Evaluating No-notice Evacuation Strategies for an Urban Area

A Thesis

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Abstract

Although the occurrence of no-notice events is not as large as short-notice events, they do occur. The prime example of this in United States history occurred on September 11, 2001 when New York, Pennsylvania, and the Pentagon were under attack by Al-Qaeda terrorists. Nearly 2,800 fatalities occurred by the end of that day (1). In response to the no-notice events, countermeasures are needed (i.e., evacuations). In short-notice evacuations (e.g., hurricane evacuations) residents of an impacted area have time to prepare for the evacuation. That amount of time given to evacuees does not exist under no-notice evacuations.

This thesis investigates the performance of no-notice evacuation strategies for Northern Virginia. No-notice evacuations can be difficult to execute especially for densely populated urban areas that have a mixed group of road types, such those that make up Northern Virginia. The objective of this thesis is to determine whether implementing a set of signal timing plans optimized for evacuation demand and a group of congestion warning Variable Message Signs are suitable strategies for no-notice evacuations. The simulation-based Dynamic Traffic Assignment model, known as *DynusT*, was used to execute the evacuation simulations. The results show that improvements to travel time were produced due to the evacuation strategies but they were quite marginal and insignificant for most of the evacuation scenarios.

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Chapter 1. Introduction

A key duty of transportation engineers is to modify or update traffic operations in order to accommodate the different variations in traffic events. Some accommodations may be easier to implement than others, such as assigning customized signal timing plans to daily traffic events (e.g., morning and evening rush hour traffic) and to oversaturated traffic brought on by sporting or musical events. Other countermeasures require more extensive work and planning due to the complex nature of an event such as an evacuation.

Factors to consider when preparing for an evacuation include: 1) severity of an event, 2) time, and 3) available resources (2). The existence of one factor affects the importance of the next factor, thereby producing a chain-like effect. For instance, the severity of an event will dictate the amount of time required to conduct a short-notice evacuation. That amount of time will influence the availability in resources (e.g., personnel and evacuation strategies).The preparation of a short-notice evacuation (e.g., hurricane evacuation) is difficult to say the least, but preparing for an evacuation becomes more difficult when there is no notice (e.g., terrorist attacks on September 11).

The following thesis consists of six chapters beginning with Chapter 1. The remainder of Chapter 1 goes into the motivation and objectives set forth in this thesis. Chapter 2 presents a literature review existing no-notice evacuation studies and existing strategies that were used for evacuation purposes. Chapter 3 discusses the methodology, Chapter 4 presents the results, Chapter 5 summarizes the findings in Chapter 4, and Chapter 6 provides future recommendations. In addition to the chapters, this thesis contains references and an appendix.

1.1. Motivation

The general public never expected for the September 11 terrorist attacks to occur. Nearly 2,800 fatalities occurred on September 11, 2001 (1). The Pentagon made up 125 fatalities of that total (3). With the chaotic situation in placed, up to one million people evacuated Lower Manhattan by ferries and tugboats across the Hudson River to New Jersey (4). It is reassuring to know that an evacuation took place on that day in New York, but what actions were taken to evacuate the Pentagon area in Arlington, Virginia? Documented accounts of the Pentagon area evacuation were not found during the duration of creating this thesis. Perhaps, an evacuation of the Pentagon area was not needed. However, what strategies will be used if another no-noticed event occurred at the Pentagon area in which an evacuation is required in Northern Virginia?

1.2. Research Questions

The following research questions prompted the analysis of this thesis:

1. Can a simulation-based Dynamic Traffic Assignment simulation tool be used to calibrate a large network such as Northern Virginia which will then be used to model no-notice evacuations?

2. Can optimized signal timing plans enhance the travel time throughout the network and for evacuees?

3. Can congestion warning Variable Message Signs improve network conditions during an evacuation? Can it improve evacuees' travel time?

1.3. Objective

The objective of this thesis is to provide a thorough analysis of evacuation strategies, particularly for optimized signal timing plans and congestion warning Variable Message Signs, once a calibrated network was reached by using a simulation-based Dynamic Traffic Assignment tool. Within that goal, it is imperative to conclude if the strategies tested in this thesis can provide benefits for an urban area evacuation.

Chapter 2. Literature Review

This literature review discusses the usage of Variable Message Signs and optimized signal timing in the field, but it also provides a discussion of existing studies that analyzed no-notice evacuations. It is imperative to provide background information on Dynamic Traffic Assignment tools since one in particular, *DynusT*, was used in this thesis.

2.1. Variable Message Signs

Two key factors must be taken in consideration when using Variable Message Signs (VMS) as a form of motorist advisory are location and information. The physical location of a Variable Message Sign is an important factor that must be taken into consideration for motorist advisories; however, the actual information that is displayed is just as important if not more. Variable Message Signs are useful sources in providing motorists with up-to-date, enroute information on traffic conditions around them. Maier-Speredelozzi *et al*. (2006) conducted a public opinion survey of licensed Rhode Island drivers in regards to the existing highway communication sources (e.g., radio, television, internet, 511, and variable message signs) (5). The survey consisted of seven questions which ranged from the public's knowledge of evacuation routes to the public's level of compliance towards the information displayed on Variable Message Signs. From the survey, 57.1% of the participants agreed that Variable Message Signs were the one of the most useful sources of highway communication following fixed signs (65.3%) (5).

2.2. Traffic Signal Timing

In addition to advisory notices, traffic signal timing is imperative especially in an emergency case like urban evacuation. Interstates are typical used in an evacuation if available; however, other non-freeway route should be available for use. It was estimated that 70% of evacuees would not use the interstates if an evacuation were to occur in Virginia (6). Therefore, customized timing plans should be implemented specifically for evacuations. A task of creating evacuation signal timing plans is far from easy because minor roads in addition to major roads need to be served at the intersections. Chen *et al* (2007) studied urban evacuation in the metropolitan area of Washington D.C. (7). Evacuation routes and signal timing plans were analyzed under different sets of evacuation demand. The study showed that timing plans with longer cycle lengths and allocated approximately the same green time of the major roads (i.e., evacuation routes) to the minor roads worked out best under full-scale evacuation demand (7). The longer cycle length allowed for more vehicles on the major road to travel through the intersection, but it also worsened the delay on the minor roads. The key take away from that study is that the signal timing plans that are implemented will correspond to the pros and cons that the decision maker is willing to accept in an evacuation.

2.3. Dynamic Traffic Assignment Models

Dynamic Traffic Assignment (DTA) models are models that use algorithms in solving a large group of formulations and problems, which include sets of system and behavioral assumptions as well as decision variables (8) (9). Unlike static traffic assignment models, DTA models take account of traffic flows and conditions that vary over time. There are four distinctive groups of DTA models: 1) mathematical programming, 2) variational inequality, 3) optimal control, 4) simulation-based.

2.3.1. Mathematical Programming DTA Models

Mathematical programming DTA models generally develop a problem for a discrete time (9). Merchant and Nemhauser created what is now known as the M-N model, which was the earliest attempt in developing a mathematical programming DTA model. Although the M-N model was probably the first of its kind in mathematical program DTA models, it lacked realness to actual traffic behaviors. It was a dynamic traffic assignment model that formulated a mathematical program under static demand assumptions (11). Such assumptions included a fixed demand and a single destination. The M-N model was a generalized version of a typical static model.

2.3.2. Variational Inequality DTA Models

Variational Inequality (VI) DTA models look into the optimization and equilibrium problems. VI models generally attempt to include the realism in traffic behavior that mathematical programming models lacked. For instance, drivers gain experience in traveling throughout a particular area over time. Eventually they will figure out the best time to travel for any given route in that area. Friesz *et al.*, (1993) took account of such driver behavior and developed a VI model that considers departure time decisions and route choices for all Origin Destination pairs (12). They also included traffic demand and penalties for early and late arrivals.

2.3.3. Optimal Control DTA Models

Unlike the constraints defined in mathematical programming DTA models, the constraints in optimal control DTA models are assumed to be continuous in time. OD trip rates and traffic flow occur continuously over time.

Although optimal control model parameters continuously over time, it has its own set of limitations. In order to develop User Equilibrium formulation, optimal control DTA models need to make rather unrealistic assumptions to acquire equilibrium conditions. Optimal control DTA models do not have the ability to guarantee First In First Out conditions. Also, a solution procedure does not exist within optimal control DTA models.

2.3.4. Simulation-based DTA models

Simulation-based DTA models use traffic simulators to model the dynamic nature of real world traffic conditions. The focus of simulation-based DTA models is providing a solution rather than formulating a problem. The downside of using simulation-based DTA models is that they lack in capturing the expected behavior once traffic conditions become more complex. However, this may not be a big issue since traffic tends to be stochastic. Simulation-based DTA models include *CONTRAM* and *DynusT*.

2.3.4.1. CONTRAM

CONTRAM incorporates origin and destination zones into modeling time-varying demand into a network (19). A simulation will output the traffic flow, the vehicle paths, and the travel times. *CONTRAM* attempts to combine the capability of modeling complex traffic conditions from microscopic simulation models with the time-dependent nature of macroscopic simulation models.

2.3.4.2. DynusT

Dynamic Urban Systems for Transportation (*DynusT)* is the most recent development in simulation-based dynamic traffic assignment models. It was created by the Department of Civil Engineering and Engineering Mechanics at the University of Arizona (13). Users of *DynusT* will also gain exposure to *NEXTA*, which is the graphical user interface for *DynusT*. With *NEXTA*, users are able to create new *DynusT* networks or modify existing networks. It is also used to analyze *DynusT* simulation results.

2.4. Model Calibration

Calibration is a necessary step traffic modeling. In standard procedures, multiple simulation runs are performed using a default set of parameters (20). Statistical tests and

X-Y plots can be used to determine whether the default parameters are suitable in accurately modeling real world traffic conditions. If they are deemed unsuitable, then an adjustment of those default parameters is needed until they can model observed traffic conditions.

Calibration is typically followed by validation. In validation, field values untried values collected from the field are tested in the simulation model (20). This is performed in order to verify that that over-fitting does not occur in calibration.

It is common to find time dependent origin destination (OD) matrices or trip tables used as the demand inputs in simulation-based DTA models (10). Traffic data, such as traffic counts obtained from detectors and travel time, can be used in calibrating the OD matrices in the simulation-based DTA models.

2.5. No-Notice Evacuation Studies

No-notice evacuation studies have been conducted in the past decade. Chiu *et al.*, (2007) created a Joint Evacuation Destination-Route-Flow-Depature (JEDRFD) problem for a no-notice evacuation using a System Optimal (SO) DTA model (14). From their study, they proposed a network transformation (from a standard transportation planning network to an evacuation network) and a demand modeling technique. They were able to solve for the traffic assignment, the optimal evacuation destination, and the evacuation departure times all at once in their demand modeling technique. They concluded that in future research additional analysis could be performed with their proposed method on different evacuation goals, thereby testing the versatility of their method in urban areas.

Unlike a short-notice evacuation, such as a hurricane evacuation, the public does not have time to prepare to evacuate by their personal vehicles in a no-notice evacuation. Zhang *et al.*, (2010) simulated no-notice evacuations in an urban area by using an optimization modeling technique with two phases (15). In the first phase, evacuees arrive to a temporary safe destination by foot. Then the evacuees are transported by public transit in the second phase. Based on the results, the model using in the study can effectively execute a no-notice evacuation.

Chapter 3. Methodology

The methodology covers the tasks that were performed in this thesis. The tasks include steps taken prior to calibration (e.g., data collection and physical network changes), steps taken in calibration, and steps taken to simulate no-notice evacuation scenarios using two strategies: 1) optimized signal timing and 2) congestion warning Variable Message Signs.

3.1. Pre-calibration

Calibration is an essential part in simulating realistic traffic conditions; however, it is necessary to perform steps prior to calibrating the *DynusT* model of Northern Virginia. Such steps include converting the MWCOG planning model to *DynusT*, implementing actual timing plans, and making physical network. Calibration can be performed without making these adjustments; however, the end product will be a calibrated, yet inaccurate representation of the actual Northern Virginia network. In other words, avoiding the pre-calibration steps would defeat the purpose of calibration.

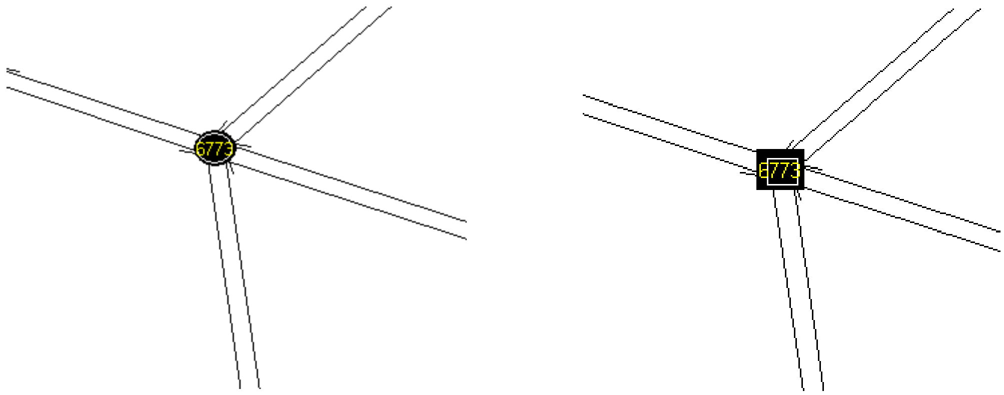
3.1.1. Network Conversion

A network conversion may be required in order obtain a dBASE format (.dbf), which is a suitable format suitable for *DynusT*. Additional tools may be needed to transfer necessary network components into the *DynusT* model. For this thesis, the Northern Virginia network was provided in a *CUBE* format. Exportation of this network into *Excel* occurred in a dBASE format (.dbf). From *Excel*, importation of the network data occurred through *DynusT*'s graphical interface known as *Nexta*. *TransCad* was used to import the network's zone and other geometric characteristics into *DynusT*.

3.1.2. Signal Timing Plans Implementation

It is imperative to present an accurate representation of a transportation network as much as possible. Therefore, signal timing plans obtained from the Synchro files of the actual transportation network should be used in the model. The implementation of such signal timing plans relies on the desired degree of fidelity for the model. For example, the *DynusT* model analyzed in this thesis only incorporated actual signal timing plans from major intersections along the 34 major arterials located throughout Northern Virginia (e.g., Route 1, Route 29, and Route 50) since the desired degree of fidelity was of a mesoscopic level (i.e., corridor-based level).

The major intersections along those arterials were transferred from the Synchro files from which they exist to the *DynusT* model through an automated process using a C# code. Syncho users may find that several intersections from their files are under a control setting of actuated-coordinated, which was the case for this thesis. Actuated-coordinated does not exist as a control setting in *DynusT*. The signalized control settings available in *DynusT* are actuated-uncoordinated and pre-timed-coordinated. Figure 15 shows the distinguishing feature among both control types in *DynusT*.



(a) **(b)**

Figure 15. (a) Actuated-Uncoordinated in *DynusT* and (b) Pre-timed-Coordinated in *DynusT*

Actuated-uncoordinated intersections are outlined with a circle while pre-timed-coordinated intersections are outlined with a square. The C# code that was used to transfer the actual signal timing plans was programmed so that the actuated-coordinated intersections from Synchro would have the control type of pre-timed- coordinated in *DynusT*.

3.1.3. Manual Update of Signal Timing Plans

A manual update of signal timing plans may be needed for intersections that remain unchanged after the automated implementation of actual signal timing plans from Synchro. Such was the case for this thesis. Intersections that were located in Arlington, Alexandria, Falls Church, and the City of Fairfax (see Figure 16) were updated with their actual signal timing plan by hand.

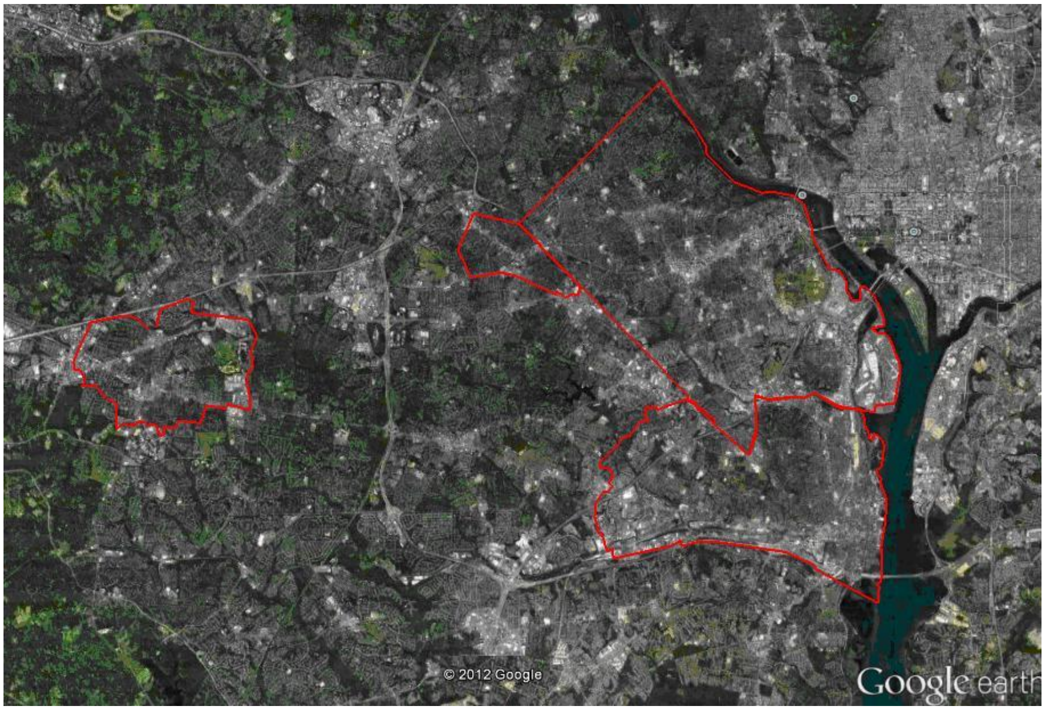
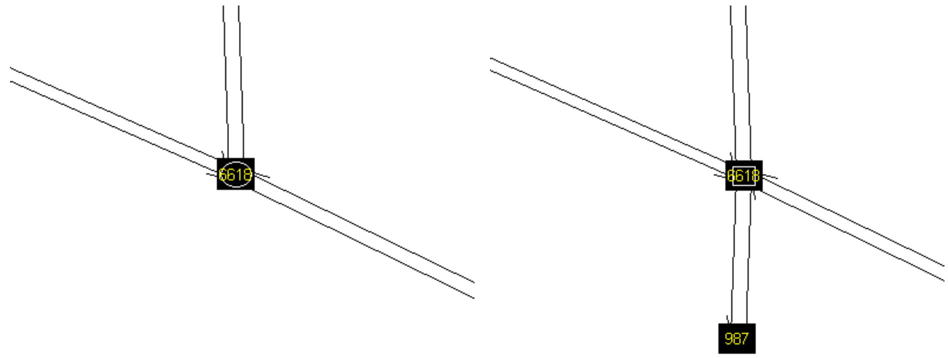


Figure 16. Locations of Manual Signal Timing Plan Implementation (17)

The signal timing plan implementation was done by hand for these locations because their Synchro files were not obtained in time for the automated transfer of signal timing plans into the *DynusT* network. The Synchro files had to be requested from each city listed above since they were not under the jurisdiction of the Virginia Department of Transportation (VDOT).

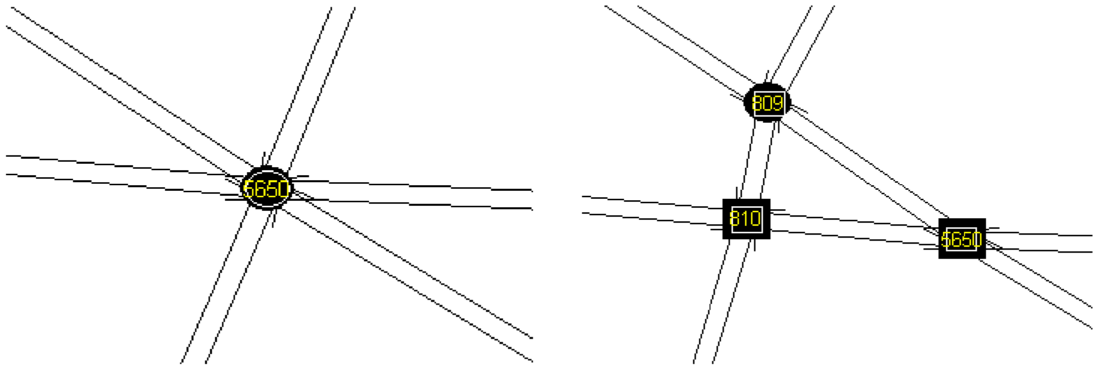
Some intersections still remained under the control setting of actuated-uncoordinated even after the automated transfer of the actual signal timing plans from Synchro to *DynusT*. The unchanged nature of the control setting was due to different physical characteristics between Syncho and *DynusT*. For instance, a missing leg from a *DynusT* intersection would prevent the transfer of the actual signal timing plan if the same intersection from Synchro had four legs. Figure 17 presents this exact example.



(a) **(b)**

Figure 17. (a) Intersection 6618 Missing Northbound Leg and (b) Intersection 6618 with 4 Legs

There were some groups of intersections that were not appropriately modeled in the *DynusT* network. For instance, in real life a certain corridor may have two intersections located very close to another, but in *DynusT* they were represented by only one node. Such a misrepresentation would also cause the intersections to remain with the actuated-uncoordinated control type setting. The corrections to the physical nature of this type of intersections had to be made before the actual signal timing plans could be implemented. Figure 18 displays the separation of one intersection into three separate intersections along Route 7, Route 402, and West Braddock Road in the *DynusT* network.



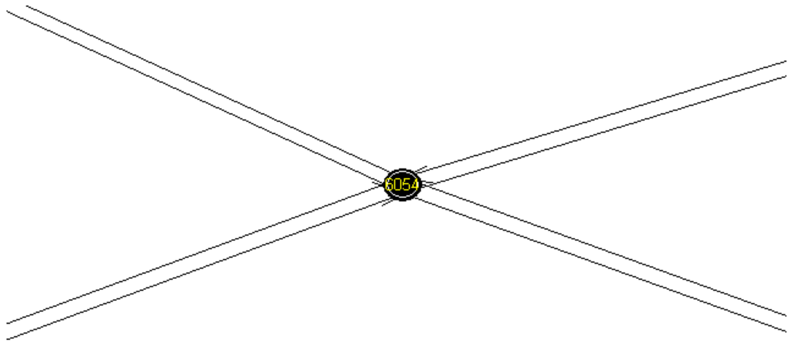
(a) **(b)**

Figure 18. (a) Inaccurate Intersection Layout and (b) Updated Intersection Layout

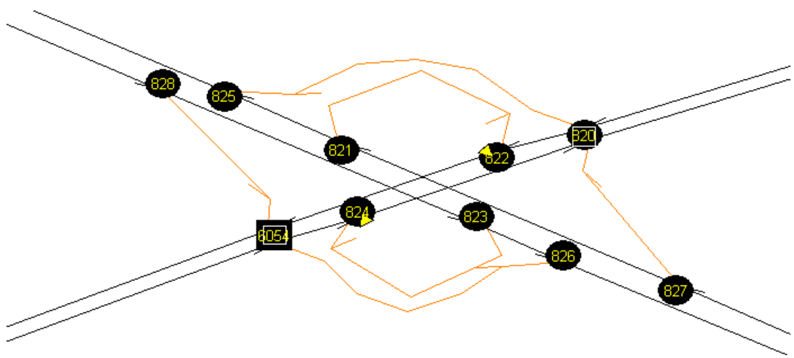
To reiterate, manual implementation of actual signal timing plans from Synchro should be conducted for intersections that were not updated after the automated transfer through the C# code. Physical changes to the intersections may be required prior to implementing the actual timing plans. Such physical changes include adding an additional leg that was missing from an intersection and producing additional intersections to correctly model a group of intersections.

3.1.4. Physical Network Changes

If needed, additional physical modifications at locations other than intersections should be made on the *DynusT* network (e.g., adjusting road connectivity). In the real world, it is common to find an arterial that overpasses another arterial. A misrepresentation in that particular layout may exist in the *DynusT* network. This was the case for the *DynusT* network analyzed for this thesis. In the *DynusT* network, one arterial should have overlapped another arterial; however they met at an at-grade intersection. In Figure 19, the at-grade intersection along Route 244 and Route 7 was changed appropriately to an interchange. Similar modifications were made at other locations in the *DynusT* network.



(a)



(b)

Figure 19. (a) Route 7 and Route 244 Intersection and (b) Route 7 and Route 244 Interchange

3.1.5. Development of Original Demand Files

It is essential to obtain or develop demand files that contain an OD matrix representing the transportation network because without the demand files no simulations can be conducted in *DynusT*. The demand files used for this thesis were based on 2010 trip data that was provided in text and binary formats. A GIS shape file, which contained the 2,191 traffic analysis zones that made up the Northern Virginia network, was provided in addition to the trip data.

The development of the original OD matrix involves the use of *CUBE*, VISUM Mulli, and Nexta. A demand file should be opened in *CUBE* and then saved as an OD table in a comma separated file. The OD table should be then formatted into a suitable *DynusT* format which contains three columns representing the origin, the destination, and the demand. Such a task can be accomplished with the use of VISUM Mulli There should be three demand files containing the OD matrices of the auto demand, the HOV demand, and the truck demand. Nexta handles the final conversion once the demand files were loaded into it.

The demand files should reflect the OD trips that occurred in the desired time frame. For this thesis, the demand files contained OD trips that were generated over a 7-hour period. This period included one hour of pre-peak demand, three hours of the PM-peak demand, and three hours of off-peak demand. The PM-peak demand was distributed nearly even in the three hour (i.e., 31.5% in the first hour, 37% in the second hour and 31.5% in the third hour). It was assumed that the demand proportion in the second PM-peak hour would reflect the peak hour factor (i.e., 0.37) from the Metropolitan Washington Council of Governments (MWCOG) network. The one hour of pre-peak demand and three hours of off-peak demand made up 10%, 8%, 5%, and 1% of the total off-peak demand. Such demand proportions were also obtained from the MWCOG network.

3.2. Calibration

3.2.1. User Equilibrium

Once the *DynusT* network models the actual transportation network geometrically and with actual signal timing plans, the calibration process may begin. As part of calibration, the user's *DynusT* network is under simulation until it reaches User Equilibrium (UE). Under an UE simulation, vehicles are assigned to several paths until the network reaches an established convergence threshold or until the simulation performs the maximum number of set iterations (13). The convergence threshold is based on the amount change in the average travel time of the network from iteration to iteration. A screen shot of the UE settings is shown in Figure 20.

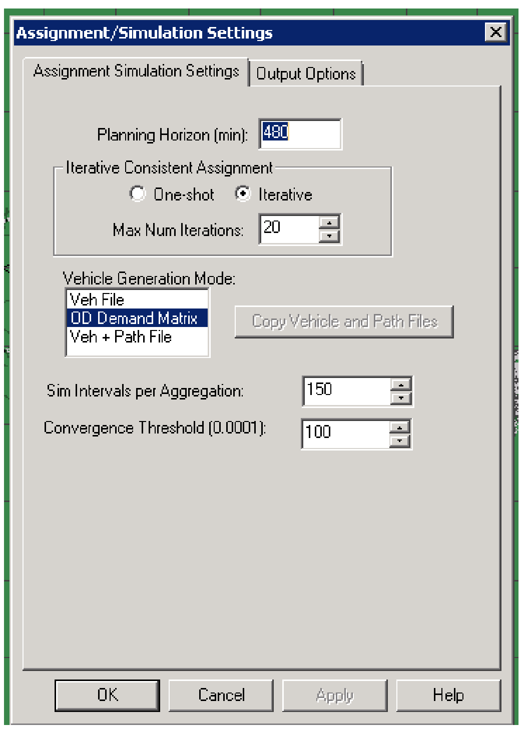


Figure 20. Simulation Settings for User Equilibrium

Prior to performing the UE run a set of assumptions should be established for the simulation settings. For this thesis, the maximum number of iterations in the UE simulation was established at 20 iterations with a planning horizon of 480 minutes. User Equilibrium is always conducted before the demand updates from OD estimation.

3.2.2. OD Estimation

Observed traffic measurements obtained from the field are needed in the OD estimation of the *DynusT* model of the desired transportation network. From the literature review, traffic counts collected from detectors are traffic measurements suitable for OD calibration. For this thesis, calibration was based on October 2010 actual traffic counts which were collected from two sources: 1) VDOT's Traffic Management System and 2) Archived Data Management System (ADMS). VDOT's Traffic Management System provided traffic counts from 16 permanent count stations and 7 short term count stations. Traffic counts from 15 ADMS stations were used for calibration. A total of 81 freeway and arterial links from the *DynusT* network were assigned with actual traffic counts. The locations of these links are presented in Figure 21.

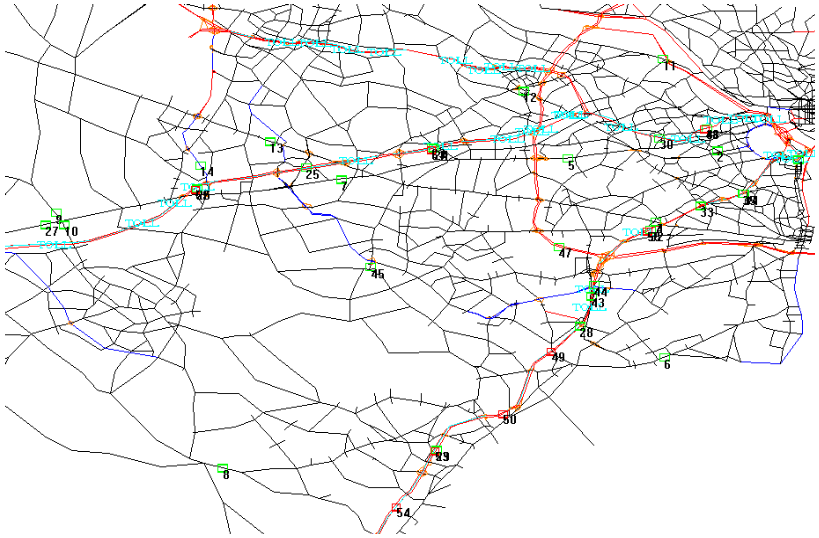


Figure 21. Actual Traffic Count Locations Used for Calibration

Calibration was performed to model normal, non-evacuation traffic conditions with the use of a tool made up of MATLAB and Python scripts which transformed the OD matrix and ultimately minimized the difference between simulated and actual traffic counts (13). In the process, the tool solves the linear quadratic optimization problem embedded in *DynusT* after the model reaches User Equilibrium. As a result, the OD matrix is updated with new OD pairs. The tool performs this iterative process (i.e., reaching user equilibrium followed by updating OD matrix) until the difference between the simulated and actual traffic counts reaches a user-defined threshold value or until calibration reaches the maximum number of established iterations.

User specifics were made in an Excel setup file prior to utilizing the calibration tool. The calibration tool required the use of this setup file which included variables such as the maximum number of calibration iterations and the activation time for calibration. The Excel setup file also includes the list of links that are associated with the actual traffic counts.

Calibration was set for 20 iterations for this thesis. The simulated traffic counts were obtained from 3:30 PM to 8:00 PM (i.e., the period that was selected for calibration purposes).

3.2.3. Traffic Flow Model Adjustments

It may be necessary to adjust the traffic flow models after calibration in order to enhance the simulated speeds. The traffic flow models contain supply parameters (e.g., breakpoint density, jam density, and minimum speed) which vary depending on the road type (e.g., freeway and arterial). In order to adjust the traffic flow models and ultimately end with a calibrated network that mimicked actual traffic conditions, the following steps should be implemented:

1. Run a one-shot simulation (i.e., non-iterative simulation).
2. Create *DynusT* time space diagrams from one-shot simulation results.
3. Compare *DynusT* time space diagrams to Inrix time space diagrams.
4. Adjust traffic flow models (particularly minimum speed and the alpha term) based on visual inspection of *DynusT* and Inrix time space diagrams.
5. Repeat Steps 1-4 until *DynusT* time space diagrams closely mimic Inrix time space diagrams.

It should be noted that the *DynusT* time space diagrams in this thesis were created using a Matlab code. This script aggregated the *DynusT* speeds, which were output into 1-minute intervals, into 5-minute intervals. Such an action would be needed since the Inrix speed data was collected into 5-minute intervals. The Inrix speed data was collected for October 2010 from 3:30 PM to 8:00 PM (i.e., time period used for calibration). The

Inrix time space diagrams were also created using a different Matlab code which used the same color scheme as the *DynusT* time space diagrams.

3.3. Evacuation Scenarios

For this thesis, evacuation scenarios were simulated with two strategies: 1) optimized signal timing and 2) congestion warning Variable Message Signs. All evacuation scenarios were conducted in the same manner, which involved simulating evacuation and background traffic using evacuation demand, vehicle, and path files. The evacuation scenarios varied in the following parameters: impacted area, demand considerations, and incidents.

3.3.1. Impacted Areas

The total study area has a 30-mile radius from the Pentagon; however, two smaller study areas were analyzed for the evacuation scenarios. The 2-mile radius and 5-mile radius evacuation study areas are presented in Figure 22.

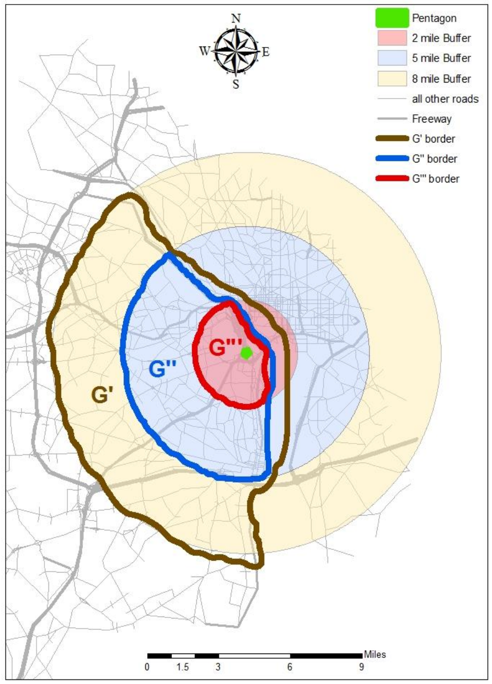


Figure 22. Impacted Study Areas (16)

The 2-mile radius and 5-mile radius study areas represent the areas that will be under mandatory evacuation. Although Figure 5 includes DC and Maryland, only the Virginia side of the two radii study areas was analyzed.

3.3.2. Demand Considerations

There were 12 groups of demand files that were generated per study area radius (i.e., 2-mile radius and 5-mile radius). The groups were based on 3 scenarios of background traffic, 2 scenarios of traffic loading, and 2 scenarios of evacuation destination. The descriptions for each parameter are provided in Table 1.

Table 1. Evacuation Demand Considerations

Background Traffic	**Description**
B1	Background traffic follows typical day levels and departure timing
B3	Background traffic depart in a shorter time span than normal (half of the peak period)
B4	Background traffic are extended in time (1.5 times the period)
Traffic Loading	
T1	a = 0.5, loading = 30 minutes
T2	a = 0.5, loading = 60 minutes
Destination	
D1	Evacuees who live in the impacted area evacuate in directions and for distances according to the planning model proportions
D2	Evacuees who live in the impact area evacuate to public shelters

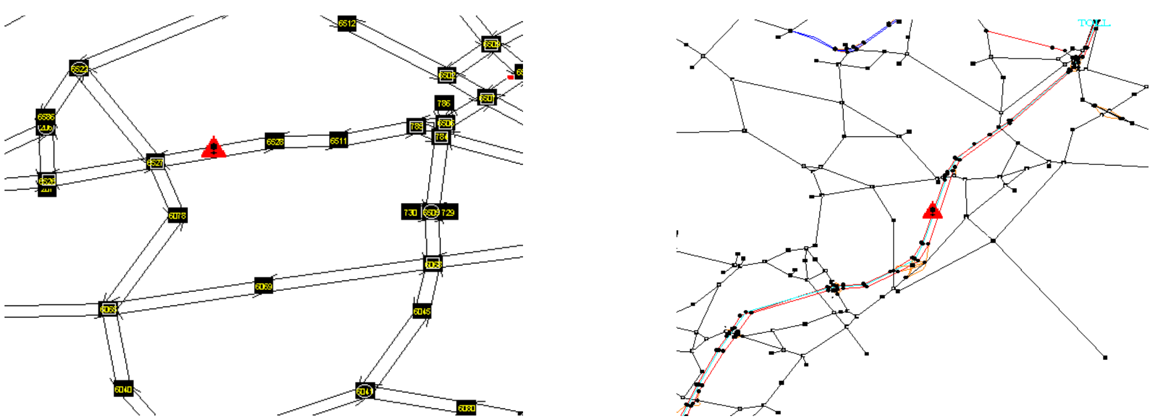
The background traffic refers to the vehicles that are in the network but they are not involved in the evacuation process. The departure time is the characteristic that differs amongst the three background traffic types. B1 uses the departure times that were obtained from the latest UE run. B3 has the departure times of the background traffic occurring in the first half of the peak period. It can be assumed that the background traffic will want to begin their trips sooner than later, thereby creating congestion in the first half of the peak period. Under B4, the departure times of the background are more spread out in the simulation period. It is assumed that the background traffic will want to take their time before beginning their trips.

The traffic loading refers to the amount of time given to load the evacuation demand into the network. Under T1, 99% of the evacuation demand will be generated in 30 minutes and under T2, 99% of the evacuation demand will be generated in 60 minutes. The retirement and unemployment rates were used to determine the number of residents in the impacted areas. The evacuation demand also includes workers, shoppers, tourists, and airport passengers.

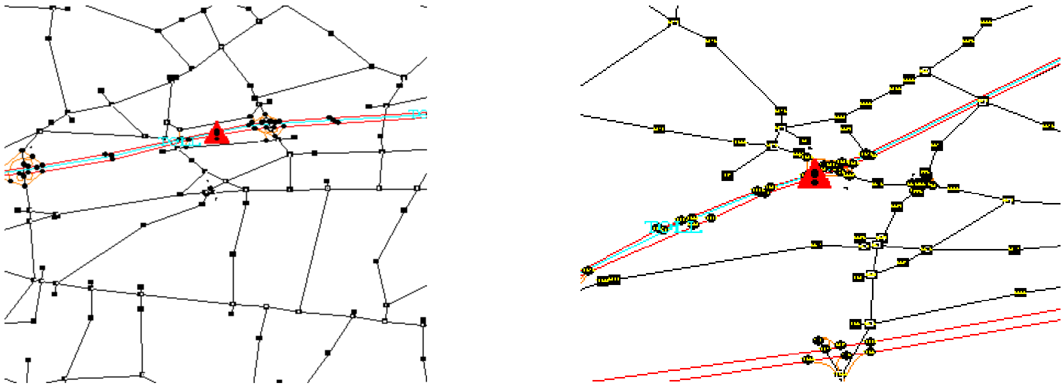
The destination assignment refers to the destinations that the evacuees will travel to during the no-notice evacuation. Demand scenarios with D1 will have the evacuees traveling to friends, family, and hotels/motel in the region. Under D2, evacuees will travel to emergency shelters.

3.3.3. Incidents

There were 5 incident files that were created for the evacuation scenarios. Four of the incident files include one location where an incident would occur (see Figure 23). The fifth incident file does not have any incidents within it (i.e., evacuation scenarios that use this file will not have any incidents that will occur). All 5 incident files were simulated separately for each evacuation scenario. They began at minute 120 and ended at minute 150. Incident 1, Incident 3, and Incident 4 all reduced the number of lanes by one-third. Incident 2 reduced the number of lanes by half.



(a) **(b)**



(c) (d)

Figure 23. (a) Incident 1: Washington St WB, (b) Incident 2: I-95 SB, (c) Incident 3: I-66 WB, (d) Incident 4: I-395 SB

3.3.4. Signal Timing Optimization

In this evacuation strategy, evacuees along the major arterials will be able to vacate the impacted area by traveling through intersections that are programmed with timing plans specifically developed for evacuations. The signal timing plans were optimized through a set of programs. Figure 24 shows the overall process of obtaining optimized signal timing plans.

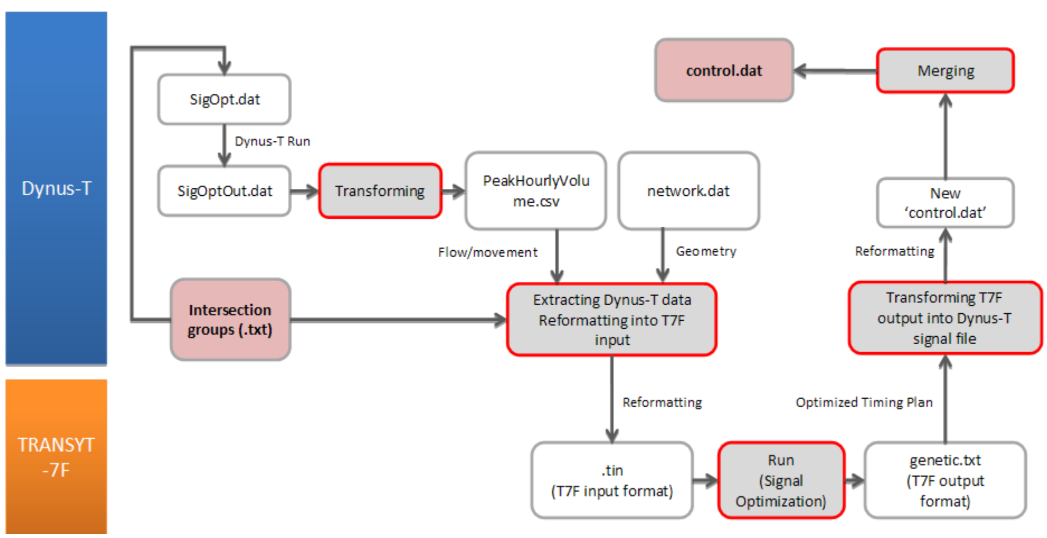


Figure 24. Optimized Signal Timing Development Process (16)

As mentioned, obtaining the optimized signal timing plans involved a set of programs. The first program handled the format and contents of *SigOpt.dat*, which contained a list of 396 intersections that made up 96 coordinated intersection groups along the major arterials. From the given Synchro files, intersections were grouped based on their cycle lengths. The 96 coordinated intersection groups were listed in a text file (*Intersection groups.txt*), which was also used in the development of the optimized signal timing plans. During a simulation, *DynusT* reads *SigOpt.dat* and produces *SigOptOut.dat*, which contains the hourly turn movement volumes at the intersections. The second program converts the hourly turn volumes from *SigOptOut.dat* to peak hour volumes for each movement (*PeakHourlyVolume.csv*).

The third program, as shown in Figure 10, uses *network.dat* (a *DynusT* input file), *PeakHourlyVolume.csv*, and *Intersection groups.txt* in order to reformat the *DynusT* data into a TRANSYT-7F input file (*.tin*). The program reads the TRANSYT-7F input file, thereby optimizing the signal timing plan components (e.g., cycle length, phase splits, and offset) through a genetic optimization algorithm. In the genetic optimization algorithm, the number of generations was set to 100 and the number of populations was set to 50. Such a setting would provide the opportunity for optimal solutions (i.e., optimal signal timing plans) to be produced for the 96 coordinated intersection groups. The 96 optimized signal timing plans are created in *genetic.txt* (a TRANSYT-7F output file) and then they are transformed to a suitable format for *control*.dat (the *DynusT* signal control file).

The new *control.dat* only contains the signal timing plans for the 96 coordinated intersection groups. The last step of the program merges the information from the new *control.dat* file to the existing *control.dat*. This was performed so that the final *control.dat* contains the optimized signal timing plans for the 96 coordinated intersection groups and all other timing plans that were not optimized.

The goal of the signal timing plan optimization was to provide enhanced intersection coordination so that there will be better flow throughout the corridors (i.e., evacuees will be able to travel to their destinations in less time due to the signal timing optimization).

The plan of action involved creating optimized signal timing plans for four demand scenarios per radius, which are listed in Table 2. B1 was chosen for the background traffic for all eight demand scenarios due to the unknown behavior of B3 and B4 in the real world.

Table 2. Development of Optimized Signal Timing for Listed Demand Scenarios

Radius	Demand Scenario
2-Mile	R1B1D1T1
	R1B1D1T2
	R1B1D2T1
	R1B1D2T2
5-Mile	R2B1D1T1
	R2B1D1T2
	R2B1D2T1
	R2B1D2T2

3.3.5. Congestion Warning Variable Message Signs

Congestion warning Variable Message Signs (VMS) were implemented along major arterials in the network. The intention of the implementation was to divert traffic from severely congested areas to less congested arterials and freeways. The congestion warning VMS were set up such that *DynusT* decides whether there is significant congestion downstream from the VMS and also whether there is an alternate route that will provide a better trip (i.e., a trip with a shorter travel time). The *DynusT* network contained a mix of three VMS that were planned for future implementation by VDOT and also three VMS recommended by consultants (two of which are already in the field). Figure 11 displays the locations of these VMS.

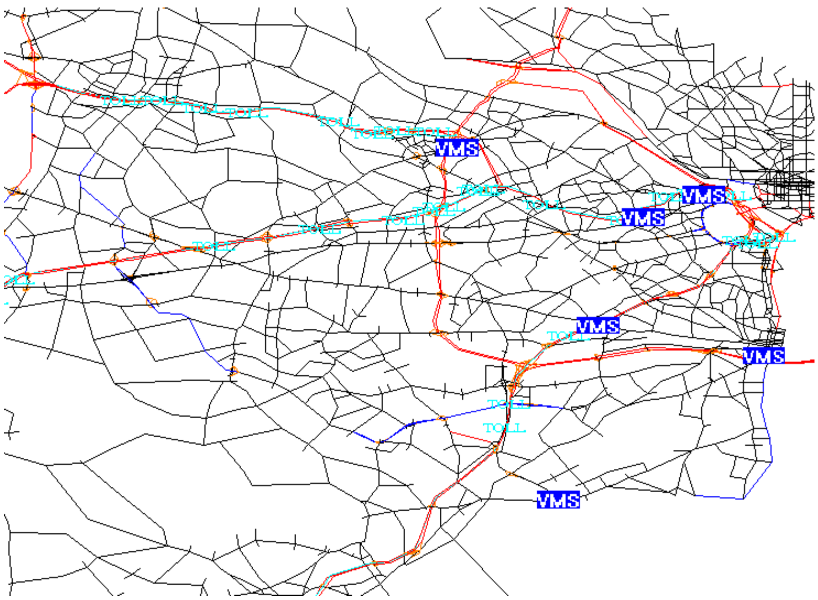


Figure 25. VMS Locations

From Figure 11, the VMS that are located below I-395/I-95 represent the fixed VMS that are in VDOT's plan for implementation. The VMS located above I-395/I-95 represent the fixed and portable VMS recommended by consultants. A sample of start and end times for the congestion warning VMS are provided in Table 3.

Table 3. Congestion Warning VMS Start and End Times Sample

#	VMS location	DynusT link #	R1B1D1T1		R1B1D1T2		R1B1D2T1		R1B1D2T2	
			start(min)	end(min)	start(min)	end(min)	start(min)	end(min)	start(min)	end(min)
1	Fairfax Dr SB at R120	5105,5100	120	360	120	360	120	330	120	370
2	R236 at R401	376, 378	70	420	70	420	70	390	70	390
3	R1 prior to Gibbons St/I-495	5570, 5720	70	330	70	330	70	330	85	290
4	R1 prior to R7100	806, 6177	70	370	105	385	70	390	105	390
5	R29 after N Scott St	5123, 5121	70	230	70	325	70	320	70	360
6	R123 @ Dulles Toll Rd interchange	10875, 10612	70	350	70	360	70	360	70	350

Several of the VMS in all of the demand scenarios had congestion that began before evacuation started at minute 60. Since the analysis in this thesis involved the performance of VMS during a no-notice evacuation, it was decided that the earliest activation time of the congestion warning VMS will begin at minute 70. The one portable VMS (at the intersection of Fairfax Dr SB and R120) was set up with an activation time beginning at minute 120 (i.e., one hour after evacuation begins). This was conducted to take account of the delay to install the portable VMS at its location.

The implementation of existing VMS may have slightly modified locations in *DynusT*. This was the case in the thesis. Some VMS in the *DynusT* network were located downstream from their actual locations. The VMS with the modified locations may not have diverted traffic as intended if they were located at their actual locations. For instance, the Route 236/Route401 VMS is suppose to advise drivers about traffic along I-395 SB or downstream on Route 236. If the VMS was placed in its actual location in the *DynusT* network, then traffic may divert on Route 401 rather than on I-395 SB.

All six congestion warning VMS required a user-defined value for the percent response. A percent response of 85% was chosen for the VMS. This selection was influenced by Robinson and Khattak's (2010) study that analyzed the number of respondents who would divert onto an alternate route after a certain amount of time in congestion (18). From their study, it was discovered that 78.9% of respondents would divert after 30 minutes in congestion, 87.5% of respondents would divert after 60 minutes in congestion, and 92.2% of respondents would divert after 120 minutes in congestion (18). The percent response of 85% is approximately in the middle of the range 78.9% and 92.2%.

A code was used to compare the travel times of the impacted OD pairs with and without the congestion warning VMS. The impacted OD pairs have origins that begin in the 2-mile radius impacted area as well as in the 5-mile radius impacted area. The destinations for those OD pairs are of zones that have emergency shelters in Northern Virginia.

3.3.6. Paired t-test

A paired t-test should be conducted in order to determine whether the average travel time improvements due to the evacuation strategies are significant or not. An alpha value of 0.05 should be used to conduct the two-tailed, paired t-test. P-values less than or equal to 0.05 represent significance in the improvements. For this thesis, a two-tailed, paired t-test was conducted between the base case evacuation scenarios and the evacuation scenarios with the evacuation strategies. A t-test was performed for the 2-mile radius evacuation scenarios as well for the 5-mile radius evacuation scenarios.

Chapter 4. Results

4.1. Initial Calibration Results

Out of 20 iterations, optimal results from the OD estimation were produced in Iteration 11. The average percent error reduced from 35% (from Iteration 0) to 6% (from Iteration 11). Scatter plots from Iteration 0 and Iteration 11 are presented in Figures 12 and 13.

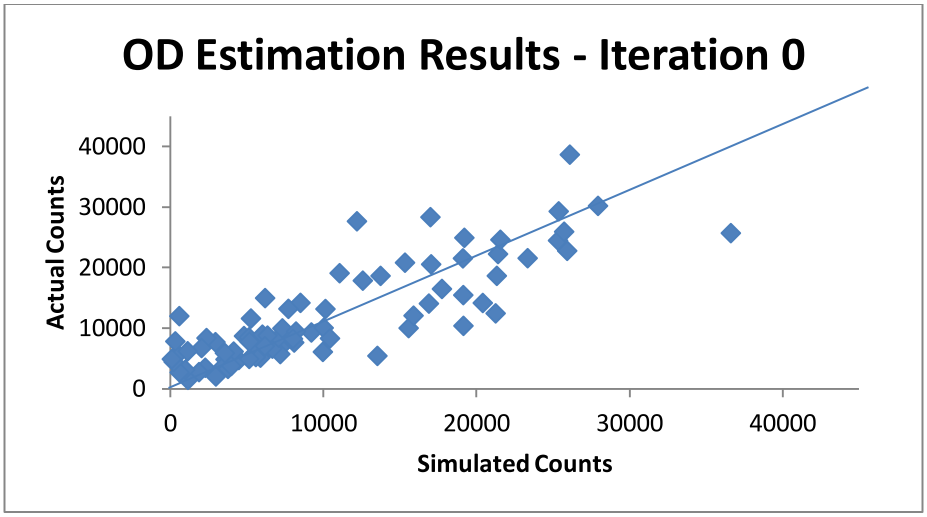


Figure 26. OD Estimation Iteration 0 Scatter Plot

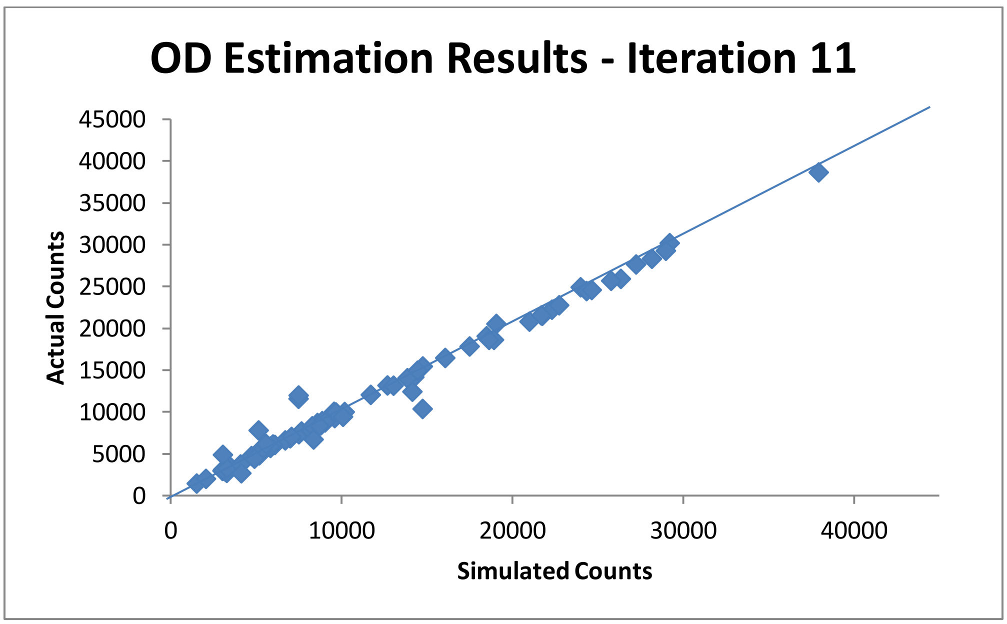


Figure 27. OD Estimation Iteration 11 Scatter Plot

A 45 degree line beginning at the origin exists in Figure 26 and Figure 27. The distance of a data point in relation to this 45 degree line represents the quality of calibration. If the data points lie close to or near the 45 degree line, then it can be said that the network is well calibrated. Based on the OD estimation comparison in Figure 12 and Figure 13, a well calibrated network was obtained in Iteration 11

The network became calibrated in one sense such that the simulated traffic counts were matching well with the observed traffic counts. However, the network still needed further calibration work when the *DynusT* simulation results showed that the freeways were under free flow conditions (i.e., no congestion) while the arterials had heavier congestion than actually observed in the field.

4.1.1. Traffic Flow Model Adjustment Results

There were seven trials that were conducted in the adjustment of traffic flow models immediately after performing the initial calibration attempt. Trial 4 produced optimal results in simulating actual traffic conditions without adversely affecting the simulated traffic counts obtained from OD calibration (see Figure 28).

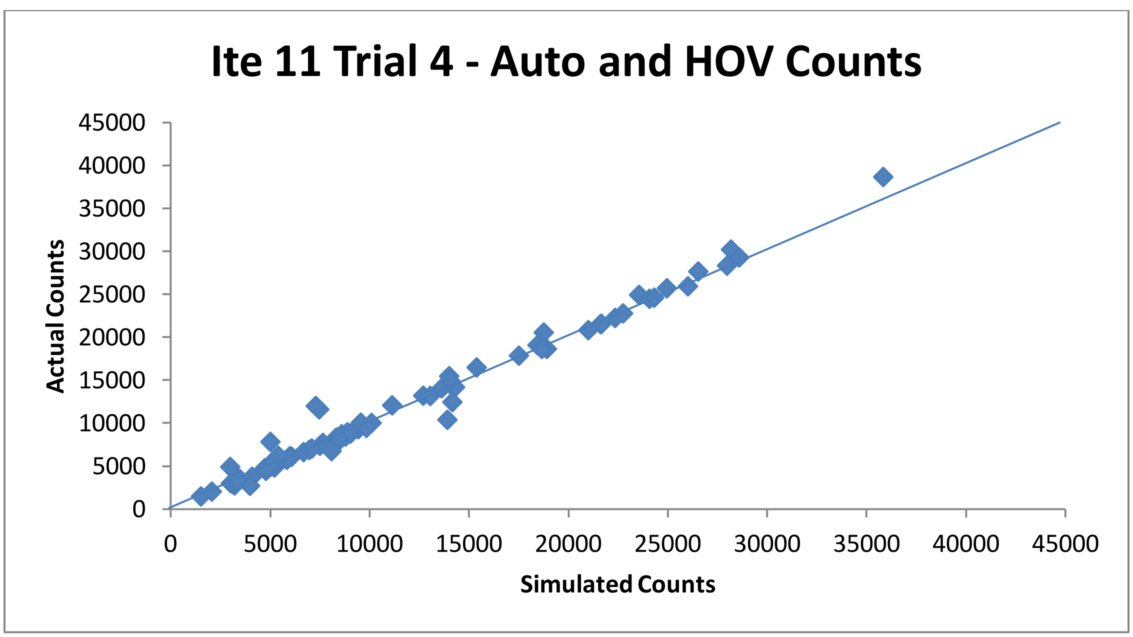
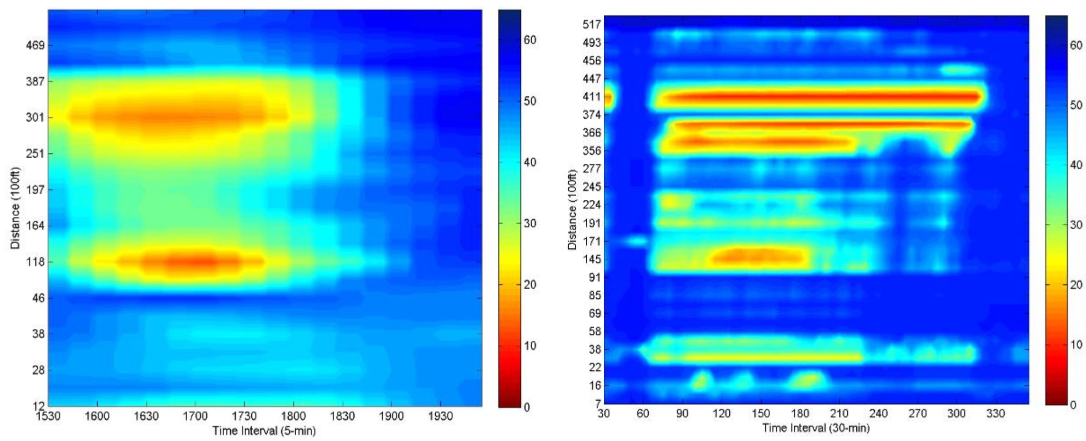


Figure 28. Simulated Traffic Counts from Iteration 11 Trial 4

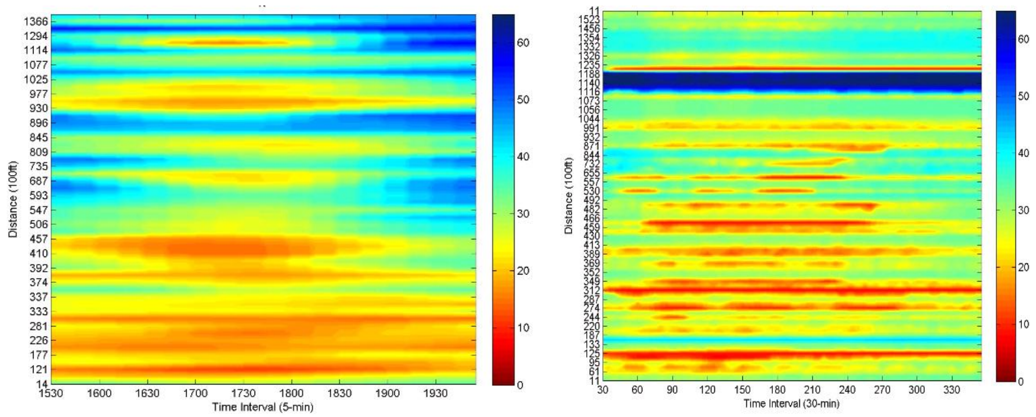
The average percent error from Iteration 11 Trial 4 was 6%, which was the same average percent error from Iteration 11 prior to the traffic flow model adjustments.

The corridors that were used in making time space diagram comparison for the traffic flow model adjustments include the following: I-395, I-495, I-66, I-95, Route 50, Route 29, and Route 7. Figures 15-17 show the corridors that had matching *DynusT* time space diagrams to Inrix time space diagrams.



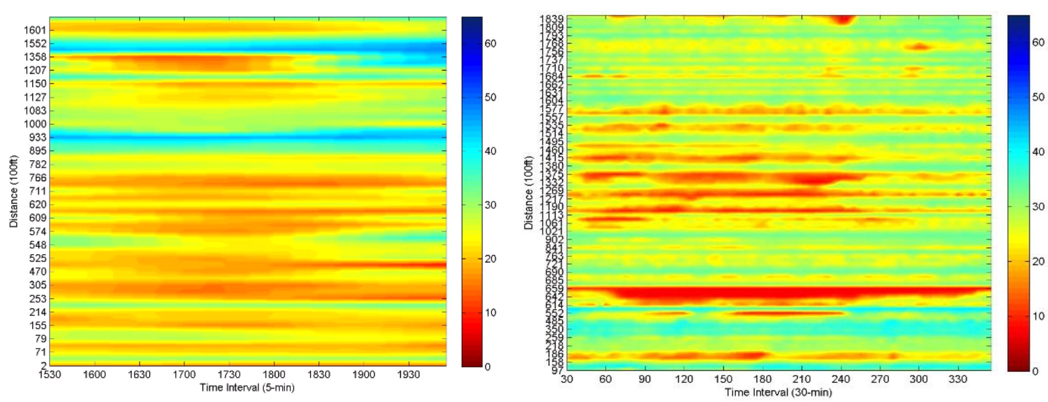
(a) **(b)**

Figure 15. I-395 SB Time Space Diagram Comparison from, a) Inrix and b) *DynusT* from Iteration 11 Trial 4



(a) **(b)**

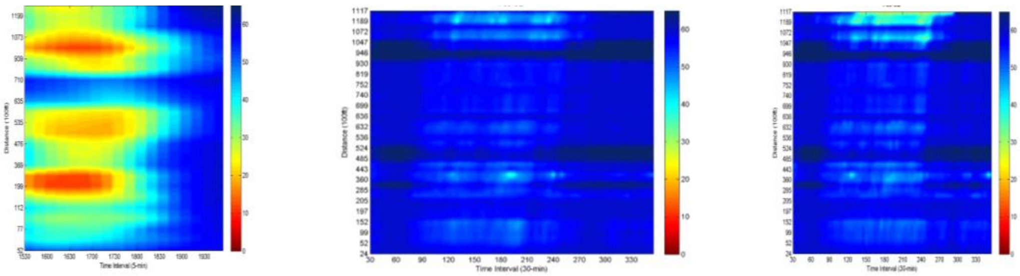
Figure 16. Route7 WB Time Space Diagram Comparison from, a) Inrix and b) *DynusT* from Iteration 11 Trial 4



(a) **(b)**

Figure 17. Route 29 SB Time Space Diagram Comparison from, a) Inrix and b) *DynusT* from Iteration 11 Trial 4

The adjustment of traffic flow models could not improve some of the corridors used for the time space diagram comparison, particularly I-95 SB. Prior to the traffic flow model adjustments, I-95 SB did not have any congestion simulated along it in Iteration 11. The uncongested traffic conditions practically remained the same in Iteration 11 Trial 4.



(a) **(b)** **(c)**

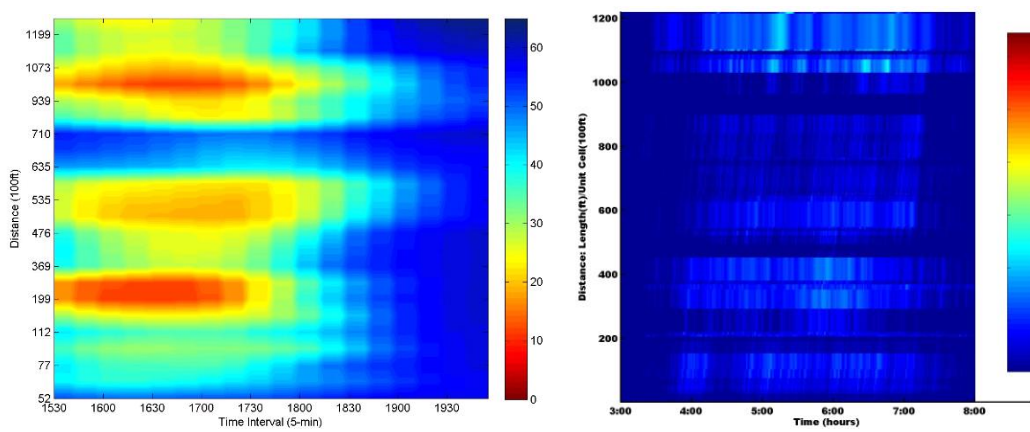
Figure 18. I-95 SB Time Space Diagram Comparisons, a) Inrix, b) *DynusT* Iteration 11, and c) *DynusT* Interation 11 Trial 4

Note that the Inrix time space diagram shows that there was heavier and slower traffic flow at two areas along the I-95 SB corridor during the peak hour period. Such traffic conditions were not present at any location along the simulated corridor.

4.1.2. I-95 SB Demand Adjustment

There was a desire to further improve the simulated traffic along I-95 SB since its traffic conditions were far from the observed conditions. A demand adjustment was implemented to resolve the issue. This demand adjustment required the utilization of a Matlab code and an Excel file, which contained the actual demand proportions of an I-95 SB link near the Beltway. Actual traffic counts were collected from an ADMS station, which were given in 15-minute intervals. The demand proportions for each interval were obtained by dividing an interval's actual traffic volume by the total traffic volume that occurred during the entire demand simulation period (i.e., 3PM to 10PM). The overall goal was to adjust the demand proportions such that the peak hour period would have a concentrated demand. Demand from the off-peak periods (i.e., 3PM to 4PM and 7PM to 10PM) would be moved to the peak hour period, which would increase the peak hour period demand but leave the total demand unchanged. The demand proportions were adjusted in a trial and error basis until the peak hour period had a traffic flow of 1800-1900 veh/ln/hr. This desired traffic flow was expected to produce the congestion along I-95 SB. The Excel file with the newly established I-95 SB demand proportions was used in the Matlab script, which created a new demand file that takes account of the demand proportion adjustments.

A UE run was performed using the new demand file, which was necessary to conduct in order to simulate the full effects of the demand proportion adjustments. The DynusT time space diagram of I-95 SB was created and compared to the Inrix time space diagram after the UE run completed. Figure 19 presents this comparison.



(a) **(b)**

Figure 19. I-95 SB Time Space Diagram Comparison after Demand Adjustment, a) Inrix and b) *DynusT*

From the comparison, it is clear that I-95 SB still lacks congestion in the simulated network. In other words, implementing the demand proportion adjustments could not create the congestion in the two areas along the I-95 SB corridor as shown in its Inrix time space diagram.

4.2. Recalibration

New traffic flow models were created for the *DynusT* network since the previous traffic flow models (from initial calibration attempt) produced unrealistic traffic conditions. From the initial calibration, traffic counts matched well and simulated speeds showed similar characteristics to Inrix speeds for some corridors; however, the average travel time was 19 minutes. Simulated traffic flows were greater than 2,500 veh/hr/ln but less than 3,000 veh/hr/ln. The previous traffic flow models were adjusted in such a manner to obtain realistic travel time and traffic flow in the network.

Calibration of the *DynusT* network had to occur again since recent network changes (e.g., signal timing updates and road connectivity issues) worsened the match between simulated traffic counts and actual traffic counts. Recalibration was set for 10 iterations using the new traffic flow models and the same list of 81 traffic links assigned with actual traffic counts that was used for the initial calibration attempt. Optimal results were produced in the 6th iteration, which had an average absolute percent error of 9%. Figure 20 presents the OD estimation results from Iteration 6.

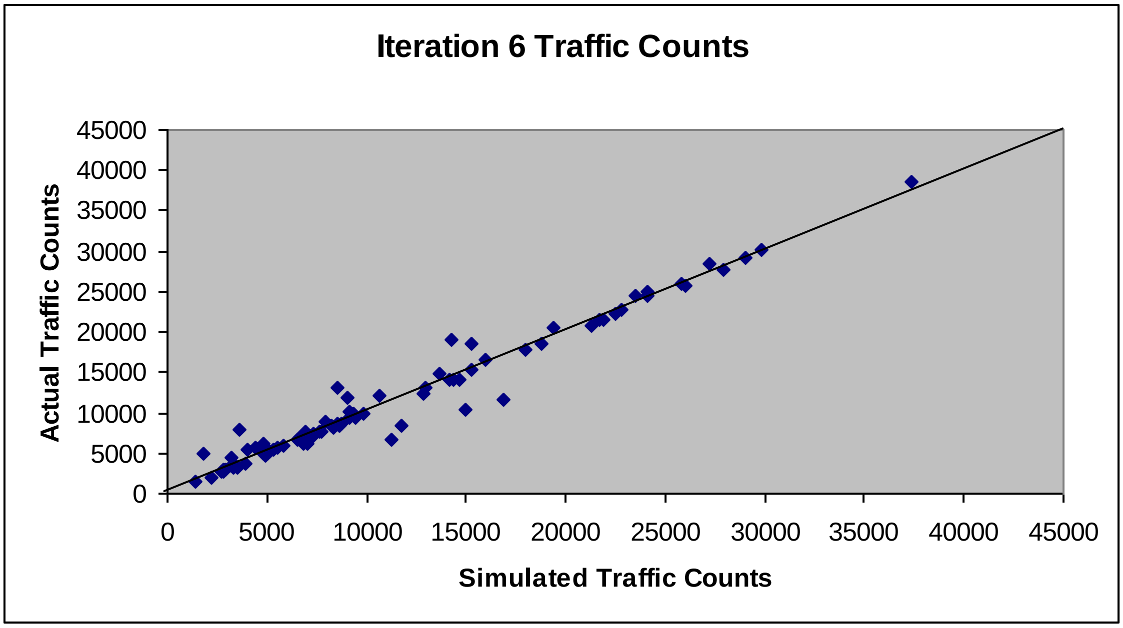
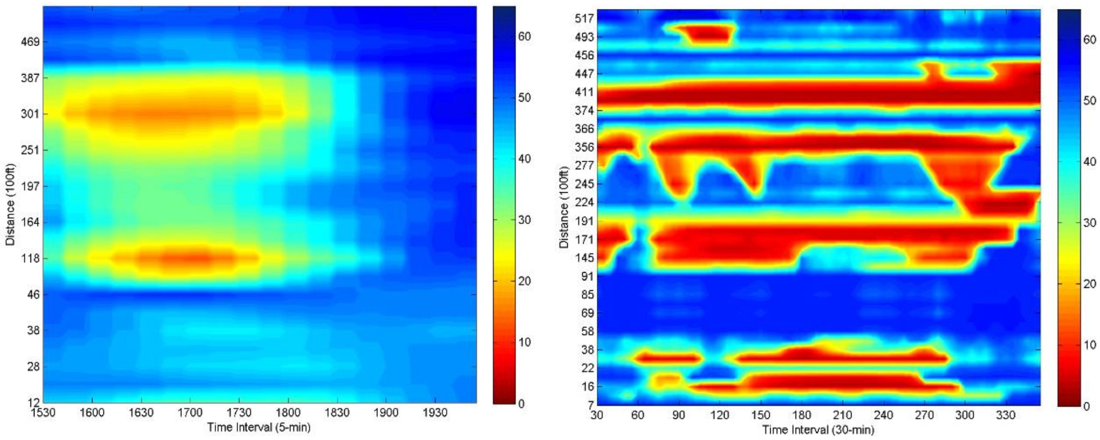


Figure 20. Recalibration Iteration 6 Results

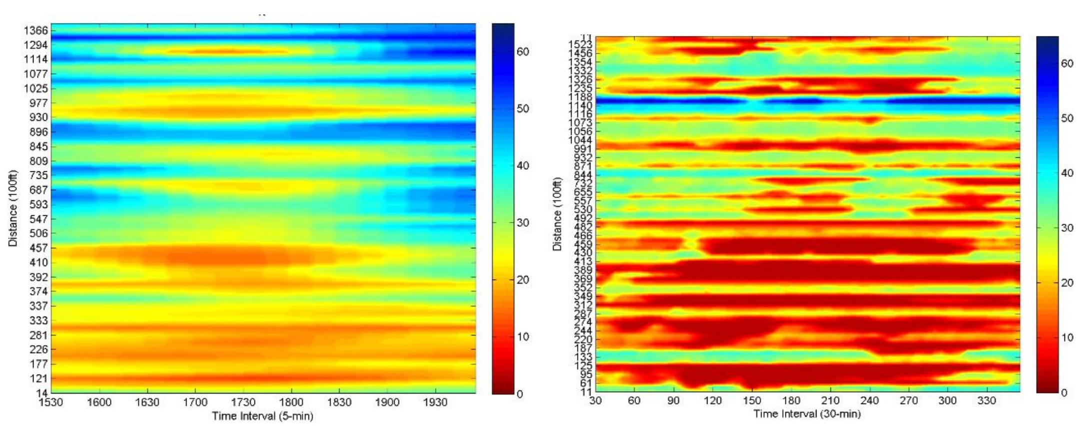
Figure 20 shows a scatter plot of simulated counts (x-axis) in relation to actual counts (y-axis). As previously discussed, counts that are near or lined up on the 45 degree line show a matching relationship between the simulated and actual counts. It can be seen that a majority of the simulated counts match very well to actual counts.

Although a calibrated OD demand was reached, the new traffic flow models produced severely congested simulated speeds in comparison to the Inrix speeds. Figure 21 and Figure 22 display the comparison of *DynusT* speeds to Inrix speeds after recalibrating with the new traffic flow models.



(a) **(b)**

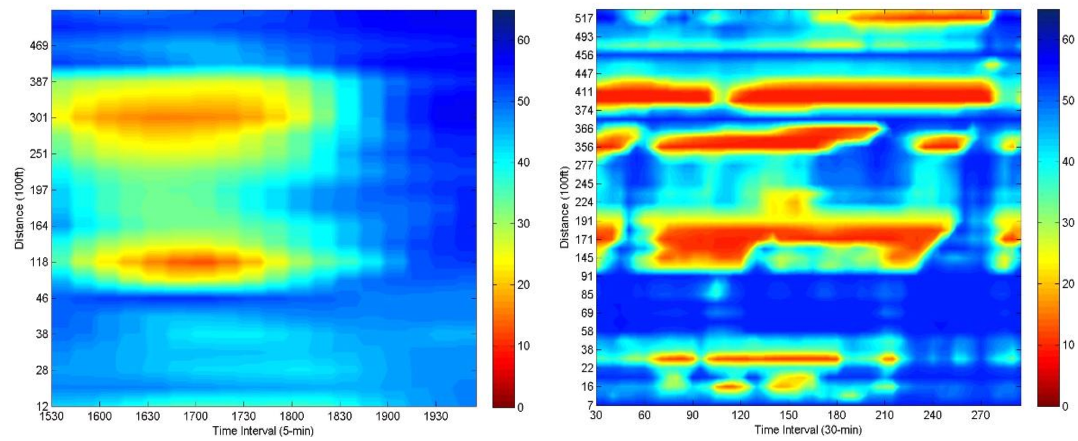
Figure 21. I-395 Time Space Diagram Comparison, (a) Inrix and (b) *DynusT* with Traffic Flow Models from Recalibration



(a) **(b)**

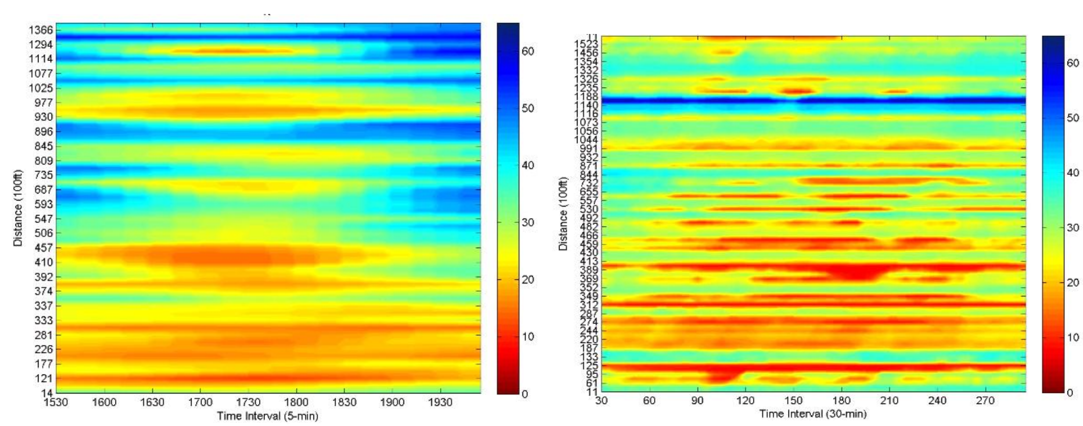
Figure 22. Route 7 WB Time Space Diagram Comparison, (a) Inrix and (b) *DynusT* with Traffic Flow Models from Recalibration

Figure 21 and figure 22 both show that vehicles were traveling at much lower speeds in the network than Inrix. Due to these traffic conditions, the traffic flow models, obtained from the initial calibration attempt, were implemented into the calibrated network. A User Equilibrium simulation run was performed on the recently calibrated network using the traffic flow models that were adjusted in the first calibration attempt. After 20 iterations of the UE run, a speed comparison between and DynusT and Inrix was performed.



(a) **(b)**

Figure 23. I-395 SB Time Space Diagram Comparison, a) Inrix and b) Recalibrated *DynusT* with Traffic Flow Models from Initial Calibration Attempt

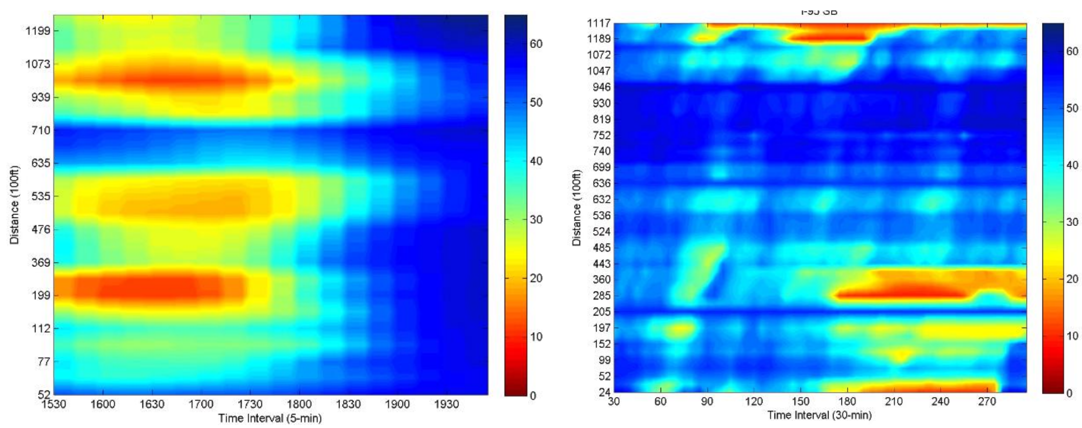


(a) **(b)**

Figure 24. Route 7 WB Time Space Diagram Comparison, a) Inrix and b) Recalibrated *DynusT* with Traffic Flow Models from Initial Calibration Attempt

The similarities between the DynusT time space diagrams to the Inrix time space diagrams are stronger in Figure 23 and Figure 24.

It should be noted that recalibration also included a traffic flow model specifically created for a portion on I-95 SB due to the lack in congestion in the modeled network. Figure 25 presents the speed comparison for I-95 SB between Inrix and the DynusT network that included the traffic flow models from the initial calibration attempt and the I-95 SB traffic flow model.



(a) **(b)**

Figure 25. I-95 SB Time Space Diagram Comparison, a) Inrix and b) Recalibrated *DynusT* with Traffic Flow Models from Initial Calibration Attempt and I-95 SB Traffic Flow Model

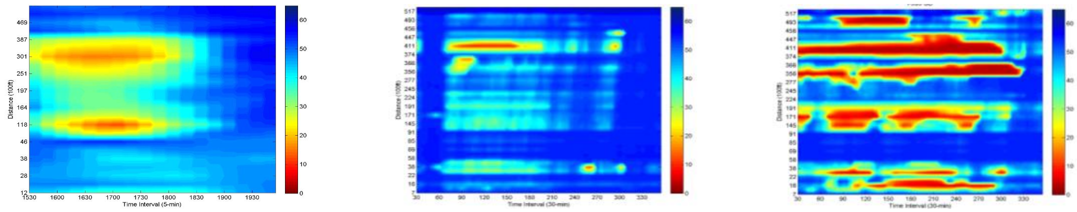
The most recent UE run with the previous traffic flow models and the I-95 SB traffic flow model was accepted as the calibrated network even though the difference between simulated and actual traffic counts increased. Simulating the evacuation scenarios with this *DynusT* network was approved since similarities existed between the *DynusT* time space diagrams and the Inrix time space diagrams. Inrix data collected from November 2009 was compared and validated against Bluetooth data in the I-95 Corridor Coalition Vehicle Probe Project. The study showed that 80% of Inrix time intervals fell within 5 mph of the 1.96 Standard Error Band for the 60+ mph speed bin of freeway segments greater than one mile in Virginia (Haghani *et al.*, 2010). A validation study is unknown to exist for the collected traffic count data. Ultimately, the Inrix data has more validity than the actual count data that was used in the project. Therefore, it was not necessary to conduct the OD estimation for a third time to get simulated traffic counts that matched very well to the actual traffic counts.

4.3. Testing Calibration Approaches

Following recalibration, a desire came about to determine the best approach for calibration. Recall that in the initial calibration stage, OD estimation was conducted first. The adjustment of traffic flow models followed OD estimation. In recalibration, the project team adjusted the traffic flow models first and then conducted the OD estimation. For testing purposes, the traffic flow models obtained from recalibration were used to conduct 10 iterations in OD estimation starting with the original demand. This allowed for an apple-to-apple comparison since the initial calibration process began with the original demand.

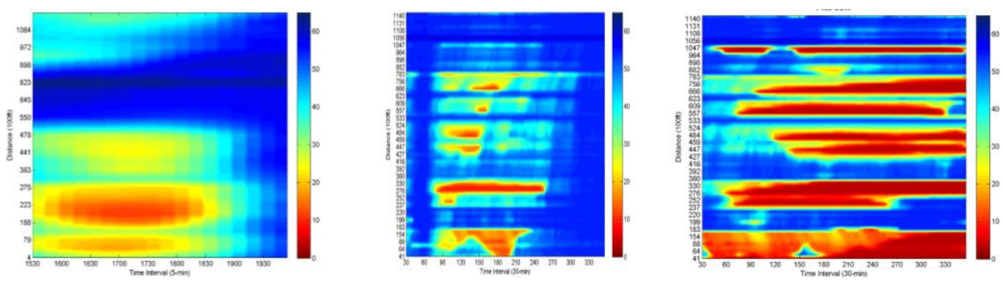
Out of 10 iterations in OD estimation, Iteration 8 produced optimal results for both calibration attempts. The averages of the absolute percent error were similar. Calibration Approach 1 (OD estimation conducted first) had an average of the absolute percent error of 10% while Calibration Approach 2 (adjusting traffic flow models first) had an average of the absolute percent error of 12%.

Determining the better approach to calibration just based on the average of the absolute percent error would be too difficult to do since both values are alike. Therefore, a comparison of time space diagrams from both approaches was the deciding factor. Two freeways and two arterials were used to make the comparison as shown in Figures 26-29.



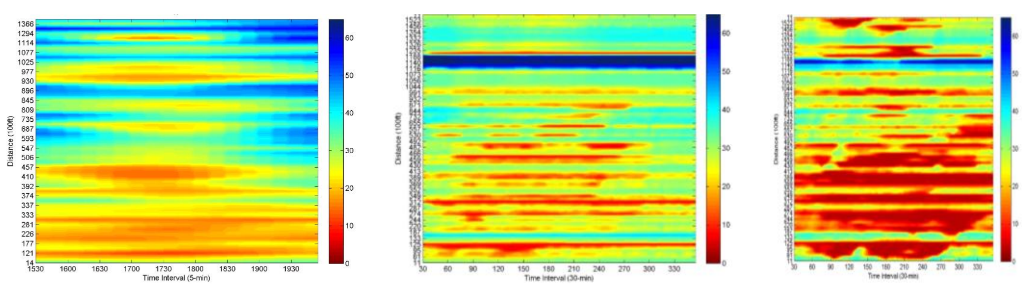
(a) **(b)** **(c)**

Figure 26. I-395 SB Time Space Diagrams, (a) Inrix, (b) Calibration Approach 1, (c) Calibration Approach 2



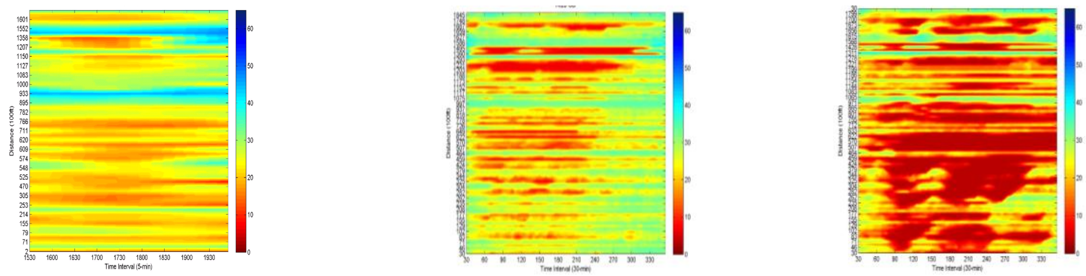
(a) **(b)** **(c)**

Figure 27. I-495 CCW Time Space Diagrams, (a) Inrix, (b) Calibration Approach 1, (c) Calibration Approach 2



(a) **(b)** **(c)**

Figure 28. Route 7 WB Time Space Diagrams, (a) Inrix, (b) Calibration Approach 1, (c) Calibration Approach 2



(a) (b) (c)

Figure 29. Route 29 SB Time Space Diagrams, (a) Inrix, (b) Calibration Approach 1, (c) Calibration Approach 2

It is evident that Calibration Approach 2 (adjusting the traffic flow models first) produced heavily congested speeds along the corridors. Both calibration approaches would require an adjustment of the traffic flow models in order to obtain simulated speeds that match the Inrix speed data. The difference between the two calibration approaches is that Calibration 2 would require an additional adjustment of the traffic flow models whereas Calibration Approach 1 would only need the traffic flow model adjustments to occur once. In other words, Calibration Approach 2 would require more effort and time to obtain a calibrated network. Calibration Approach 1 (OD estimation conducted first) was declared as the better approach for calibration.

4.4. Optimized Signal Timing Results

4.4.1. Optimized Signal Timing Network Performance

The performance of the optimized signal timing plans was compared to the existing PM Peak signal timing plans. As summarized in Table 4 and Table 5, the optimized signal timing plans increased throughput for all eight demand scenarios. However, only two out of the eight demands produced improvements in average travel time. The maximum increase in throughput was 0.57%. As for average travel time, the maximum percent of improvement was 0.62%.

Table 4. Optimized Signal Timing Performance: 2-mile Radius

Network	Vehicles Outside Network	Average Travel Time (minutes)	Average Stop Time (minutes)	Average Trip Distance (miles)	Difference in Throughput (Base - Opt Sig)	Difference in Average Travel Time (Base - Opt Sig)	Difference in Average Stop Time (Base - Opt Sig)	Difference in Average Trip Distance (Base - Opt Sig)	Percentage of Improvement in Throughput	Percentage of Improvement in Average Travel Time
R1B1D1T1 - Base	5259050	44.358	31.389	7.371	-30172	-0.302	-0.154	-0.089	0.57%	-0.68%
R1B1D1T1 - Opt Sig	5289222	44.66	31.543	7.46						
R1B1D1T2 - Base	5265352	44.245	31.272	7.395	-16778	0.275	0.393	-0.047	0.32%	0.62%
R1B1D1T2 - Opt Sig	5282130	43.97	30.879	7.442						
R1B1D2T1 - Base	5254664	44.781	31.762	7.399	-18251	-0.016	0.104	-0.048	0.35%	-0.04%
R1B1D2T1 - Opt Sig	5272915	44.797	31.658	7.447						
R1B1D2T2 - Base	5267734	44.258	31.214	7.423	-1855	-0.054	-0.022	-0.019	0.04%	-0.12%
R1B1D2T2 - Opt Sig	5269589	44.312	31.236	7.442						

Table 5. Optimized Signal Timing Performance: 5-mile Radius

Network	Vehicles Outside Network	Average Travel Time (minutes)	Average Stop Time (minutes)	Average Trip Distance (miles)	Difference in Throughput (Base - Opt Sig)	Difference in Average Travel Time (Base - Opt Sig)	Difference in Average Stop Time (Base - Opt Sig)	Difference in Average Trip Distance (Base - Opt Sig)	Percentage of Improvement in Throughput	Percentage of Improvement in Average Travel Time
R2B1D1T1 - Base	5084921	54.159	40.41	7.594	-18709	-0.261	-0.204	0.01	0.37%	-0.48%
R2B1D1T1 - Opt Sig	5103630	54.42	40.614	7.584						
R2B1D1T2 - Base	5081890	52.097	38.388	7.596	-13993	-0.402	-0.351	-0.023	0.28%	-0.77%
R2B1D1T2 - Opt Sig	5095883	52.499	38.739	7.619						
R2B1D2T1 - Base	5055018	54.487	40.577	7.723	-26592	0.005	0.081	-0.004	0.53%	0.01%
R2B1D2T1 - Opt Sig	5081610	54.482	40.496	7.727						
R2B1D2T2 - Base	5052914	51.96	38.07	7.74	-12338	-0.283	-0.25	0.023	0.24%	-0.54%
R2B1D2T2 - Opt Sig	5065252	52.243	38.32	7.717						

Table 6 and Table 7 present the results from the two-tailed, paired t-tests for the 2-mile radius evacuation scenarios and the 5-mile radius evacuation scenarios. From both tables, the p-values were greater than 0.05 which prove that the percentages of inprovement in the average travel time due to the optimized signal timing were insignificant.

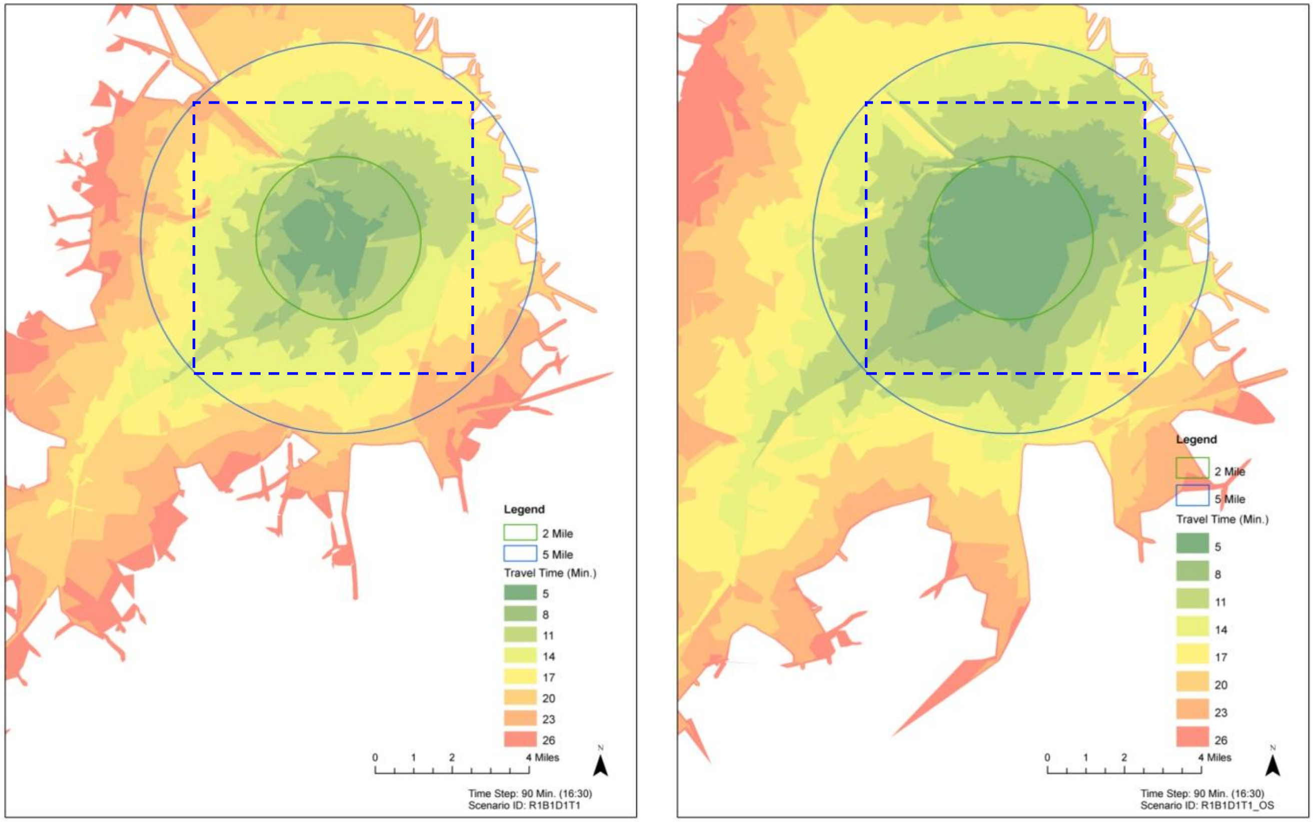
Table 6. t-test Results between Base Case and Optmized Signal Timing: 2-mile Radius

Evacuation Scenario	Average Travel Time (minutes)		P-value
	Base	Opt Sig	
R1B1D1T1	44.358	44.66	0.851
R1B1D1T2	44.245	43.97	
R1B1D2T1	44.781	44.797	
R1B1D2T2	44.258	44.312	

Table 7. t-test Results between Base Case and Optmized Signal Timing: 5-mile Radius

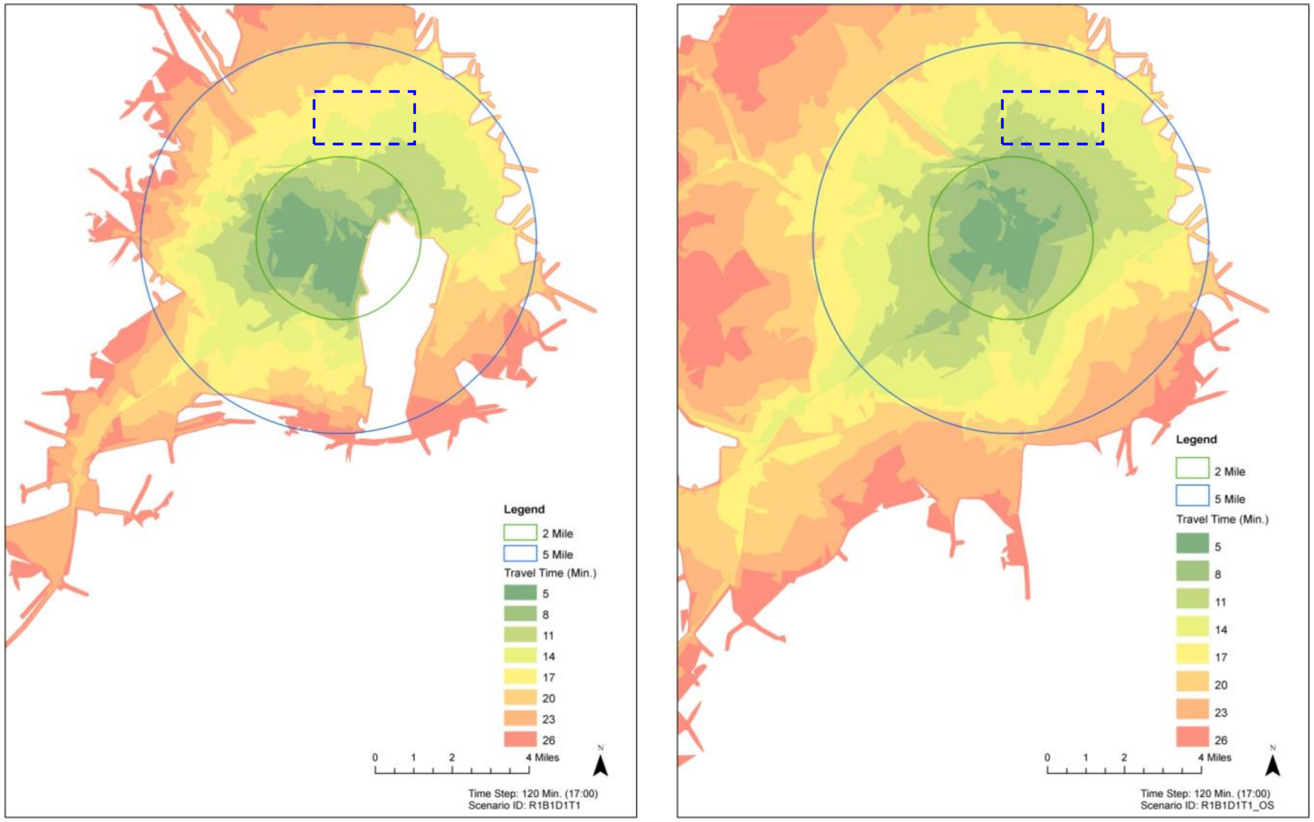
Evacuation Scenario	Average Travel Time (minutes)		P-value
	Base	Opt Sig	
R2B1D1T1	54.159	54.42	0.071
R2B1D1T2	52.097	52.499	
R2B1D2T1	54.487	54.482	
R2B1D2T2	51.96	52.243	

The percentages of improvement for the network-wide performance performance were lack luster and insignificant; however, that was not the case when such an evaluation was conducted for a more localized area. Figure 30 through Figure 32 present a side-to-side comparison of the average travel time found at the two radii impacted areas for specific times in the simulation period. The left portion of the comparison is of the base network (i.e., network with no strategies) while the right portion is the network with optimized signal timing plans. From those images, it is clear that the amount of benefits in travel time existed at the 2-mile radius impacted area as well as the 5-mile radius impacted area, but it decreased as the simulation moved forward in time. In other words, the optimized signal timing plans worked well when there was an onslaught of volume during the evacuation (i.e., at minute 90), but the performance of the optimized signal timing diminished beyond that onslaught (i.e., at minute 120 and at minute 150). Negative impacts are seen in at minute 150 (see Figure 32).



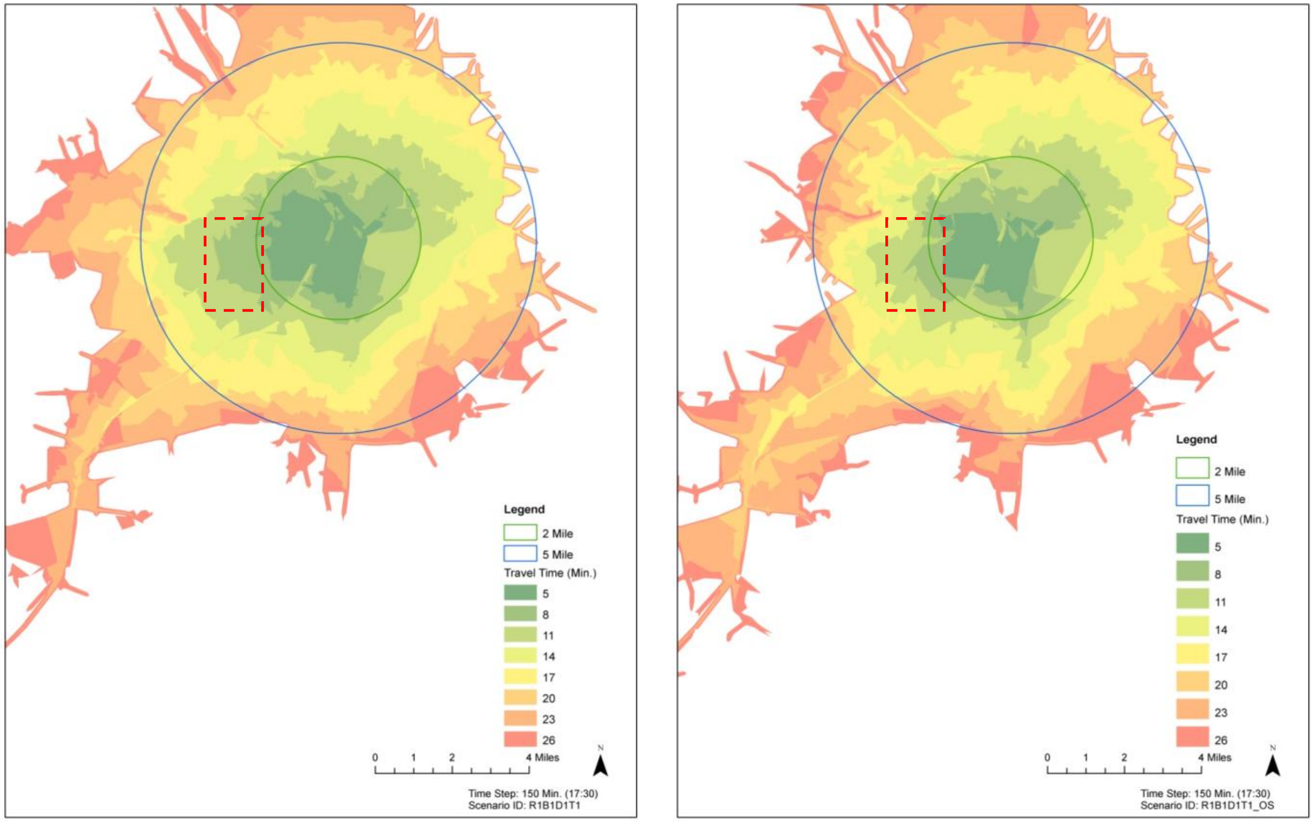
(a) (b)

Figure 30. Effect of Optimized Signal Timing Strategy for R1B1D1T1 at Minute 90, a) Base Network and b) Optimized Signal Timing Network (16)



(a) **(b)**

Figure 31. Effect of Optimized Signal Timing Strategy for R1B1D1T1 at Minute 120, a) Base Network and b) Optimized Signal Timing Network (16)



(a) **(b)**

Figure 32. Effect of Optimized Signal Timing Strategy for R1B1D1T1 at Minute 150, a) Base Network and b) Optimized Signal Timing Network (16)

4.4.2. Effect of Optimized Signal Timing on Evacuees' Travel Times

Unlike the network performance results, the optimized signal timing improved the total travel time of the evacuees for all eight demand scenarios. The percents of improvement ranged from 0.02% to 4.81%. It should be noted that seven out of the eight demand scenarios had percents of improvement greater than 1%.

A two-tailed paired t-test was also performed to determine the significance in the total travel time improvements for the evacuees due to the optimized signal timing. The results show that the improvements observed for the 2-mile radius evacuation scenarios were insignificant (i.e., p-value was greater than 0.05). However, the improvements to the evacuees' total travel time were significant (i.e., p-value was less than 0.05). The results are presented in Table 8 and Table 9.

Table 8. Effect to Evacuees' Total Travel Time Due to Optimized Signal Timing: 2-mile Radius

Evacuation Scenario	Evacuees' Total Travel Time (minutes)		Percentage of Improvement	P-value
	Base	Opt Sig		
R1B1D1T1	20511173	20507075	0.02%	0.0912
R1B1D1T2	20925694	19918622	4.81%	
R1B1D2T1	23056941	22143299	3.96%	
R1B1D2T2	22450036	22065376	1.71%	

Table 9. Effect to Evacuees' Total Travel Time Due to Optimized Signal Timing: 5-mile Radius

Evacuation Scenario	Evacuees' Total Travel Time (minutes)		Percentage of Improvement	P-value
	Base	Opt Sig		
R2B1D1T1	130844273	128054035	2.13%	0.0049
R2B1D1T2	126444800	123993799	1.94%	
R2B1D2T1	136266453	134386749	1.38%	
R2B1D2T2	130900266	129397352	1.15%	

4.4.3. Optimized Signal Timing Sensitivity Analysis

Two demand scenarios, R1B3D1T1 and R1B4D1T1, were simulated using the optimized signal timing from demand scenario R1B1D1T1 in order to analyze the sensitivity of the benefits to different demand. The results show that the evacuees' travel time from R1B3D1T1 improved by 1.20%. However, the evacuees' travel time from R1B4D1T1 worsened by 0.75%. The lack in benefits in R1B4D1T1 may be due to the influence of the background traffic in that scenario. In B4, the departure times of the background demand are more spread out throughout the simulation period than B1. The R1B1D1T1 optimized signal timing may not be suitable in handling smaller demand that occur at a specific time.

4.5 Congestion Warning Variable Message Signs Results

4.5.1. VMS Network Performance

A comparison of network average travel times showed that 67% of the 2-mile radius-no incident demand scenarios had improved average travel times when using VMS. Out of the 12 demand scenarios, only six demand scenarios had improved throughput (i.e., the number of vehicles that exit the network). Although improvements were observed, the maximum percentages of improvement for the throughput and the average travel time due to the implementation of the congestion warning VMS were 0.15% and 0.81% (see Table 10).

Similar comparisons were conducted for the 5-mile radius-no incident demand scenarios. From the analysis, only 33% of the 5-mile radius-no incident demand scenarios showed improvements in throughput due to the VMS. Only 25% of the demand scenarios improved in average travel time due to the VMS. The maximum percentages of improvements for throughput and average travel time were 0.10% and 0.47% (see Table 11).

Table 10. Summary of VMS Network Performance – 2-Mile Radius, No Incident

Network	Vehicles Outside Network	Average Travel Time (minutes)	Average Stop Time (minutes)	Average Trip Distance (miles)	Difference in Throughput (Base - VMS)	Difference in Average Travel Time (Base - VMS)	Difference in Average Stop Time (Base - VMS)	Difference in Average Trip Distance (Base - VMS)	Percentage of Improvement in Throughput	Percentage of Improvement in Average Travel Time
R1B1D1T1 - Base	5259050	44.358	31.389	7.371	-7716	-0.4	-0.344	-0.023	0.15%	-0.90%
R1B1D1T1 - VMS	5266766	44.758	31.733	7.394						
R1B1D1T2 - Base	5265352	44.245	31.272	7.395	3589	0.358	0.356	0.019	-0.07%	0.81%
R1B1D1T2 - VMS	5261763	43.887	30.916	7.376						
R1B1D2T1 - Base	5254664	44.781	31.762	7.399	1264	0.011	0.01	-0.003	-0.02%	0.02%
R1B1D2T1 - VMS	5253400	44.77	31.752	7.402						
R1B1D2T2 - Base	5267734	44.258	31.214	7.423	9095	0.033	-0.029	0.015	-0.17%	0.07%
R1B1D2T2 - VMS	5258639	44.225	31.243	7.408						
R1B3D1T1 - Base	5192992	68.087	53.448	7.275	989	0.02	0.019	0.014	-0.02%	0.03%
R1B3D1T1 - VMS	5192003	68.067	53.429	7.261						
R1B3D1T2 - Base	5190359	67.417	52.85	7.254	-66	0.063	0.13	-0.014	0.00%	0.09%
R1B3D1T2 - VMS	5190425	67.354	52.72	7.268						
R1B3D2T1 - Base	5177661	68.172	53.573	7.247	2912	-0.02	-0.031	0	-0.06%	-0.03%
R1B3D2T1 - VMS	5174749	68.192	53.604	7.247						
R1B3D2T2 - Base	5177609	67.344	52.792	7.247	-647	-0.083	-0.075	-0.017	0.01%	-0.12%
R1B3D2T2 - VMS	5178256	67.427	52.867	7.264						
R1B4D1T1 - Base	5405004	36.65	23.916	7.661	-5244	0.035	0.063	-0.025	0.10%	0.10%
R1B4D1T1 - VMS	5410248	36.615	23.853	7.686						
R1B4D1T2 - Base	5408304	36.756	24.017	7.677	1759	0.268	0.267	0.007	-0.03%	0.73%
R1B4D1T2 - VMS	5406545	36.488	23.75	7.67						
R1B4D2T1 - Base	5394634	36.858	24.127	7.67	-2659	-0.073	-0.052	-0.007	0.05%	-0.20%
R1B4D2T1 - VMS	5397293	36.931	24.179	7.677						
R1B4D2T2 - Base	5396863	36.741	23.985	7.677	-673	0.063	0.039	-0.002	0.01%	0.17%
R1B4D2T2 - VMS	5397536	36.678	23.946	7.679						

Table 11. Summary of VMS Network Performance – 5-Mile Radius, No Incident

Network	Vehicles Outside Network	Average Travel Time (minutes)	Average Stop Time (minutes)	Average Trip Distance (miles)	Difference in Throughput (Base - VMS)	Difference in Average Travel Time (Base - VMS)	Difference in Average Stop Time (Base - VMS)	Difference in Average Trip Distance (Base - VMS)	Percentage of Improvement in Throughput	Percentage of Improvement in Average Travel Time
R2B1D1T1 - Base	5084921	54.159	40.41	7.594	4898	-0.051	-0.098	0.011	-0.10%	-0.09%
R2B1D1T1 - VMS	5080023	54.21	40.508	7.583						
R2B1D1T2 - Base	5081890	52.097	38.388	7.596	4875	0.213	0.171	-0.005	-0.10%	0.41%
R2B1D1T2 - VMS	5077015	51.884	38.217	7.601						
R2B1D2T1 - Base	5055018	54.487	40.577	7.723	-511	-0.005	0.008	-0.008	0.01%	-0.01%
R2B1D2T1 - VMS	5055529	54.492	40.569	7.731						
R2B1D2T2 - Base	5052914	51.96	38.07	7.74	-1940	-0.109	-0.155	0.015	0.04%	-0.21%
R2B1D2T2 - VMS	5054854	52.069	38.225	7.725						
R2B3D1T1 - Base	5037994	74.473	59.101	7.52	-2437	-0.218	-0.23	-0.003	0.05%	-0.29%
R2B3D1T1 - VMS	5040431	74.691	59.331	7.523						
R2B3D1T2 - Base	5030664	72.019	56.791	7.541	-5103	-0.316	-0.287	0.006	0.10%	-0.44%
R2B3D1T2 - VMS	5035767	72.335	57.078	7.535						
R2B3D2T1 - Base	5013119	74.464	58.931	7.657	-3931	0.054	0.082	-0.022	0.08%	0.07%
R2B3D2T1 - VMS	5017050	74.41	58.849	7.679						
R1B3D2T2 - Base	5004182	71.552	56.117	7.669	-3462	-0.265	-0.241	-0.004	0.07%	-0.37%
R1B3D2T2 - VMS	5007644	71.817	56.358	7.673						
R2B4D1T1 - Base	5244387	50.57	36.902	7.928	-432	-0.132	-0.119	0.001	0.01%	-0.26%
R2B4D1T1 - VMS	5244819	50.702	37.021	7.927						
R2B4D1T2 - Base	5240467	49.208	35.594	7.925	4703	-0.059	-0.1	0.023	-0.09%	-0.12%
R2B4D1T2 - VMS	5235764	49.267	35.694	7.902						
R2B4D2T1 - Base	5231386	51.516	37.458	8.198	-1360	-0.299	-0.265	0.008	0.03%	-0.58%
R2B4D2T1 - VMS	5232746	51.815	37.723	8.19						
R2B4D2T2 - Base	5225998	50.222	36.255	8.159	4053	0.234	0.2	0.011	-0.08%	0.47%
R2B4D2T2 - VMS	5221945	49.988	36.055	8.148						

Two-tailed, paired t-tests were conducted between the network-wide average travel times from the base evacuation scenarios and the network-wide average travel times from the congestion warning VMS scenarios. The analysis showed that the improvements in average travel time from the 2-mile radius evacuation scenarios as well as the 5-mile radius evacuation scenarios were insignificant. The p-values were 0.676 and 0.162 (see Table 12 and Table 13).

Table 12. t-test Results between Base Case and VMS: 2-mile Radius

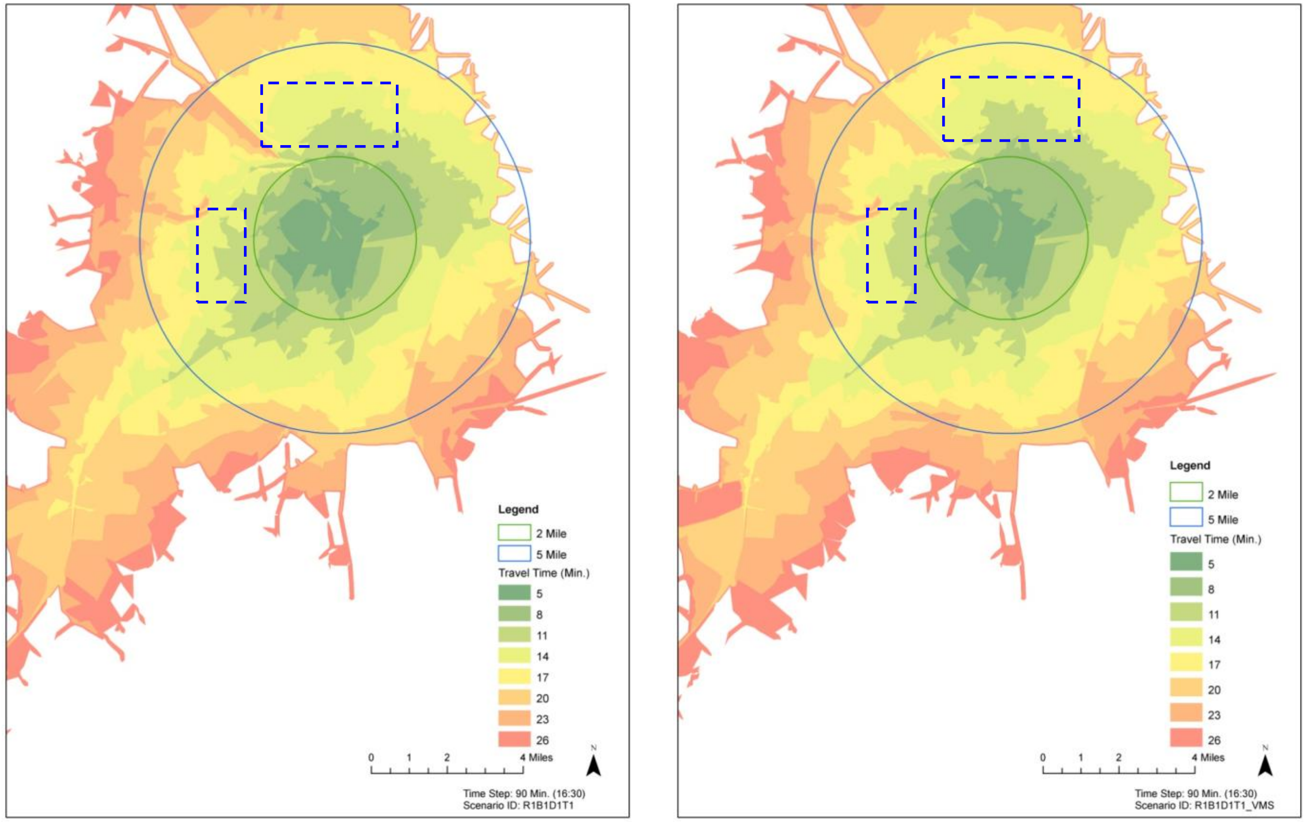
Evacuation Scenario	Average Travel Time (minutes)		P-value
	Base	VMS	
R1B1D1T1	44.358	44.758	0.676
R1B1D1T2	44.245	43.887	
R1B1D2T1	44.781	44.77	
R1B1D2T2	44.258	44.225	
R1B3D1T1	68.087	68.067	
R1B3D1T2	67.417	67.354	
R1B3D2T1	68.172	68.192	
R1B3D2T2	67.344	67.427	
R1B4D1T1	36.65	36.615	
R1B4D1T2	36.756	36.488	
R1B4D2T1	36.858	36.931	
R1B4D2T2	36.741	36.678	

Table 13. t-test Results between Base Case and VMS: 5-mile Radius

Evacuation Scenario	Average Travel Time (minutes)		P-value
	Base	VMS	
R2B1D1T1	54.159	54.21	0.162
R2B1D1T2	52.097	51.884	
R2B1D2T1	54.487	54.492	
R2B1D2T2	51.96	52.069	
R2B3D1T1	74.473	74.691	
R2B3D1T2	72.019	72.335	
R2B3D2T1	74.464	74.41	
R2B3D2T2	71.552	71.817	
R2B4D1T1	50.57	50.702	
R2B4D1T2	49.208	49.267	
R2B4D2T1	51.516	51.815	
R2B4D2T2	50.222	49.988	

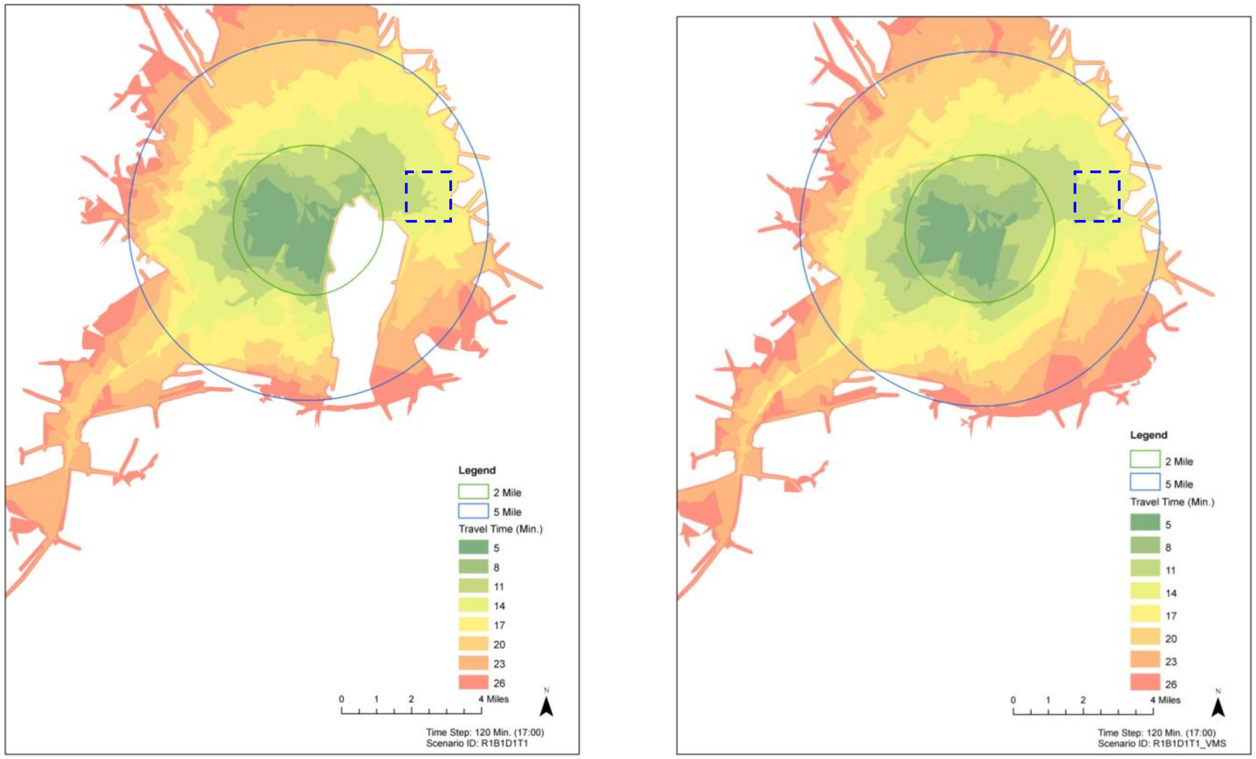
A trend was not evident in regards to which demand components ultimately produced larger overall travel times when VMS were used. The VMS evacuation demand scenarios that resulted in larger travel times contained a varied mix of the demand components D1, D2, T1, and T2. In other words there was not a definite combination of those demand components (e.g., D1T2 or D2T2) that produced larger travel times when VMS were implemented.

Maps of the average travel time across the two radii impacted areas were also generated for the congestion warning VMS strategy. The VMS did produce improvements for specific areas at certain times in the simulation period, but they were not as visually obvious as the optimized signal timing plan strategy.



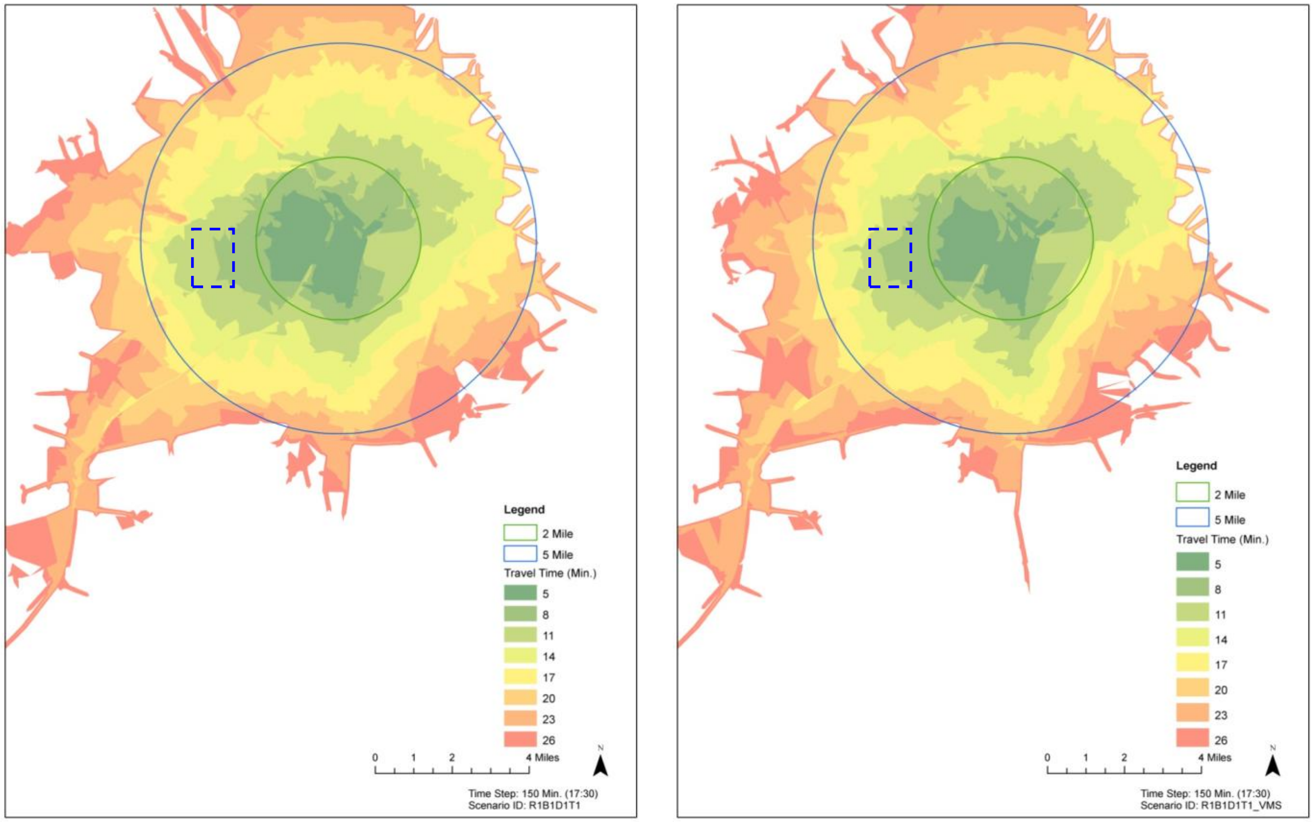
(a) **(b)**

Figure 33. Effect of Congestion Warning VMS for R1B1D1T1 at Minute 90, a) Base Network and b) Optimized Signal Timing Network (16)



(a) **(b)**

Figure 34. Effect of Congestion Warning VMS for R1B1D1T1 at Minute 120, a) Base Network and b) Optimized Signal Timing Network (16)



(a) **(b)**

Figure 35. Effect of Congestion Warning VMS for R1B1D1T1 at Minute 150, a) Base Network and b) Optimized Signal Timing Network (16)

It should be noted that the congestion warning VMS were set up such that *DynusT* decides whether there is significant congestion downstream from the VMS and also whether there is an alternate route that will provide a better trip (i.e., a trip with a shorter travel time). Diversion may not have occurred since congestion was seen downstream from the VMS and also along the possible alternative route. The congestion that occurred on the paths nears the established VMS occurred roughly around the same time and had very similar durations. Therefore, little improvements were viewed network-wide.

4.5.2. Effect of VMS on Evacuees' Travel Times

The travel times of the evacuees were collected from all 24 demand scenarios. Within the 2-mile radius impacted area, five of the demand scenarios contained smaller travel times for evacuees when the VMS were used in the networks. However the smaller travel times did not seem very significant. The percentage of improvement due to the VMS ranged from 0.01% to 1.46%.

Of the 5-mile radius demand scenarios, there were seven demand scenarios that produced smaller travel times for evacuees when the VMS were implemented. The percentages of improvement ranged from 0.07% to 0.84%. Although, the 2-mile radius demand scenarios had a higher percentage of improvement, three out of five demand scenarios had percentages of improvements that were 0.10% or less. Four out of the seven 5-mile radius demand scenarios had percentages of improvement that ranged from 0.44% to 0.84%

From the two-tailed, paired t-tests, the improvements to the evacuees' total travel time seen from the implementation of the congestion warning VMS were insignificant (i.e., estimated p-values were greater than 0.05). The p-value from the 2-mile radius evacuation scenarios was 0.618. The p-value obtained from the 5-mile radius evacuation scenarios was 0.269. Table 14 and Table 15 present the results of the two-tailed, paired t-tests.

Table 14. Effect to Evacuees' Total Travel Time Due to VMS: 2-mile Radius

Evacuation Scenario	Evacuees' Total Travel Time (minutes)		Percentage of Improvement	P-value
	Base	VMS		
R1B1D1T1	20511173.32	20650447.75	-0.68%	0.618
R1B1D1T2	20925694.4	20903934.19	0.10%	
R1B1D2T1	23056940.64	23148383.43	-0.40%	
R1B1D2T2	22450036.21	22566401.15	-0.52%	
R1B3D1T1	23354556.12	23013407.87	1.46%	
R1B3D1T2	23422904.81	23247613.52	0.75%	
R1B3D2T1	25551356.54	25681517.09	-0.51%	
R1B3D2T2	25063704.04	25083038.72	-0.08%	
R1B4D1T1	18932379.42	18947821.5	-0.08%	
R1B4D1T2	19325784.60	19319665.31	0.03%	
R1B4D2T1	21608638.14	21940152.45	-1.53%	
R1B4D2T2	22007792.16	22006422.65	0.01%	

Table 15. Effect to Evacuees' Total Travel Time Due to VMS: 5-mile Radius

Evacuation Scenario	Evacuees' Total Travel Time (min)		Percentage of Improvement	P-value
	Base	VMS		
R2B1D1T1	130844273.4	130678993.7	0.13%	0.269
R2B1D1T2	126444799.7	125876186.7	0.45%	
R2B1D2T1	136266453.20	136790266.3	-0.38%	
R2B1D2T2	130900265.52	131312523.7	-0.31%	
R2B3D1T1	134315525.7	134476811.4	-0.12%	
R2B3D1T2	129471677.5	128902424.4	0.44%	
R2B3D2T1	139798554	139453923.6	0.25%	
R2B3D2T2	133570770.5	132704904	0.65%	
R2B4D1T1	137760762	136606342.2	0.84%	
R2B4D1T2	135028142.3	134929854.8	0.07%	
R2B4D2T1	144087329.6	144099874.9	-0.01%	
R2B4D2T2	140458153.8	140941548.5	-0.34%	

4.5.3. Effect of VMS on OD Pairs

The OD pairs' travel times were analyzed for the demand scenario R1B1D2T2. Under D2, evacuees travel from the 2-mile radius impacted area to destination zones that contain the emergency shelters. The results are presented in Figure 36 to Figure 40. From these figures, the congestion warning VMS reduced the travel times for OD pairs under a no incident case as well for the incident cases. However, they did not produce benefits in travel time for other OD pairs. In all five figures, a 45 degree line was drawn from the origin. Above that line, the OD pairs had greater average travel times in the VMS network compared to the no VMS network. Below that line, the OD pairs had smaller average travel times in the VMS network compared to no VMS network. It should be noted that the average travel times are from completed trips (i.e., vehicles reached their destinations).

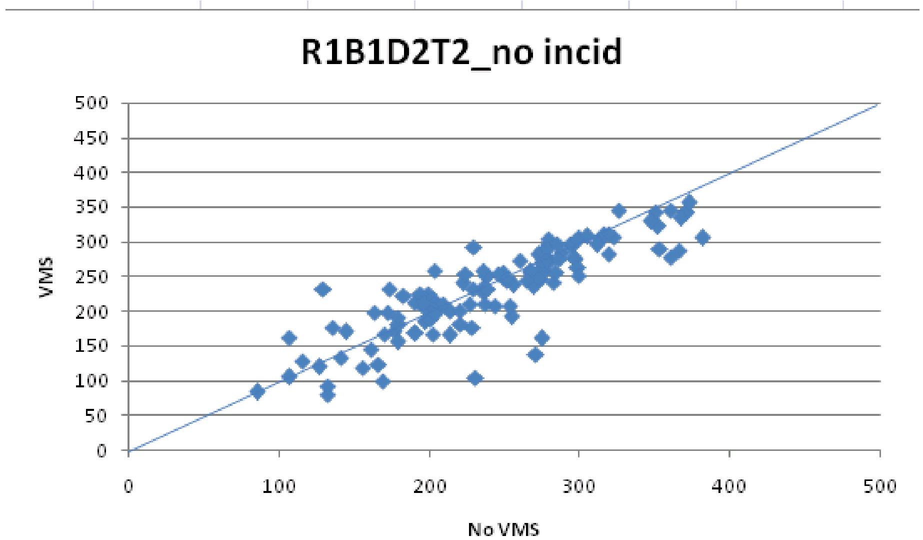


Figure 36. Comparison of OD Pairs' Average Travel Time between VMS Network and No VMS Network, R1B1D2T2, No Incident

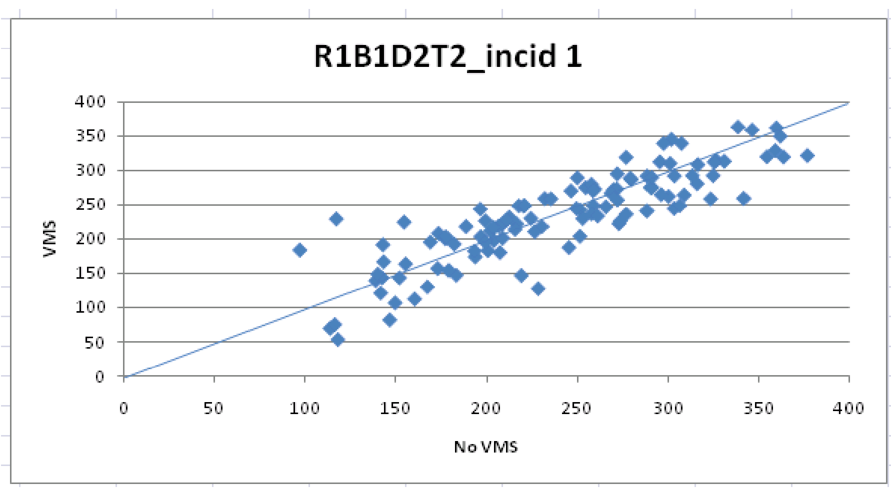


Figure 37. Comparison of OD Pairs' Average Travel Time between VMS Network and No VMS Network, R1B1D2T2, Incident 1

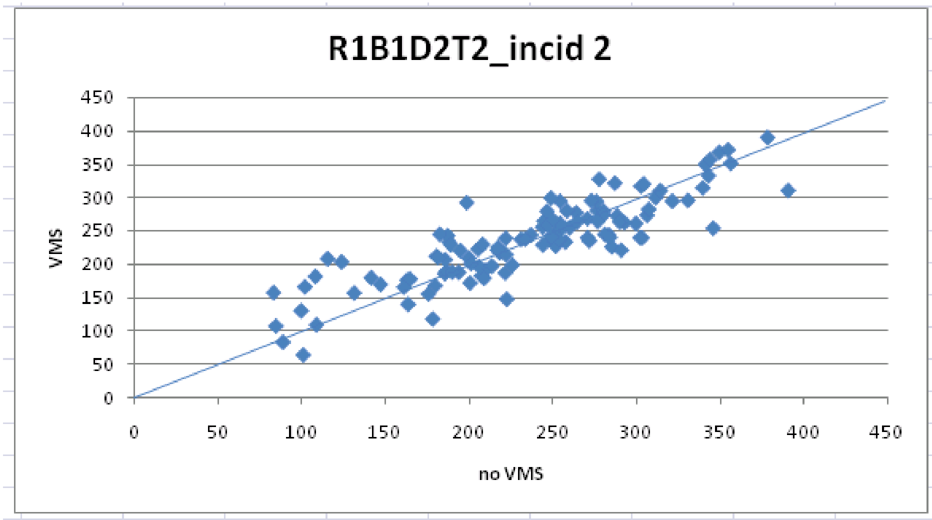


Figure 38. Comparison of OD Pairs' Average Travel Time between VMS Network and No VMS Network, R1B1D2T2, Incident 2

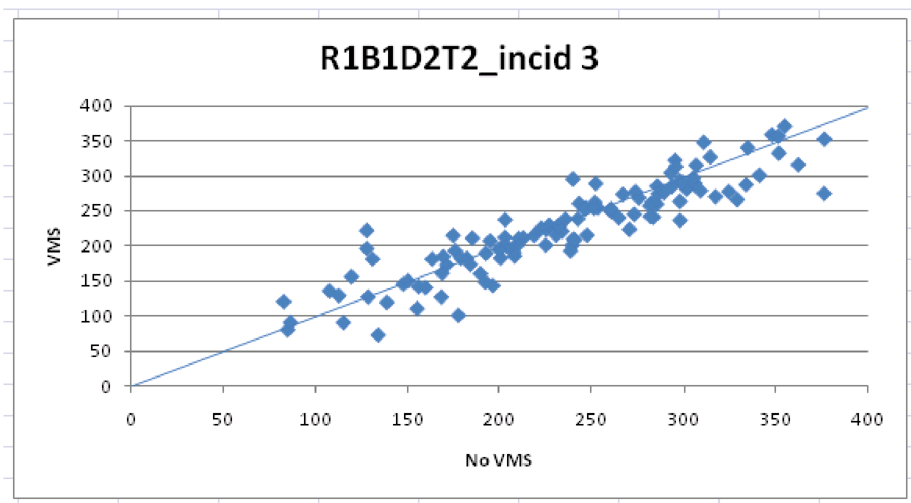


Figure 39. Comparison of OD Pairs' Average Travel Time between VMS Network and No VMS Network, R1B1D2T2, Incident 3

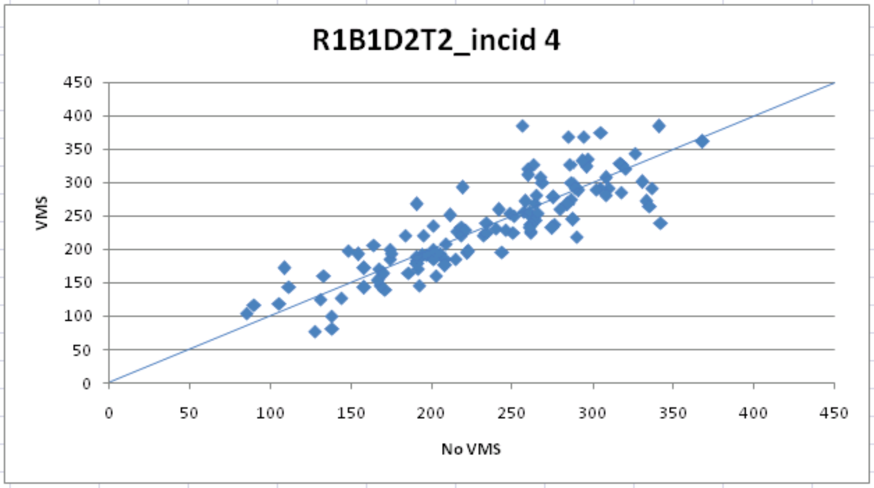


Figure 40. Comparison of OD Pairs' Average Travel Time between VMS Network and No VMS Network, R1B1D2T2, Incident 4

4.6. Variance in *DynusT*

Performing multiple simulation runs for each evacuation scenario was unnecessary due to the lack in major variance observed amongst the evacuation demand scenarios. The evacuation traffic and background traffic corresponding to either the 2-mile radius evacuation scenarios or the 5-mile radius evacuation scenarios have similar amount of overall demand generated in the network. They should differ by the demand considerations (i.e., background traffic type, traffic loading, and destination assignment). For instance, the difference in demand between R1B1D1T1 with the optimized signal timing and R1B1D1T2 with the optimized signal timing was approximately 7,000 vehicles (0.13% difference).

4.7. *DynusT* Modeling Limitations

Conducting the OD estimation and simulating the evacuation strategies may have be impacted by the modeling limitations in *DynusT*. All simulations conducted in *DynusT* produced demand from generation links rather than a centroid. As an effect, the intersections containing the generation links experienced excessively congested traffic conditions that would not be observed in the field.

Some HOV links could not be modeled exactly in *DynusT* particularly for HOV links that were not physically separated from the general purpose lanes by barriers. Outside the Beltway, a portion of I-66 WB contains general purpose lanes that exist adjacent to the HOV lane without a barrier separating the two lane types. However in *DynusT*, the HOV lane was modeled separately from the general purpose lanes as if it were a reversible HOV lane. In the real world, drivers along this portion of I-66 WB would be able to change lanes from general purpose to HOV and vise versa, but such a lane change cannot occur freely in *DynusT*. Vehicles in *DynusT* would only be able to make such a lane change only when there are available links connecting the two types of roadway lane types.

Chapter 5. Conclusion

This thesis included an analysis of two evacuation strategies implemented for no-notice disasters in Northern Virginia. Calibration of a network representing existing, non-evacuation traffic conditions was conducted prior to testing the evacuation strategies.

The signal timing of 396 intersections from 96 coordinated intersection groups were optimized for the evacuation demand created for the analysis. Four groups of evacuation demand were tested per radius for the optimized signal timing strategy. Based on results, the optimized signal timing improved throughput for all eight demand scenarios, but improvements were marginal. The maximum percentage of improvement was 0.57% for the throughput. Improvements in average travel time were only observed for two demand scenarios network-wide. The maximum percentage of improvement for those two demand scenarios was 0.62%. The two-tailed, paired t-tests proved that the improvements to the network-wide average travel times were marginal and insignificant for all eight evacuation scenarios. The p-values from those paired t-tests were 0.851 and 0.071.

From a view localized specifically within the 5-mile radius from the Pentagon, the effect of the optimized signal timing varied at different periods in the simulation. The results showed that the optimized signal timing worked well when there was a large surge in the evacuation volume (i.e., at minute 90) but the effectiveness of this strategy degraded as time elapsed in the simulation.

Improvements of the evacuees' travel time due to the optimized signal timing ranged from 0.02% to 4.81%. However, the two-tailed, paired t-tests showed that the improvements to the evacuees' total travel time were marginal and insignificant for the 2-mile radius evacuation scenarios. It should be noted that the p-value from the 2-mile radius evacuation scenarios was 0.0912 even though some of the 2-mile radius evacuation scenarios experienced improvements to the evacuees' total travel time by 3.96% and 4.81%. It is believed that the percentage of improvement from R1B1D1T1 (0.02%) degraded the estimation in the p-value for the 2-mile radius evacuation scenarios. Excluding R1B1D1T1 from the paired t-test, the p-value would be 0.0581. The t-test would still show insignificance in the improvements due to the optimized signal timing, but the improvements are closer to be considered as significant based on the smaller p-value.

Implementing the optimized signal timing in the 5-mile radius evacuation scenarios produced significant improvements in terms of the evacuees' total travel time. The p-value from the two-tailed, paired t-test was 0.0049.

A sensitivity analysis was conducted on the effect of optimized signal timing from one demand scenario onto different demand scenarios. The demand scenarios R1B3D1T1 and R1B4D1T1 were simulated with the optimized signal timing from the demand scenario R1B1D1T1. The results showed improvements for R1B3D1T1 but not for R1B4D1T1.

There were six congestion warning VMS that were established in the network. They were assigned customized activation times based on the congestion levels surrounding them. On a network-wide level, the VMS lacked significant improvements in travel time. The maximum percent of improvement in travel time due to the VMS was 0.81% for the all demand scenarios. The p-values from the paired t-tests were 0.676 and 0.162 for the 2-mile radius evacuation scenarios and the 5-mile radius evacuation scenarios. Based on the t-test analyses, the improvements to network-wide average travel time were insignificant due to the congestion warning VMS.

Improvements were seen at a more localized area; however they were more subtle than the optimized signal timing. When there were no incidents during an evacuation, the congestion levels were quite similar for sections that were downstream from the VMS location and from the possible alternate route. If congestion is severe all around the VMS, then this presents a difficulty for *DynusT* to choose a suitable route for divergence (i.e., path with shorter travel time).

The congestion warning lacked a positive effect on the evacuees' total travel time for all evacuation scenarios. The maximum percentage of improvement to the evacuees' total travel time was 1.46%. The two-tailed, paired t-tests further proved that the benefits gained from implementing the congestion warning VMS were rather marginal since the p-values from the 2-mile radius evacuation scenarios and 5-mile radius evacuation scenarios were 0.618 and 0.269.

An analysis of the impacted OD pairs' travel times was also conducted in this analysis. A decisive conclusion cannot be made on the effect of the congestion warning VMS on the impacted OD pairs since only one demand scenario was involved in the analysis. The results show that about half of the impacted OD pairs had improved average travel times for the no incident case and also for the four incident cases.

Chapter 6. Recommendations

This thesis presents recommendations for future attempts in calibrating a *DynusT* network and it also provides future recommendations for the two evacuation strategies to obtain greater enhancements.

Calibration can be conducted using traffic counts obtained from detectors. The downside of solely using traffic counts is that they can represent a particular traffic that can occur at two different speeds. Additional traffic measurements, such as Inrix speed data, should be used to ensure that observed volumes and speeds are modeled in the *DynusT* network.

For this thesis, time space diagram comparisons were performed as a qualitative analysis between the Inrix speeds and the *DynusT* speeds. For future research, conducting a quantitative analysis between the *DynusT* speeds and the Inrix speeds should be done following the time space diagram comparisons. The quantitative analysis can consist of estimating the coefficients of correlation for two cases: 1) Inrix speeds and the *DynusT* speeds from the uncalibrated network and 2) Inrix speeds and the *DynusT* speeds from the calibrated network. It may be found in future research that the number of *DynusT* links and the number of Inrix links covering the same portion of a corridor to not match, which was the case for this thesis. A common observation in regards to the time space diagram comparisons is that an Inrix link typically comprised of several smaller *DynusT* links. In other words, a portion of a corridor would only be made up of one Inrix link, which would take three or four *DynusT* links to cover the same area. As a result, additional data manipulation will be necessary to obtain the same number of *DynusT* links as Inrix links. A researcher can calculate an estimated speed that is averaged from the group of *DynusT* links that correspond to correct Inrix link. Performing this task may result in equivalent numbers of Inrix speed data and *DynusT* speed data, which then can be used to calculate the coefficients of correlation. It should be expected that the *DynusT* speeds from the calibrated network should have a closer relationship (i.e., higher coefficient of correlation) to the Inrix speeds data than the comparison of the *DynusT* speeds from the uncalibrated network and Inrix speeds.

In future works involving the calibration of a *DynusT* network, it may be best to go with Calibration Approach 1. In this approach, OD estimation was conducted first. Then the traffic flow model adjustments followed the OD estimation. Calibration Approach 2 adjusted the traffic flow models first and then conducted the OD estimation.

Another adjustment of the traffic flow models would be needed after the OD estimation in Calibration Approach 2.

One set of optimized signal timing plans were used to evaluate the optimized signal timing strategy. The results showed degradation as more time elapsed in the simulation. Therefore, a time of day condition should be established in the field. There should be at least three sets of timing plans: 1) typical day timing plans (i.e., prior to evacuation), 2) evacuation timing plans (i.e., during the large evacuation surge), and 3) post evacuation timing plans (i.e., after the large evacuation surge).

In terms of applying a set of optimized signal timing plans to different sets of evacuation demands, the R1B1D1T1 optimized signal timing produced benefits for one demand (R1B3D1T1) but not the other (R1B4D1T1). From the results, it may be best to develop multiple sets of optimized signal timing plans to accommodate the variations in the evacuation demand size. Further analysis should be conducted for other evacuation demand scenarios.

From the results of the VMS strategy, the congestion warning VMS were not that effective in diverging vehicles from severe congestion. VMS that advise mandatory detours may be more useful in diverging vehicles during an evacuation. The congestion located downstream from the VMS will have a better chance of subsiding due to the mandatory detours.

Further analysis should be conducted in order to conclude whether the VMS were an aid in reducing the travel time of the impacted OD pairs. The results for one demand scenario showed that roughly half of the OD pairs gained benefits in travel time.

Manipulation of the Indifference Band and/or the Threshold Bound should be performed in future research. The Indifference Band and the Threshold Bound are user-defined values that represent when vehicles should divert onto another path. The Indifference Band is the percentage of improvement to a trip. Under the assumption that the Indifference Band is set to 0.20, vehicles will divert onto the alternate route if their travel time can be improved by 20% using that alternate route. The Threshold Bound represent the minimum value (in minutes) that will cause vehicles to change paths. Vehicles will divert onto an alternate route if their travel time will improve by the user-defined minute value. Default values for both parameters were used for this thesis.

The VMS response rate in *DynusT* should also be tested in future analysis to determine its sensitivity in modeling the effects of the congestion warning VMS. It can be argued that a lower response rate (i.e., smaller than 85%) could be used since a no-notice evacuation would produce a hectic environment where evacuees unintentionally notice the advisory warnings on the VMS. On the other hand, a higher response rate (i.e., greater than 85%) could be used in future analysis since evacuees may utilize whatever warnings that are provided to them to evacuate from the impacted area as soon as possible.

Additional strategies should be tested in future analysis of no-notice evacuations. This thesis showed that the optimized signal timing and the congestion warning VMS did not produce significant benefits in travel time for a majority of the evacuation scenarios. Implementing one strategy may not be the solution in effectively moving evacuees during a no-notice evacuation. A combination of strategies may be needed. The optimized signal timing was the only strategy that produced significant improvements to the evacuees' total travel time for the 5-mile radius evacuation scenarios. Due to that outcome, additional analysis should be conducted with the optimized signal timing. One analysis could be of implementing the optimized signal timing along some arterials with the use of contraflow along different arterials.

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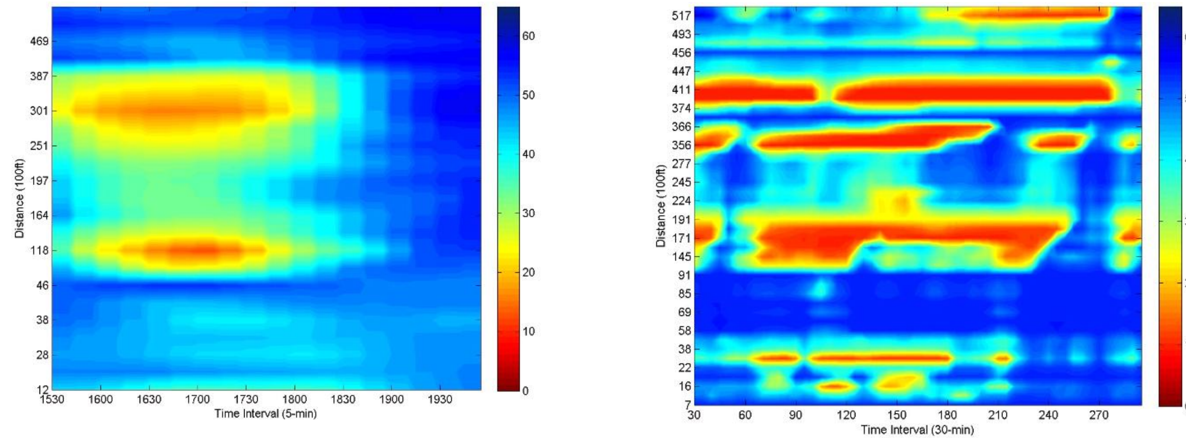
Appendix A



(a) **(b)**

Figure A1. I-395 SB: (a) Inrix and (b) *DynusT*

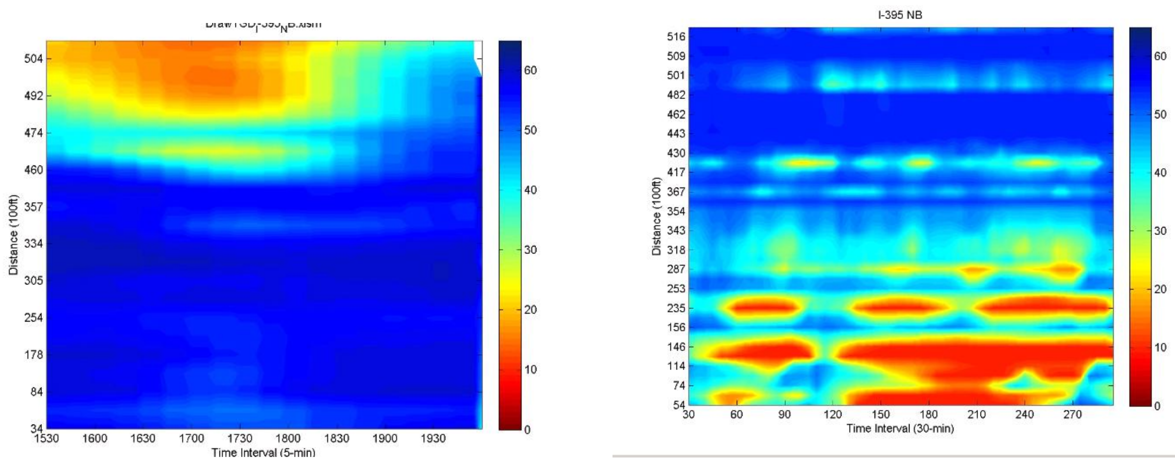


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Figure A2. I-395 NB: (a) Inrix and (b) *DynusT*

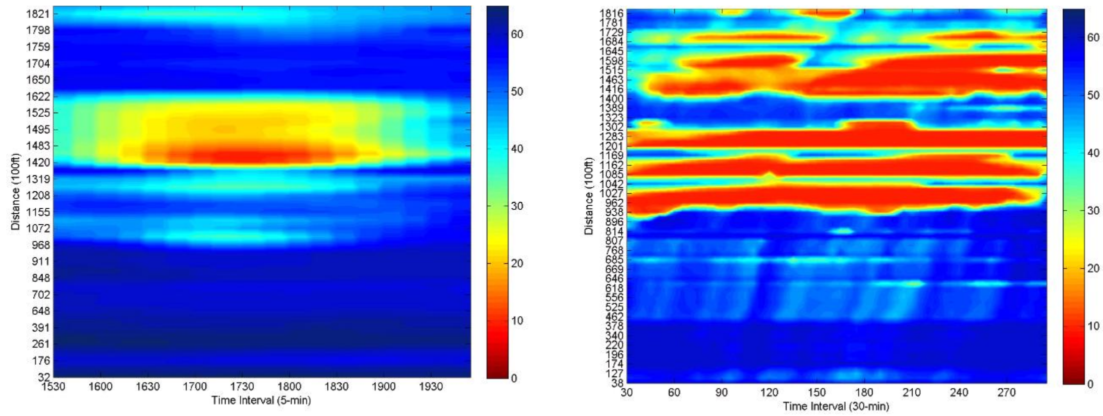

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Figure A3. I-66 EB: (a) Inrix and (b) *DynusT*

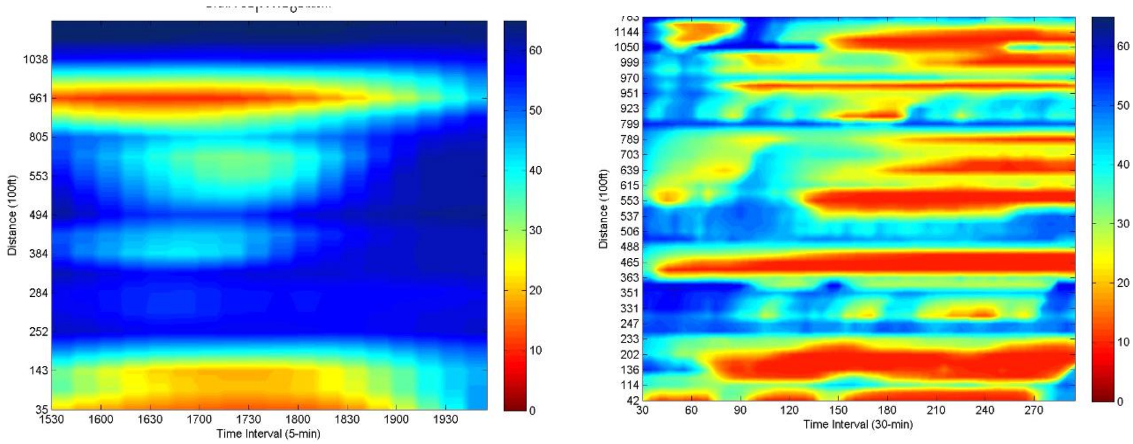

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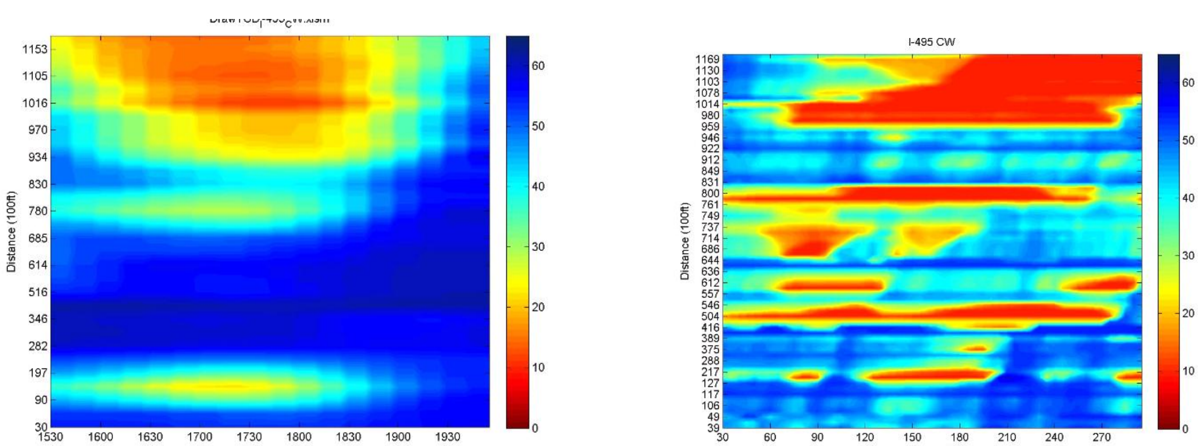
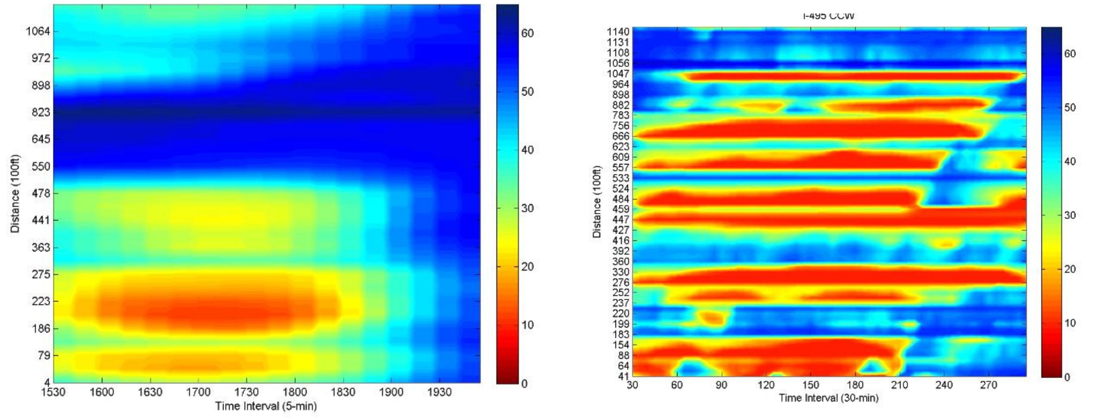
Figure A4. I-66 WB: (a) Inrix and (b) *DynusT*



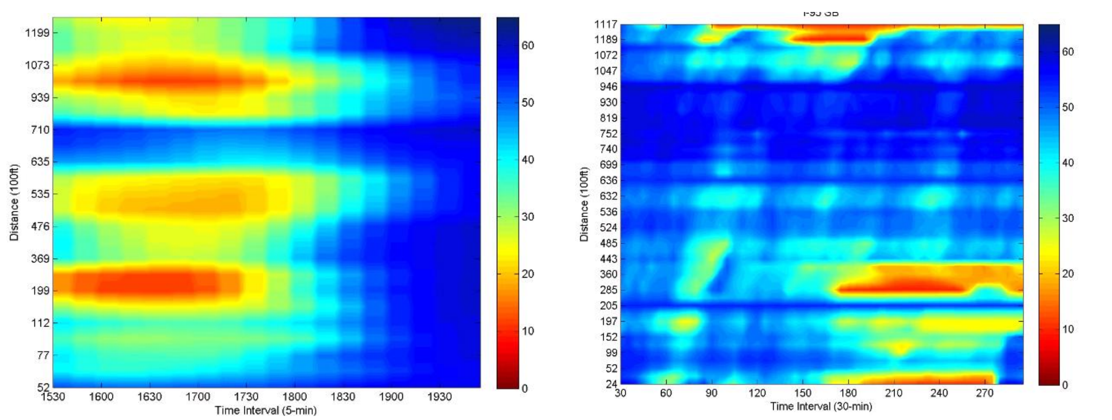
(a) **(b)**

Figure A5. I-495 CW: (a) Inrix and (b) *DynusT*



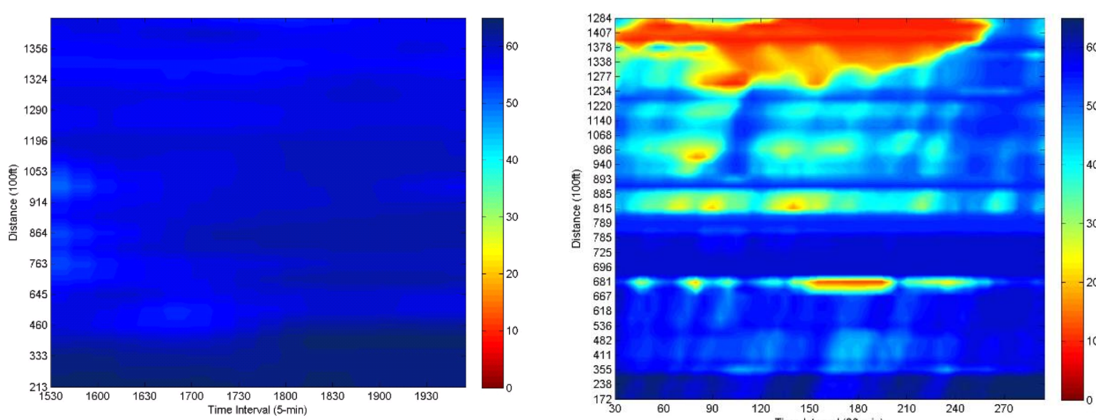
(a) **(b)**

Figure A6. I-495 CCW: (a) Inrix and (b) D*ynusT*



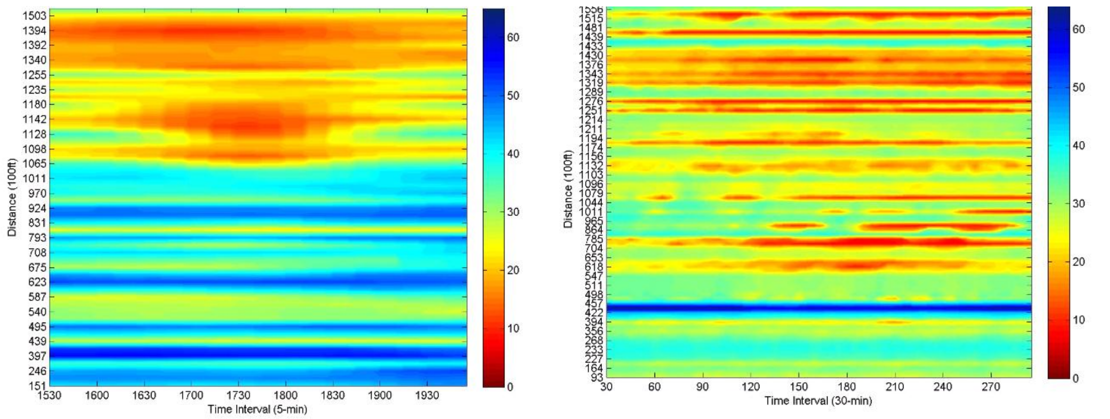
(a) **(b)**

Figure A7. I-95 SB: (a) Inrix and (b) *DynusT*



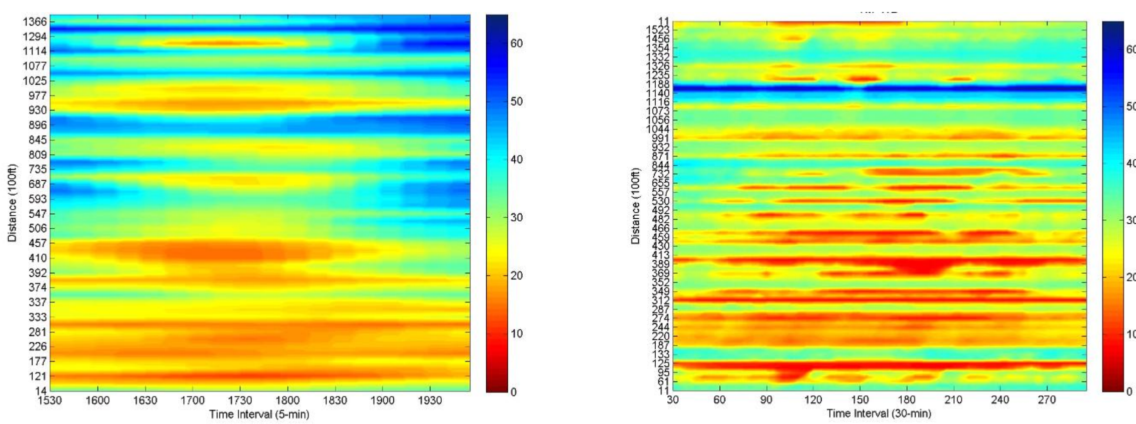
(a) **(b)**

Figure A8. I-95 NB: (a) Inrix and (b) *DynusT*



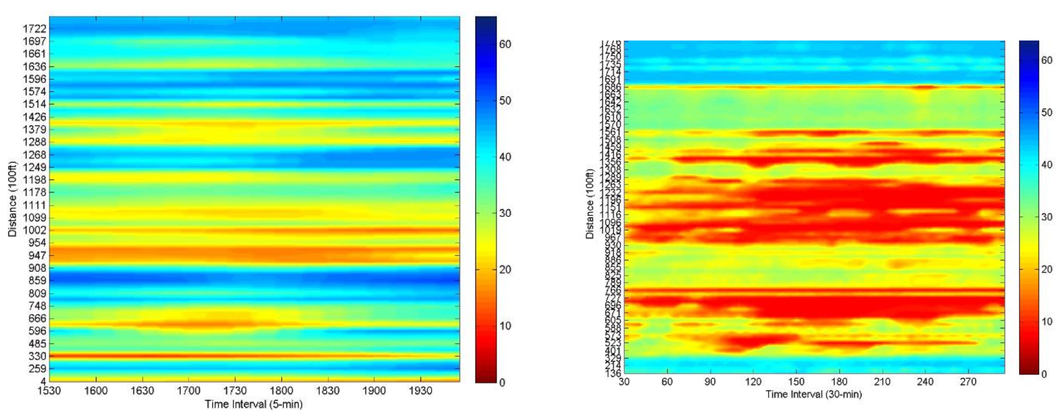
(a) **(b)**

Figure A9. Route 7 EB: (a) Inrix and (b) *DynusT*



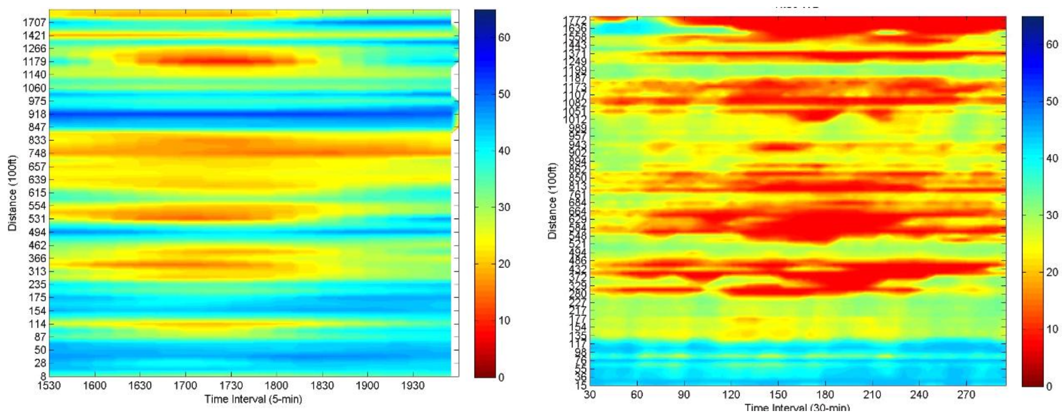
(a) **(b)**

Figure A10. Route 7 WB: (a) Inrix and (b) *DynusT*



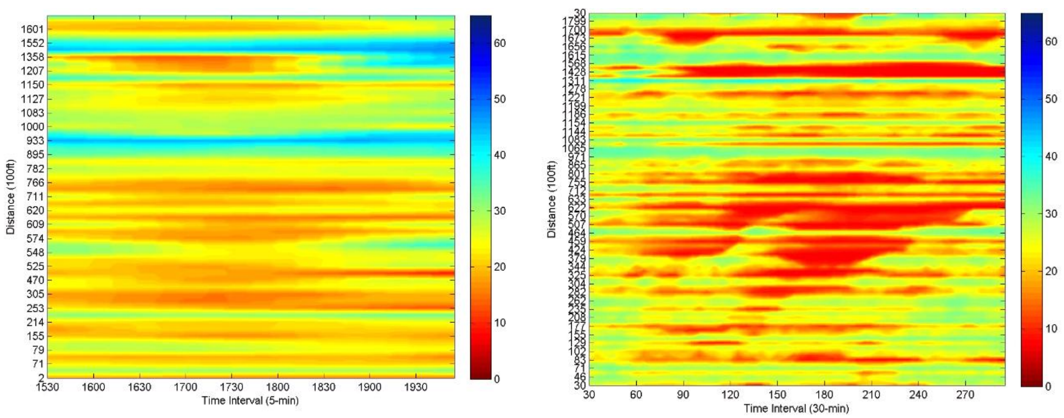
(a) **(b)**

Figure A11. Route 50 EB: (a) Inrix and (b) *DynusT*



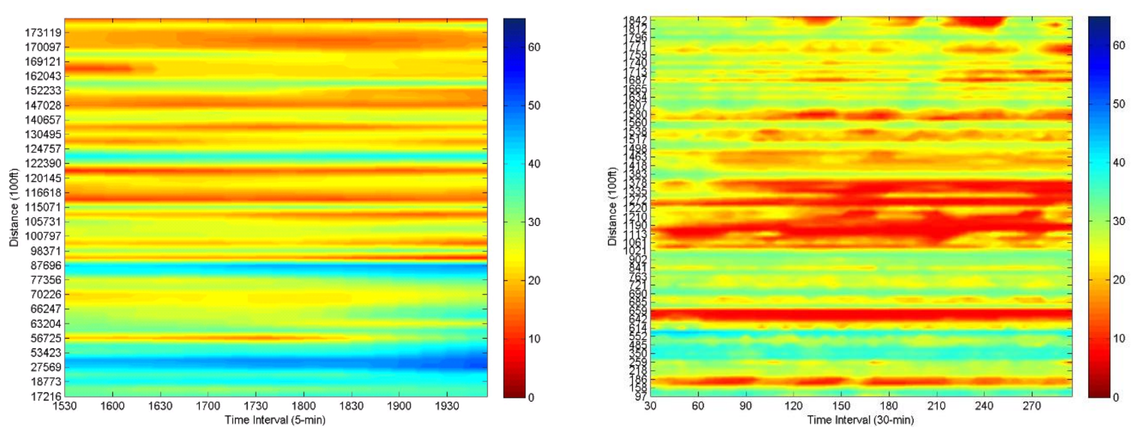
(a) **(b)**

Figure A12. Route 50 WB: (a) Inrix and (b) *DynusT*



(a) **(b)**

Figure A13. Route 29 SB: (a) Inrix and (b) *DynusT*



(a) **(b)**

Figure A14. Route 29 NB: (a) Inrix and (b) *DynusT*

Appendix B

Table B1. VMS Activation Times for 2-mile Radius Impacted Area

#	VMS location	DynusT link #	R1B1D1T1		R1B1D1T2		R1B1D2T1		R1B1D2T2	
			start(min)	end(min)	start(min)	end(min)	start(min)	end(min)	start(min)	end(min)
1	Fairfax Dr SB at R120	5105,5100	120	360	120	360	120	330	120	370
2	R236 at R401	376, 378	70	420	70	420	70	390	70	390
3	R1 prior to Gibbons St/I-495	5570, 5720	70	330	70	330	70	330	85	290
4	R1 prior to R7100	806, 6177	70	370	105	385	70	390	105	390
5	R29 after N Scott St	5123, 5121	70	230	70	325	70	320	70	360
6	R123 @ Dulles Toll Rd interchange	10875, 10612	70	350	70	360	70	360	70	350

Table B2. VMS Activation Times for 2-mile Radius Impacted Area (Continued)

#	VMS location	DynusT link #	R1B3D1T1		R1B3D1T2		R1B3D2T1		R1B3D2T2	
			start(min)	end(min)	start(min)	end(min)	start(min)	end(min)	start(min)	end(min)
1	Fairfax Dr SB at R120	5105,5100	120	310	120	290	120	325	120	285
2	R236 at R401	376, 378	*100*	390	70	410	70	390	70	400
3	R1 prior to Gibbons St/I-495	5570, 5720	*80*	270	70	270	70	270	70	270
4	R1 prior to R7100	806, 6177	*70*	270	70	390	90	390	70	390
5	R29 after N Scott St	5123, 5121	*70*	240	70	285	70	300	70	270
6	R123 @ Dulles Toll Rd interchange	10875, 10612	*70*	350	70	280	70	300	70	310

Table B3. VMS Activation Times for 2-mile Radius Impacted Area (Continued)

#	VMS location	DynusT link #	R1B4D1T1		R1B4D1T2		R1B4D2T1		R1B4D2T2	
			start(min)	end(min)	start(min)	end(min)	start(min)	end(min)	start(min)	end(min)
1	Fairfax Dr SB at R120	5105,5100	120	305	120	290	120	310	120	345
2	R236 at R401	376, 378	70	405	70	420	70	415	70	420
3	R1 prior to Gibbons St/I-495	5570, 5720	70	270	70	330	70	340	70	240
4	R1 prior to R7100	806, 6177	90	370	100	390	105	370	105	390
5	R29 after N Scott St	5123, 5121	70	300	70	300	70	300	70	300
6	R123 @ Dulles Toll Rd interchange	10875, 10612	70	405	70	360	70	420	70	360

Table B4. VMS Activation Times for 5-mile Radius Impacted Area

#	VMS location	DynusT link #	R2B1D1T1		R2B1D1T2		R2B1D2T1		R2B1D2T2	
			start(min)	end(min)	start(min)	end(min)	start(min)	end(min)	start(min)	end(min)
1	Fairfax Dr SB at R120	5105,5100	120	420	120	530	120	420	120	535
2	R236 at R401	376, 378	70	500	70	540	70	540	70	540
3	R1 prior to Gibbons St/I-495	5570, 5720	70	330	70	365	70	360	70	370
4	R1 prior to R7100	806, 6177	90	395	70	385	90	435	100	410
5	R29 after N Scott St	5123, 5121	70	440	70	520	70	420	70	525
6	R123 @ Dulles Toll Rd interchange	10875, 10612	70	340	70	340	70	345	70	330

Table B5. VMS Activation Times for 5-mile Radius Impacted Area (Continued)

#	VMS location	DynusT link #	R2B3D1T1		R2B3D1T2		R2B3D2T1		R2B3D2T2	
			start(min)	end(min)	start(min)	end(min)	start(min)	end(min)	start(min)	end(min)
1	Fairfax Dr SB at R120	5105,5100	120	525	120	540	120	510	120	540
2	R236 at R401	376, 378	70	540	70	540	70	540	70	540
3	R1 prior to Gibbons St/I-495	5570, 5720	70	300	70	255	70	315	70	300
4	R1 prior to R7100	806, 6177	70	395	70	410	90	475	70	405
5	R29 after N Scott St	5123, 5121	70	520	70	540	70	510	70	540
6	R123 @ Dulles Toll Rd interchange	10875, 10612	70	300	70	300	70	300	70	300

Table B6. VMS Activation Times for 5-mile Radius Impacted Area (Continued)

#	VMS location	DynusT link #	R2B4D1T1		R2B4D1T2		R2B4D2T1		R2B4D2T2	
			start(min)	end(min)	start(min)	end(min)	start(min)	end(min)	start(min)	end(min)
1	Fairfax Dr SB at R120	5105,5100	120	410	120	495	120	420	120	505
2	R236 at R401	376, 378	70	480	70	600	70	615	70	660
3	R1 prior to Gibbons St/I-495	5570, 5720	90	340	70	330	70	300	70	320
4	R1 prior to R7100	806, 6177	105	510	100	390	100	540	90	520
5	R29 after N Scott St	5123, 5121	70	410	70	480	70	420	70	510
6	R123 @ Dulles Toll Rd interchange	10875, 10612	70	330	70	300	70	315	70	340