
	Emergency Vehicle Trips	3.000	5.000	1.000	1.500
	Trips along EV Route	4.338	4.078	4.444	4.312
	Trips opposing EV route	3.979	3.946	4.115	4.121
Average Travel-time (s)	All Vehicle Trips	265.039	273.769	276.252	274.334
	Emergency Vehicle Trips	210.195	218.201	180.295	192.632
	Trips along EV Route	337.826	312.564	338.604	338.126
	Trips opposing EV route	293.213	290.205	297.419	299.243
Average Speed (mph)	Emergency Vehicle	17.709	17.060	20.646	19.324

D-6 Average Values of Performance Measures for Incident 6

Response Route Length = 0.500 miles

Performance Measure	Vehicle Trip Class	No Preemp-tion	Traditional Preemption	Simultane-ous Offset Adjustment Algorithm	Progressive Offset Ad-justment Algorithm
Average Delay (%)	All Vehicle Trips	2.880	2.885	2.852	2.854
	Emergency Vehicle Trips	0.937	0.954	0.640	0.621
	Trips along EV Route	4.424	4.471	5.066	4.781
	Trips opposing EV route	4.015	3.935	4.227	4.113
Average Stop-time(s)	All Vehicle Trips	1.509	1.497	1.467	1.471
	Emergency Vehicle Trips	0.298	0.270	0.042	0.089
	Trips along EV Route	2.344	2.431	2.793	2.617
	Trips opposing EV route	1.991	1.991	2.172	2.045
Average Stops (no.)	All Vehicle Trips	3.760	3.819	3.718	3.726
	Emergency Vehicle Trips	2.000	2.500	1.000	0.500
	Trips along EV Route	6.315	6.315	6.876	6.772
	Trips opposing EV route	5.742	5.674	5.751	5.521
Average Travel-time (s)	All Vehicle Trips	272.784	272.652	272.389	272.447
	Emergency Vehicle Trips	94.882	95.894	77.034	75.025
	Trips along EV Route	405.238	399.586	452.467	440.216
	Trips opposing EV route	371.871	364.836	382.914	375.124
Average Speed (mph)	Emergency Vehicle	18.971	18.771	23.366	23.992

D-7 Average Values of Performance Measures for Incident 7

Response Route Length = 0.846 miles

Performance Measure	Vehicle Trip Class	No Preemption	Traditional Preemption	Simultaneous Offset Adjustment Algorithm	Progressive Offset Adjustment Algorithm
Average Delay (%)	All Vehicle Trips	2.810	2.777	2.837	2.811
	Emergency Vehicle Trips	4.572	2.996	1.476	1.516
	Trips along EV Route	3.879	3.887	4.133	4.128
	Trips opposing EV route	3.669	3.747	3.977	3.954
Average Stop-time(s)	All Vehicle Trips	1.431	1.397	1.445	1.435
	Emergency Vehicle Trips	3.677	1.934	0.521	0.579
	Trips along EV Route	2.394	2.368	2.506	2.466
	Trips opposing EV route	2.071	2.097	2.246	2.148
Average Stops (no.)	All Vehicle Trips	3.679	3.575	3.677	3.678
	Emergency Vehicle Trips	5.000	4.000	3.500	3.500
	Trips along EV Route	4.553	4.713	4.877	4.853
	Trips opposing EV route	5.074	5.031	5.350	5.244
Average Travel-time (s)	All Vehicle Trips	268.734	268.253	272.096	271.025
	Emergency Vehicle Trips	344.051	249.438	158.275	159.587
	Trips along EV Route	342.020	345.891	365.305	256.872
	Trips opposing EV route	325.272	331.591	351.094	344.196
Average Speed (mph)	Emergency Vehicle	8.852	12.210	19.242	19.084

D-8 Average Values of Performance Measures for Incident 8

Response Route Length = 0.754 miles

Performance Measure	Vehicle Trip Class	No Preemption	Traditional Preemption	Simultaneous Offset Adjustment Algorithm	Progressive Offset Adjustment Algorithm
Average Delay (%)	All Vehicle Trips	2.778	2.871	2.767	2.788
	Emergency Vehicle Trips	1.806	1.194	0.783	0.874
	Trips along EV Route	3.871	4.342	4.026	3.989
	Trips opposing EV route	3.122	3.307	3.091	3.042
Average Stop-time(s)	All Vehicle Trips	1.399	1.478	1.385	1.391
	Emergency Vehicle Trips	0.779	0.156	0.092	0.098
	Trips along EV Route	2.154	2.511	2.275	2.248
	Trips opposing EV route	1.811	1.957	1.839	1.842
Average Stops (no.)	All Vehicle Trips	3.644	3.742	3.628	3.632
	Emergency Vehicle Trips	3.000	2.500	2.000	2.000
	Trips along EV Route	4.978	5.459	5.069	5.097
	Trips opposing EV route	4.272	4.577	4.191	4.341
Average Travel-time (s)	All Vehicle Trips	270.069	273.749	268.004	271.887
	Emergency Vehicle Trips	170.323	133.619	109.134	115.254
	Trips along EV Route	359.469	393.162	378.154	379.174
	Trips opposing EV route	277.063	289.243	273.035	281.647
Average Speed (mph)	Emergency Vehicle	15.937	20.314	24.872	23.551

D-9 Average Values of Performance Measures for Incident 9

Response Route Length = 0.835 miles

Performance Measure	Vehicle Trip Class	No Preemption	Traditional Preemption	Simultaneous Offset Adjustment Algorithm	Progressive Offset Adjustment Algorithm
Average Delay (%)	All Vehicle Trips	2.855	2.833	2.885	2.904
	Emergency Vehicle Trips	2.563	2.972	2.286	2.241
	Trips along EV Route	5.081	5.465	5.123	5.251
	Trips opposing EV route*	-	-	-	-
Average Stop-time(s)	All Vehicle Trips	1.463	1.432	1.492	1.511
	Emergency Vehicle Trips	1.670	1.933	1.270	1.272
	Trips along EV Route	2.406	2.756	2.413	2.421
	Trips opposing EV route*	-	-	-	-
Average Stops (no.)	All Vehicle Trips	3.700	3.714	3.777	3.784
	Emergency Vehicle Trips	3.500	3.500	3.000	3.000
	Trips along EV Route	7.933	8.415	7.731	7.741
	Trips opposing EV route*	-	-	-	-
Average Travel-time (s)	All Vehicle Trips	272.393	272.790	273.961	273.812
	Emergency Vehicle Trips	227.220	251.773	210.691	213.450
	Trips along EV Route	475.481	511.982	483.125	485.235
	Trips opposing EV route*	-	-	-	-
Average Speed (mph)	Emergency Vehicle	13.229	11.939	14.267	14.083

*Since the response route is along one-way streets, there are no trips opposite to it.

D-10 Average Values of Performance Measures for Incident 10

Response Route Length = 0.704 miles

Performance Measure	Vehicle Trip Class	No Preemption	Traditional Preemption	Simultaneous Offset Adjustment Algorithm	Progressive Offset Adjustment Algorithm
Average Delay (%)	All Vehicle Trips	2.888	2.902	2.878	2.887
	Emergency Vehicle Trips	2.477	1.921	1.209	1.214
	Trips along EV Route	3.184	3.703	3.589	3.680
	Trips opposing EV route	3.180	3.141	3.137	3.145
Average Stop-time(s)	All Vehicle Trips	1.498	1.530	1.477	1.468
	Emergency Vehicle Trips	1.398	0.540	0.119	0.112
	Trips along EV Route	1.700	1.918	1.848	1.847
	Trips opposing EV route	1.698	1.729	1.693	1.681
Average Stops (no.)	All Vehicle Trips	3.787	3.903	3.734	3.728
	Emergency Vehicle Trips	4.000	4.000	2.000	2.000
	Trips along EV Route	4.559	5.504	4.640	4.441
	Trips opposing EV route	4.505	4.335	4.331	4.345
Average Travel-time (s)	All Vehicle Trips	275.475	273.530	273.642	274.741
	Emergency Vehicle Trips	207.072	174.486	131.808	138.124
	Trips along EV Route	292.965	342.119	326.972	329.114
	Trips opposing EV route	290.531	280.697	281.358	285.337
Average Speed (mph)	Emergency Vehicle	12.239	14.525	19.228	18.349

D-11 Average Values of Performance Measures for Incident 11

Response Route Length = 0.703 miles

Performance Measure	Vehicle Trip Class	No Preemp-tion	Traditional Preemption	Simultane-ous Offset Adjustment Algorithm	Progressive Offset Ad-justment Algorithm
Average Delay (%)	All Vehicle Trips	2.851	2.868	2.809	2.812
	Emergency Vehicle Trips	1.963	0.685	0.775	0.741
	Trips along EV Route	2.947	2.459	1.242	1.248
	Trips opposing EV route	1.932	2.274	2.255	2.287
Average Stop-time(s)	All Vehicle Trips	1.454	1.477	1.423	1.434
	Emergency Vehicle Trips	1.199	0.138	0.151	0.143
	Trips along EV Route	1.442	1.185	0.478	1.044
	Trips opposing EV route	1.000	1.199	1.171	1.211
Average Stops (no.)	All Vehicle Trips	3.781	3.756	3.666	3.813
	Emergency Vehicle Trips	3.000	3.000	2.000	2.500
	Trips along EV Route	4.500	4.080	2.190	3.146
	Trips opposing EV route	3.234	3.603	3.242	3.499
Average Travel-time (s)	All Vehicle Trips	272.323	273.660	266.570	271.191
	Emergency Vehicle Trips	180.010	103.316	108.713	105.584
	Trips along EV Route	287.450	256.194	236.954	242.476
	Trips opposing EV route	185.257	218.085	211.760	215.746
Average Speed (mph)	Emergency Vehicle	14.059	24.496	23.280	23.970

D-12 Average Values of Performance Measures for Incident 12

Response Route Length = 0.814 miles

Performance Measure	Vehicle Trip Class	No Preemption	Traditional Preemption	Simultaneous Offset Adjustment Algorithm	Progressive Offset Adjustment Algorithm
Average Delay (%)	All Vehicle Trips	2.748	2.729	2.888	2.874
	Emergency Vehicle Trips	1.923	1.154	0.895	1.064
	Trips along EV Route	3.031	2.956	3.182	2.911
	Trips opposing EV route*	-	-	-	-
Average Stop-time(s)	All Vehicle Trips	1.384	1.370	1.513	1.462
	Emergency Vehicle Trips	0.835	0.273	0.039	0.089
	Trips along EV Route	1.601	1.561	1.713	1.666
	Trips opposing EV route*	-	-	-	-
Average Stops (no.)	All Vehicle Trips	3.583	3.594	3.816	3.798
	Emergency Vehicle Trips	3.000	3.000	1.000	1.500
	Trips along EV Route	4.313	4.274	4.595	4.425
	Trips opposing EV route*	-	-	-	-
Average Travel-time (s)	All Vehicle Trips	266.737	263.319	275.581	272.926
	Emergency Vehicle Trips	189.270	143.060	127.598	131.917
	Trips along EV Route	273.295	269.755	283.985	280.753
	Trips opposing EV route*	-	-	-	-
Average Speed (mph)	Emergency Vehicle	15.483	20.484	22.966	22.214

*Since the response route is along one-way streets, there are no trips opposite to it.