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Evaluation of Driveway Assistance Device (DAD) Systems in One-Lane Two-Way Work Zone

MM Shakiul Haque, PhD
Post-Doctoral Research Associate
Mid-America Transportation Center
Department of Civil and Environmental Engineering
University of Nebraska-Lincoln

Aemal J. Khattak, PhD
Director, Mid-America Transportation Center
Professor, Department of Civil and Environmental Engineering
University of Nebraska-Lincoln

Li Zhao, PhD
Research Assistant Professor
Department of Civil and Environmental Engineering
University of Nebraska-Lincoln

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MM Shakiul Haque, Ph.D.
Post-Doctoral Research Associate
Mid-America Transportation Center
Department of Civil & Environmental Engineering
University of Nebraska-Lincoln
Email: mhaque4@unl.edu

Aemal J. Khattak, Ph.D.
Director, Mid-America Transportation Center
Professor, Department of Civil and Environmental Engineering
University of Nebraska-Lincoln
Email: khattak@unl.edu

Li Zhao, Ph.D.
Research Assistant Professor
Department of Civil & Environmental Engineering,
University of Nebraska-Lincoln
Email: lizhao@unl.edu

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16. Abstract

Lane closure on two-lane highways due to the presence of work zones negatively impacts traffic safety and operational efficiency. Additionally, traffic from access points (e.g., commercial and residential driveways, or minor side roads) within work zones make operations more complicated and inefficient. Deploying a driveway assistance device (DAD) system can enable more efficient traffic control for work zones with access points. While traffic agencies are becoming interested in DAD deployments, research on such systems is relatively sparse. This research was the first in-depth operational investigation of the DAD system under different signal strategies, traffic conditions, and work zone characteristics. This study modeled DAD-operated work zones for single-lane closure on two-lane highways using microsimulation software calibrated to field-observed Nebraska work zone data. First, this study modeled and evaluated different signal control strategies using 192 scenarios and identified the most efficient strategy for DAD operations using statistical comparisons. Second, this research conducted a sensitivity analysis on various factors including traffic volumes, truck percentages, work zone lengths, and numbers of DAD-controlled access points. A total of 3,456 traffic scenarios were established to assess the effect of the DAD system in terms of delays and queues. Furthermore, this study has reviewed research related to the signal head designs, placement, and driver compliance of the DAD system. This report highlights important findings and discusses the practical implications of the DAD system in work zones, which may help traffic agencies improve operation and safety. While the work zone data used from Nebraska represents characteristics typical of the U.S. Midwest, the research methods and tools used are transferable to study DAD-operated work zones in other locations across the U.S. without a loss of generality. Future studies should cover more data from access points under the DAD system when such experiments are permitted by the Federal Highway Administration (FHWA).

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Abstract

Lane closure on two-lane highways due to the presence of work zones negatively impacts traffic safety and operational efficiency. Additionally, traffic from access points (e.g., commercial and residential driveways, or minor side roads) within work zones make operations more complicated and inefficient. Deploying a driveway assistance device (DAD) system can enable more efficient traffic control for work zones with access points. While traffic agencies are becoming interested in DAD deployments, research on such systems is relatively sparse.

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Chapter 1 Introduction

1.1 Background

When one lane of a two-lane, two-way roadway is closed as a result of a work zone, traffic in each direction will take turns utilizing the one open lane. The alternating one-way traffic will be controlled using various methods including flagger, pilot car, or portable temporary traffic signal control. However, these control methods are not always feasible for controlling work zone access points located in the work zone such as residential driveways, business driveways, or minor side streets. These access points, in many cases, may contribute to substantial traffic.

Depending on conditions (e.g., work duration, traffic volume, time of day, and project cost), typical control strategies of the Nebraska Department of Transportation (NDOT), along with other states' Departments of Transportation (DOT), include utilizing flagging or a temporary R-Y-G (i.e., Red, Yellow, Green) signal in the access points of one-lane two-way work zones. When either of these systems are applied in the access points, they need to be coordinated with the control method utilized at each end of the work zone. Unfortunately, the use of these approaches has issues including (1) an inefficient use of personnel conducting flagger control; (2) an increase in cycle length which increases delay; (3) a lack of clear direction for driveway vehicles turning onto the single open lane; and (4) multiple access points contributing to complexities in allocating the best coordination technique between mainline and access points controls.

These issues arise because there are three traffic flow directions (i.e., two on the main road and one from the driveway) or more directions (in case of more than one access point located on both sides of the single open lane) that need to share the conflicting one-lane two-way work zone. These issues are particularly problematic in the case of a long work zone where it may not be possible to see the traffic entering the work zone from the opposing direction (Daniels et al., 2000). In addition, drivers entering the work zone from a driveway may be confused as to the current direction of traffic on the main roadway and enter the roadway in the wrong direction. This is particularly true if the main road traffic volume is low. Intuitively, traveling in the wrong direction would increase the potential of a head-on collision with the main road traffic.

In recent years, driveway assistance device (DAD) systems have been developed. These devices aid drivers who are entering the work zone from a driveway located in the work zone. The goal is to eliminate or mitigate the issues discussed above. Figure 1.1 shows an illustration of two DAD layouts in a one-lane two-way work zone.

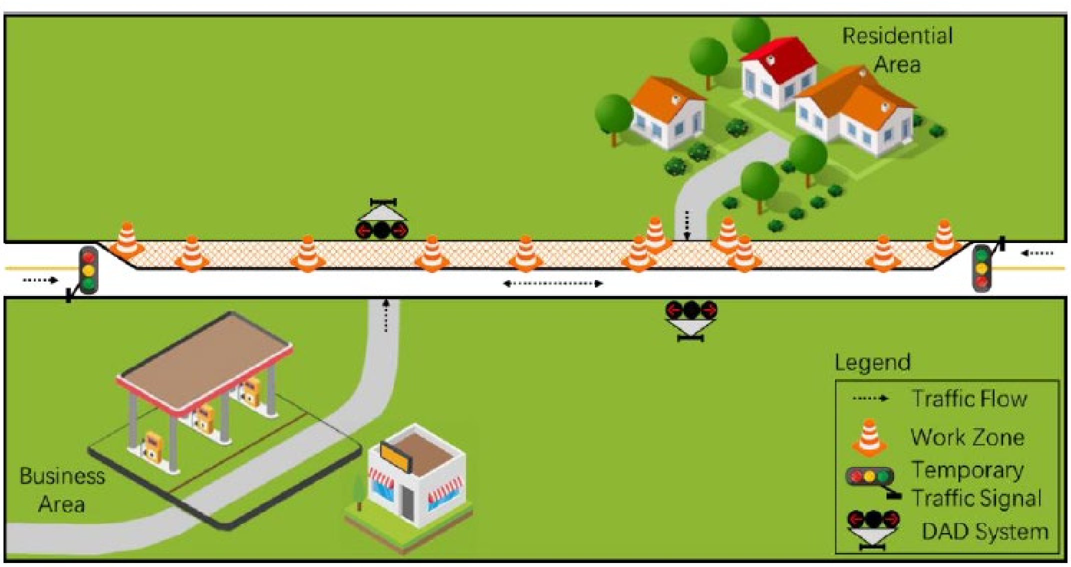


Figure 1.1 A Typical layout of a DAD system with temporary traffic control signals

In Figure 1.1, there are two driveways located in the work zone and each driveway has a DAD placed across from its entry point and synchronized with the portable traffic signals located at each end of the work zone. The DAD systems have directional arrows that either show red or flashing yellow. The flashing yellow arrows indicate the driver may turn into the work zone in the direction of the yellow arrow if there are no conflicts with oncoming traffic. The red light indicates that a driver is not allowed to enter the work zone. The DAD system is synchronized with the mainline traffic control system to achieve work zone operational safety and efficiency.

There are three needs that motivated this research:

1. Develop control strategies for DAD systems for the most efficient operational outputs:

   When a one-lane two-way work zone has multiple access points, it becomes essential to coordinate DADs with the mainline signal. The use of actuated or fixed-timed methods with various signal phases in this coordination has not been thoroughly investigated. Creating different control strategies will help traffic agencies implement the most effective approaches when using DADs.

2. Evaluate the operational impacts of DAD systems on overall work zone performance:

   One-lane two-way work zones, even without access points (i.e., without DAD), significantly affects operational performance such as delays and queues (Haque, 2022; Washburn et al., 2008; Tufuor et al., 2022). Therefore, traffic, signals, and work zone characteristics like main road and access point traffic volumes, truck percentage, work zone length, number of access points (i.e., number of DAD), and signal control methods (e.g., various DAD signal combinations with main road signals) are crucial and will profoundly impact operations (Haque, 2022) of DAD-operated work zones. However, the full scope of these effects has not yet been examined. This project will evaluate the operational impacts of DAD systems on overall work zone performance.

3. Develop guidelines for implementing DAD systems based on operation and safety implications:

   At present, DAD systems are not included in the Manual on Uniform Traffic Control Devices (MUTCD). Consequently, research is ongoing regarding various alternative signal heads for DADs, drivers' compliance rates with various DAD configurations, and the placement of DADs. This project will review the outcomes of this research to find recommended practices in terms of safety. Furthermore, considering the traffic, signal, and work zone characteristics, the project will conduct Nebraska work zone simulated studies to develop best practices for efficient DAD operations.

1.2 Research Objectives

The major objectives of this study are as follows.

1. Model a DAD-operated one-lane two-way work zone lane closure system.
2. Model and evaluate signal control strategies to regulate the DAD system.
3. Conduct a sensitivity analysis of work zone and traffic characteristics impacting DAD operations.
4. Find best practices regarding DAD-related work zone safety from the existing research.
5. Highlight the critical findings of DAD operation and safety for practitioners and researchers.

1.3 Research Outline

The following tasks were conducted over the course of this project:

1. Review of traffic control practice in one-lane two-way work zones with and without access points.
2. Modeling of one-lane two-way work zones with DAD system.
3. Development and evaluation of signal control strategies for DAD system.
4. Impact assessment of DAD system for work zone operations.
5. Review of the DAD system in terms of its safety and design implications.

This report is structured as follows. Chapter 2 conducts the literature review. Chapter 3 discusses the modeling effort of a one-lane two-way work zone lane closure system with DAD, followed by Chapter 4, which includes the modeling and evaluation of different signal control techniques. Chapter 5 presents the sensitivity analyses of DAD-operated work zones using different traffic and work zone characteristics. Chapter 6 discusses the safety and design aspects of the DAD System. Finally, Chapter 7 concludes with a summary of the key findings, recommendations for researchers and practitioners, and a discussion of potential directions for future research. Note that this report has Appendix A, B, and C, which present additional tables and charts from the performance analysis of different signal control strategies using different numbers of access points.

Chapter 2 Literature Review

This chapter describes the state-of-the-practice regarding the installation and operations of traffic controls for one-lane two-way work zones in the U.S. Additionally, the standard of practice of different states including Nebraska from the Midwest, and related literature are discussed.

2.1 Traffic Controls on One-Lane Two-Way Work Zone

The current edition of the Manual on Uniform Traffic Control Devices (MUTCD) (MUTCD, 2023) provides guidance on how to control traffic at lane closures on one-lane two-way roads. It states that "...when traffic in both directions must use a single lane for a limited distance, movements from each end shall be coordinated. Provisions should be made for alternate one-way movement through the constricted section via methods such as flagger control, a flag transfer, a pilot car, traffic control signals, or stop or yield control. Control points at each end should be chosen to permit easy passing of opposing lanes of vehicles." The MUTCD makes it clear that if the entry/exits of the closed lane do not make traffic visible from both ends, then a flagger control, a pilot car with flagger, or a temporal signal head control should be used. Otherwise, if the visibility of opposing traffic is not an issue on a low-volume road with a short work zone, then the movement of traffic may be self-regulated with STOP or YIELD signs. The traffic movement in one open lane on two-lane highways can be controlled using methods generally grouped into four types, which are human flagger, automated flagger, pilot car, and temporary traffic signal. These methods are described in the following sections.

2.1.1 Human Flagger Control Method

Deploying personnel with flags showing stop or slow down at the entry/exit points of the constricted roadway sections is the most frequently used flagging method for one-lane two-way roads (Farid et al. 2018) as shown in Figure 2.1. Though using personnel as flaggers may be done during night operations (when stations are illuminated), short-term operations in the day are the most common setup (Finley et al., 2014). Important factors to consider when choosing the human flagger technique are topography, length of lane closure, alignment, time of work (e.g., nighttime, or daytime), and work duration (short-term or long-term). Note that reported crashes involving flaggers are often severe and it is a function of the flagger's position and the car's speed (Finley et al., 2014).

Figure 2.1 Human flagger (WZTC, 2024)

2.1.2 Automated Flagger Control Method

Automated flagger assistance devices (AFAD) are designed to perform tasks similar to flaggers without needing humans to stay near traffic lanes. The AFAD typically includes a gate system with a flag at its arm that signals and closes a traffic lane to stop traffic in one direction. AFAD are portable devices that are remotely operated by a flagger who is positioned in a safe environment or off the roadway to reduce flaggers' exposure to traffic movement. It ascends to an upright position when traffic is allowed to proceed (MUTCD, 2009). To improve the conspicuity of the arm, a flag should also be added to the end of the gate arm. AFADs can be either STOP/SLOW paddles or RED/YELLOW lenses. AFADs are commonly used on sites for short-term use with sufficient sight distance and a relatively shorter length of lane closure. Figure 2.2 shows a typical example of an AFAD system. The most common factors for considering AFADs include topography, length of the closure, sight distance, and duration of work.

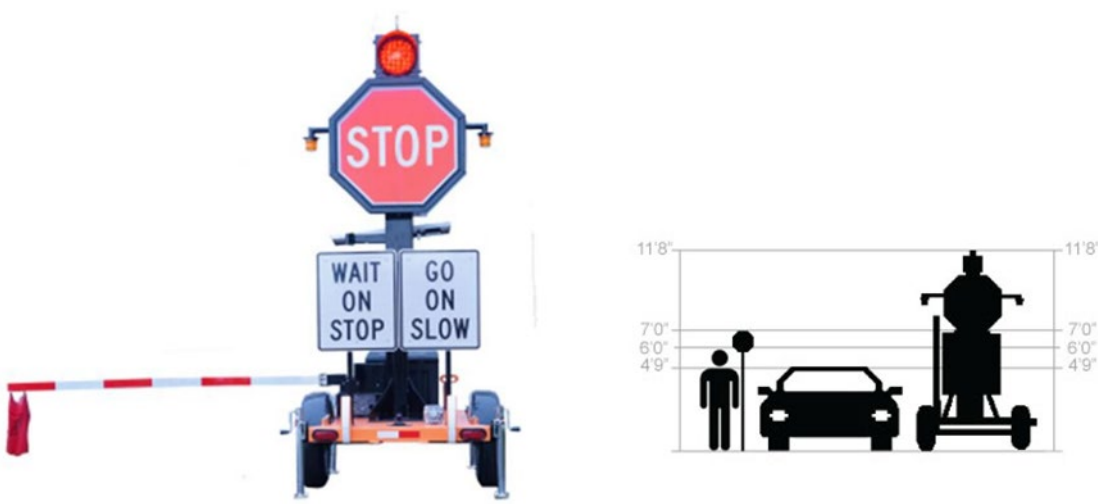


Figure 2.2 Automated Flagging Assistance Device (AutoFlagger 76-X, 2024)

Human flagger and AFAD are the two main categories of flagger control. According to the MUTCD, when either of these methods are applied, traffic should be regulated and coordinated on both sides (i.e., at the entry/exit points of work zone). The only exception where only one flagger control can be used is when both entry/exit points are visible, and the constricted roadway section is short.

2.1.3 Pilot Car Method

A pilot car can be used to guide a stream or queue of vehicles through the constricted area or on a detour route. According to the MUTCD, a flagger should be positioned at the control points to direct vehicular traffic until the pilot car makes the round trip. This method is often preferred for long and/or complex conditions to avoid driver confusion and maintain vehicle speed. The MUTCD recommends that the "PILOT CAR FOLLOW ME" sign should be mounted on the rear of the pilot car for motorists (MUTCD, 2023). A typical example is shown in Figure 2.3 below.

Figure 2.3 A typical pilot car for work zone traffic control

2.1.4 Temporary Traffic Control Signal Method

Traffic control signal heads can also be used to control the traffic movement within a one-lane two-way work zone without employing flaggers as shown in Figure 2.4. According to the MUTCD, a temporary traffic control signal (TTCS) setup must meet the display and operational requirements of a two-phase conventional signal control (MUTCD, 2023). The TTCS can be programmed to work as a pre-timed or actuated signal control system with a longer duration of red clearance time to clear the conflicting vehicle movement before the opposing traffic is given the green light. The TTCS system is most likely to be deployed for long-term durations and operate effectively during the day and night. Note that NDOT only applies the TTCS system for one-lane two-way work zones for bridge related activities.

Figure 2.4 Example of TTCS in Texas (Finley et al. 2015)

It is important to note that these four control methods can be used in combination depending on the characteristics of the work zone (e.g., road topography, length of active work zone, alignment, work duration, time periods, etc.). For example, NDOT frequently uses human flaggers along with a pilot car. Table 2.1 lists some of the potential advantages and disadvantages of the four systems discussed here (Haque, 2022). Details of the advantages and disadvantages of each method can be found elsewhere (Farid et al. 2018, Finley et al. 2014).

Table 2.1 Potential advantages and disadvantages of traffic control methods (Haque, 2022)

Techniques	Advantages	Disadvantages
Human flagger	• Least expensive • Quick set-up and removal time. • Handle irregular, emergency, or unprecedented situations	• Safety concern for flaggers. • Flagger fatigues and stress. • Personnel management can be problematic
AFAD	• Better driver response • Quick set-up and removal • Flaggers not exposed to traffic • One can operate multiple devices	• Potential for device malfunction and need for maintenance • Training and expertise required • More expensive
Pilot car	• Clear travel direction guidance • Multiple access points • Safer for construction workers	• Incur additional waiting time • May result work zone intrusion • Require additional personnel
TTCS	• Better driver response • Suitable for long-term operation • No vehicle-flagger conflict. • Save human effort	• Expensive • Potential for device malfunction • Long set-up and removal time • Coordinate with roadside signals

2.2 Traffic Control Practice among State DOTs for One-Lane Two-Way Work Zone

The survey of the one-lane two-way operation techniques at rural highways conducted by Farid et al. (20218) found that thirty-seven state DOTs use the human flagger control frequently or exclusively, making it the most used traffic control technique. On the other hand, the TTCS and the pilot car are less used, and the AFAD is the least used method among the four operation techniques mentioned before. While different DOTs follow the general recommendations from MUTCD, the field practices may differ. Table 2.2 summarizes various DOT traffic control methods for one-lane two-way work zones. It may be seen from Table 2.2 that each state DOT has adopted a criterion that best fits its operations of the one-lane two-way traffic control conditions.

Table 2.2 State DOTs unique traffic control methods for one-lane two-way work zone

Reference	Flagger	AFAD	TTCS	Pilot car
Nebraska DOT (2017)				Allowable round trip within 15 minutes
Missouri DOT (2017)		Not allowed for long-term stationary operation.		
Kansas DOT (2015)		Allows a single flagger to operate two AFADs	Allows one flagger operation if both ends are visible to each other	Max speed should be 40 mph and reduce to 20 mph.
Iowa DOT (2015)	Allows single flagger in adequate sight distance @ low volume < 2000 vpd, and closure length < 100 ft.			
Minnesota DOT (2014) & Nevada DOT (2017)		Allows a single flagger to operate two AFADs		The last vehicle from a platoon greater than 300ft should not enter the work zone
Florida DOT (2017)			Only used when the flagger can control for signal malfunction	Allow for use along with TTCSs when work zone distance is greater 0.5 mi
Montana DOT (2014)	Does not approve one flagger operation if more than 10 vehicles stop at flag station 50% of the time			
Oregon DOT (2016)	Does not allow one flagger in nighttime operation, closure length > 200 ft., sight dist. < 750 ft., and ADT > 400 vpd			For nighttime operations or the approaching vehicles cannot see one flagger station to another
Pennsylvania DOT (2014)		The min all-red clearance ranges from 12 to 45 seconds		
Virginia DOT (2015)		Allow AFADs with ADT < 12,000 vpd. Permits a single flagger to operate two AFADs		

State DOTs may have their own criteria to select traffic control methods, which may include the maximum length of the closure, maximum vehicle delay, traffic volume, and speed (Farid et al. 2018). In general, a human flagger is used in short lane closure, while a pilot car is used in longer lane closure. Table 2.3 lists examples of State DOTs allowing maximum length of lane closure when applying the appropriate traffic operation control techniques in the one-lane two-way work zone.

Table 2.3 Example of maximum lane closure length for one-lane two-way work zone

Traffic Control Technique	Maximum lane closure length (Additional conditions in parentheses)	Example DOTs
Human flagger	2000 feet, 100 feet (single flagger)	Iowa
	500 feet (single flagger)	Minnesota
	3 miles (along with TTCSs)	Missouri
	2000 feet	Ohio
	1 mile	Oregon
	2 miles, 200 feet (single flagger)	South Carolina
	1 mile (flag transfer)	Virginia
AFAD	800 feet	Florida
	0.5 miles	Missouri
	2 miles	South Carolina
	800 feet	Virginia
	800 feet	Washington
TTCS	960 feet, 1340 feet (< 3 days)	Iowa
	1000 feet	Oregon
	1500 feet	Washington
Pilot car	2.5 miles (ADT < 2500) 2 miles (ADT: 2500-5000) 1.5 miles (ADT > 5000)	Iowa
	3 to 5 miles	Oregon
	4 miles	Pennsylvania

Maximum vehicle delays may vary from 5 to 30 minutes based on the traffic control techniques used and the preference of different DOTs. For example, for the pilot car control method, Iowa and Nevada DOTs allow a maximum vehicle delay of 15 and 30 minutes, respectively. Under the human flagger technique, South Carolina DOT allows a maximum delay of 5 minutes for a work zone less than 1-mile in length, 7.5 minutes for 1 to 2 miles in length, and 20 minutes when side roads are present within the work zone. Note that these criteria are supposed to be impacted if access points exist within the work zone that generate substantial traffic.

2.3 Modeling of Traffic Operations on One-Lane Two-Way Work Zone

Modeling the four traffic operation methods described in Section 2.1 is crucial to test the effectiveness of these methods using a deterministic approach (i.e., spreadsheet-based analysis) or stochastic approach (i.e., traffic microsimulation software) as experiments through field implementation are not feasible for many traffic scenarios of interests.

These four traffic operation methods for one-lane two-way work zones are generally modeled using either the flagger control model or the signal control model (Haque, 2022). In general, the flagger control model uses three techniques, i.e., the pre-specified queue length, the distance gap out, the fixed green time methods, or a combination of these techniques. The pre-specified queue length technique provides the right of way to waiting vehicles when a specified queue length is reached (Al-Kaisy and Kerestes, 2006). On the other hand, the distance gap out method alters the right of way to allow an approaching vehicle with a specific gap distance at the back of the queue (Washburn et al., 2008). The fixed green time method gives the right of way at a specified time interval (Zhu, 2015).

The signal control model for a one-lane two-way work zone is similar to a typical two-phase signal controlled intersection. The optimal green time and cycle length can be determined by either using the HCM method (HCM 2016, Schoen et al., 2015), the classic Webster model (Webster, 1958), or the queue theory-based model (Schonfeld, 1999).

According to the study by Hua et al. (2019), the flagger model using the optimized gap-out distance technique better minimizes queue lengths and stop delays, especially for volumes less than 200 passenger car per hour per direction (pc/h/d) or high traffic volumes ranging from 420 – 580 pc/h/d. Pre-timed signal control will be appropriate for substantially high volume conditions.

2.4 Traffic Control at Access Points within the One-Lane Two-Way Work Zone

2.4.1 Flagger Based Traffic Control at Access Points

Sections 2.1, 2.2, and 2.3 discuss different traffic control methods and their applications for one-lane two-way work zones. The presence of access points within a one-lane two-way work zone can make the traffic operation more complex. Therefore, the work zone system needs to consider the control of access point traffic.

Although flagger controls are typically used as temporary traffic controls at access points within a one-lane two-way work zone, some DOTs also use barricades and cones to block low-volume access points and notify users of alternative routes (Finley et al., 2014). Others also alternate the work zone lengths to accommodate traffic from access points. According to a survey by the Texas DOT, the top-ranked factor that influences the use of flagger control at access points is traffic demand or volume on the access point which is often based on knowledge of the affected areas and engineering judgment on a case-by-case basis (Finley, et al., 2014). Other factors included the demand on the main road, number of access points, work zone duration and length, site distance, availability of flaggers, type of location, and safety. To avoid the use of flaggers at every access point, an additional pilot vehicle is sometimes included in the stream of vehicles to signal waiting vehicles at access points to join the mainstream of vehicles.

Even though these temporary methods may work for work zones with fewer access points and negligible amount of traffic, there are several challenges or difficulties associated with such temporary provisions. For example, 43% of respondents in a survey of Texas DOT personnel reported motorist inattention and distractions as a major challenge (Finley et al., 2014). This was followed by the lack of manpower as flaggers, insufficient signage, or driver information at access points, wrong turnings into work zones, and backing up queues at access points, etc. In the same survey, over 91% of the respondents requested guidance for temporally controlled access points with the objective of directing drivers on when to stop or proceed and determining which direction to go.

2.4.2 Non-Flagger Based Traffic Control at Access Points

The use of flaggers is shown to have several challenges as previously discussed. Deploying portable traffic control signals with the typical circular red, yellow, and green bulbs performing 3-phase signaling can result in a number of issues and inefficiencies. For example, because the portable traffic control signal setup is often not actuated, there is a tendency for high delays in high-volume main road traffic. This would typically happen when green time is wasted on access points with no vehicles. Alternatively, if the signals are actuated it will be expensive to procure portable controls at all of the access points. A low-cost alternative solution that can successfully coordinate with the mainline portable traffic control signals would be the best approach. In recent years, there has been a rise in the proposal and evaluation of several low-cost devices for low-volume access point controls on one-lane two-way work zones. These devices are termed s Driveway Assistance Devices (DADs).

One important characteristic of the DAD system is that it should be synchronized with either the temporary traffic control signals or flaggers on the main road. Moreover, multiple DAD installations need to communicate with each other as well as the TTCSs to avoid head-on collision. There are DAD systems that have been proposed with the objective of serving vehicles on driveways in an effective and safe manner. Some have been tested but did not work over time because of challenges that evolved in their implementation. For example, a push button system that operated with an electric gate where the driver on the access point pushes a button to signal its presence. The signal is sent to the flaggers/TTCS on the main road and traffic in both directions on the main road is stopped. The access point vehicle is allowed to travel any direction in the open lane. Some of the key challenges in operating this system were the following:

1. There was no two-way communication between main road flaggers/TTCS and the access point driver. In other words, the driver at the access point did not know if the flaggers/TTCS had received the signal.
2. There was no equipment to verify whether the vehicle had left the access point or cleared the work zone.
3. It was not feasible for multiple access point operation.
4. There was a need for clear space indication at entry points for vehicles from the main road entering access points.

To overcome the challenges mentioned above, different types of DAD devices have been proposed and implemented in the U.S. since 2009. Figure 1.1 shows a typical DAD system. As depicted in Figure 1.1, there are two driveways located in the work zone and each driveway has a typical DAD placed across from its entry point and synchronized with the portable traffic signals located at each end of the one-lane two-way work zone. The DAD systems have directional arrows that can either show red or flashing yellow. The flashing yellow arrows indicate that the driver may turn into the work zone in the direction of the yellow arrow if there are no conflicts with oncoming traffic. On the other hand, the red light indicates drivers are not allowed to enter the work zone in the direction indicated. The DAD system is synchronized with the mainline traffic control system to achieve the intended goal of work zone operational safety and efficiency. The next section discusses the operational aspects of a typical DAD system.

2.4.3 Operational Aspects of Typical Driveway Assistance Device

Due to the lack of DAD guidelines in MUTCD, many states utilized DADs with varying configurations and displays (Finley et al., 2014; Gates and Savolainen, 2022; Hankin et al., 2023). Even though more research is needed to develop guidelines for DAD configuration and display, studies have so far indicated that the use of DADs resulted in a high proportion of safe movements. Thus, after MUTCD principles are established and drivers are familiar with DAD systems, approximately 100% safe and legal movements may be expected, and then the operational impacts of DAD can be the sole crucial factor in its overall performance and applicability due to the complications and various potential combinations of mainline and DAD signals. Despite several studies on DAD safety, which will be highlighted in Chapter 6, the operational effects of this system have not been thoroughly addressed in the literature. Notably, research from Texas DOT (Finley et al., 2014) and Ohio DOT (McAvoy et al., 2023) were the only two studies to model operational delays caused by work zone access points.

Finley et al. (2014) simulated delays for novel devices controlling a low-volume access point (i.e., 20 vehicles per hour at a single access point). The Highway Capacity Manual (HCM) (HCM 2000), which did not contain a one-lane two-way work zone model, was used to aid the simulation model. Instead of a work zone, a fixed-timed regular intersection delay method was used as a proxy for the modeling component (Finley et al., 2014). Note that the HCM 2016 introduced the methodology for a one-lane two-way work zone lane closure model (HCM, 2016) and our study has considered the application of the HCM 2016 model which will be discussed in detail in Chapter 3.

A recent study by McAvoy et al. (2023) compared the operational performance of a portable traffic signal (which is analogous to TTCS) and DAD devices at work zones with low-volume access points and found that the DAD performed better. This study had a 1000-foot work zone and the access points had low volume. It should be noted that although a DAD was initially applied to access points under low volume, several studies indicated that access points, such as commercial driveways and side streets from residential areas, can produce a considerable amount of traffic for the DAD system (MDOT, 2018; NDOT, 2020; McAvoy et al., 2023). For example, the Michigan Department of Transportation (MDOT) recommended that DAD performance should be evaluated for access points with high volumes, as they found the traffic volume in their DAD-equipped access points can be as high as 80 veh/hour (MDOT, 2018).

Note that both operational studies of Finley et al. (2014) and McAvoy et al. (2023), calibrated the microsimulation model based on the mean performance metrics in work zones. However, Haque, Zhao, Rilett, et al. (2023) showed that the approach of using the distribution of the performance metrics, instead of the approach of using the mean of the performance metrics, results in accurate traffic movements within the one-lane two-way work zone system in the microsimulation platform. Therefore, our study used the distribution approach to ensure accurate modeling of one-lane two-way work zones, which will be discussed in Chapter 3.

2.5 Summary of Literature Review

Work zone operations on two-lane highways often require closure of a lane, causing traffic in each direction to alternately use the remaining available lane. Various methods are available to control traffic entry at opposing ends of the work zone, including temporary traffic signals, flaggers, and/or pilot cars (Haque, 2022). The presence of any traffic access points (e.g., driveways, or minor side roads) within the work zone complicates traffic operations because traffic from two directions of the main road and all the access points need to share the available single lane (Finley et al., 2014).

Drivers approaching access points within a work zone may be confused about which direction to enter the work zone. Situations like long work zones, low-volume main roads, horizontal and vertical curves may exacerbate the issue by compromising drivers' ability to observe vehicles on the main road to prevent head-on collisions (Daniels et al. 2000). Driveway assistance device (DAD) systems enable traffic control within work zones from the access points. These devices correctly guide drivers into work zones to avoid potential collisions. At present, DAD systems are not included in the MUTCD.

In summary, the literature revealed the following major findings.

1. Devices to be used for the mainline of one-lane two-way work zones are well researched and practiced. Sufficient guidelines are provided in MUTCD and practices from different DOTs.
2. Previous research was limited by focusing on the safety aspects of the DAD system for access points within one-lane two-way work zones, and operational impacts were not focused on.
3. Detailed comparative studies among different control strategies were not conducted for operational efficiency.
4. The performance of DAD-operated work zones under various traffic conditions (including moderate to high volume) and work zone characteristics were not studied.
5. Simulation models are calibrated using the mean performance metrics, not their distributions, of the work zone.

6. There is no guideline on the type of control techniques for DAD and traffic conditions and work zone features that should be addressed by the traffic agency before the deployment of the DAD system at the work zone.

Therefore, this project aims to resolve many of these shortcomings as stated in the project objectives.

Chapter 3 Modeling of One-Lane Two-Way Work Zone with DAD System

This chapter will develop a microsimulation model for closures in one-lane two-way work zones using field observed Nebraska work zone data. The microsimulation model is calibrated and validated using empirical data so that the model is able to replicate actual traffic movements during the lane closure conditions. Then the DAD system is modeled and applied to the one-lane two-way work zone microsimulation model.

3.1 Data Preparation for Microsimulation Model Development

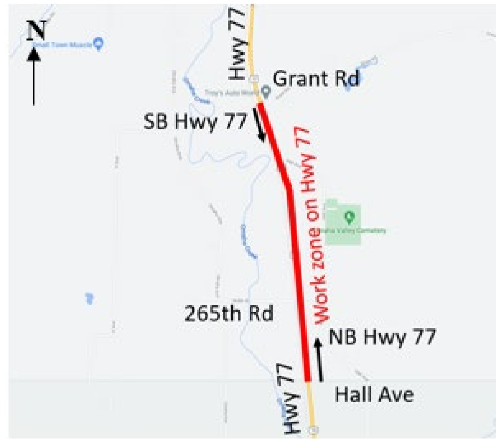
3.1.1 Test Site and Data Collection System

This study selected two work zones on two-lane highways on U.S. Route 30 southwest of Clarks, Nebraska (Figure 3.1.a) and U.S. Highway 77 south of Winnebago, Nebraska (Figure 3.1.b) which were active in the fall of 2020. The first test site was a 1.1-mile work zone where the non-work zone speed limit was 65 miles per hour and the annual average daily traffic was 1600 (AADT, 2024). Access to the work zone was controlled using flaggers and a pilot car. The second site was 1.5-mile work zone with a non-work zone speed limit of 65 miles per hour. The annual average daily traffic was 3000 (AADT, 2024). Similar to the first site, a flagger and pilot car were used for traffic control at the work zone. One lane was closed out of two lanes for work zone activities on both sites. Drivers encountered assorted warning signs before the work zone.

The data collection system included three main components: i) two Miovision Scout detectors, ii) two Wavetronix HD detectors, and iii) a Contour camera (Miovision, 2024; Wavetronix, 2024; Contour, 2024) for each site. Figure 3.1.c shows pictures of these devices from the test sites. Note that both Miovision and Wavetronix HD detectors were placed in the field whereas the Contour camera was placed in the pilot car at each work zone.

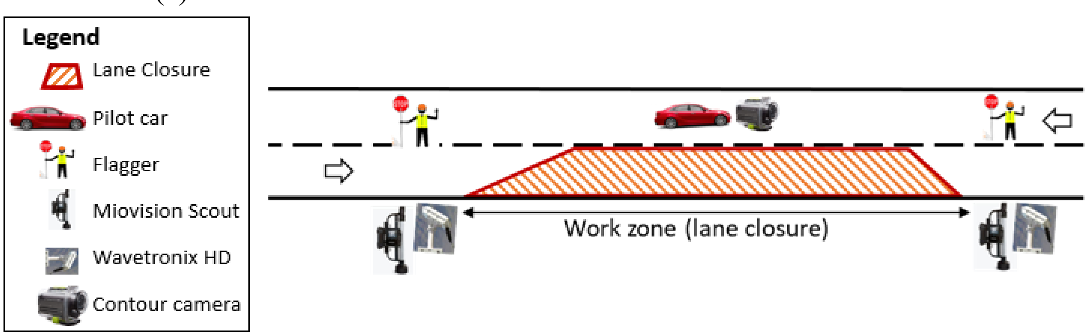
Figure 3.1.d shows the layouts of the data collection system. The Wavetronix HD and Miovision devices were placed inside the work zone and near the flagger position at both ends of the work zone. A contour camera equipped with GPS was installed in the pilot car. The flaggers showed the “SLOW” sign or the “STOP” sign at the work zone entry and exit points. The flaggers communicated by short-range radio to ensure that the information provided to drivers was consistent.

(a) Highway 30 test site near Clarks city, Nebraska



(b) Highway 77 test site near Winnebago, Nebraska

(c) Data collection devices installed at the work zone test sites



*Drawing not in scale

(d) Schematic diagram of a work zone and the layout of the data collection system

Figure 3.1 Test site location and schematic diagram of work zone operation

The contour camera was used to obtain the relative speed and geographical coordinates of the pilot car within the work zone, including a video recording. This camera confirmed that the work zone was operating under normal conditions and that there were no issues (e.g., pilot car stopping to facilitate the movement of construction equipment) that would make any of the collected data invalid.

The Wavetronix HD was used to record data such as length-based vehicle classification, headways, and the instantaneous speed (i.e., spot mean speed) of each vehicle as they entered and exited the work zone.

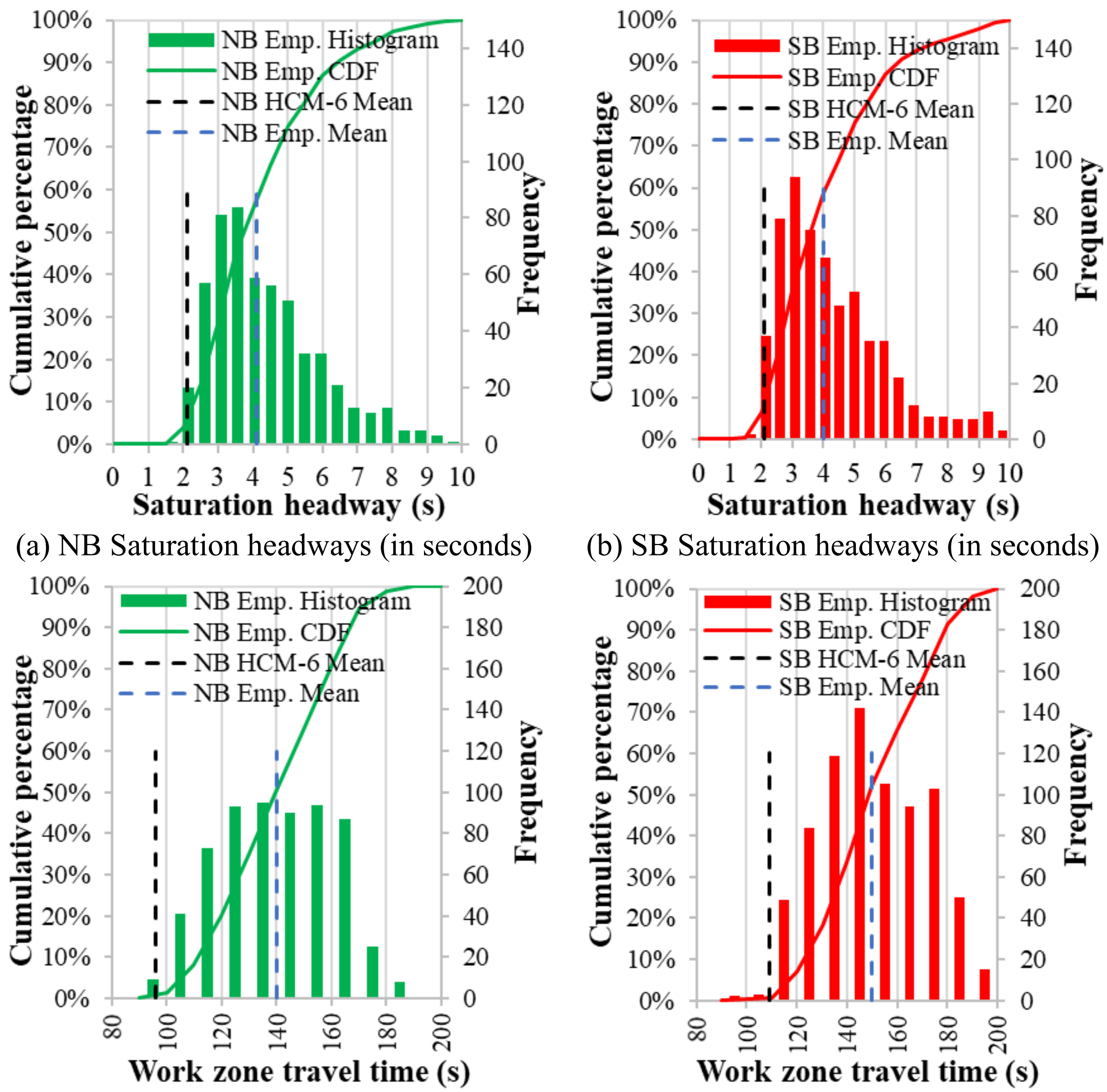
The Miovision device used in the site had the capability to identify and store MAC address signatures and timestamps from passing vehicles that had WiFi-enabled electronic devices. This information was later used in the lab to "match" MAC addresses and to estimate the distributions of work zone travel times. Most importantly, the Miovision detectors were also used to record visual activities at the work zone entry and exit points.

Note that MAC addresses collected by the Miovision devices are only from WiFi-enabled vehicles. To consider all individual vehicles' information for the modeling approach, the research team used the Miovision video data. Approximately twenty hours of active work zone video were collected on October 12, 13, and 14 at the Highway 30 test site, and twelve hours of video were collected on October 30 and 31 at the Highway 77 test site. Traffic volumes, vehicle classification, saturation headways, and work zone travel times were manually observed through video footage as well.

3.1.2 Data Processing for Microsimulation Model Calibration

The test site on Highway 30 was used as the base work zone for field data collection for the microsimulation modeling approach. Among the twenty hours of active work zone data collected from the Highway 30 test site, six hours of data were used for the purpose of model calibration. These six hours represent the most congested times and occurred from 4 pm to 6 pm on October 12, 2020, and from 2 pm to 6 pm on October 13, 2020.

The headway was defined and measured using the time between two consecutive vehicles' front axle passing a specific point near the flagger. Following the standard practice defined in the HCM (2016), the first three vehicles discharged from the queue were ignored (HCM, 2016). A total of 1145 vehicles from Miovision video record were used to collect saturation headway data. Figure 3.2.a and Figure 3.2.b show the distribution of saturation headway in the northbound (NB) and southbound (SB) directions, respectively.



(a) NB Saturation headways (in seconds) (b) SB Saturation headways (in seconds)

(c) NB Travel time (in seconds) (d) SB Travel time (in seconds)

Figure 3.2 Empirical data from Highway 30 work zone test site used in microsimulation model calibration for northbound (NB) and southbound (SB)

Figure 3.2.a and 3.2.b shows that the mean saturation headway for NB and SB directions were 4.1 seconds (sec) and 4.0 sec, respectively, which are represented by the dashed blue lines. Note that using Equation 26-B4 of the HCM (2016) would result in an estimated saturation headway of 2.2 sec for this test site and it is shown by the black dashed lines in Figure 3.2.a and 3.2.b. A Welch two-sample t-test was used to test whether these observed and estimated

saturation headways were statistically different. Both tests rejected the null hypothesis that HCM (2016)'s prediction and field observation are the same at the 5% significance level for both the NB (t-stat= 28.6, p-value<0.001) and the SB (t-stat= 26.7, p-value<0.001) directions.
The work zone travel time was measured as the difference in timestamps between when the vehicle entered the work zone (i.e., defined by the fixed location of the upstream flagger) and exited the work zone (i.e., defined by the fixed location of the downstream flagger). Travel time data were estimated by manual observation from the Miovision video from samples of 1381 vehicles. Among these vehicles, 632 and 749 were traveling in NB and SB directions, respectively.

Figures 3.2.c and Figure 3.2.d show the distribution of work zone travel times for the NB and SB directions, respectively. These figures show that the travel times within the work zone range from 90 to 200 sec. The mean values were approximately 140 sec and 150 sec for NB and SB directions, respectively. The mean values are marked with dashed blue lines in Figure 3.2.c and Figure 3.2.d.

The HCM (2016) work zone travel time estimation methodology uses factors such as posted speed limit (outside of work zone), lane and shoulder width, and access point density. The formulae are labeled Equation 26-B1 and Equation 26-B2 in the HCM, 2016. Using these equations, the work zone travel times were estimated to be 96 sec and 109 sec for NB and SB directions, respectively. These are shown as dashed black lines in Figure 3.2.c and Figure 3.2.d. It may be seen that the predicted work zone travel times using the HCM (2016) are much lower than the observed travel times. This is confirmed by the Welch two-sample t-test, which rejected the hypothesis that HCM (2016)'s prediction and field observation are the same at the 5%

significance level. This was true for both NB (t-stat= 53.2, p-value<0.001) and SB (t-stat=-55.2, p-value<0.001) directions.

The results of the statistical tests from both saturation headway and travel time indicate the mean headway and travel time measured from the test site are significantly different than the corresponding headway and travel time means predicted using the appropriate HCM (2016) methods. This means the HCM (2016) model could not accurately estimate the saturation flow rate and the work zone travel time for this test site. For these reasons, the research team decided to use a microsimulation model, similar to that used in the original HCM (2016) research, to see if it could capture the stochastic features and variable nature of headways and travel times at the test site. The first step would be to calibrate the microsimulation model to local conditions (Spiegelman, Park and Rilett, 2010), followed by a validation of the model. Therefore, the following sections outline the design of lane closure in microsimulation software, and the calibration and validation studies.

3.2 Development of Microsimulation Model of Regular One-Lane Two-Way Work Zone

3.2.1 Design of Lane Closure Operation in Microsimulation Software

The research team used VISSIM microsimulation software to model the lane closure on two-lane highway work zones. To mimic the lane closure condition, the following three steps were programmed:

1. Before work zone condition, when the network runs as a regular two-lane highway;
2. During work zone condition, when the work zone signal control system is activated. Both directions of traffic use one open single lane by alternating the right of way; and

3. After work zone condition, when the work zone is deactivated, and the traffic goes back to its regular movement as the two-lane highway system.

The screenshots of the three conditions are shown in Figure 3.3. The simulation model was programmed in VISSIM through VisVAP control logic, sensors, and Visual Basic Application (VBA) script.

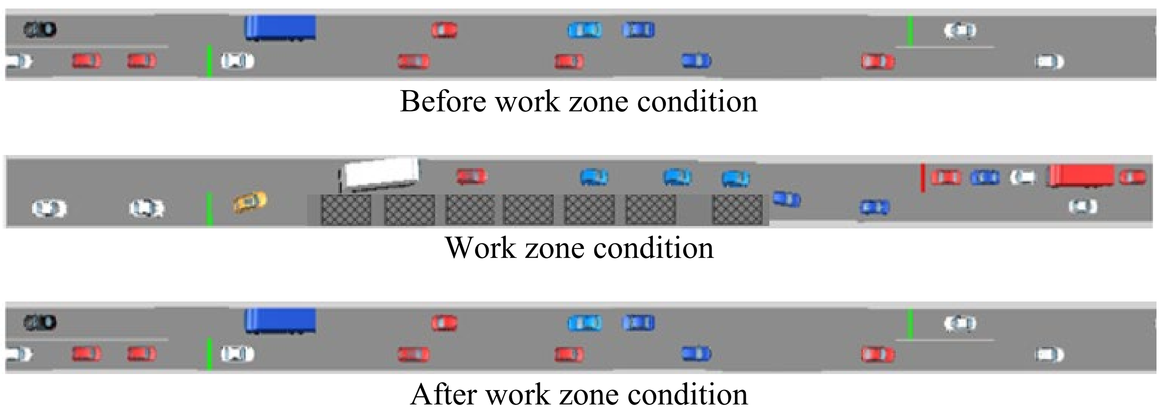


Figure 3.3 VISSIM microsimulation model of the one-lane two-way work zone Operation

3.2.2 Calibration of Microsimulation Model for One-Lane Two-Way Work Zone

A microsimulation model requires proper calibration to reflect field-observed driving behaviors and operational outcomes (Haque, Zhao, Rilett, et al., 2023; Tufuor and Rilett, 2021). Out of several available traffic microsimulation tools (FHWA, 2016; Haque and Sangster, 2018), this research used VISSIM because it has the capability to model all operational aspects of work zones, access points, and two-lane highways (Haque et al., 2024; Haque, 2022; Finley et al, 2014; Khattak et al., 2023) and it was used as an aid in developing the HCM macroscopic work zone equations (HCM, 2016). A robust calibration methodology (Haque, Zhao, Rilett, et al., 2023) is applied to model the microsimulation model, with the procedure shown in Figure 3.4.

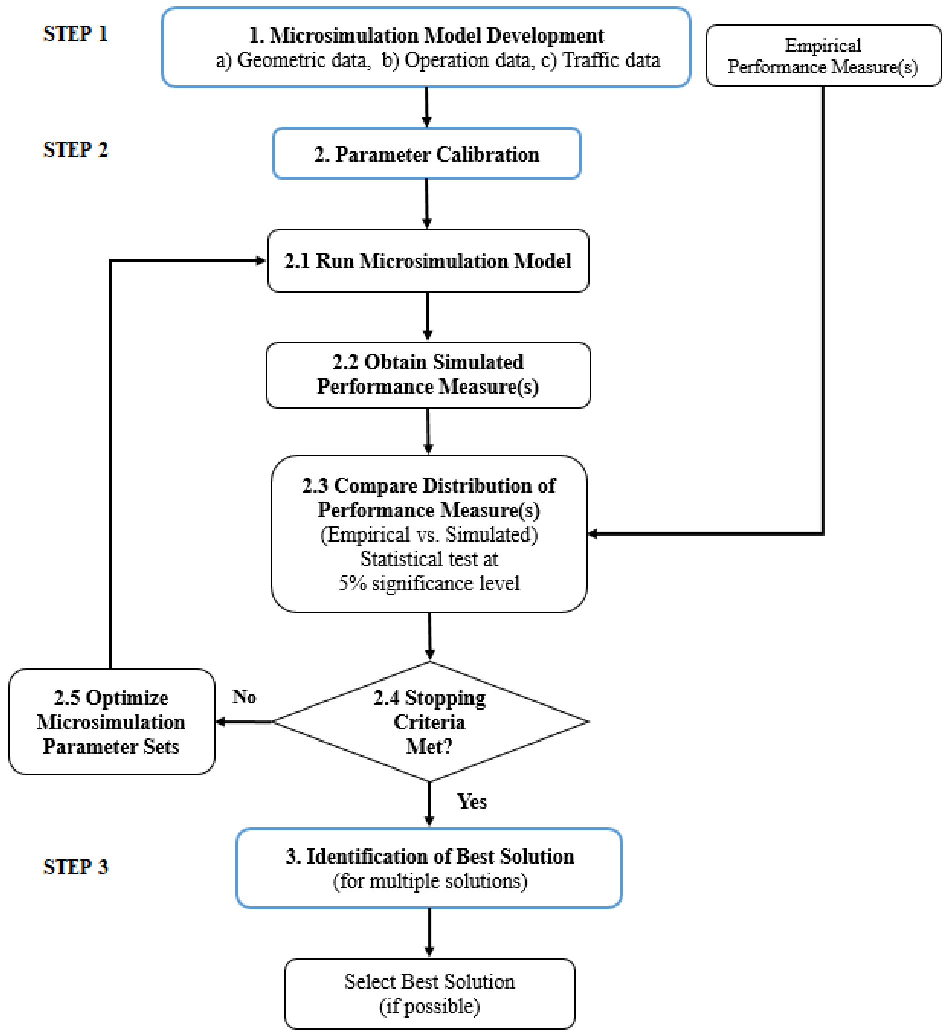


Figure 3.4 Microsimulation model calibration algorithm for work zone (Haque, Zhao, Rilett, et al. 2023)

Major Steps from Figure 3.4 are described below.

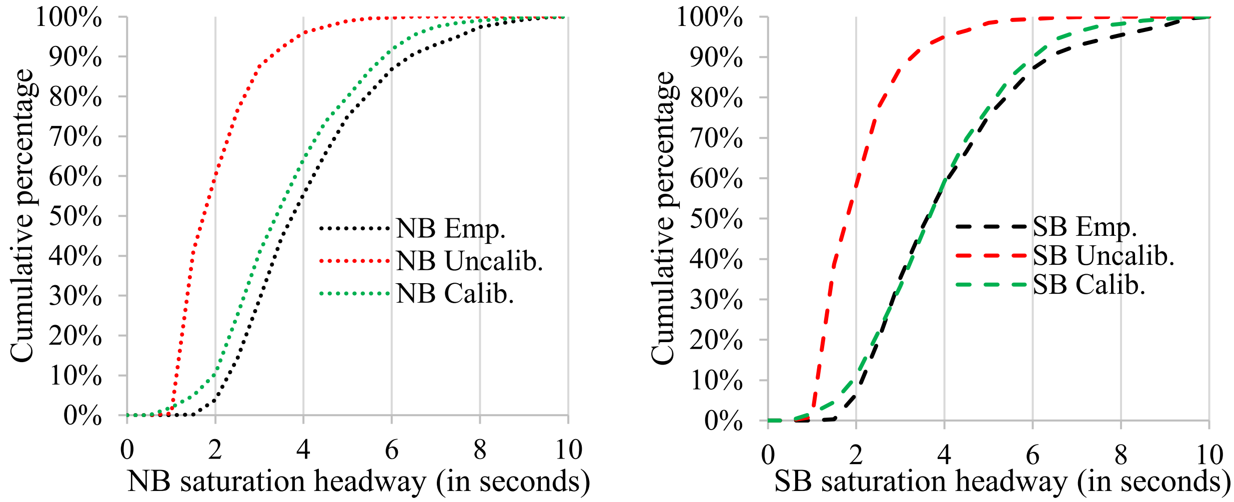
Step 1 in Figure 3.4 requires the use of a microsimulation model calibrated to match field-observed work zone conditions. Therefore, approximately twenty hours of work zone data were obtained from the test site (in Figure 3.1.a). Among them, six were used for model calibration, which represents the most congested times that occurred from 4 pm to 6 pm on October 12, 2020, and from 2 pm to 6 pm on

October 13, 2020. The input data of the microsimulation model included traffic demand, and heavy truck proportion, the geometry of the test site, posted speed limit, and control mechanism that mimics flagger behavior by actuated signal control (Haque, 2022; Schoen et al., 2015; Yang et al., 2018; Zhu et al., 2017). As an output, the performance data, such as travel time and delay, were obtained for use in the following steps.

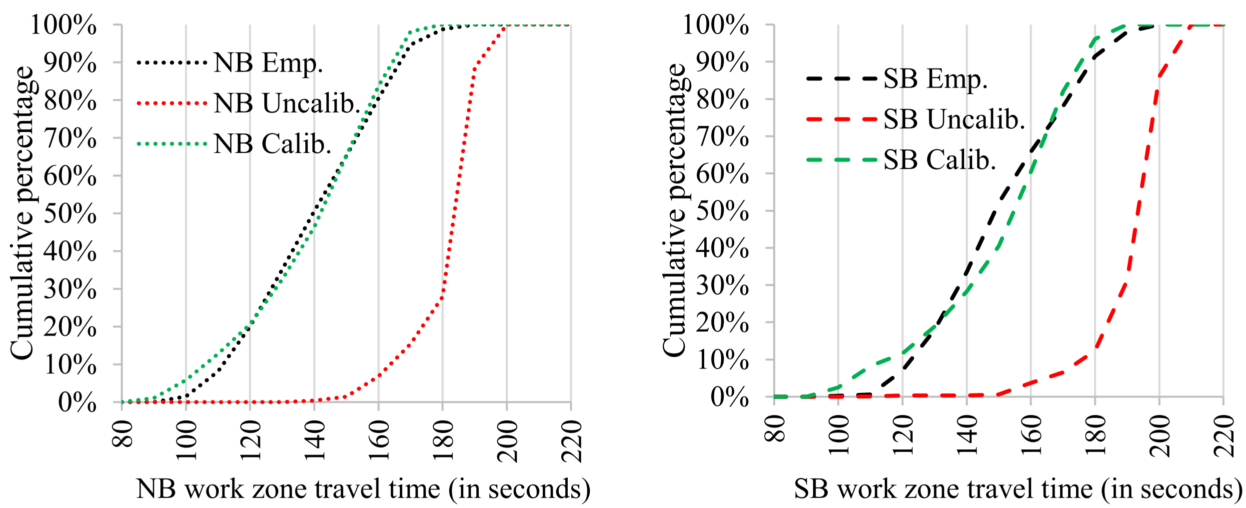
Step 2 calibrated model parameters to match field-observed saturation headway distribution (SHD) and work zone travel time distribution (WZTTD). As described in the background section of this report, the distribution approach is better at modeling simulated work zones than the naïve mean approach. In this study, seven car-following parameters were calibrated (Buck et al., 2017; Zhao et al., 2022; Haque, Rilett, Zhao, 2023), which were CC0 (standstill distance), CC1 (headway time), CC2 (following variation), CC3 (threshold for entering "following" mode), CC4 (negative following threshold), CC5 (positive following threshold), and CC6 (speed dependency of oscillation). These model parameters are discussed elsewhere (PTV VISSIM, 2020). A genetic algorithm (Kochenderfer and Wheeler, 2019) was used to find optimized model parameters from one iteration to the next to match field-observed SHD and WZTTD at 95% confidence level. Note that this statistical approach of calibration conforms to the recommendation of the FHWA simulation guideline (FHWA, 2024).

The algorithm in Figure 3.2 was automated using MATLAB, R, and Visual Basic scripts (Haque, 2022). After the completion of Step 2, Step 3 was used to find the “best” calibrated solution (using the least error approach) to represent the final calibrated model.

Figure 3.5 shows the cumulative distribution function (CDF) graph of the empirical (i.e., field-observed), uncalibrated (i.e., using default car-following parameters), and ‘best’ calibrated solutions (i.e., using calibrated car-following parameters) for SHD and WZTTD for both NB and SB directions. The dark, red, and green colors show empirical, uncalibrated, and best calibrated results, respectively.



(a) Comparisons of cumulative distribution of saturation headway



(b) Comparisons of cumulative distribution of work zone travel time

Figure 3.5 Comparison of empirical (Emp.), Uncalibrated (Uncalib.), and best calibrated (Calib.) performance metrics distribution of one-lane two-way work zone

Figure 3.5.a shows the shape of CDF for empirical and uncalibrated SHD were visually different (i.e., dark lines vs. red lines). Therefore, it shows the default car-following parameters from the microsimulation model (i.e., uncalibrated) were not able to capture the field observed condition. This is the reason Step 2 from Figure 3.4 was applied for model calibration. After

using the algorithm presented in Figure 3.4, a visual inspection showed the shape of the calibrated and empirical CDF closely matched (dark lines vs. green lines).

Using statistical analysis, data representing Figure 3.5.a revealed that for the NB direction, the calibrated SHD had an interquartile range (IQR) of 2.7–4.8 s, against the empirical SHD's IQR of 2.8 – 5.0 s. In contrast, the uncalibrated SHD had an IQR of 1.3–2.5 s. On the other hand, for the SB direction, the IQR of calibrated, empirical, and uncalibrated SHD are 2.7–4.8 s, 2.7–5.0 s, and 1.3–2.4 s, respectively. Most importantly, it was found using the Kolmogorov Smirnov (KS) tests that there was no statistically significant difference between the empirical and calibrated SHD at a 95% confidence level.

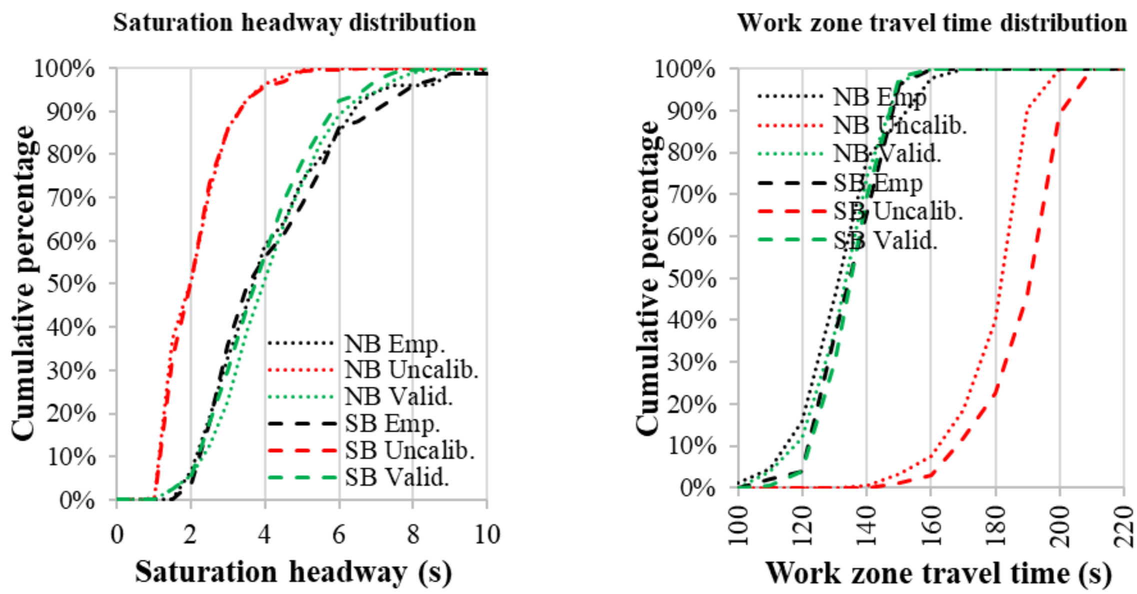
Figure 3.5.b demonstrates that the CDF shape of the empirical and uncalibrated WZTTD were considerably different (i.e., dark lines vs. red lines). This was similar to the findings from the SHD analysis. After the calibration, the shape of the calibrated CDF (black lines) and empirical CDF (green lines) matched closely. The calibrated WZTTD from the NB direction had an IQR of 124.6–155.5 sec. This was similar to the empirical WZTTD's IQR of 125.0–157.0 sec. In contrast, the uncalibrated IQR is 179.1–188.2 sec. Similar results were found for the SB direction where the IQR of the calibrated, empirical, and uncalibrated WZTTD were 137.7–166.9 sec, 136.0–168.0 sec, and 188.4–198.6 sec, respectively. The KS tests confirmed that there was no statistically significant difference between the empirical and calibrated WZTTD at the 95% confidence level.

Based on the findings from Figure 3.5, unlike traditional adjustments to the mean applied to the previous work zone studies (e.g., Finley et al., 2014; McAvoy et al., 2023), the calibrated VISSIM in our study was able to capture the field-observed distribution of traffic performance (i.e., travel time and saturation headway) of the test site resulting in an accurate work zone model. The next section discusses the validation and spatial transferability of this calibrated model.

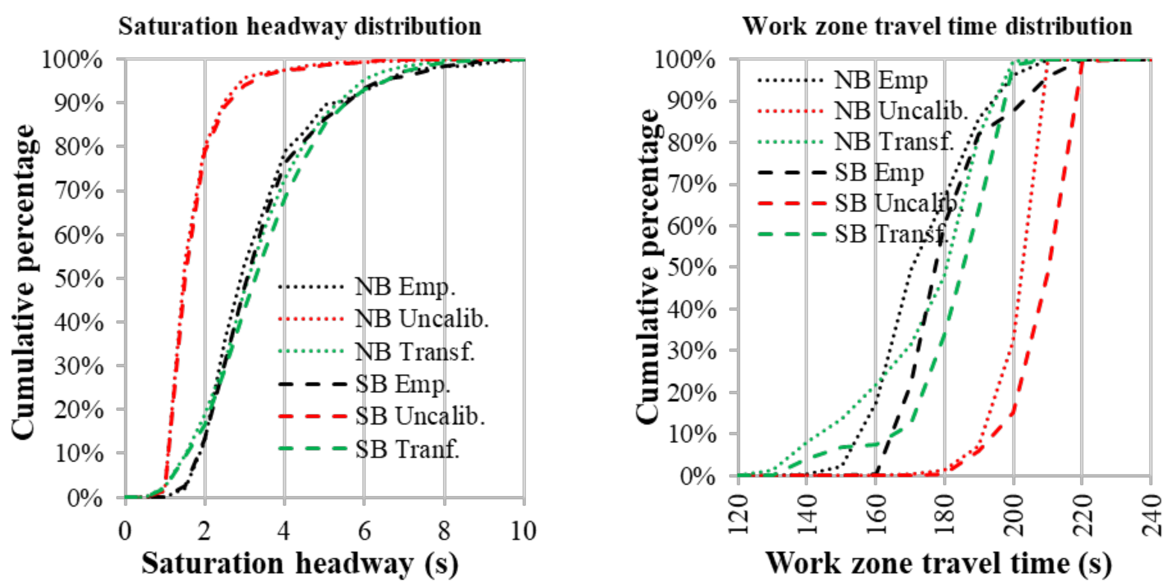
3.2.3 Validation and Spatial Transferability of the Calibrated Model

This section further discusses the validation and spatial transferability of calibrated model parameters to test the effectiveness of the microsimulation model. The validation was performed by predicting performance using the same work zone (i.e., Highway 30), but utilizing a dataset not applied in the calibration process. Spatial transferability refers to the performance prediction of the work zone calibrated model parameters when applied to a geographically different work zone location. In both cases, the best-calibrated model parameters were used to predict SHD and WZTTD.

For the model validation, Figure 3.6.a shows the comparison of work zone performance when the calibrated model parameters were applied for the work zone on Highway 30. Data from the morning peak hour on October 14, 2020 was used. The calibrated model was able to predict the variability of saturated headway and work zone travel time performance for both NB and SB directions compared to the empirical observations. All of them passed the KS test criteria at the 5% significance level to indicate field observations and simulation predictions were statistically the same.



Saturation headways and work zone travel time (in seconds)
(a) Model validation



Saturation headways and work zone travel time (in seconds)
(b) Spatial transferability

Figure 3.6 Validation and transferability of calibrated model parameters

On the other hand, for the spatial transferability, the performance of 1.5-mile work zones on Highway 77 was predicted using the calibrated model parameters. The Highway 77 work zone was approximately 140 miles northeast of the Highway 30 test site. The performance of

Highway 77 was predicted using data from the evening peak hours (4 pm to 6 pm) on October 30, 2020.

Figure 3.6.b shows the predicted performance of Highway 77 when compared to the empirical observations. It can be seen that the predicted SHD of both NB and SB directions matched the empirical observation since they passed the KS test criteria at the 5% significance level.

From Figure 3.6.b the shape of the CDF of predicted work zone travel time was close to the empirical observation. However, the KS test revealed that the predicted distribution was statistically different than the field observations at the 5% significance level. For the SB direction, the statistic suggests that the prediction of the calibrated model for median, mean, standard deviation, and interquartile range were 186.5, 182.2, 14.9, and 14.8 sec, respectively against the empirical observation of 178.0, 180.5, 13.3, and 14.0 sec. Therefore, this model was able to capture the median and mean values closely (within an accuracy of 4.7%). However, the predicted standard deviation was approximately 13% higher than the field observed findings.

This case study shows that as the calibrated model was transferred spatially, it was able to capture the SHD. Therefore, it may be hypothesized that the saturated headway did not vary across drivers. However, the WZTTD was a function of the work zone characteristics e.g., the intensity of work zone activities, operation of the pilot car, and different work zone lengths. It may have explained the underlying results of the transferred calibrated model parameter for work zone travel time. Regardless, it was found that using a calibrated model developed elsewhere produced better results than using an uncalibrated model as demonstrated by the shape of the CDF of work zone travel time in Figure 3.6.b. In summary, this study has produced a microsimulation model that has successfully replicated the operations of work zone lane closure conditions for two-lane highways. The next section describes the inclusion of the DAD system into the simulated work zone.

3.3 Modeling of DAD System within One-Lane Two-Way Work Zone

Once the model for single lane closures in work zones on two-lane highways is developed, the DAD system is incorporated into the microsimulation platform to control access point traffic. This report refers to the movement of vehicles on mainline two-lane highways and access point entrances (e.g., minor roads, driveways from residential or commercial areas, etc.) as the movement on the "Main approach" and the "DAD approach", respectively. The microsimulation model enables the DAD approach to generate different traffic volumes with varying truck percentages. DAD approach traffic is distributed equally between the eastbound and westbound directions of the main road.

Figure 3.7 shows example layouts of DAD-operated work zones on two-lane highways, where one of the two lanes is closed off due to construction or maintenance activities. Consequently, the remaining single lane is used alternately by both eastbound and westbound traffic. This report considers zero, one, three and five DADs within the work zones. While a single-DAD work zone is on one side of the two-lane highways, three- or five-DADs are distributed on both sides of the main road. Such distribution of DAD locations impacts signal phasing, which will be discussed later. It is assumed that 1) the DAD is equally spaced within the work zone, and 2) drivers understand the signal phasing and do not violate the mainline or DAD signal.

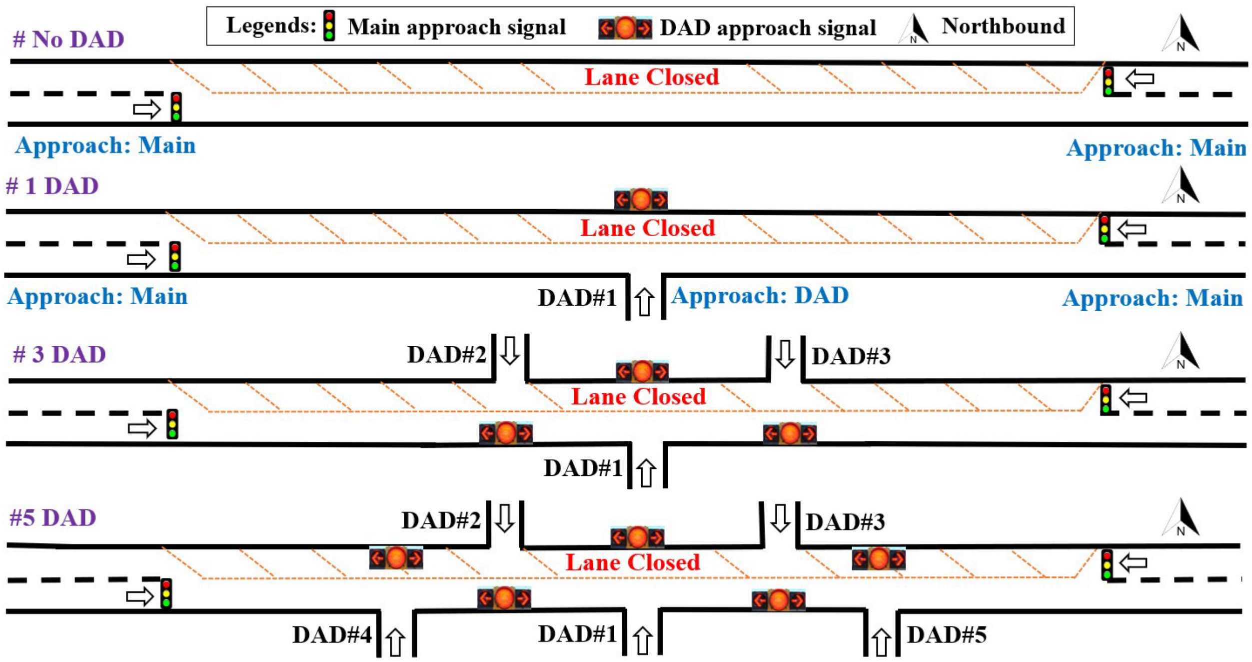


Figure 3.7 Example layouts of DAD-operated work zone lane closure on two-lane highways

Figure 3.7 demonstrates signal drawings for both the Main approach and DAD approach. The DAD signals are drawn as round red and red arrows for the left or right turns. In practice, these DAD signal heads and signs may come in different shapes and sizes to show the permitted and allowed movement (Finley et al. 2014; Gates and Savolainen, 2022). These variations are not relevant in the simulation model. The simulation model is coded to measure queues and delays for the DAD approach.

The next chapter discusses DAD approach signal control options and their relationship to Main approach signal control including the selection of the best control strategy.

Chapter 4 Development and Evaluation of Singal Control Strategies

This chapter will evaluate the performance of four signal control (SC) strategies using the test site shown in Figure 3.1.a. This 1.1-mile work zone was simulated with various traffic volumes and multiple DADs to compare average delay for Main, DAD, and All (i.e., combination of Main and DAD) approaches. Then the results from the four SC strategies was evaluated using statistical comparisons. The primary goal of the comparisons was to find the best SC strategy for DAD-operated work zones.

4.1 Modeling of Signal Control Strategies for Main and DAD Approach

This section modeled four types of signal control strategies for DADs based on its practical and potential use at work zones. Work zone operations are complicated since traffic in both directions of the Main approach as well as the traffic on the DAD approach share a single open lane. Thus, the challenge in the microsimulation modeling is to prevent vehicles on the DAD approach from entering the wrong direction. To overcome these challenges, red clearance time must be provided in VISSIM so that all vehicles leave the single open lane before the next phase begins. VisVAP (PTV VISSIM, 2020) was used to establish such a system. To be specific, several vehicle detectors were placed throughout the single open lane section, and near the Main and DAD approach. VisVAP was used to link vehicle presence/absence information from these different detectors with actuated signal control parameters (e.g., minimum green, maximum green, green extension, max-out, gap-out (FHWA, 2023)) to model four SC strategies, labeled as SC1, SC2, SC3, and SC4 in Figure 4.1.

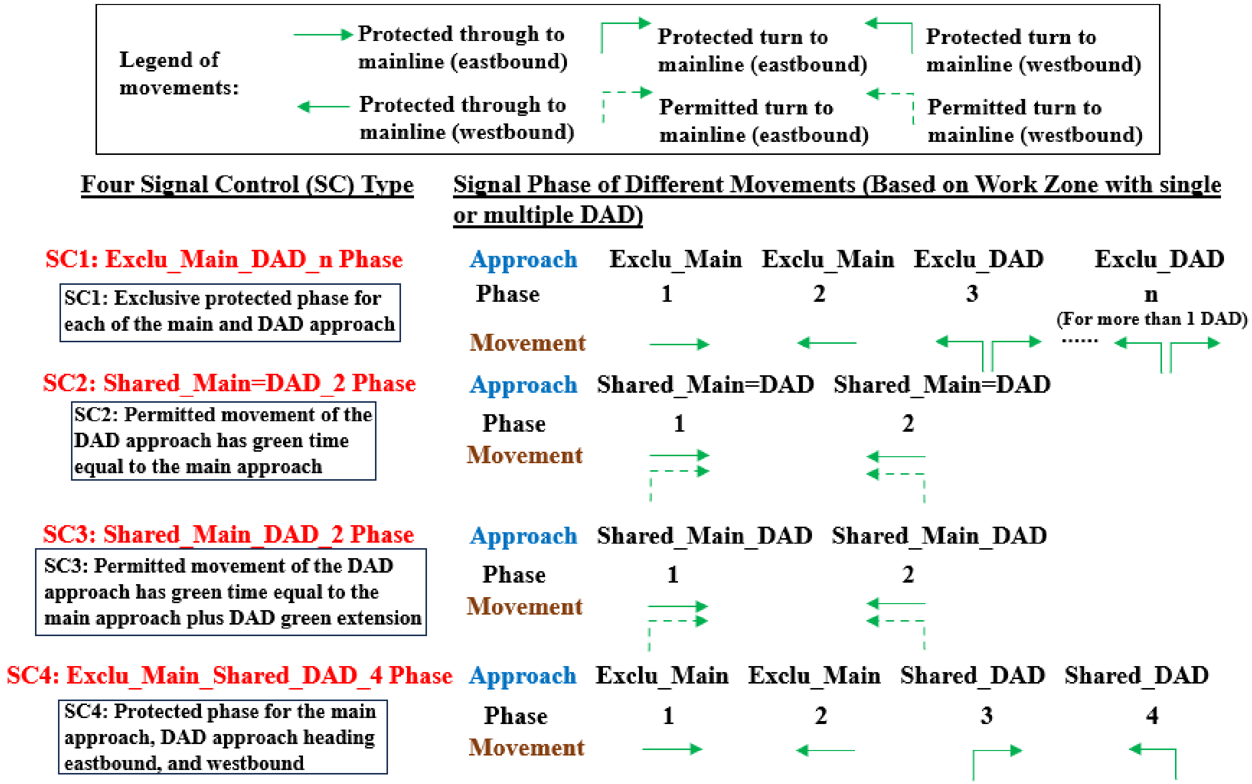


Figure 4.1 Phase and movement of four signal control strategies for DAD-operated work zone

SC1 (expressed as Exclu_n Phase) allows protected and exclusive movements for both Main approaches as Phase 1 and 2. Phase 3 allows protected right- and left-turning movements from a DAD approach, as depicted in Figure 4.1. There could be “n” different phases, where “n” is the total number of DADs plus two (i.e., phases for Main approach). For instance, work zones with three DADs will have five phases. Note that typically, the DAD is not given its own phase (mostly it is aligned to the mainline signal phase). However, engineers may want to evaluate the performance of DADs when given its own phase. Contractors from an NDOT (2020) study suggested independent phasing for DADs. Note that previous studies (Finley et al., 2014; McAvoy et al, 2023) used a portable TTCS (which is similar to a regular round shape red, green, and yellow signal without the right or left directions) in the access point with its own phase. Then its performance was compared against DADs. In this report, SC1 (similar to temporary TTCS), will evaluate access point performance when it is given its own signal phase.

SC2 (expressed as Shared Main=DAD_2 Phase) has two phases. Phase 1 allows two protected movements for traffic approaching Main that is eastbound, and at the same time allows permitted movement for the DAD approach using left- or right-turn signals (depending on which side of the main road the DAD is located) towards eastbound direction. Phase 2 functions like Phase 1 for westbound traffic. Note that the effective green time of the DAD approach matches the Main approach. Thus, when the Main approach's green signal starts and stops, so does the DAD approach.

SC3 (expressed as Shared_Main_DAD_2 Phase) has two phases. SC3 functions like SC2 except that after the Main approach effective green time ends, SC3 allows the DAD approach additional green time (depending on the presence of vehicles) by an actuated control system. Note that the DAD signal does not typically have sensors for detecting traffic for actuation. However, several studies (including NDOT 2019, MDOT, 2018) recommend it. Perhaps, MDOT (2018) installed DADs with the capability to adjust variable release times similar to adding green time in the DAD approach so that vehicles can exit the access point after the end of Main line green. This, though, necessitates additional clearance time for traffic to safely exit the work zone area (MDOT, 2018).

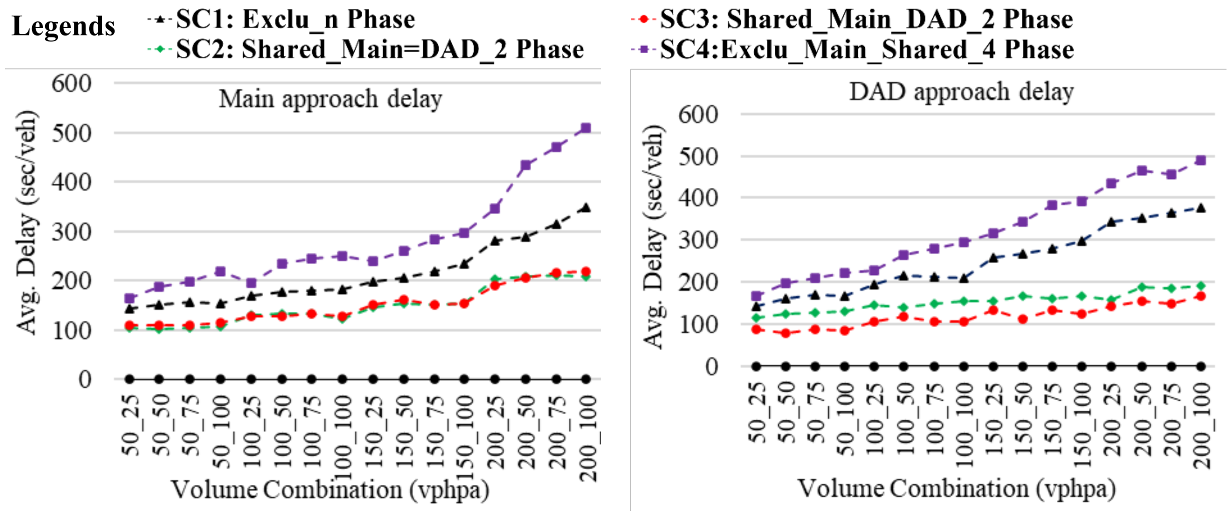
SC4 (expressed as "Exclu_Main_Shared_4 Phase") has four phases. Phases 1 and 2 are like SC1. Phase 3 allows protected movement for all DAD approach traffic that turns (left or right) to the mainline and heads eastbound. Phase 4 functions like Phase 3 for westbound traffic. Similar to SC1, while in the DAD phase, traffic engineers may want to measure the access point performance when these DADs are coordinated to indicate left and right-turn phases for all access points.

All SC types used 300-foot loop detectors in VISSIM for determining the gap-out conditions (based on test site observation). The maximum green times for the Main and DAD approaches were determined based on factors such as maximum volumes, work zone length, saturation headway, and vehicle speed within the work zone. Nebraska work zone data were applied to the HCM one-lane two-way work zone optimum green time method (Haque, 2022; HCM, 2016; Zhu et al., 2017) to determine the allowable maximum green time. Note that work zones with lower volume will simply gap-out and will not use the entire allowable maximum green. Thus, this actuated control is analogous to flagger control behavior and performs superior to any fixed control technique where the green time is predefined regardless of the traffic conditions and work zone characteristics (Haque, 2022; HCM, 2016; Zhu et al., 2017; Finley et al. 2014).

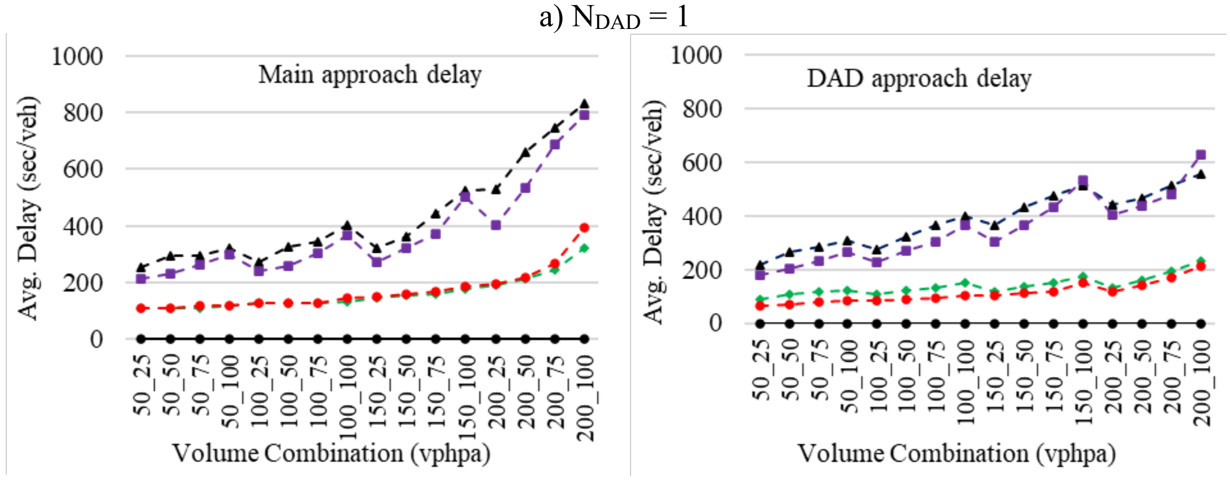
4.2 Delay Analysis of SC Strategies

Four Main approach volumes (V_{Main}) of 50, 100, 150, and 200 vehicles per hour per approach (vphpa) are combined with four DAD approach volumes (V_{DAD}) of 25, 50, 75, and 100 vphpa, resulting in 16 volume scenarios. This report denotes, for example, V_{Main} of 200 and V_{DAD} of 50 as volume combination (V_{Comb}) of 200_50, as used in the x-coordinates of Figure 4.2. Therefore, 200_100 means 200 vphpa for Main and 100 vphpa for DAD. Note that the number of DAD (N_{DAD}) applied within the work zone is 1, 3, and 5. Main approach truck percentage ($T_{\%Main}$) and DAD approach truck percentage ($T_{\%DAD}$) are considered 20% and 5%, respectively.

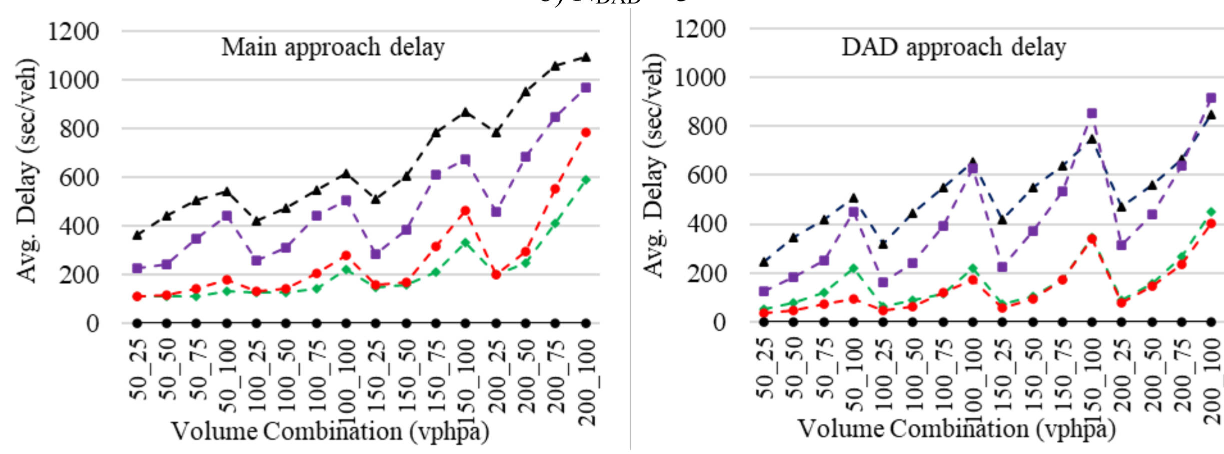
Therefore, 16 V_{Comb}, 4 SC strategies, and 3 DAD make 192 (16*4*3) scenarios. Figure 4.2 shows average delay results for the Main and DAD approaches for these scenarios. Each scenario was simulated 10 times (using varied seed numbers) with sufficient warm-up period before data collection.



a) $N_{DAD} = 1$



b) $N_{DAD} = 3$



c) $N_{DAD} = 5$

Figure 4.2 Delay performance of four signal control strategies under different volume combination for DAD-operated work zone

4.3 Statistical Comparisons

Figure 4.2 shows four color-coded SC techniques, which visualize performance patterns of delays. Visually, Figure 4.2 suggests that SC2 and SC3 have lower delays compared to SC1 and SC4. Table 4.1 lists the percentage of delay reduction by SC2 and SC3 compared to SC1 for Main, DAD, and All approach for all V_{Comb} (negative value represents delay reduction). T-tests were also conducted (with 95% confidence level) between SC2 and SC1, and SC3 and SC1 to examine if SC2/SC3 were able to reduce delay and the corresponding p-values are listed in Table 4.1. Similarly, SC2 and SC3 were compared with SC4 and the corresponding results of delay reduction in percentage and p-value of t-tests are shown in the lower part of Table 4.1. It was found that SC2/SC3 reduced the average delay by approximately 45%-75% (range) compared to SC1/SC4. Eventually, the p-values of all the scenarios were less than 0.05, which means that there was statistical evidence that SC2/SC3 were able to reduce the average delay compared to SC1/SC4.

Table 4.1 Delay comparisons of four signal control strategies under different volume combination for DAD-operated work zone

SC2 and SC3 performance compared to SC1 in terms of average delay reduction in %												
Volm Comb	**Main approach**				**DAD approach**				**All approach**			
	SC2		SC3		SC2		SC3		SC2		SC3	
	%	P-val	%	P-val	%	P-val	%	P-val	%	P-val	%	P-val
50_25	-56.5	<0.05	-58.0	<0.05	-60.0	<0.05	-71.1	<0.05	-57.8	<0.05	-63.4	<0.05
50_50	-62.6	<0.05	-62.1	<0.05	-59.2	<0.05	-73.1	<0.05	-60.6	<0.05	-68.6	<0.05
50_75	-62.9	<0.05	-60.1	<0.05	-49.2	<0.05	-73.1	<0.05	-53.0	<0.05	-68.9	<0.05
50_100	-63.7	<0.05	-63.3	<0.05	-31.4	<0.05	-73.7	<0.05	-39.4	<0.05	-71.0	<0.05
100_25	-53.4	<0.05	-54.3	<0.05	-60.6	<0.05	-70.4	<0.05	-55.6	<0.05	-58.8	<0.05
100_50	-60.5	<0.05	-60.1	<0.05	-61.8	<0.05	-71.8	<0.05	-61.0	<0.05	-65.3	<0.05
100_75	-62.7	<0.05	-62.6	<0.05	-64.3	<0.05	-73.9	<0.05	-63.4	<0.05	-68.8	<0.05
100_100	-67.7	<0.05	-63.9	<0.05	-62.1	<0.05	-74.6	<0.05	-64.3	<0.05	-70.3	<0.05
150_25	-54.5	<0.05	-53.1	<0.05	-67.6	<0.05	-72.2	<0.05	-57.3	<0.05	-57.4	<0.05
150_50	-57.4	<0.05	-55.7	<0.05	-68.7	<0.05	-74.3	<0.05	-61.8	<0.05	-62.8	<0.05
150_75	-64.3	<0.05	-61.9	<0.05	-68.3	<0.05	-75.0	<0.05	-66.1	<0.05	-67.7	<0.05
150_100	-65.9	<0.05	-64.2	<0.05	-66.2	<0.05	-71.1	<0.05	-66.0	<0.05	-67.6	<0.05
200_25	-64.0	<0.05	-63.4	<0.05	-70.1	<0.05	-73.7	<0.05	-64.9	<0.05	-64.9	<0.05
200_50	-67.5	<0.05	-66.9	<0.05	-65.7	<0.05	-69.5	<0.05	-67.0	<0.05	-67.3	<0.05
200_75	-67.4	<0.05	-64.2	<0.05	-62.4	<0.05	-66.9	<0.05	-65.2	<0.05	-64.3	<0.05
200_100	-61.2	<0.05	-52.7	<0.05	-58.1	<0.05	-61.8	<0.05	-58.7	<0.05	-54.2	<0.05
SC2 and SC3 performance compared to SC4 in terms of average delay reduction in %												
	Main approach				**DAD approach**				**All approach**			
	SC2		SC3		SC2		SC3		SC2		SC3	
	%	P-val	%	P-val	%	P-val	%	P-val	%	P-val	%	P-val
50_25	-47.9	<0.05	-49.7	<0.05	-51.4	<0.05	-64.9	<0.05	-49.2	<0.05	-56.0	<0.05
50_50	-52.2	<0.05	-51.6	<0.05	-47.1	<0.05	-65.1	<0.05	-49.2	<0.05	-59.5	<0.05
50_75	-58.4	<0.05	-55.4	<0.05	-49.7	<0.05	-66.5	<0.05	-54.4	<0.05	-62.9	<0.05
50_100	-61.0	<0.05	-60.6	<0.05	-54.8	<0.05	-69.5	<0.05	-59.2	<0.05	-67.0	<0.05
100_25	-47.0	<0.05	-47.9	<0.05	-52.4	<0.05	-64.2	<0.05	-48.4	<0.05	-52.2	<0.05
100_50	-50.4	<0.05	-50.0	<0.05	-54.7	<0.05	-66.6	<0.05	-52.4	<0.05	-57.6	<0.05
100_75	-57.8	<0.05	-57.7	<0.05	-57.1	<0.05	-68.7	<0.05	-57.3	<0.05	-63.6	<0.05
100_100	-64.4	<0.05	-60.2	<0.05	-58.6	<0.05	-72.3	<0.05	-61.0	<0.05	-67.5	<0.05
150_25	-45.8	<0.05	-44.1	<0.05	-60.8	<0.05	-66.4	<0.05	-49.1	<0.05	-49.2	<0.05
150_50	-52.0	<0.05	-50.1	<0.05	-62.8	<0.05	-69.4	<0.05	-55.9	<0.05	-57.1	<0.05
150_75	-57.4	<0.05	-54.6	<0.05	-65.2	<0.05	-72.5	<0.05	-61.0	<0.05	-62.9	<0.05
150_100	-64.4	<0.05	-62.6	<0.05	-67.4	<0.05	-72.1	<0.05	-65.9	<0.05	-67.4	<0.05
200_25	-52.9	<0.05	-52.1	<0.05	-67.2	<0.05	-71.2	<0.05	-55.3	<0.05	-55.3	<0.05
200_50	-59.9	<0.05	-59.1	<0.05	-63.5	<0.05	-67.5	<0.05	-60.6	<0.05	-60.9	<0.05
200_75	-64.6	<0.05	-61.2	<0.05	-60.0	<0.05	-64.7	<0.05	-62.6	<0.05	-61.6	<0.05
200_100	-59.1	<0.05	-50.1	<0.05	-62.7	<0.05	-66.0	<0.05	-60.1	<0.05	-55.7	<0.05

Note: Volm Comb (Volume Combination); P-val (P value of t-test); % (change of delay in percentage (negative value means delay reduction).

Therefore, as a next step, the performance of SC2 and SC3 were compared, and the results of percentage of delay reduction by SC3 and the corresponding p-value of the t-test are shown in Table 4.2. Out of 144 (16*3*3) data points presented in Table 4.2, 71 are statistically significant (p-value less than 0.05). Out of 71 data points, 55 are associated with delay reduction by SC3. Therefore, SC3 is selected as the best control strategy to conduct studies for the rest of the report.

Table 4.2 Delay comparisons of SC2 and SC3 under different volume combination for DAD-operated work zone

Performance of SC3 compared to SC2 (Negative % means decrease in delay)							
		Main approach		DAD Approach		All approach	
	Volume Combination	%	P-value	%	P-value	%	P value
N_{DAD} = 1	**50_25**	4.3	0.21	-24.4	**<0.05**	-1.6	0.35
	50_50	5.6	0.15	-40.3	**<0.05**	-13.5	**<0.05**
	50_75	6.0	0.11	-49.4	**<0.05**	-25.5	**<0.05**
	50_100	5.9	0.09	-60.3	**<0.05**	-38.9	**<0.05**
	100_25	-2.1	0.33	-28.4	**<0.05**	-4.8	0.17
	100_50	-3.2	0.25	-15.5	**<0.05**	-5.6	0.11
	100_75	1.7	0.37	-27.4	**<0.05**	-6.4	0.10
	100_100	4.7	0.17	-30.8	**<0.05**	-9.0	**<0.05**
	150_25	3.2	0.23	-13.7	0.06	1.9	0.29
	150_50	4.5	0.14	-32.1	**<0.05**	-0.9	0.41
	150_75	0.1	0.49	-16.4	**<0.05**	-3.5	0.18
	150_100	0.7	0.44	-24.4	**<0.05**	-6.2	**<0.05**
	200_25	-7.5	0.06	-9.5	0.08	-7.7	0.05
	200_50	-1.2	0.42	-17.7	**<0.05**	-3.2	0.28
	200_75	3.2	0.28	-18.8	**<0.05**	-0.1	0.49
	200_100	4.9	0.24	-13.6	**<0.05**	-0.9	0.41
N_{DAD} = 3	**50_25**	-3.6	0.23	-27.8	**<0.05**	-13.4	**<0.05**
	50_50	1.3	0.39	-34.1	**<0.05**	-20.4	**<0.05**
	50_75	7.4	0.05	-47.0	**<0.05**	-33.9	**<0.05**
	50_100	1.1	0.39	-61.6	**<0.05**	-52.2	**<0.05**
	100_25	-1.8	0.35	-24.8	**<0.05**	-7.3	0.07
	100_50	0.9	0.43	-26.3	**<0.05**	-10.9	**<0.05**
	100_75	0.2	0.48	-27.1	**<0.05**	-14.8	**<0.05**
	100_100	11.7	**<0.05**	-33.1	**<0.05**	-16.8	**<0.05**
	150_25	3.0	0.27	-14.2	0.10	-0.2	0.48
	150_50	3.9	0.21	-17.7	**<0.05**	-2.6	0.25
	150_75	6.6	0.09	-21.1	**<0.05**	-4.7	0.07
	150_100	5.0	0.15	-14.4	**<0.05**	-4.5	0.05
	200_25	1.7	0.36	-12.0	0.14	0.1	0.49
	200_50	1.8	0.37	-11.1	**<0.05**	-0.8	0.43
	200_75	9.6	0.08	-11.9	**<0.05**	2.6	0.33
	200_100	22.0	**<0.05**	-8.9	**<0.05**	11.1	**<0.05**
N_{DAD} = 5	**50_25**	-1.8	0.36	-32.5	**<0.05**	-13.4	**<0.05**
	50_50	3.5	0.20	-38.1	**<0.05**	-23.7	**<0.05**
	50_75	28.7	**<0.05**	-42.0	**<0.05**	-29.3	**<0.05**
	50_100	35.3	**<0.05**	-58.1	**<0.05**	-48.4	**<0.05**
	100_25	4.1	0.23	-24.4	**<0.05**	-2.5	0.32
	100_50	13.8	**<0.05**	-29.6	**<0.05**	-6.4	**<0.05**
	100_75	47.4	**<0.05**	3.7	0.36	21.0	0.19
	100_100	27.2	**<0.05**	-20.9	**<0.05**	-7.6	0.17
	150_25	7.8	**<0.05**	-18.4	**<0.05**	3.6	0.19
	150_50	4.5	0.23	-11.8	**<0.05**	-1.4	0.39
	150_75	51.5	**<0.05**	0.3	0.47	24.3	0.11
	150_100	39.9	**<0.05**	-1.5	0.39	13.5	**<0.05**
	200_25	1.0	0.41	-11.5	0.09	-0.4	0.45
	200_50	18.0	**<0.05**	-6.4	0.11	11.9	0.08
	200_75	34.6	**<0.05**	-11.4	**<0.05**	14.2	**<0.05**
	200_100	33.1	**<0.05**	-9.9	0.10	8.5	0.13

One important finding is that the highest delays were made by SC4 with a single DAD (Figure 4.2.a) with SC1 being the second highest. However, their position switched when more than one DAD was applied (Figure 4.2.b, 4.2.c) and SC1 caused the highest delays. For practitioners, this implies that providing an exclusive phase to the DAD (or using TTCS) may be feasible with a lower number of access points. However, doing such will not be feasible as the number of access points or DADs increases.

Chapter 5 Impacts of DAD System on Work Zone Operations

The goal of this section is to find how traffic composition and work zone characteristics influence the performance of DAD-operated work zones using the SC3 developed here. The use of best control ensures that the operational impacts emerge from the traffic and work zone conditions, not from improper signal control.

5.1 Factors Affecting Work Zone Operations and Sensitivity Analysis Design

Various traffic and work zone characteristics are known to impact the operational outcomes of work zone lane closures on two-lane highways (Washburn et al., 2008; Haque, 2022). Logically, the inclusion of DAD systems within the work zone can further impact the operational metrics. Therefore, six factors were chosen to study their impact on DAD-operated work zones in terms of average delay and average maximum queue length. These are i) Main approach traffic volumes, ii) DAD approach traffic volumes, iii) work zone length (WZL), iv) number of DADs, v) Main approach truck percentage, and vi) DAD approach truck percentage.

For the sensitivity analysis, V_{Main} of 50, 100, 150, 200, 250, and 300 vphpa were combined with V_{DAD} of 25, 50, 75 and 100 vphpa. Note that in these combinations, there are few cases when the traffic volume in the DAD approach is higher than the Main approach. These scenarios are considered to represent cases where the side street may have commercial businesses such as gas stations, grocery stores, etc., which may cause a higher traffic demand for few hours during the day such as morning or evening peak periods (e.g., MDOT 2018). Additionally, when a two-lane highway passes through a residential area, the side street volumes may be higher.

Four WZLs of 0.25, 0.50, 1.1, and 2 miles were considered. As WZL increases, the maximum allowable V_{Main} is reduced to exclude oversaturation conditions (Haque, 2022). The highest V_{Main} for 0.25, 0.50, 1.1, and 2.0 miles work zone were selected as 300, 250, 200, and 150 vphpa, respectively. Combining WZL with their respective volume level constituted 72 scenarios.

$T_{\%Main}$ of 0%, 20%, and 40% were considered. Note that Midwest highways often deal with higher truck presence (Haque, 2022). On the other hand, $T_{\%DAD}$ of 0%, 5%, 10%, and 20% were used in this study, making 12 truck percentage scenarios.

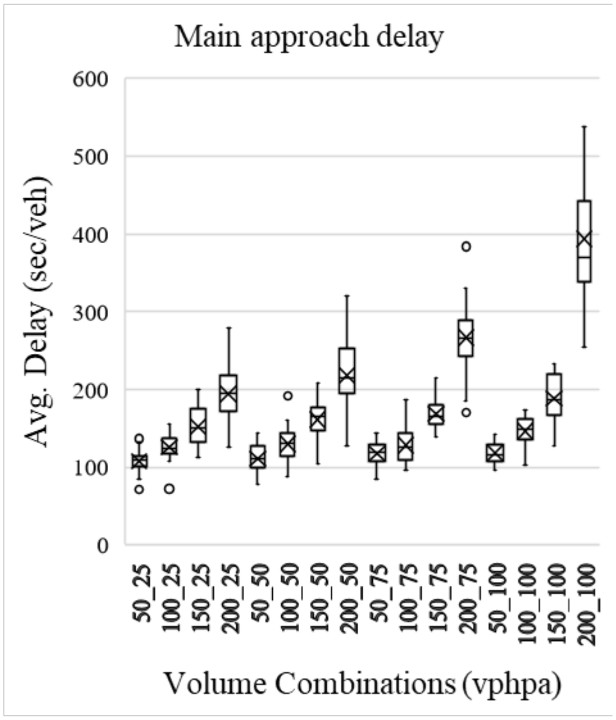
N_{DAD} applied within the work zone was 0, 1, 3, and 5. Zero N_{DAD} represents a work zone without DAD.

WZL, Volume, truck percentage, and N_{DAD} created 3,456 (72*12*4) scenarios. For sensitivity studies, VISSIM was run 10 times (with varied seed numbers) for each scenario totaling 34,560 simulation runs. The simulated network was warmed up before collecting one-hour data for each scenario. For each simulation run, delay and maximum queue data were extracted from the Main and DAD approaches, totaling 293,760 data points.

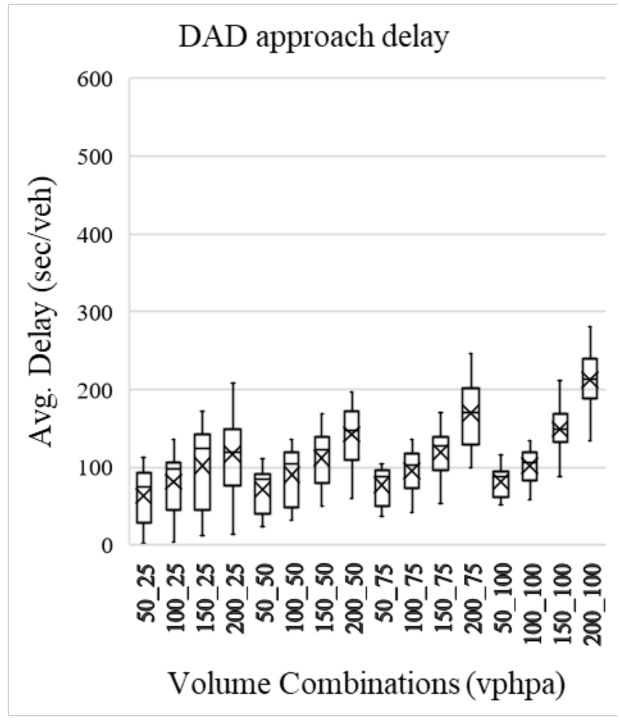
As described in the background sections, the general hypothesis is that the factors considered here will impact the operational metrics (i.e., delays and queues) for DAD operations at work zone lane closure condition. From 3,456 scenarios, this report will focus on a subset of them to examine the effects of traffic volumes, WZL, and N_{DAD} for DAD-operated work zone using $T_{\%Main}$ and $T_{\%DAD}$ of 20% and 5%, respectively. Note that many of the results are shown in Appendix A, B, and C. Also, note that the other truck percentage combinations were not included in this report because of their lesser impacts compared to other factors. This report aims to use the numerical values of factors that would be more realistic for traffic agencies in real-world scenarios.

5.2 Impact of Traffic Volume

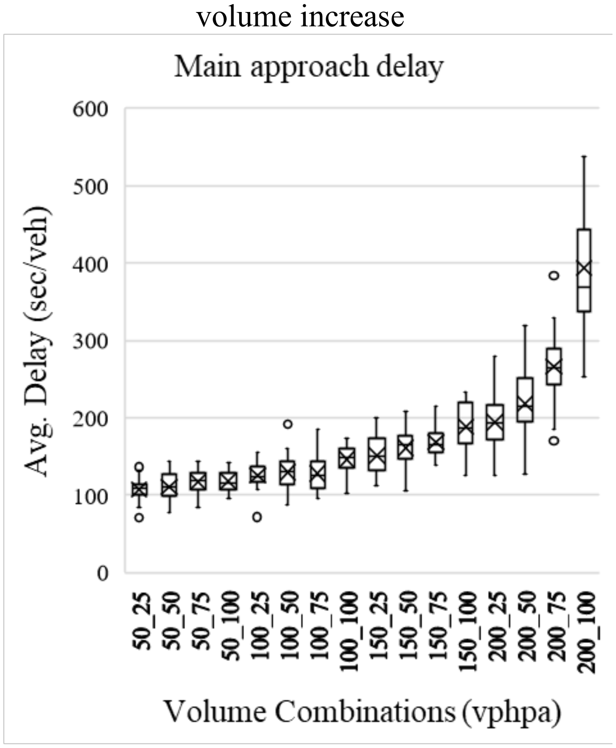
Figure 5.1 demonstrates traffic volume impact for a scenario consisting of a 1.1-mile work zone and N_{DAD} value of 3. For both the Main and DAD approaches, Figures 5.1.a and 5.1.b show the effect of increasing V_{Main} for various levels of constant V_{DAD}, and Figures 5.1.c and 5.1.d show the vice-versa. The boxplot represents the average, median, percentiles (i.e., 25, 50, 75, and 100), and any outlier values of average delays.



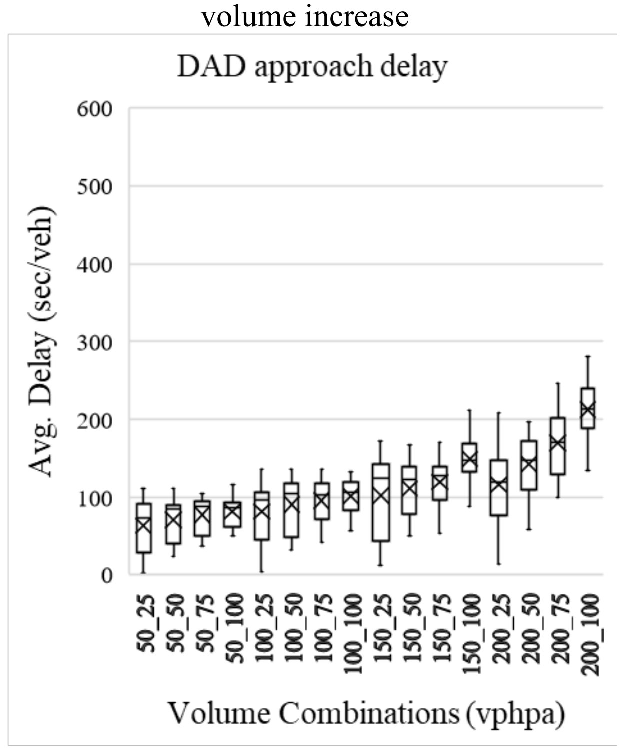
a. Main approach delay for Main approach volume increase



b. DAD approach delay for Main approach volume increase



c. Main approach delay for DAD approach volume increase



d. DAD approach delay for DAD approach volume increase

Figure 5.1 Impact of traffic volume on average delay for DAD-operated work zone

Figure 5.1.a shows that for V_{Comb} values of 50_25, 100_25, 150_25, and 200_25, the Main approach average delay was 107.4, 125.5, 151.6, and 194.3 seconds per vehicle (sec/veh), respectively. Therefore, increasing V_{Main} from 50 to 200 (with V_{DAD} = 25) increases the Main approach average delay by 80.9%. This percentage became 96.4% (218.3), 127.6% (266.4), and 234.1% (393.7) for V_{DAD} of 50, 75, and 100, respectively (values in the parentheses are the original average delays). Note that the highest delay of 393.7 sec/veh found here was the average and the boxplot suggests that this delay could be as high as 538.2 seconds (around 9 minutes).

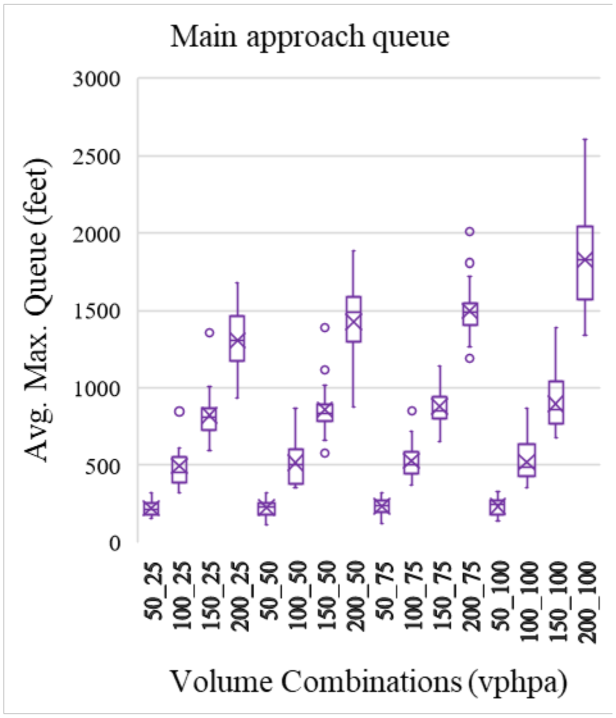
Figure 5.1.b shows that for V_{Comb} values of 50_25, 100_25, 150_25, and 200_25, the DAD approach suffered 41.1% (63.2), 35.3% (81.2), 32.7% (101.9) and 40.2% (116.2) lesser delays than Main approach. However, like Figure 5.1.a, increasing V_{Main} from 50 to 200 (with V_{DAD} = 25) increased the DAD approach delay by 83.8% (116.2). This percentage became 100.1% (142.1), 120.3% (169.6), and 161.7% (212.5) for V_{DAD} values of 50, 75, and 100, respectively. The boxplot suggests that even though the highest average DAD approach delay was 212.5 sec/veh, a few vehicles may experience delays around 280.6 seconds (around 4.5 minutes).

Figures 5.1.c and 5.1.d rearrange the x-coordinates of V_{Comb} to depict the impact of V_{DAD} for a given V_{Main}. Visually, the shape of the boxplots of Figures 5.1.c and 5.1.d (compared to Figures 5.1.a and 5.1.b) suggests that the increase of V_{DAD} for a given V_{Main} still increases the delay for both the Main and DAD approach but to a lesser extent. For example, V_{DAD} from 25 to 100, raised the average delay of the Main approach by 9.7%, 16.3%, 24.2%, and 102.6%, and the DAD approach by 28.5%, 25.0%, 45.9%, 82.8% for V_{Main} values of 50, 100, 150, and 200, respectively. These increase rates of average delay due to the increase of V_{DAD} are lesser in magnitude compared to the scenario when V_{Main} increased.

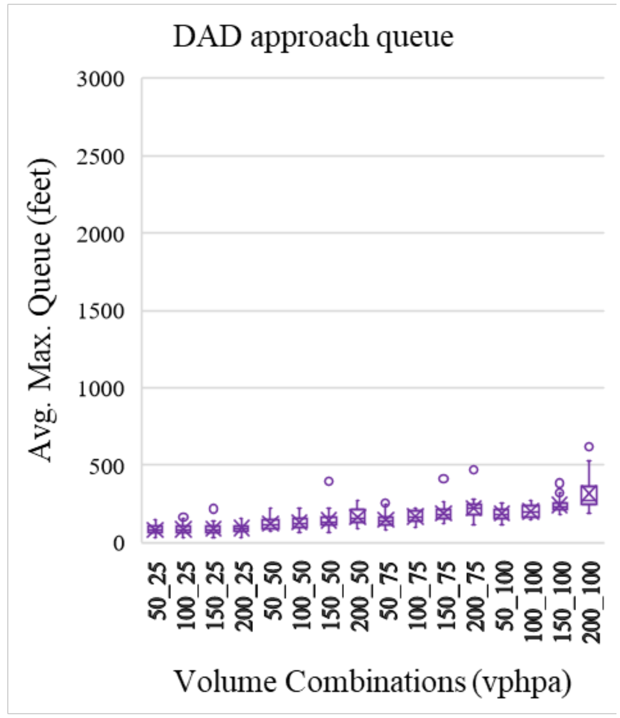
The standard deviation (SD) of average delay for V_{Comb} values of 50_25, 100_25, 150_25, and 200_25 was 17.3, 18.5, 25.9, and 34.6 seconds for the Main approach (from Figure 5.1.a), and 35.7, 39.8, 50.7, and 52.7 seconds for the DAD approach (from Figure 5.1.b), respectively. Therefore, a change in V_{Main} from 50 to 200 (for V_{DAD} = 25) increased the SD around 99.8% and 47.9%, respectively, for the Main and DAD approaches. For higher V_{DAD} values of 50, 75, and 100, the increase of V_{Main} from 50 to 200 increased the Main approach SD by 127.2%, 216.6%, and 531.6%, and the DAD approach SD by 29.1%, 70.1%, and 114.8%, respectively. Note that the practical implication of the SD increase is that operation at DAD-operated work zones becomes less reliable. Reliability is an important metric of transportation operations for road users and traffic agencies (Tufuor and Rilett, 2021). Transportation system users are more likely to remember the longest wait time than any shorter wait.

The increase of V_{DAD} in Figures 5.1.c and 5.1.d Shows an interesting SD phenomenon. The SD of the DAD approach average delay decreases as V_{DAD} increases for a certain V_{Main}. For example, for V_{Comb} values of 150_25, 150_50, 150_75, and 150_100, the respective SD of DAD approach delay was 39.8, 34.4, 26.7, and 22.2 seconds. This pattern occurs when a smaller number of vehicles arrive in the DAD approach because their wait time before proceeding to the work zone might vary depending on which part of the cycle length they arrive. Vehicles arriving at the onset of the red light will wait longer than those arriving during the green signal. However, for higher volumes, vehicles will more likely arrive around various parts of the cycle time, reducing the delay SD. Therefore, while V_{DAD} increase is associated with higher delays, it may reduce the systems' SD for scenarios studied here.

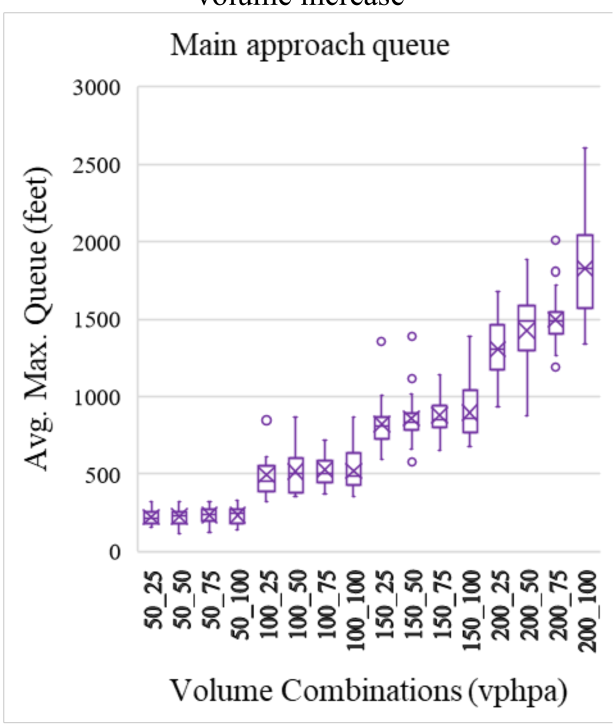
The findings above suggest that an increase in V_{Main} (given a V_{DAD}) leads to the average delay and delay SD at the Main approach raising with a higher magnitude than the DAD approach. Therefore, the growth of V_{Main} made DAD-operated work zones less reliable. On the other hand, an increase in V_{DAD} for a given V_{Main} still increases the delay for the Main and DAD approaches, but the rate of increase is less in magnitude compared to the V_{Main} increase case. Interestingly, a lower V_{DAD} tends to increase the average delay SD for the DAD approach and makes the operation less reliable. These findings are important for engineers and traffic agencies to make informed decisions about the traffic operation of DAD-operated work zones.



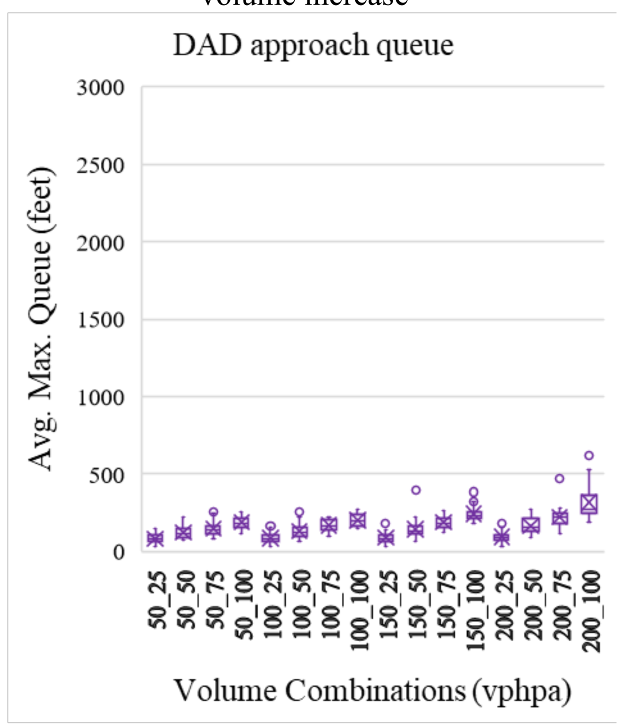
a. Main approach queue for Main approach volume increase



b. DAD approach queue for Main approach volume increase



c. Main approach queue for DAD approach volume increase



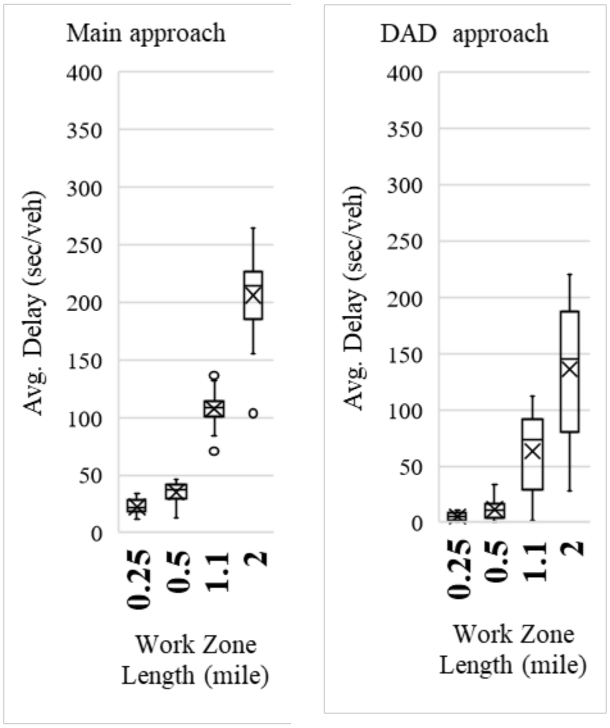
d. DAD approach queue for DAD approach volume increase

Figure 5.2 Impact of traffic volume on average maximum queue

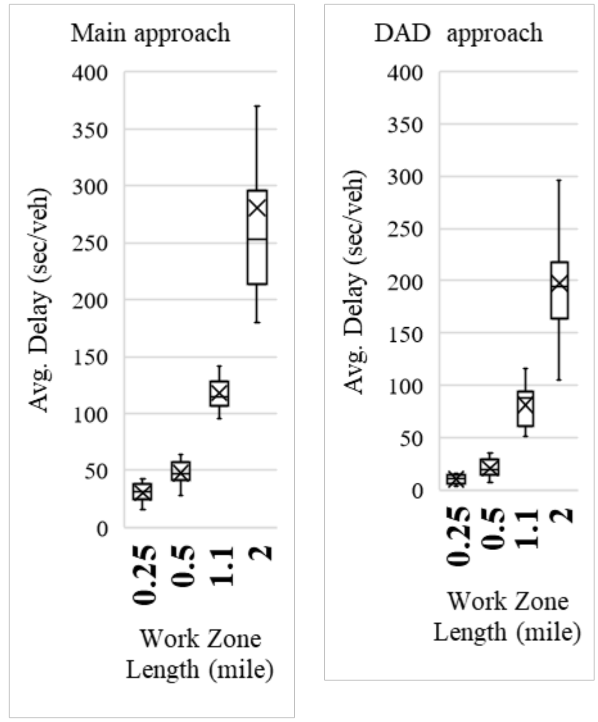
Maximum queue length is one of the most important performance metrics. Excessive queues can extend upstream from the Main or DAD approaches to important crossroads, intersections, or infrastructure and cause blockage and bottlenecks. Excessive queues are often associated with rear-end collisions in work zones (Farid et al., 2018). Like Figure 5.1, readers can observe the trend of volume impacts on maximum queue in Figure 5.2. The impact pattern of V_{Main} and V_{DAD} on the average (avg.) maximum (max.) queue length at the Main and DAD approaches are similar to the average delay. For example, a change in V_{Main} from 50 to 200 (with V_{DAD} = 100) enlarges the queue of the Main approach from 218.8 to 1857.4 feet (an increase of 748.9%) and of the DAD approach from 188.5 to 316.4 feet (an increase of 67.9%). On the other hand, a change in V_{DAD} from 25 to 100 (with V_{Main} = 200) enlarges the maximum queue from 1215.7 to 1857.4 feet (an increase of 52.8%) for the Main approach and from 96.5 to 316.4 feet (an increase of 228.1%) for the DAD approach. Note the boxplots reveal that queue length on the Main and DAD approaches can reach as high as 2603.1 feet (half a mile) and 321.8 feet, respectively.

5.3 Impact of Work Zone Length

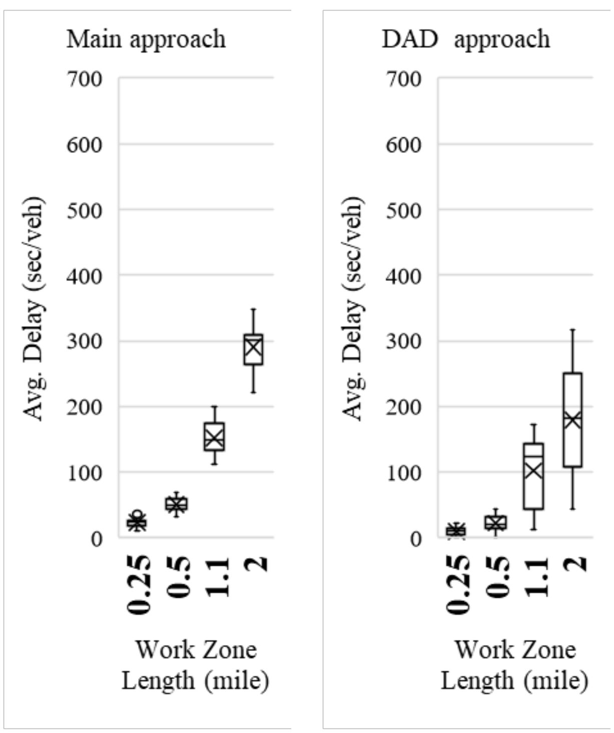
As WZL increases, more red clearance time is required, and it causes delays for traffic waiting in the Main and DAD approaches. Therefore, the scope and character of these repercussions should be investigated. Figure 5.3 shows a WZL comparison of 0.25, 0.5, 1.1, and 2.0 miles, and average delay for V_{Comb} values of 50_25, 50_100, 150_25, and 150_100 with an N_{DAD} of 3.



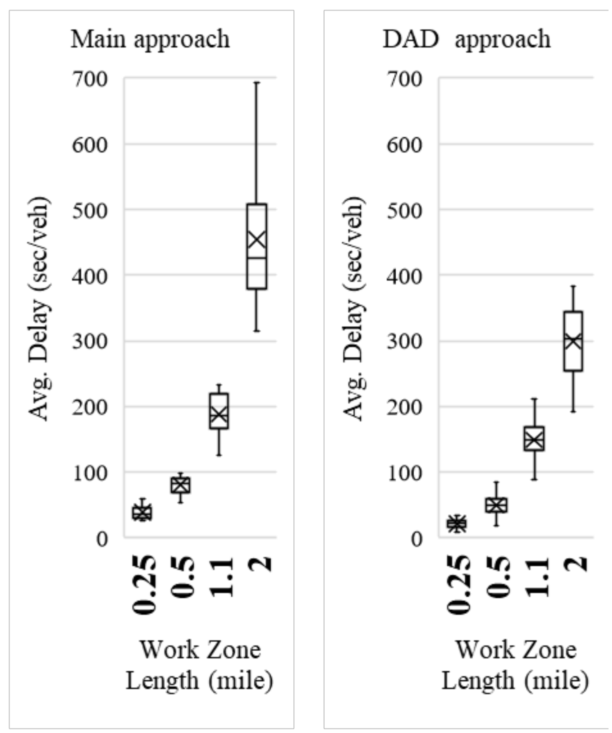
a. Delay for V_{Comb} of 50_25



b. Delay for V_{Comb} of 50_100



c. Delay for V_{Comb} of 150_25



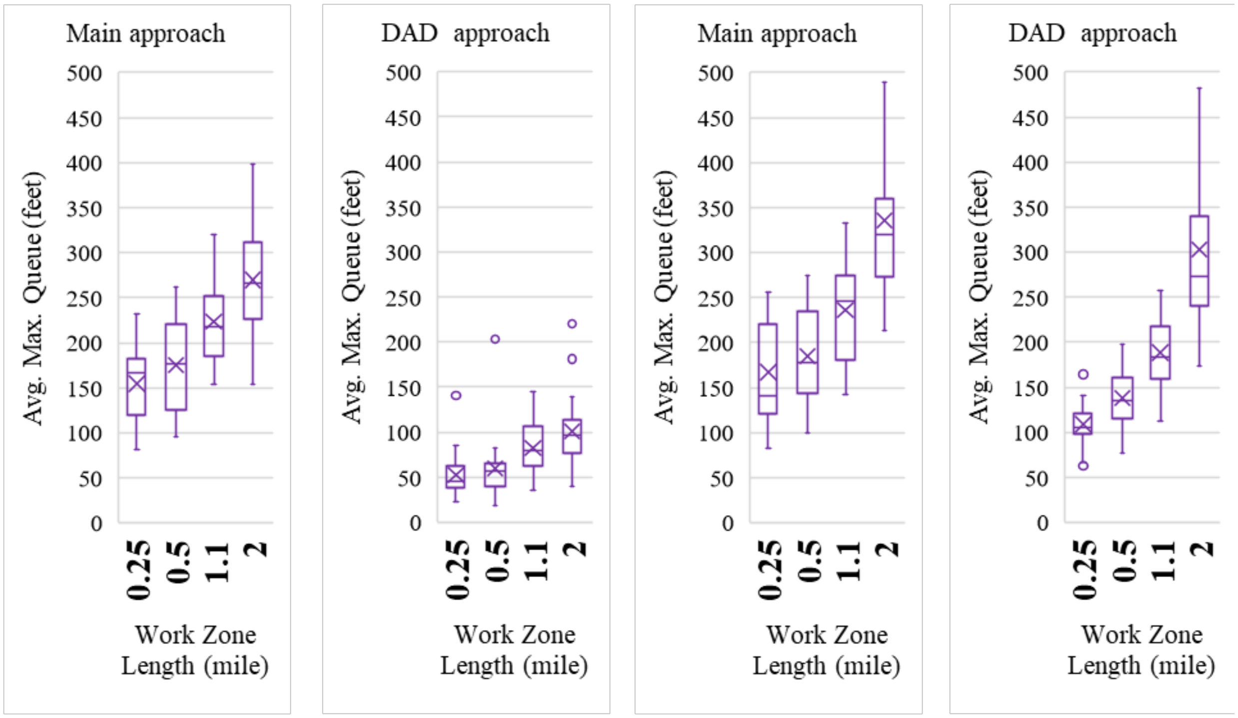
d. Delay for V_{Comb} of 150_100

Figure 5.3 Impact of work zone length on average delay

Figure 5.3.a (V_{Comb} of 50_25) shows the average delay for 0.25-, 0.50-, 1.1-, and 2.0-mile long work zones was 22.2, 35.1, 107.4, and 206.0 sec/veh for the Main approach, and 5.1, 11.2, 63.2, and 136.1 sec/veh for the DAD approach, respectively. Not surprisingly, as WZL increased, work zone delay increased at an increasing rate. For example, for a change in WZL from 0.25 to 0.50 miles, the Main approach delay increased by approximately 59%—in other words by a factor of 1.5 times. But, at 2.0 miles, the Main approach delay climbed to a 9.0 times larger delay. Note that the delay increase rate is more severe for the DAD approach; a rate of 2.0 and 27.0 times for WZLs of 0.50 and 2.0 miles, respectively, compared to 0.25 miles. Therefore, even with lower volume conditions, work zones suffer considerable delays due to longer WZLs.

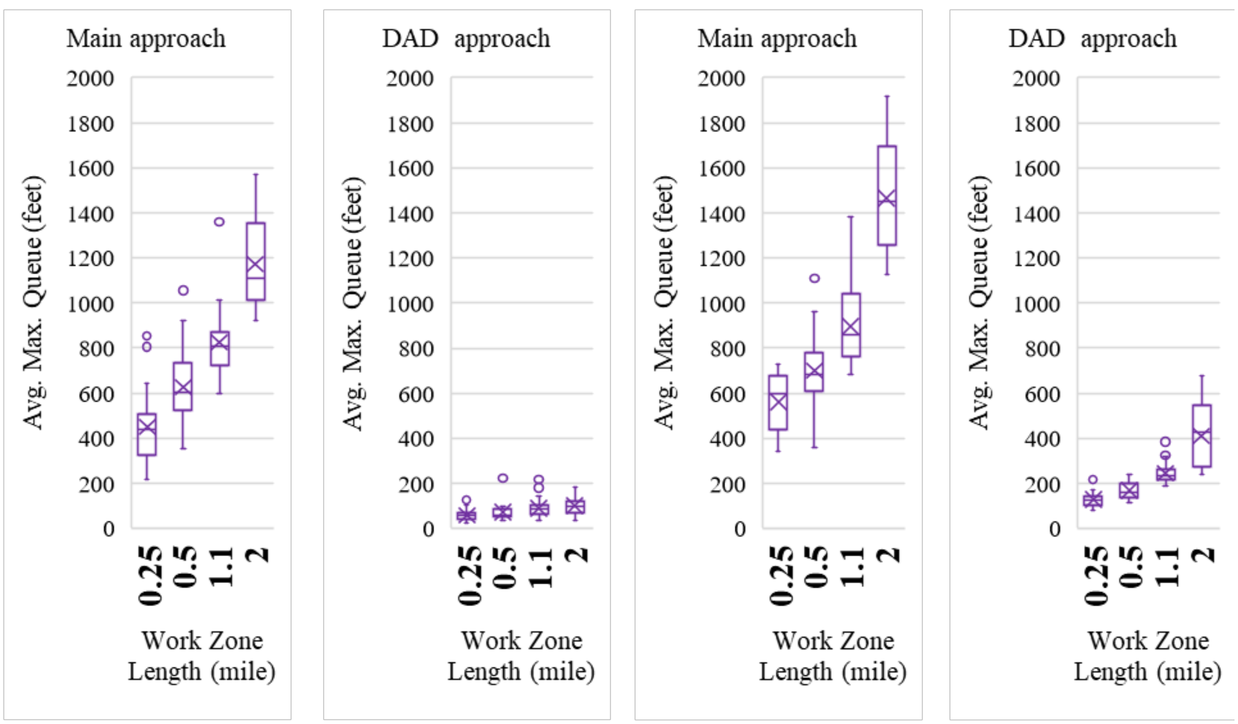
WZL impacts became more severe with higher volumes. Notably for a V_{Comb} of 150_100 (from Figure 5.3.d), the average delay for a WZL of 2.0 miles for the Main and DAD approaches became 453.7 (around 7.5 minutes) and 299.4 sec/veh (around 5.0 minutes), respectively. The boxplot suggests a few vehicles experienced delays of 11.5 minutes for the Main approach. In contrast, a WZL of 0.25 miles caused only approximately 39.0 and 21.0 sec/veh delay, for the Main and DAD approaches. Therefore, a longer WZL with higher volumes may immensely impact work zone operations, causing driver frustration and monetary loss for road users and traffic agencies. Furthermore, for higher V_{Comb} and WZL combinations, a higher average delay SD (i.e., 109.9 and 50.7 seconds, respectively for the Main and DAD approaches and a 2.0-mile WZL) was observed, causing less reliable work zone operations.

In summary, longer WZLs caused higher average delays and higher SD of delay for the Main approach compared to the DAD approach. However, the rate of increase of these two metrics for the DAD approach were higher than the Main approach.



a. Queue for V_{Comb} of 50_25

b. Queue for V_{Comb} of 50_100



c. Queue for V_{Comb} of 150_25

d. Queue for V_{Comb} of 150_100

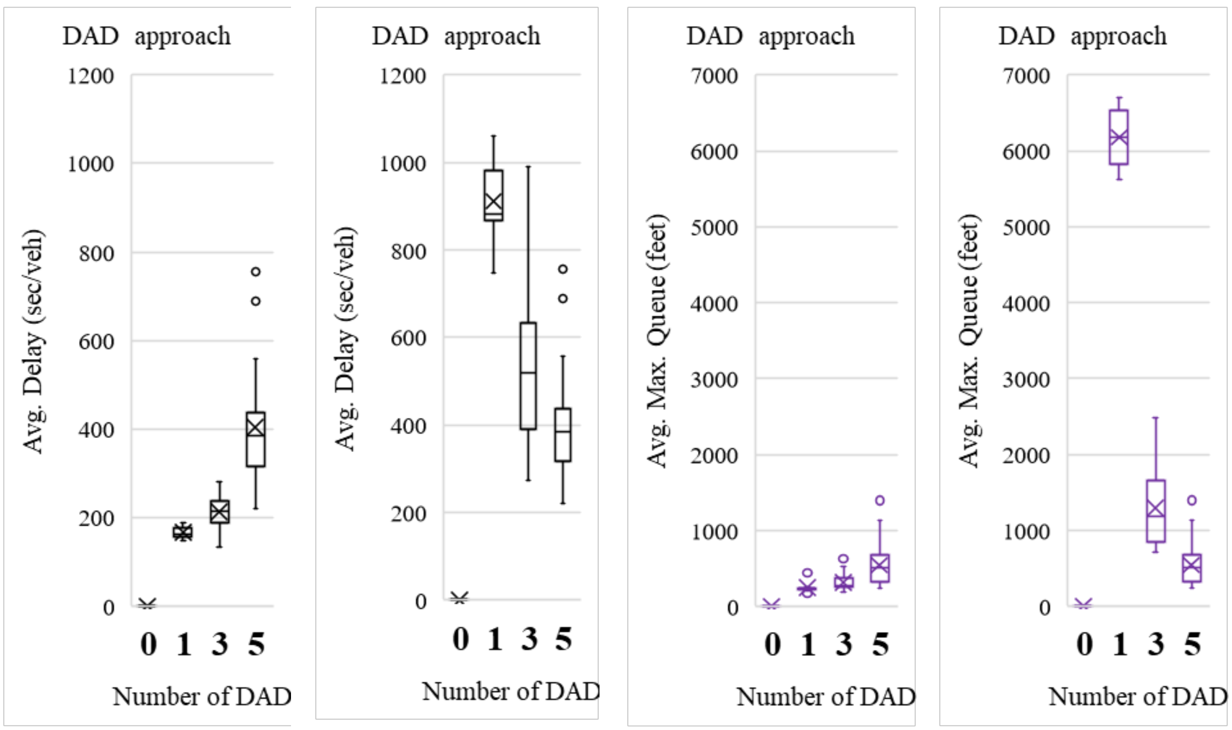
Figure 5.4 Impact of work zone length on average maximum queue

Figure 5.4 shows the average maximum queue for the same scenario presented in Figure 5.3. Not surprisingly, like the delay, higher WZLs causing excessive queueing hampered the work zone operations. For example, for a V_{Comb} of 150_100 (from Figure 5.4.d), WZLs of 0.25, 0.50, 1.1, and 2.0 miles caused average maximum queues of 559.7, 699.3, 894.9, and 1465.5 feet for the Main approach and 168.4, 244.1, and 410.2 feet for the DAD approach, respectively. The Main approach queue observed for 2.0 miles could be as high as 1900 feet according to the boxplot, and averaged 1464.5 feet. Furthermore, the shape of the boxplots from Figure 5.4 demonstrated that the SD of queue length also increased as a result of WZL increases, which makes the work zone operations less reliable.

It is common for transportation agencies or work zone contractors to change WZL as road construction or rehabilitation work progresses (Haque, 2022; Farid et al., 2018). This study provides guidelines on how much change in WZL is feasible given traffic demand for efficient work zone operation and putting constraints like maximum allowable queue length.

5.4 Impact of Number of DAD

This section discusses the impact of N_{DAD} (using values of 1, 3, and 5) with 1.1-mile work zones on the DAD approach delay and queue with two different volume combinations of 200_100 and $200\_500_{TotalDAD}$. Results are depicted in Figure 5.5. The 100 in 200_100 means 100 vehicles per hour per DAD approach. The $500_{TotalDAD}$ in $200\_500_{TotalDAD}$ means a total DAD volume (access point volume) of 500 vehicles per hour regardless of the number of DADs. The former settings would simply reveal what happens if N_{DAD} increases given each of the DAD approaches has equal traffic demand. However, the latter would reveal how different N_{DAD} values impact work zone performance when the total DAD approach traffic demand is known. These simulation scenarios can help decide the selection of a work zone site or segment when all of them have around the same total traffic demand from access points while the number of access points (i.e., number of DAD equipment required) varies. Note that engineers/contractors often select roadway segments of their choice to run the construction/rehabilitation work as a work zone, the outcome found from these simulated scenarios can be beneficial in decision making for efficient work zone operations.



a. Delay for V_{Comb} of 200_100

b. Delay for V_{Comb} of $200\_500_{totalDAD}$

c. Queue for V_{Comb} of 200_100

d. Queue for V_{Comb} of $200\_500_{totalDAD}$

Figure 5.5 Impact of N_{DAD} on average delay and average maximum queue length of DAD approach

Note that Figure 5.5 uses higher V_{DAD} values for its operational impacts. Boxplots from Figures 5.5.a and 5.5.c show that for 200_100, when N_{DAD} increases, both delay and queue increases for the DAD approach. An change in N_{DAD} from 1 to 5 increased delay by 143.2% and queue length by 120.5%. However, $200\_500_{TotalDAD}$ shows the opposite pattern in Figures 5.5.b and 5.5.d—the delay and queue reduced by 54.7% and 92.9%. This may seem counterintuitive as the increase of conflicting points (i.e., higher N_{DAD}) decreased the traffic delays and queues. The reason for such a performance improvement is that with the increase of N_{DAD}, work zones have more traffic-releasing points. In other words, this case is similar to increasing the number of lanes given the same total traffic demand to improve operational performance. Therefore, this is an interesting phenomenon that traffic agencies may pay attention to.

Note that this report includes Appendix A, B, and C where the delay and queue (analysis of mean, standard deviations, and distributions through boxplots) from SC1, SC2, SC3, and SC4 are presented in figures and tables for DAD numbers of 1, 3, and 5, respectively. These tables and figures can be used to find delays and queues using different signal control strategies and volume combinations for the Main, DAD, and All approaches.

Chapter 6 Safety and Design Aspects of the DAD System

One of the major advantages of deploying the DAD system is to improve safety in one-lane two-way work zones. The DAD system helps guide drivers entering the work zone from driveways, reducing confusion and preventing potential collisions. The goal of this chapter is to provide a summary of the field applications, designs, and safety aspects of the DAD system based on its deployments in the U.S. and findings from simulated studies from this project.

There are several settings (i.e., designs and placements) that have been proposed because the DAD system is not fully incorporated into the MUTCD. Consequently, DADs are considered experimental as any application and new designs of devices that are not covered in the MUTCD can only be used after FHWA experimentation approval is received. Figure 6.1 shows the utilization of the DAD system in the U.S.

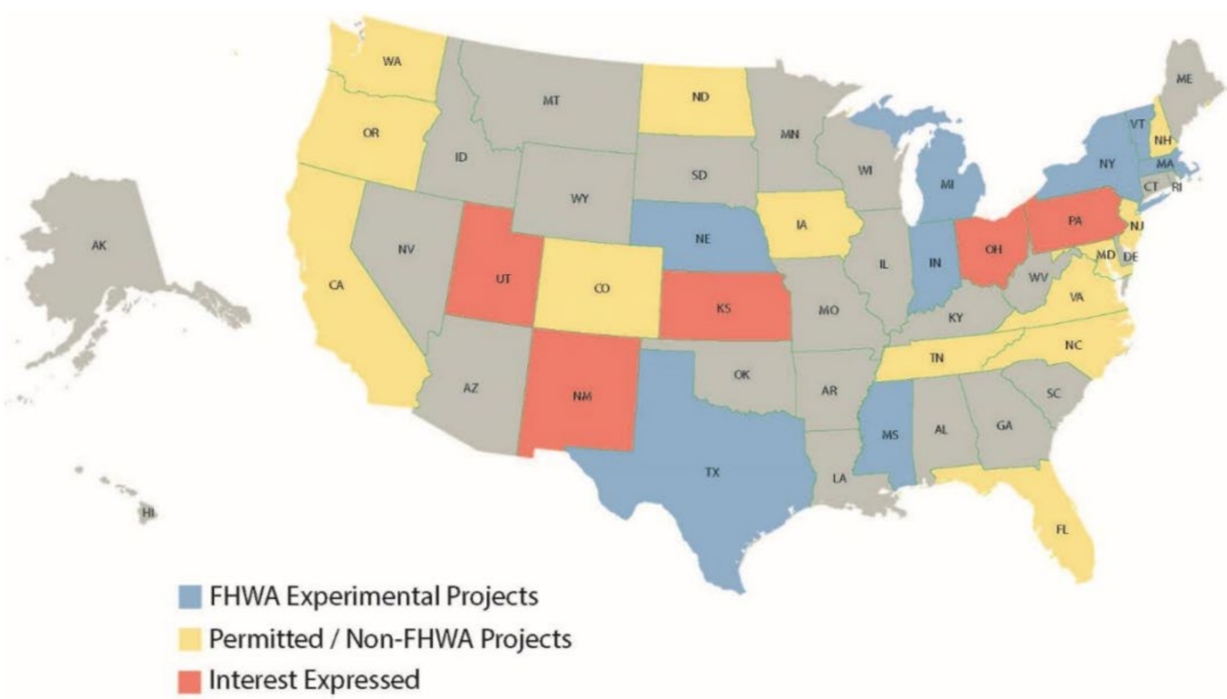


Figure 6.1 DAD utilization in the U.S. as of late 2021 (Gates and Savolainen, 2022)

It may be seen from Figure 6.1 that there is a fair amount of utilization and interest for DAD systems in the U.S. FHWA experimental projects have been utilized in only a few states including Nebraska, New York, Massachusetts, Michigan, Mississippi, and Texas. It is important to note that the original implementation of DADs on a large scale was in New York during the reconstruction in Long Island after Hurricane Sandy (Heydt, 2012). As of 2021, the Federal Highway Administration (FHWA) allowed eight states to experiment with DADs, thirteen states approved DADs for specific projects, and five states expressed interest (Gates and Savolainen, 2022). As there is no specific guidance on DADs in MUTCD, there have been several different DAD configurations and displays. Figure 6.2 shows an illustration depicting different DAD display variations in the U.S.

Iowa & Massachusetts

Michigan

North Carolina

Vermont

Virginia

Figure 6.2 DAD displays variations in the U.S.

The variation of DAD displays in the U.S. are probably because of the lack of DAD guidelines in the MUTCD. However, several experimental designs have been conducted over the past decade to evaluate motorists' comprehension of various display formats and arrangements to ensure safe driving within work zones. For example, Finley et al. (2014) developed a motorist survey to evaluate two devices with or without a NO TURN ON RED sign (shown in Figure 6.3.a) to ascertain the need for including the sign in combination with the electronic display arrows during the stop phase to control turn movements. A total of 320 drivers who were 18 years and older and not color blind participated in the survey. It was found that the addition of the NO TURN ON RED sign in the stop phase at the access point increased the percentage of drivers that would remain stopped. In other words, there was an improved understanding with the inclusion of the NO TURN ON RED sign.

MDOT conducted pilot studies (from 2015 to 2018) with five DAD systems (shown in Figure 6.3.b) that classified DAD turning movement data as ‘proper’ or ‘improper’, and ‘safe’ or ‘unsafe’ (MDOT, 2018). They reported that 82.8% of drivers made proper turns, while 15.7% proceeded improperly but with safe movements. This constituted in 98.5% safe movements. A recent study by the Smart Work Zone Deployment Initiative (SWZDI) found that DADs led to 93% safe movements (Gates and Savolainen, 2022; Hankin et al. 2023).

(a) Modified Hybrid Device

(b) Hybrid Signal Device

Figure 6.3 DAD display experiment survey setups (Finley et al., 2014; MDOT, 2018)

Understandably, driver compliance is crucial for the effectiveness of the DAD system. Other studies have shown that the design and placement of DAD signage significantly impacts driver behavior (Chen, 2024; Gates et al., 2022). Compliance rates increase when drivers clearly understand the instructions and can easily see the signs. Gates et al. (2022) found that the addition of signs increased the percentage of drivers who remained stopped during the red phase (Gates et al., 2022). For instance, the inclusion of a NO TURN ON RED sign (similar to Finley et al., 2014) during the stop phase at access points has been shown to improve compliance. The study involved evaluating various signage configurations to determine the most effective methods for guiding drivers. The results indicated that clear and unambiguous signage is essential for achieving high compliance rates in a one-lane two-way work zone.

Other studies have reinforced the importance of clear signage and effective communication with drivers. For example, research conducted by the Ohio Department of Transportation (ODOT) during 2022 to 2023 consisted of a field and microsimulation analysis to quantify the safety benefits of DADs in the signalized work zone (Camcho, 2024; MacAvoy et al., 2023). The overall results indicate that the DADs provided higher levels of driver compliance, reducing the potential for crashes throughout work zones. The roadway users understood the operation of the DADs and the benefit-to-cost ratio supports the utilization of the DADs over the temporary traffic signal devices. The findings emphasize the importance of carefully designed and placed signs in effectively guiding drivers to improve driver understanding and compliance and reduce the risk of accidents.

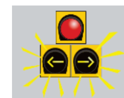
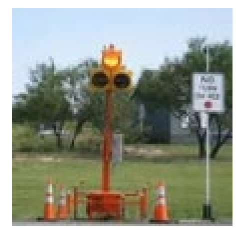
Since the introduction of the DAD systems in 2009, there has not been a standardized configuration for the DAD signation configuration. Therefore, different types of DAD signage have been tested to determine their effectiveness (Chen, 2024; Finley, 2016; Finley et al., 2014; Gates et al., 2022). Notably, the primary types include:

1. Blank-Out Signs: These signs display a steady red indication to stop traffic and flashing yellow arrows to permit turns. They are relatively expensive but effective in clear communication.
2. Hybrid Signs: These combine steady red indications with flashing yellow arrows, providing clear instructions during different phases. However, the non-standard order of signals can sometimes confuse drivers.

3. Doghouse or Modified Hybrid Signs: These emphasize yellow arrows placed under the red indication, providing a clearer visual cue for drivers. Like the hybrid signs, they need to be standardized to avoid confusion.

Table 6.1 lists some descriptions of these typical DAD types and functionalities.

Table 6.1 Description of typical DAD systems

Description	**Blank-Out Sign**	**Hybrid**	**Doghouse or Modified Hybrid**
Equipment	• Circular red indication (12 inches) • Two blank-out signs (rectangular)	• Steady circular red indication (12 inches) • Standard flashing yellow arrows (8 inches)	• Steady circular red indication (12 inches) • Standard flashing yellow arrows (12 inches)
Setup	 		 
Operation	• A steady red indication is shown in the 'STOP' phase with both directional prohibited signs illuminated. • At the 'YIELD' phase the red indication flashes and the permitted turn (either left or right) arrow is indicated. • The signal is synchronized with the main road flaggers/TTCS.	• A steady red indication is shown in the 'STOP' phase for drivers to remain stopped. • At the 'YIELD' phase the yellow arrow flashes to indicate the permitted turn (e.g., left/right). • A steady yellow arrow is used to show a change interval between the flashing yellow and the red indicator. • Signal is also synchronized with the main road flaggers/TTCS.	• Same operation as the hybrid. However, the yellow arrows are more emphasized and are placed under the red circular indication. • Signal is also synchronized with the main road flaggers/TTCS.
Limitations or Challenges	• Display technologies are relatively expensive. • The need to coordinate multiple access points to allow for movements in one direction on the main road at a time.	• Signal head order is not standard and may be confuse drivers. • Whether flashing arrow indicates a permissible or protector turn is not clear. • The need to coordinate multiple access points.	• Signal head order is not standard and may confuse drivers. • Whether flashing arrow indicates a permissible or protector turn is not clear. • The need to coordinate multiple access points.

In summary, there are several DAD display alternatives or configurations that are currently being utilized in some U.S. DOTs. The variability in these systems may have contributed to the lack of a unified procedure in the MUTCD. Moreover, existing DAD systems have a few challenges that need to be rectified. Based on the literature review and the simulation study conducted in this research project, several general guidelines should be followed to ensure the safe design of the DAD system. They are:

1. Location and placement of DAD: There should be a natural gap between the DAD locations in reference to the mainline flagger or TTCS positions (i.e., mainline signal) to avoid confusion and ensure smooth traffic flow. DADs should be placed where they are easily visible to drivers approaching access points. They should not be obstructed by construction equipment or other visual barriers.
2. Traffic volumes and length of lane closure: The volumes of the main two-lane roads and access points (i.e., driveways, side roads) need to be considered in the design of the signal timing for both mainline and DAD signals. In addition, the length of closure must be considered in the design of the signal timings. In the case of wide variations in traffic demand, the mainline signal should use the actuated traffic control system to reduce the system's delay.

   A left and/or right packet lane may be required on high volume access points to avoid stacking of other turning movements in the access points.
3. Mainline signal design: It would be safer to provide additional lead time to allow gaps in the main road traffic for smooth merging at the DAD locations. Additionally, the increase of all red times by programming signals at a lower speed limit can allow vehicles to join the end of the queue at the DAD locations.

4. Synchronization of DAD with mainline signals: The DAD systems should be programmed to be synchronized with the mainline traffic heads and allowed to release traffic ahead of the mainline queue in the same travel direction (MDOT, 2018). The synchronization ensures that access point vehicles can safely enter the main road without conflicting with oncoming traffic.

   There will be the need to optimize these variables based on site characteristics. For example, adjusting signal timing after the initial DAD installation or changes in work zone layout should be a priority.

5. Functional capabilities of DAD signals: In current practice, DAD does not typically have sensors for detecting traffic enabling actuated signal control. However, several studies (NDOT 2019; MDOT 2018) recommended considering it. MDOT (2018) installed DADs with the capability to adjust variable release time similar to additional green time for the DAD approach so that vehicles can exit the access point after the end of the green mainline phase. This, though, necessitates additional clearance time for traffic to safely exit the work zone area. Therefore, DAD signals with actuated control capacity will aid in efficient and safe work zone operations and reduce driver frustration of waiting in the driveways and side roads.

6. Variations in DAD configurations: As mentioned previously, different states have implemented various DAD configurations due to the lack of standardization in the MUTCD. Michigan's pilot tests with the DAD system showed that drivers made correct turns with the specific configuration used, indicating the need for standardized designs to improve driver understanding and compliance (Hankin et al., 2023).

It should be noted that several low-cost DAD alternatives have been proposed and tested by Finley et al. (Finley et al., 2014; Finley et al., 2015; Finley, 2016; Finley and Theiss, 2017; Finley et al., 2020). These systems need to address challenges such as two-way communication between drivers and mainline controllers and ensuring vehicles have cleared the work zone. Future improvements to DAD systems should focus on standardizing display formats to reduce driver confusion, optimizing signal timings based on site-specific characteristics, and improving the visibility and placement of DADs. There is also a need to incorporate DAD systems into the MUTCD to provide clear guidance for their use in work zones.

Chapter 7 Summary and Conclusions

This study modeled DAD-operated work zone lane closures on two-lane highways on a microsimulation platform using field-observed work zone data. Further, it modeled and evaluated different SC strategies using 192 scenarios and identified the most efficient strategy using statistical comparisons. Using best signal control, sensitivity analyses of different traffic and work zone characteristics, consisting of 3,456 scenarios, were studied to realize the impact of DAD-operated work zones. Furthermore, this study has reviewed research related to the signal head designs, placement, and driver compliance of the DAD system. Important safety and operational trends and practices found from the sensitivity analyses are as follows:

1. The SC study showed that work zone systems work best when they are equipped with actuated control for the mainline with the capability of green extension settings for the DAD signal and the Main and DAD approaches share the same phase for each direction of travel (i.e., two phases). The use of exclusive phases for the DAD signal or traditional portable signal for the access point traffic was found to not be feasible in the simulation study, similar to the finding from another study (McAvoy et al., 2023).
2. In general, DADs do not have sensors for detecting traffic enabling actuated signal controls. However, several studies (NDOT 2019; MDOT 2018) recommended considering it. MDOT (2018) installed a DAD with the capability to adjust variable release times similar to additional green time for the DAD approach so that vehicles can exit the access point after the end of the main line green. This, though, necessitates additional clearance time for traffic to safely exit the work zone area. Therefore, DAD signals with actuated control capacity will

aid in efficient and safe work zone operations and reduce driver frustration waiting in the driveways and side roads.

3. The main approach is more susceptible to producing substantial delays due to the DAD traffic. The increase in volumes on the DAD approach also caused delays but with a lesser magnitude compared to the increase in volumes of the Main approach. Traffic volume increase for both the Main and DAD approaches produced a higher SD of delay, making the work zone operation less reliable.
4. Longer work zone lengths caused higher average delays and a higher SD of average delay for the Main approach compared to the DAD approach. However, the rate of increase of these two metrics for the DAD approach was higher than the Main approach for the subsequent increase of WZLs. Work zones may experience higher delays even with a lower traffic volume if the work zone is longer.
5. Similar to delays, queue length was substantially impacted by traffic volumes for both approaches. It is important to monitor how far back the queue extends to check if it causes blockages of facilities (e.g., minor roads, buildings at driveways) upstream from the traffic releasing point. Therefore, traffic agencies, for given scenarios, may prioritize minimizing the maximum allowable queue length over the delay experienced.
6. In general, as the number of DADs increases, work zones suffer bigger delays and longer queues. However, if the total traffic demand from all access points is equal for two sites/segments, this study revealed that the site/segment with the higher number of access points/DADs may produce less delays.

7. There should be a natural gap between the DAD locations in reference to the mainline flagger or TTCS positions (i.e., mainline signal) to avoid confusion and ensure smooth traffic flow. DADs should be placed where they are easily visible to drivers approaching access points. They should not be obstructed by construction equipment or other visual barriers.

   A left and/or right packet lane may be required on high volume access points to avoid stacking of other turning movements in the access points.
8. Different states have implemented various DAD configurations due to the lack of standardization in the MUTCD. Therefore, there is a need for standardized designs to improve driver understanding and compliance.

Apart from the general trends and mechanism of the work zone impacts listed above, practitioners may estimate potential quantitative impacts on work zones for different volumes from the figures provided in this report. In general, if an average delay of 160 sec/veh or 750 feet (around 25 vehicles) of average maximum queue length for the Main approach and average delay of 80 sec/veh (LOS E for regular signalized intersection) or 150 feet (around 5 vehicles) of average queue length for DAD approach are set as thresholds, then the maximum allowable traffic volumes should be less than 150 vph (i.e., 300 vph for both directions) for the Main approach and less than 50 vph for each DAD approach while the work zone is less than a mile. Note that this is a generalized guideline from the study conducted herein. Practitioners may replicate the methodology presented in this report to find accurate estimations of a scenario they are interested in.

While lane closure alone (without access points) on a two-lane highway negatively impacts traffic operational performance, adding DADs to assist the traffic movements of access points may make the overall management of work zones and efficient operation of the traffic in a shared, single open lane more challenging. Therefore, the operational impacts of DAD-operated work zones should be carefully studied to ensure efficient usage of the DAD systems. While most DAD research focused on safety-related issues, its operational impacts have not received adequate attention. The authors hope that this report fills the research gap by conducting the first in-depth investigation of the operations of the DAD-equipped access points in work zone lane closures on two-lane highways.

This study resulted in a DAD-operated work zone model for prospective users and provides a detailed simulation methodology. This will enable transportation agencies to identify operational impacts on traffic metrics considering various aspects without having to run the DAD-operated work zone in real-world scenarios. This research provides guidelines for transportation agencies or work zone contractors when making decisions on work zone parameters (e.g., work zone length) during rehabilitation or construction projects. By investigating potential work zone characteristics such as traffic demand and its fluctuation during the day for both approaches and the number of access points, transportation agencies may use this model to determine the number of DADs required (i.e., access points to be considered within the work zone) and choosing appropriate signal control techniques to plan for efficient work zone operations. Furthermore, they can make reasonable economic assessments of work zone impacts (e.g., user costs, agency costs, environmental costs).

This project aimed to conduct a field study of DADs. However, as the approval could not be achieved to test such a system, this project reviewed the existing field study related research of DADs and listed the important findings. Nonetheless, this project has conducted a comprehensive microsimulation-based study of DAD-operated work zones using Nebraska field data from the regular one-lane two-way work zone. The work zone data used from Nebraska represents U.S. Midwest characteristics. However, the research methods and tools used in this report can be used for other locations across the U.S. Scenarios other than those covered here should be investigated to further analyze the operational impacts of the DAD work zone. Future studies should cover more data from access points under the DAD system when such experiments are permitted by FHWA.

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Appendix A Performance Analysis of Different Signal Control Strategies (N_{DAD}=1)

A.1 Average Delay Analysis

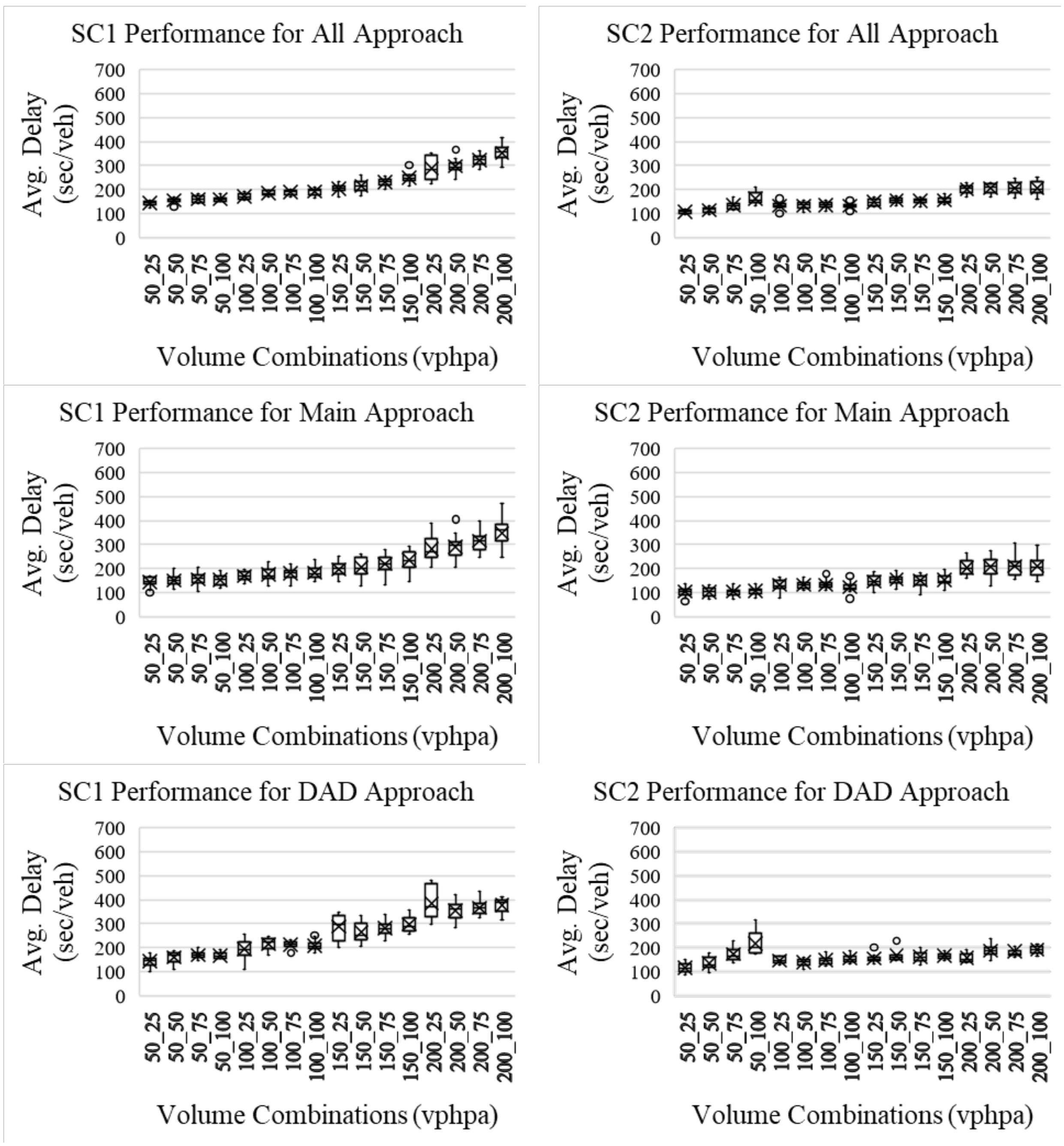

Figure A.1 Average delay for All, Main and DAD approach under SC1 and SC2 for DAD approach volume increase for various levels of constant Main approach volume (WZL=1.1 mile, N_{DAD}=1, $T_{M\%}$=20, $T_{DAD\%}$=5)

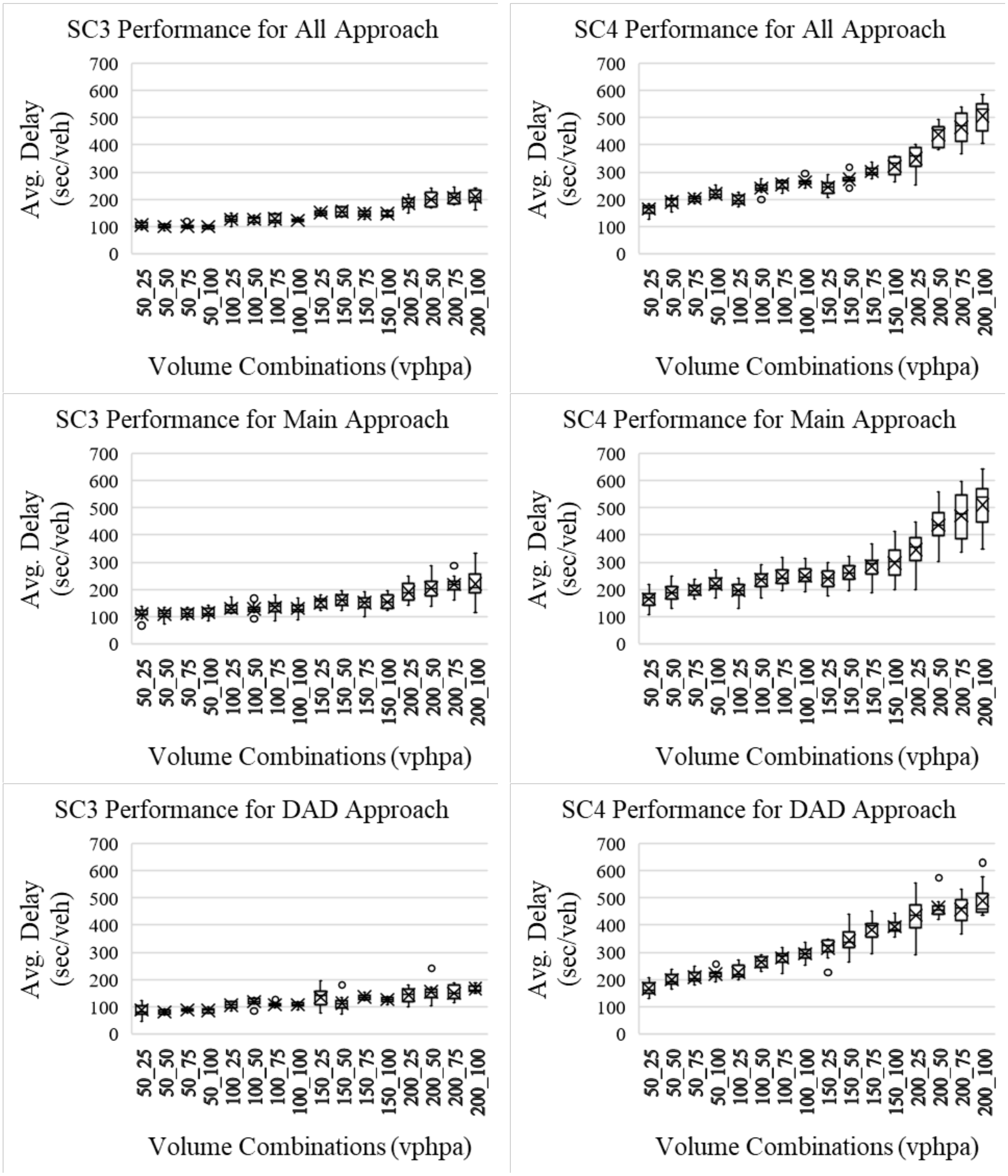

Figure A.2 Average delay for All, Main and DAD approach under SC3 and SC4 for DAD approach volume increase for various levels of constant Main approach volume (WZL=1.1 mile, N_{DAD}=1, $T_{M\%}$=20, $T_{DAD\%}$=5)

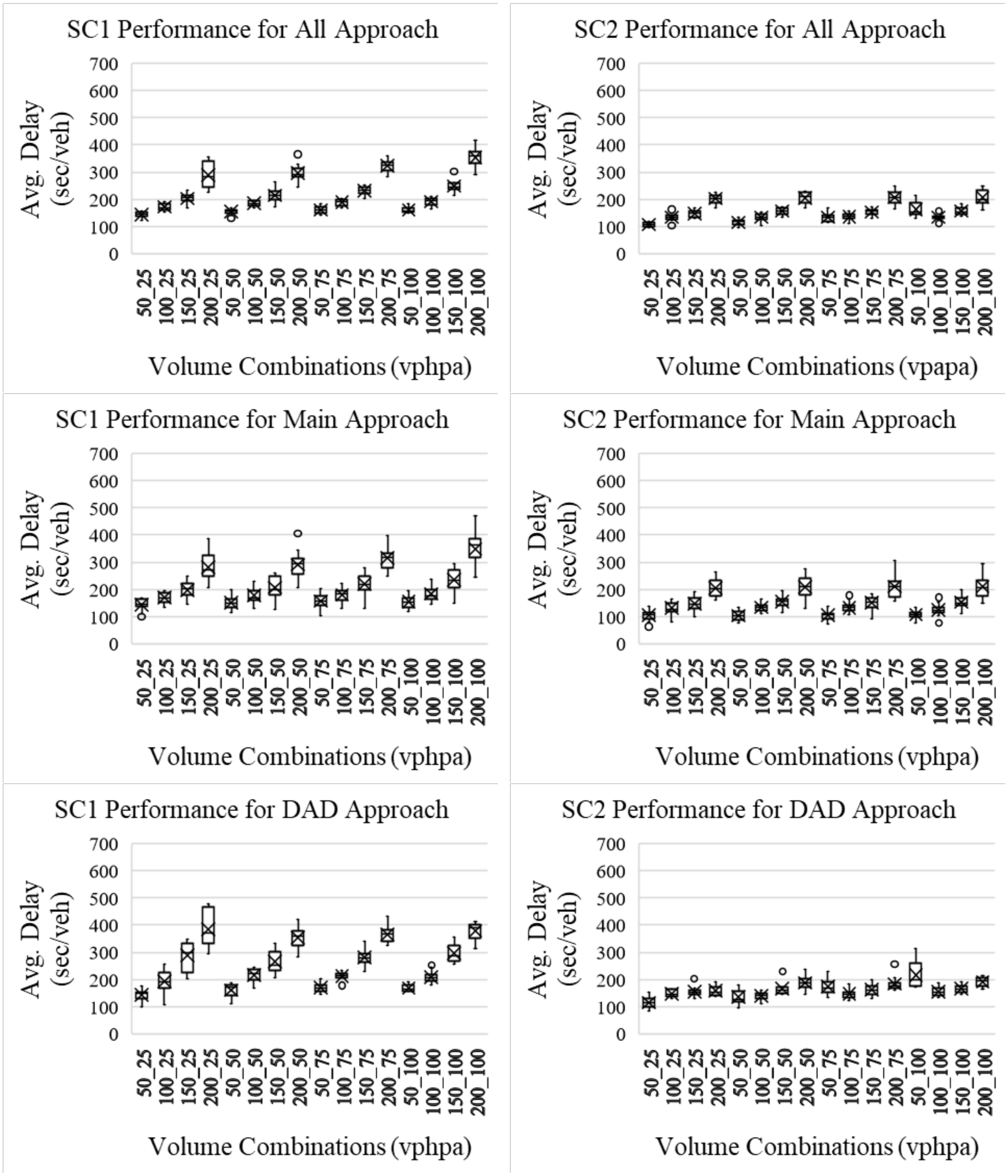

Figure A.3 Average delay for All, Main and DAD approach under SC1 and SC2 for Main approach volume increase for various levels of constant DAD approach volume (WZL=1.1 mile, N_{DAD}=1, $T_{M\%}$=20, $T_{DAD\%}$=5)

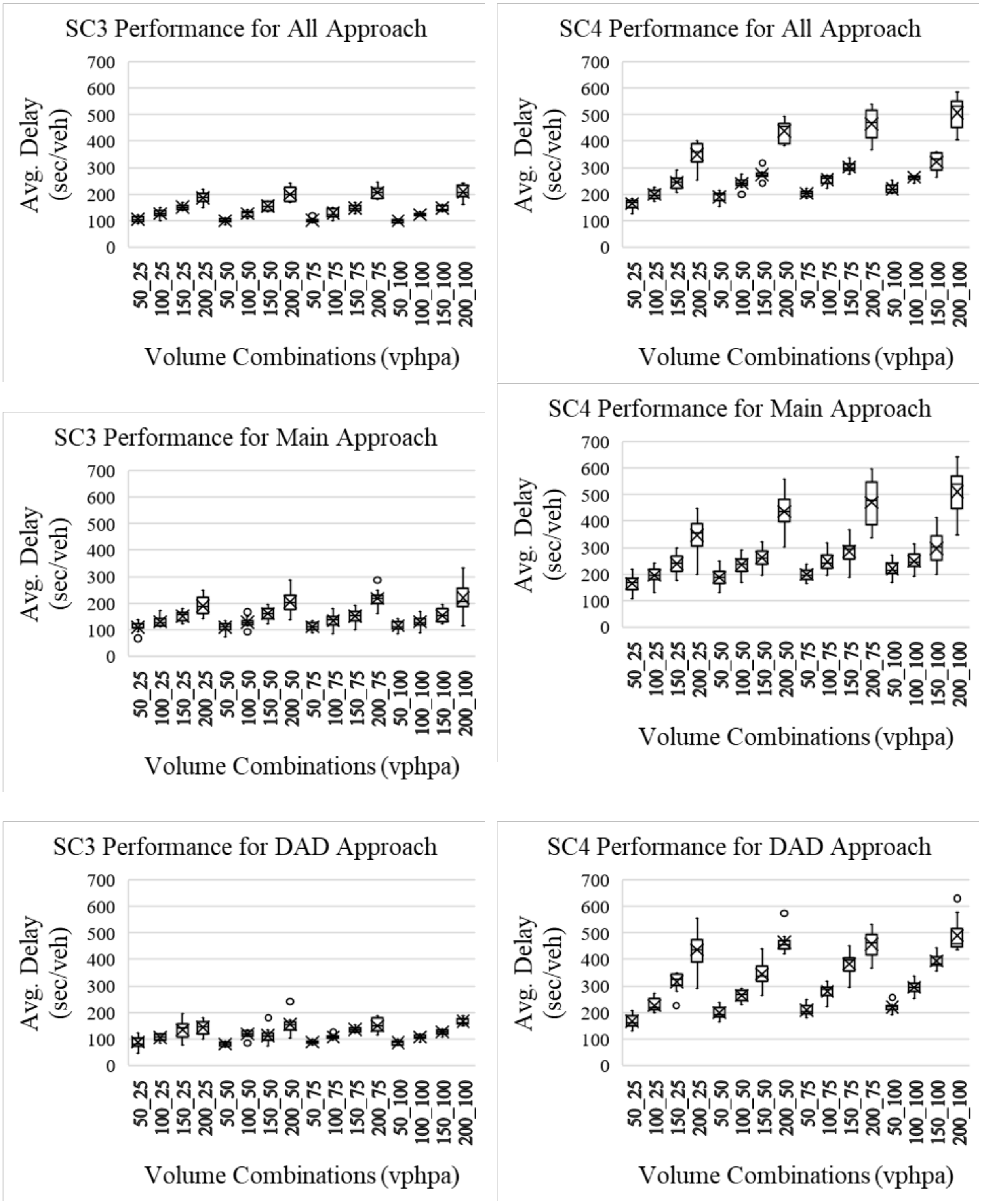

Figure A.4 Average delay for All, Main and DAD approach under SC3 and SC4 for Main approach volume increase for various levels of constant DAD approach volume (WZL=1.1 mile, N_{DAD}=1, $T_{M\%}$=20, $T_{DAD\%}$=5)

A.2 Average Maximum Queue Analysis

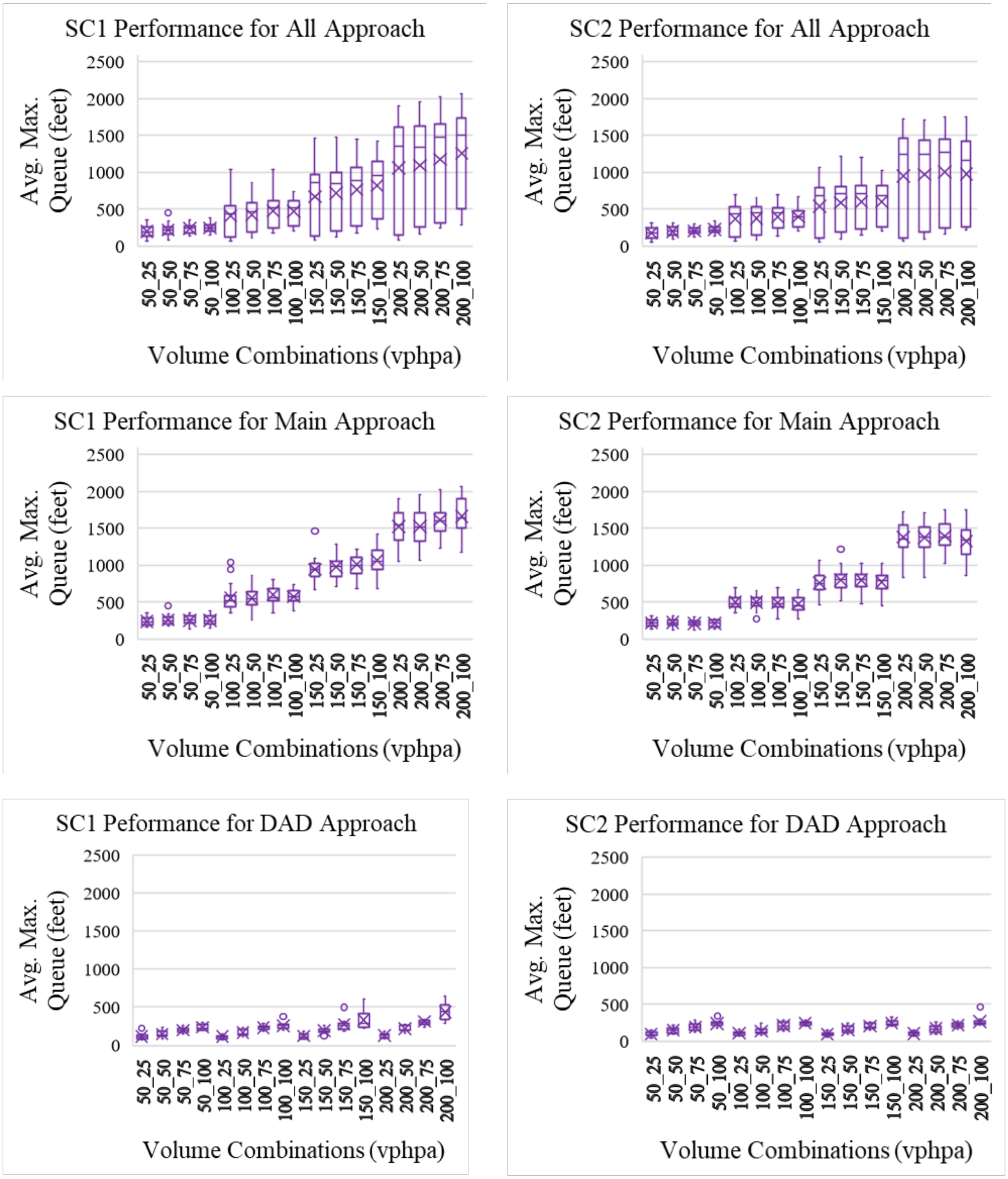

Figure A.5 Average maximum queue for All, Main and DAD approach under SC1 and SC2 for DAD approach volume increase for various levels of constant Main approach volume (WZL=1.1 mile, N_{DAD}=1, $T_{M\%}$=20, $T_{DAD\%}$=5)

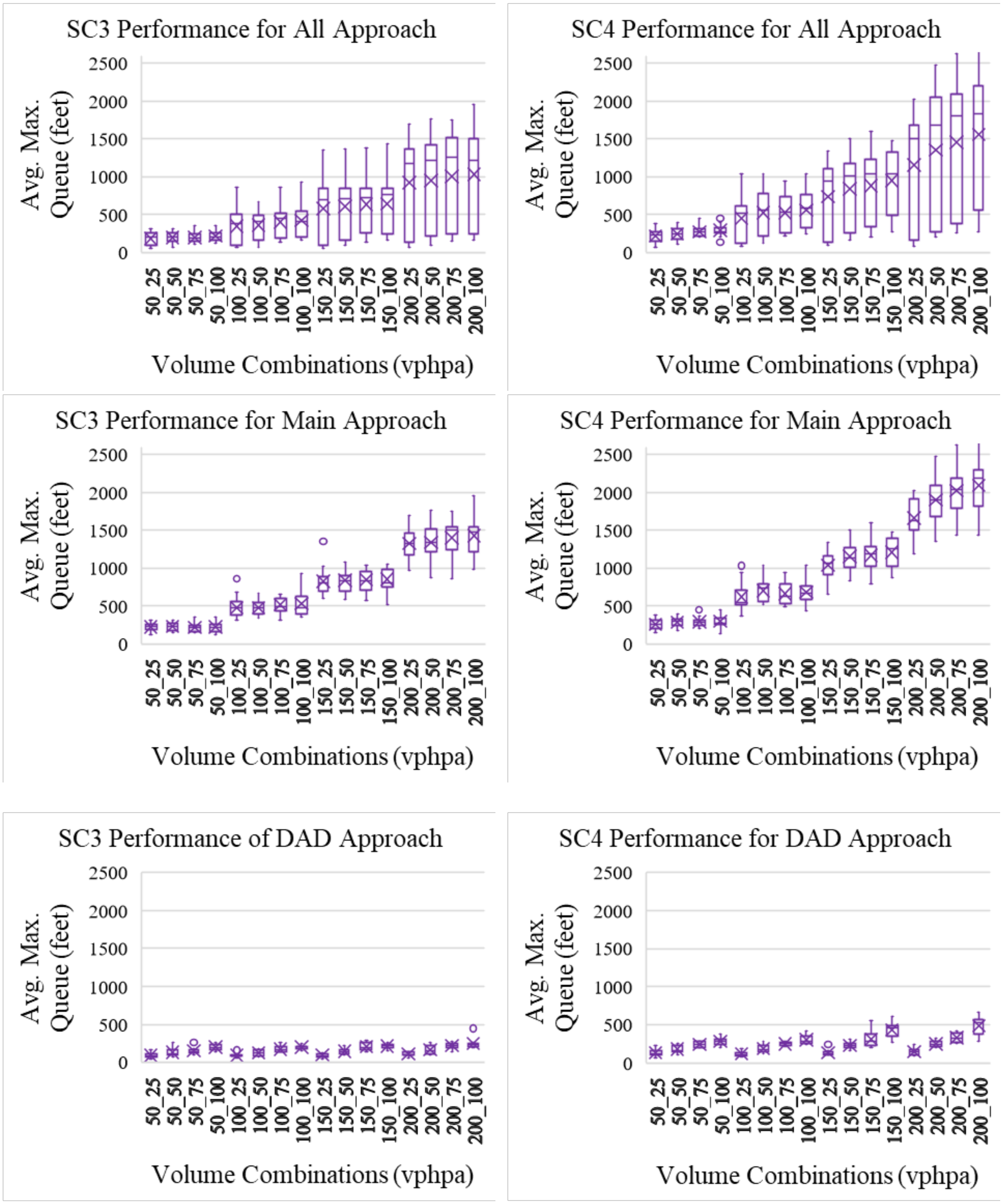

Figure A.6 Average maximum queue for All, Main and DAD approach under SC3 and SC4 for DAD approach volume increase for various levels of constant Main approach volume (WZL=1.1 mile, N_{DAD}=1, $T_{M\%}$=20, $T_{DAD\%}$=5)

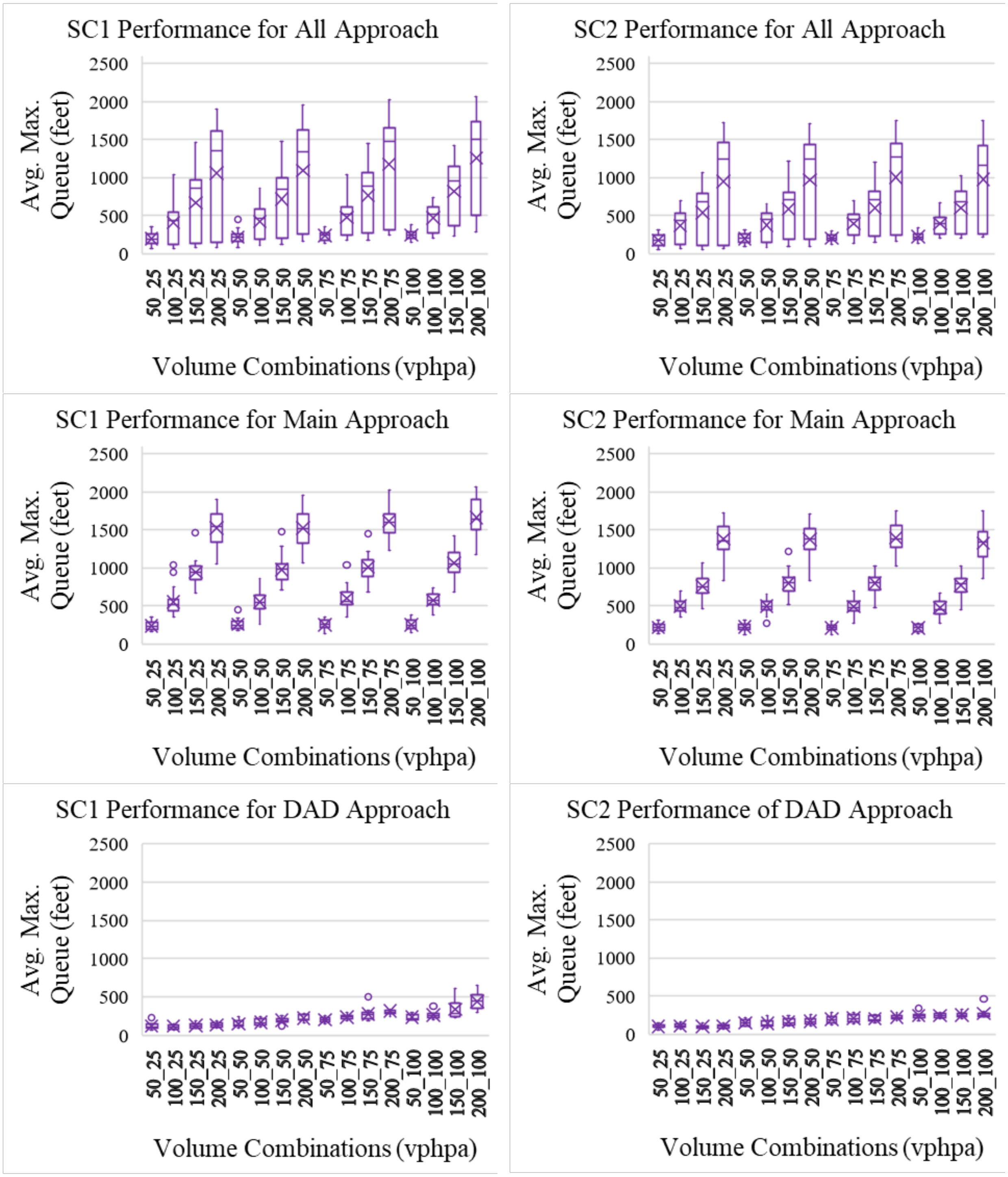

Figure A.7 Average maximum queue for All, Main and DAD approach under SC1 and SC2 for Main approach volume increase for various levels of constant DAD approach volume (WZL=1.1 mile, N_{DAD}=1, $T_{M\%}$=20, $T_{DAD\%}$=5)

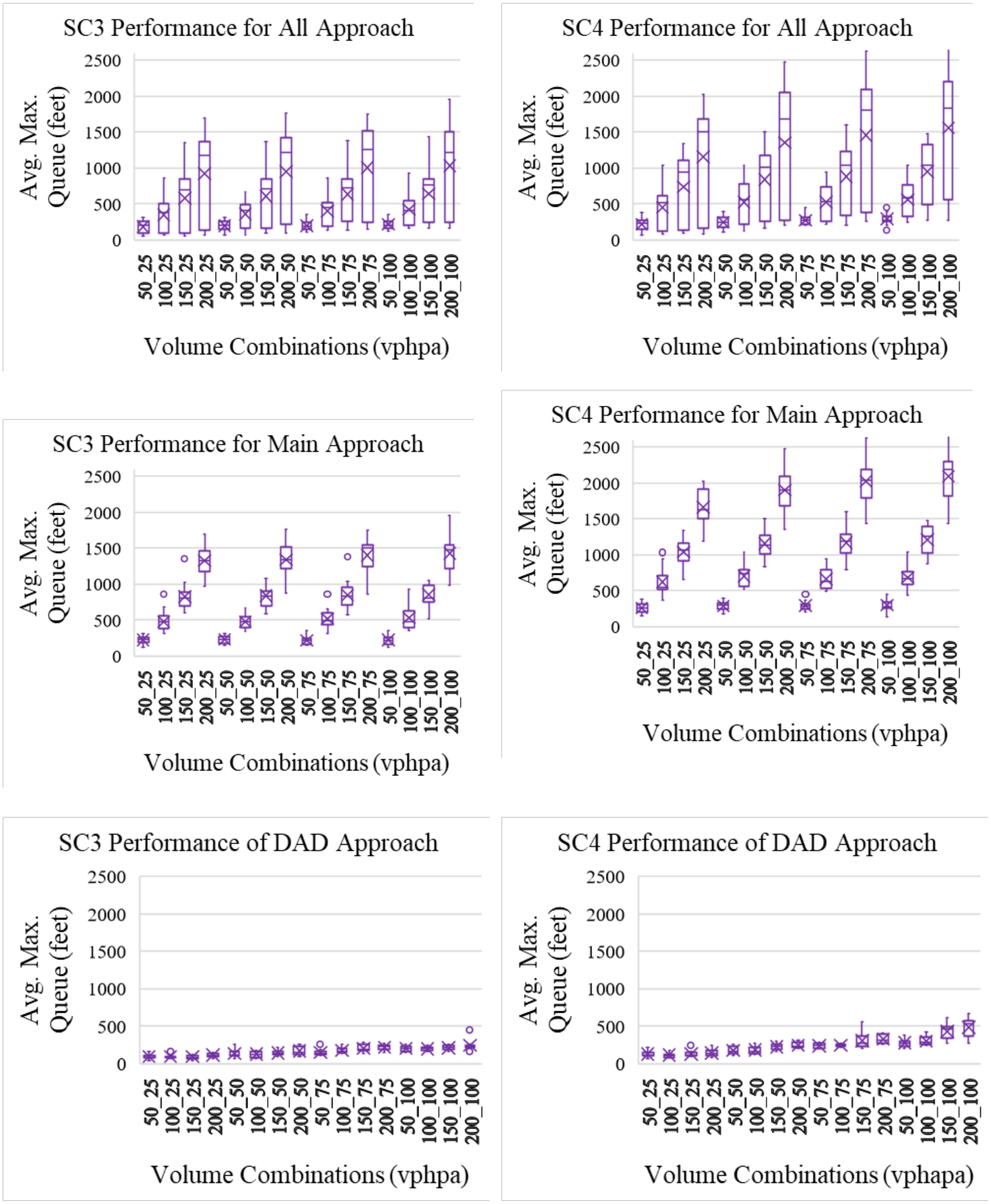

Figure A.8 Average maximum queue for All, Main and DAD approach under SC3 and SC4 for Main approach volume increase for various levels of constant DAD approach volume (WZL=1.1 mile, N_{DAD}=1, $T_{M\%}$=20, $T_{DAD\%}$=5

A.3 Average Delay Reduction Comparisons

Table A.1 Performance analysis of SC2 and SC3 compared to SC1 in terms of average delay reduction (WZL=1.1 mile, N_{DAD}=1, $T_{M\%}$=20, $T_{DAD\%}$=5)

	SC2 and SC3 performance compared to SC1 in terms of avg. delay reduction in % (negative value means delay reduction)					
Volm	**Major**		**DAD**		**All**	
Comb	SC2	SC3	SC2	SC3	SC2	SC3
50_25	-26.8	-23.6	-19.2	-63.8	-26.0	-27.2
50_50	-32.0	-28.1	-16.1	-99.6	-25.7	-35.7
50_75	-33.4	-29.3	2.2	-93.4	-16.4	-37.7
50_100	-30.1	-26.0	29.2	-94.9	1.4	-38.0
100_25	-22.2	-23.9	-24.1	-84.0	-22.5	-26.2
100_50	-25.0	-27.4	-35.6	-83.7	-27.6	-31.6
100_75	-26.6	-25.4	-30.8	-99.0	-28.1	-32.7
100_100	-32.5	-29.3	-26.1	-95.4	-30.3	-36.6
150_25	-25.4	-23.1	-46.2	-115.4	-27.4	-26.0
150_50	-25.2	-21.8	-37.6	-135.7	-27.3	-27.9
150_75	-31.5	-31.4	-42.5	-108.1	-33.9	-36.2
150_100	-35.0	-34.6	-44.1	-136.4	-37.3	-41.2
200_25	-27.4	-32.8	-58.8	-168.2	-30.1	-35.5
200_50	-28.5	-29.3	-46.9	-128.9	-30.8	-33.0
200_75	-33.2	-31.1	-49.6	-144.4	-35.9	-36.0
200_100	-39.9	-36.9	-49.2	-127.8	-43.1	-43.7

Table A.2 Performance analysis of SC2 and SC3 compared to SC4 in terms of average delay reduction (WZL=1.1 mile, N_{DAD}=1, $T_{M\%}$=20, $T_{DAD\%}$=5)

	SC2 and SC3 performance compared to SC4 in terms of avg. delay reduction in % (negative value means delay reduction)					
Volm	**Major**		**DAD**		**All**	
Comb	SC2	SC3	SC2	SC3	SC2	SC3
50_25	-36.0	-33.3	-30.3	-47.3	-34.7	-35.7
50_50	-44.7	-41.6	-32.0	-59.4	-39.7	-47.8
50_75	-47.5	-44.3	-16.9	-57.9	-33.3	-50.3
50_100	-51.1	-48.2	-1.8	-61.0	-26.1	-54.8
100_25	-32.3	-33.7	-35.0	-53.5	-32.8	-36.0
100_50	-43.6	-45.4	-47.3	-55.4	-44.4	-47.5
100_75	-46.3	-45.4	-47.1	-61.6	-46.7	-50.1
100_100	-50.5	-48.2	-47.6	-63.8	-49.4	-54.0
150_25	-38.4	-36.5	-50.8	-57.6	-39.5	-38.3
150_50	-40.9	-38.3	-51.7	-67.2	-43.0	-43.5
150_75	-47.0	-46.9	-57.8	-64.7	-49.4	-51.2
150_100	-48.6	-48.2	-57.8	-68.1	-51.5	-54.5
200_25	-40.9	-45.3	-63.7	-67.2	-42.3	-46.8
200_50	-52.4	-52.9	-59.5	-66.7	-53.1	-54.6
200_75	-55.2	-53.8	-59.7	-67.3	-55.6	-55.6
200_100	-59.0	-57.0	-60.8	-66.1	-59.6	-59.9

Table A.3 Performance analysis of SC2 and SC3 compared to SC1 in terms of standard deviation reduction of average delay (WZL=1.1 mile, N_{DAD}=1, $T_{M\%}$=20, $T_{DAD\%}$=5)

	SC2 and SC3 performance compared to SC1 in terms of SD (avg. delay) reduction in % (negative value means delay reduction)					
Volm Comb	**Major**		**DAD**		**All**	
	SC2	SC3	SC2	SC3	SC2	SC3
50_25	-79.7	-78.7	-74.2	-230.2	-63.4	-60.4
50_50	-80.4	-79.8	-70.7	-164.3	-73.2	-68.8
50_75	-81.9	-79.9	-74.8	-355.8	-79.8	-75.4
50_100	-81.7	-74.6	-81.0	-518.9	-81.0	-76.8
100_25	-84.0	-75.2	-75.6	-321.9	-50.8	-47.0
100_50	-82.9	-84.2	-71.7	-299.8	-54.8	-56.4
100_75	-83.2	-79.6	-76.6	-501.2	-66.2	-59.8
100_100	-81.6	-71.7	-88.9	-931.4	-69.8	-55.6
150_25	-85.7	-81.6	-79.3	-149.9	-49.7	-43.8
150_50	-84.6	-81.7	-75.6	-419.4	-53.6	-49.0
150_75	-85.0	-81.9	-86.1	-449.8	-59.1	-55.5
150_100	-87.9	-81.7	-88.1	-903.8	-66.7	-57.7
200_25	-86.1	-86.3	-79.2	-368.7	-40.0	-42.7
200_50	-86.3	-85.4	-77.2	-288.9	-44.6	-45.8
200_75	-87.6	-85.6	-88.8	-696.5	-50.2	-49.3
200_100	-85.6	-84.6	-83.6	-484.4	-56.5	-51.9

Table A.4 Performance analysis of SC2 and SC3 compared to SC4 in terms of standard deviation reduction of average delay (WZL=1.1 mile, N_{DAD}=1, $T_{M\%}$=20, $T_{DAD\%}$=5)

	SC2 and SC3 performance compared to SC4 in terms of SD (avg. delay) reduction in % (negative value means delay reduction)					
Volm Comb	**Major**		**DAD**		**All**	
	SC2	SC3	SC2	SC3	SC2	SC3
50_25	-14.6	-10.5	-34.9	-23.5	-12.2	-5.1
50_50	-20.2	-17.9	-13.8	11.1	-24.4	-12.0
50_75	-22.3	-13.9	44.6	25.8	-16.8	1.3
50_100	-31.2	-4.3	-12.7	-25.8	-24.3	-7.8
100_25	-46.4	-17.3	-9.3	-11.9	-27.7	-22.0
100_50	-35.6	-40.3	-8.0	-18.8	-31.1	-33.5
100_75	-27.2	-12.1	159.2	84.5	-29.9	-16.6
100_100	-24.7	15.8	-51.9	-58.1	-35.0	-4.3
150_25	-25.2	-3.2	-42.9	10.3	-26.6	-18.0
150_50	-16.5	-1.1	13.5	-10.4	-29.1	-22.1
150_75	-20.2	-3.8	-63.9	-52.9	-29.2	-23.0
150_100	-35.3	-2.6	-61.8	-68.1	-33.8	-15.9
200_25	-6.8	-8.2	-44.9	-43.6	-15.5	-19.2
200_50	-27.8	-23.1	24.8	41.0	-27.2	-28.8
200_75	-31.3	-20.1	-41.1	-34.2	-30.5	-29.2
200_100	-33.2	-28.4	-40.1	-37.5	-33.9	-26.8

A.4 Average Maximum Queue Reduction Comparisons

Table A.5 Performance analysis of SC2 and SC3 compared to SC1 in terms of average maximum queue reduction (WZL=1.1 mile, N_{DAD}=1, $T_{M\%}$=20, $T_{DAD\%}$=5)

	SC2 and SC3 performance compared to SC1 in terms of avg. max. Queue reduction in % (negative value means delay reduction)					
Volm	**Major**		**DAD**		**All**	
Comb	SC2	SC3	SC2	SC3	SC2	SC3
50_25	-8.8	-5.3	-15.3	-20.9	-10.1	-7.6
50_50	-13.9	-11.2	2.9	-6.7	-10.2	-10.1
50_75	-16.0	-13.7	-3.1	-31.7	-12.3	-16.6
50_100	-15.8	-11.4	3.3	-15.9	-9.8	-12.2
100_25	-10.4	-13.8	-6.7	-25.2	-10.1	-14.4
100_50	-9.6	-13.3	-17.0	-31.0	-10.6	-14.7
100_75	-17.9	-13.7	-10.7	-32.2	-16.7	-15.4
100_100	-17.3	-7.1	-6.5	-30.7	-15.3	-10.1
150_25	-19.5	-12.8	-21.5	-25.7	-19.6	-13.2
150_50	-17.9	-13.9	-17.3	-34.5	-17.8	-15.0
150_75	-20.7	-16.5	-26.8	-33.7	-21.4	-17.5
150_100	-27.5	-19.6	-25.3	-56.2	-27.2	-21.8
200_25	-9.5	-12.7	-21.3	-15.0	-10.0	-12.7
200_50	-9.9	-12.2	-24.2	-31.5	-10.9	-13.0
200_75	-13.2	-12.9	-29.7	-43.2	-14.7	-14.5
200_100	-20.1	-14.2	-38.7	-77.9	-22.2	-17.7

Table A.6 Performance analysis of SC2 and SC3 compared to SC4 in terms of average maximum queue reduction (WZL=1.1 mile, N_{DAD}=1, $T_{M\%}$=20, $T_{DAD\%}$=5)

	SC2 and SC3 performance compared to SC4 in terms of avg. max. Queue reduction in % (negative value means delay reduction)					
Volm	**Major**		**DAD**		**All**	
Comb	SC2	SC3	SC2	SC3	SC2	SC3
50_25	-16.4	-13.1	-25.0	-26.8	-18.1	-15.8
50_50	-21.8	-19.4	-15.4	-22.9	-20.3	-20.2
50_75	-26.4	-24.4	-19.2	-36.7	-24.3	-28.0
50_100	-28.2	-24.4	-13.0	-27.3	-23.4	-25.4
100_25	-19.7	-22.7	-5.2	-18.9	-18.5	-22.4
100_50	-29.0	-31.9	-24.9	-31.0	-28.6	-31.8
100_75	-26.3	-22.5	-16.1	-28.9	-24.7	-23.5
100_100	-30.6	-21.9	-19.9	-34.5	-28.6	-24.2
150_25	-26.8	-20.7	-26.8	-25.8	-26.8	-21.0
150_50	-30.5	-27.1	-29.7	-36.8	-30.4	-28.0
150_75	-31.2	-27.5	-34.4	-33.0	-31.5	-28.2
150_100	-36.2	-29.3	-42.1	-50.3	-37.1	-32.5
200_25	-17.1	-20.1	-28.9	-21.5	-17.6	-20.1
200_50	-27.8	-29.6	-31.6	-31.4	-28.0	-29.7
200_75	-30.8	-30.6	-33.0	-33.5	-31.0	-30.8
200_100	-36.4	-31.8	-44.6	-49.2	-37.3	-33.6

Table A.7 Performance analysis of SC2 and SC3 compared to SC1 in terms of standard deviation reduction of average maximum queue (WZL=1.1 mile, N_{DAD}=1, $T_{M\%}$=20, $T_{DAD\%}$=5)

Volm Comb	SC2 and SC3 performance compared to SC1 in terms of SD (avg. max. Queue) reduction in % (negative value means delay reduction)					
	Major		**DAD**		**All**	
	SC2	SC3	SC2	SC3	SC2	SC3
50_25	-23.0	-19.2	-34.6	-30.1	-12.7	-5.6
50_50	-22.9	-20.6	-8.5	15.2	-26.6	-14.4
50_75	-27.5	-19.6	28.1	10.3	-22.8	-6.0
50_100	-30.0	-2.6	22.1	3.7	-18.9	-1.2
100_25	-49.9	-22.6	-43.5	-82.2	-21.7	-15.6
100_50	-30.9	-35.9	7.6	-5.3	-11.9	-15.0
100_75	-34.0	-20.2	78.1	21.1	-25.0	-10.8
100_100	10.9	70.7	-42.7	-100.5	-17.8	21.1
150_25	-19.8	3.8	-30.5	25.6	-19.2	-9.7
150_50	-16.4	-0.9	21.8	-4.0	-17.6	-9.6
150_75	-11.1	7.2	-56.6	-76.5	-17.8	-10.6
150_100	-35.4	-2.7	-68.7	-282.2	-30.6	-11.8
200_25	-9.5	-10.9	-20.0	-22.1	-8.5	-12.6
200_50	-17.2	-11.9	19.6	26.0	-8.3	-10.3
200_75	-0.1	16.2	-51.5	-84.4	-8.8	-7.1
200_100	-8.7	-2.0	-36.3	-50.5	-13.0	-3.7

Table A.8 Performance analysis of SC2 and SC3 compared to SC4 in terms of standard deviation reduction of average maximum queue (WZL=1.1 mile, N_{DAD}=1, $T_{M\%}$=20, $T_{DAD\%}$=5)

Volm Comb	SC2 and SC3 performance compared to SC4 in terms of SD (avg. max. Queue) reduction in % (negative value means delay reduction)					
	Major		**DAD**		**All**	
	SC2	SC3	SC2	SC3	SC2	SC3
50_25	-14.6	-10.5	-34.9	-23.5	-12.2	-5.1
50_50	-20.2	-17.9	-13.8	11.1	-24.4	-12.0
50_75	-22.3	-13.9	44.6	25.8	-16.8	1.3
50_100	-31.2	-4.3	-12.7	-25.8	-24.3	-7.8
100_25	-46.4	-17.3	-9.3	-11.9	-27.7	-22.0
100_50	-35.6	-40.3	-8.0	-18.8	-31.1	-33.5
100_75	-27.2	-12.1	159.2	84.5	-29.9	-16.6
100_100	-24.7	15.8	-51.9	-58.1	-35.0	-4.3
150_25	-25.2	-3.2	-42.9	10.3	-26.6	-18.0
150_50	-16.5	-1.1	13.5	-10.4	-29.1	-22.1
150_75	-20.2	-3.8	-63.9	-52.9	-29.2	-23.0
150_100	-35.3	-2.6	-61.8	-68.1	-33.8	-15.9
200_25	-6.8	-8.2	-44.9	-43.6	-15.5	-19.2
200_50	-27.8	-23.1	24.8	41.0	-27.2	-28.8
200_75	-31.3	-20.1	-41.1	-34.2	-30.5	-29.2
200_100	-33.2	-28.4	-40.1	-37.5	-33.9	-26.8

Appendix B Performance Analysis of Different Signal Control Strategies (N_{DAD}=3)

B.1 Average Delay Analysis

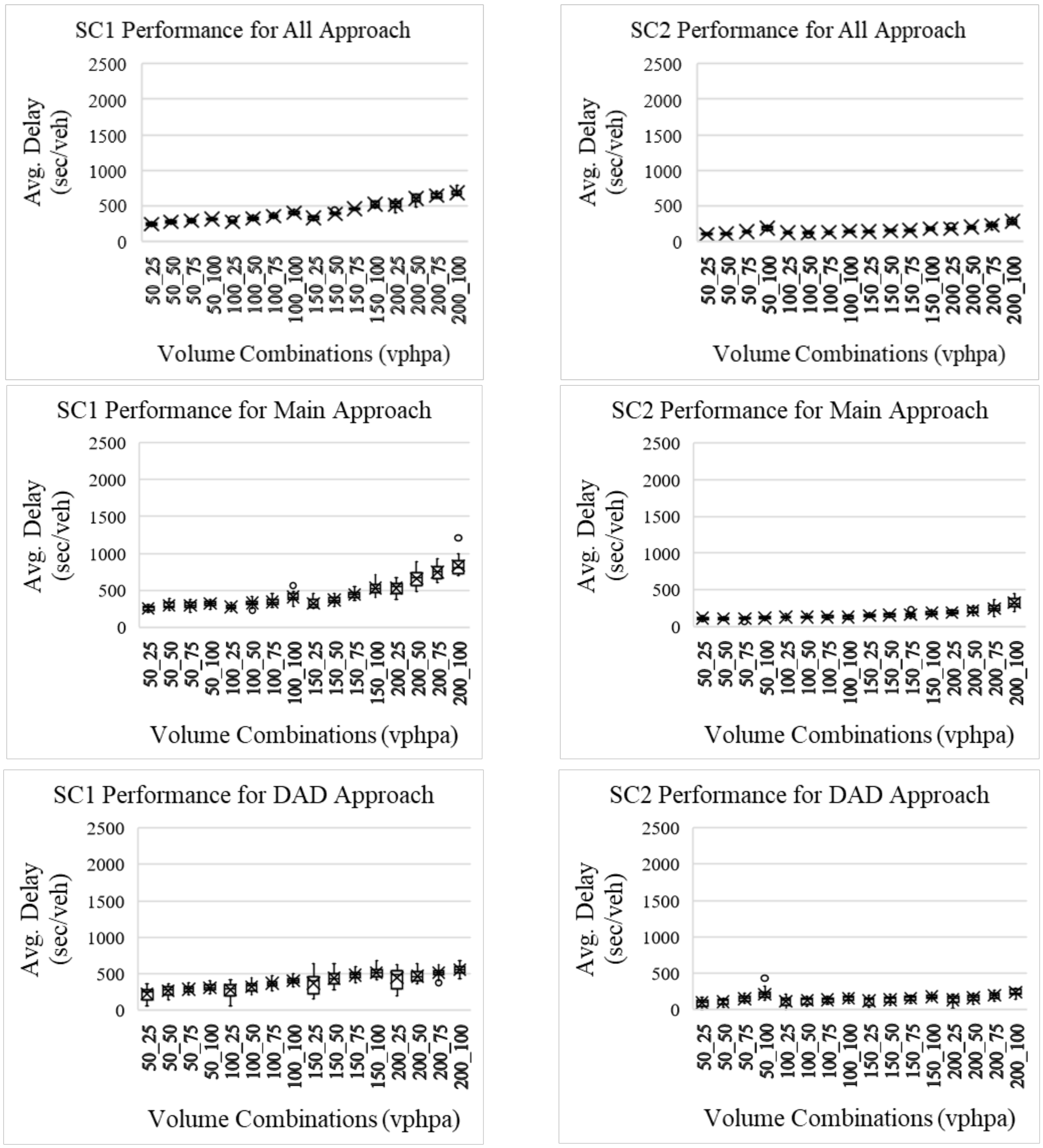

Figure B.1 Average delay for All, Main and DAD approach under SC1 and SC2 for DAD approach volume increase for various levels of constant Main approach volume (WZL=1.1 mile, N_{DAD}=3, $T_{M\%}$=20, $T_{DAD\%}$=5)

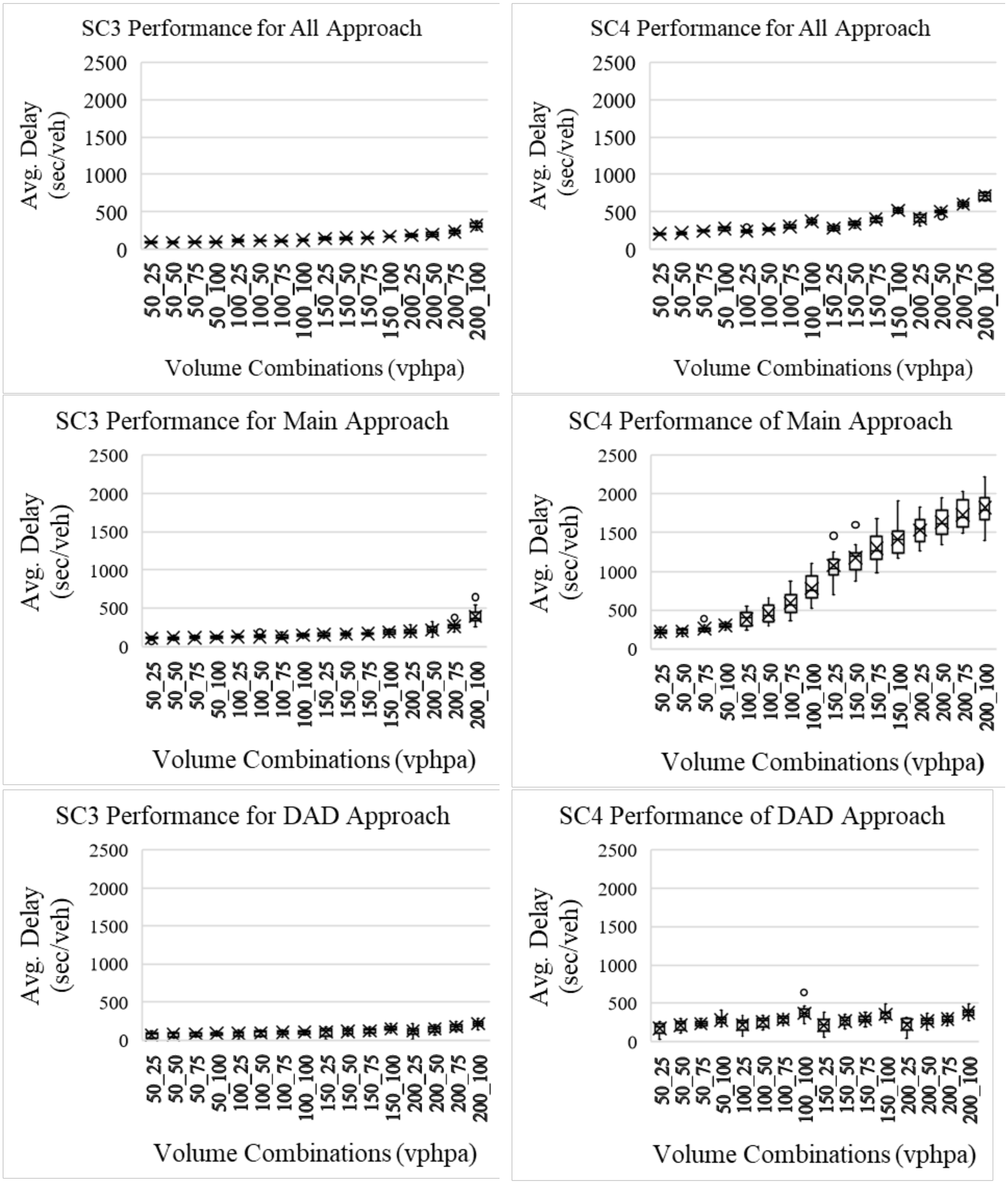

Figure B.2 Average delay for All, Main and DAD approach under SC3 and SC4 for DAD approach volume increase for various levels of constant Main approach volume (WZL=1.1 mile, N_{DAD}=3, $T_{M\%}$=20, $T_{DAD\%}$=5)

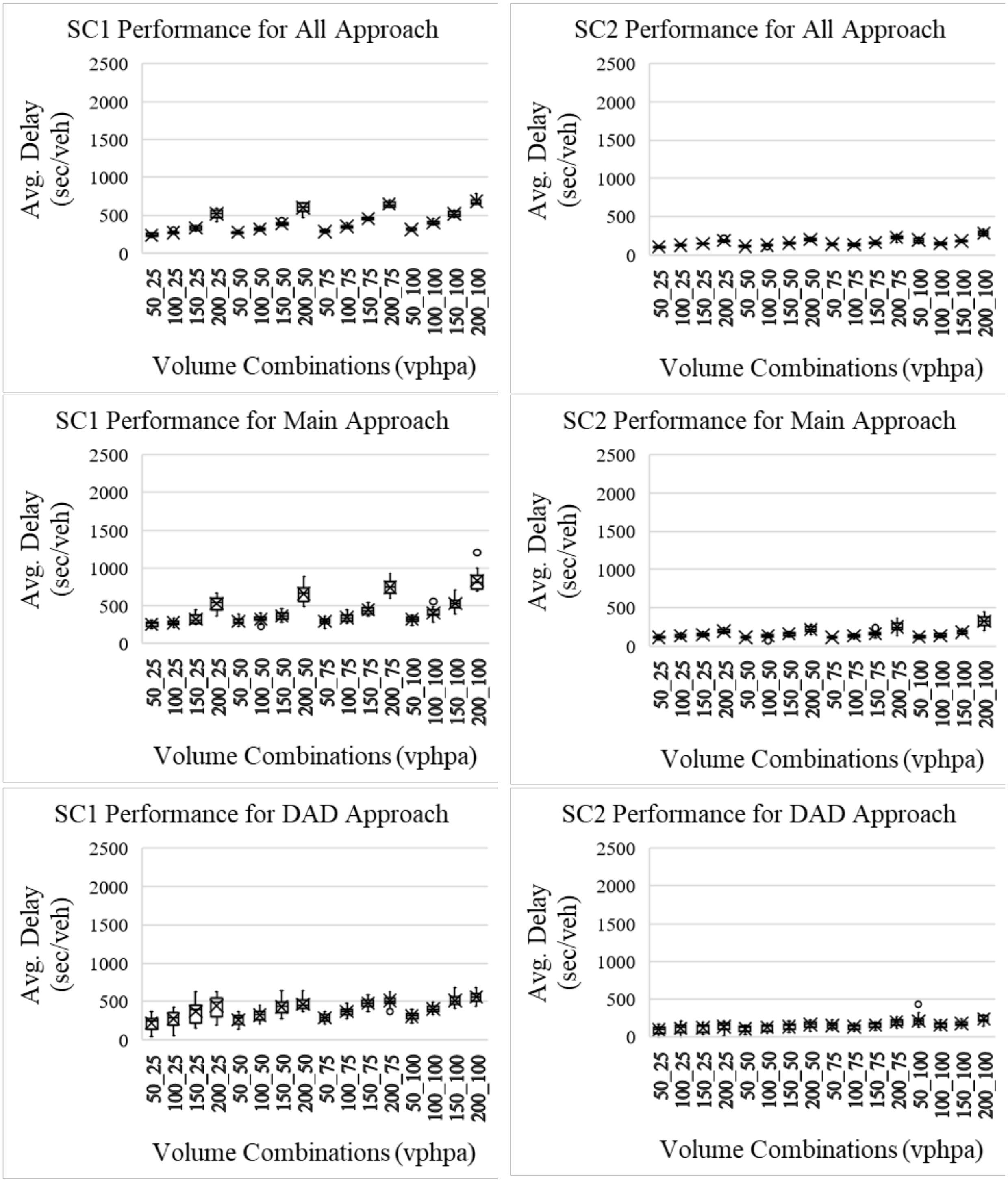

Figure B.3 Average delay for All, Main and DAD approach under SC1 and SC2 for Main approach volume increase for various levels of constant DAD approach volume (WZL=1.1 mile, N_{DAD}=3, $T_{M\%}$=20, $T_{DAD\%}$=5)

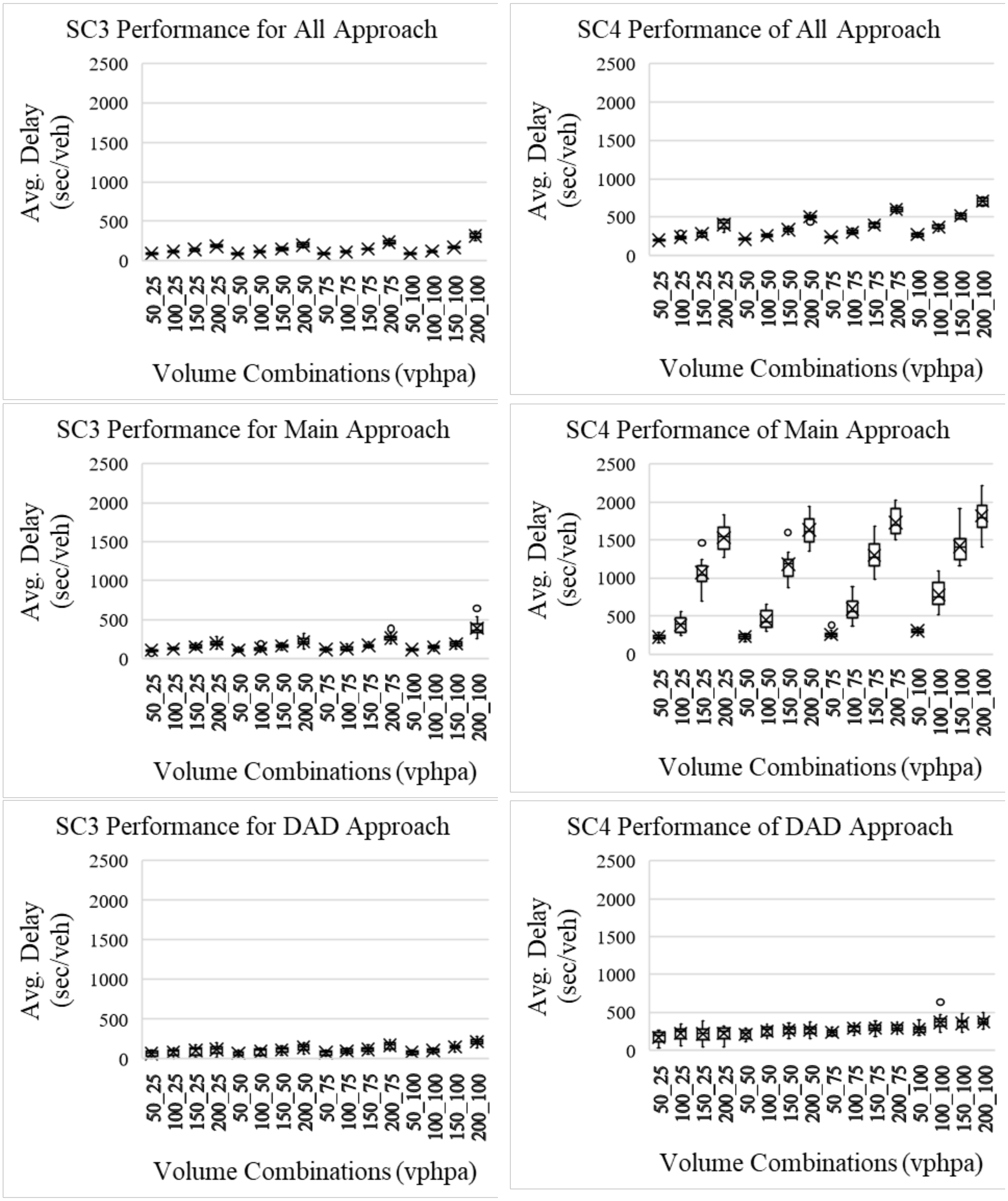

Figure B.4 Average delay for All, Main and DAD approach under SC3 and SC4 for Main approach volume increase for various levels of constant DAD approach volume (WZL=1.1 mile, N_{DAD}=3, $T_{M\%}$=20, $T_{DAD\%}$=5)

B.2 Average Maximum Queue Analysis

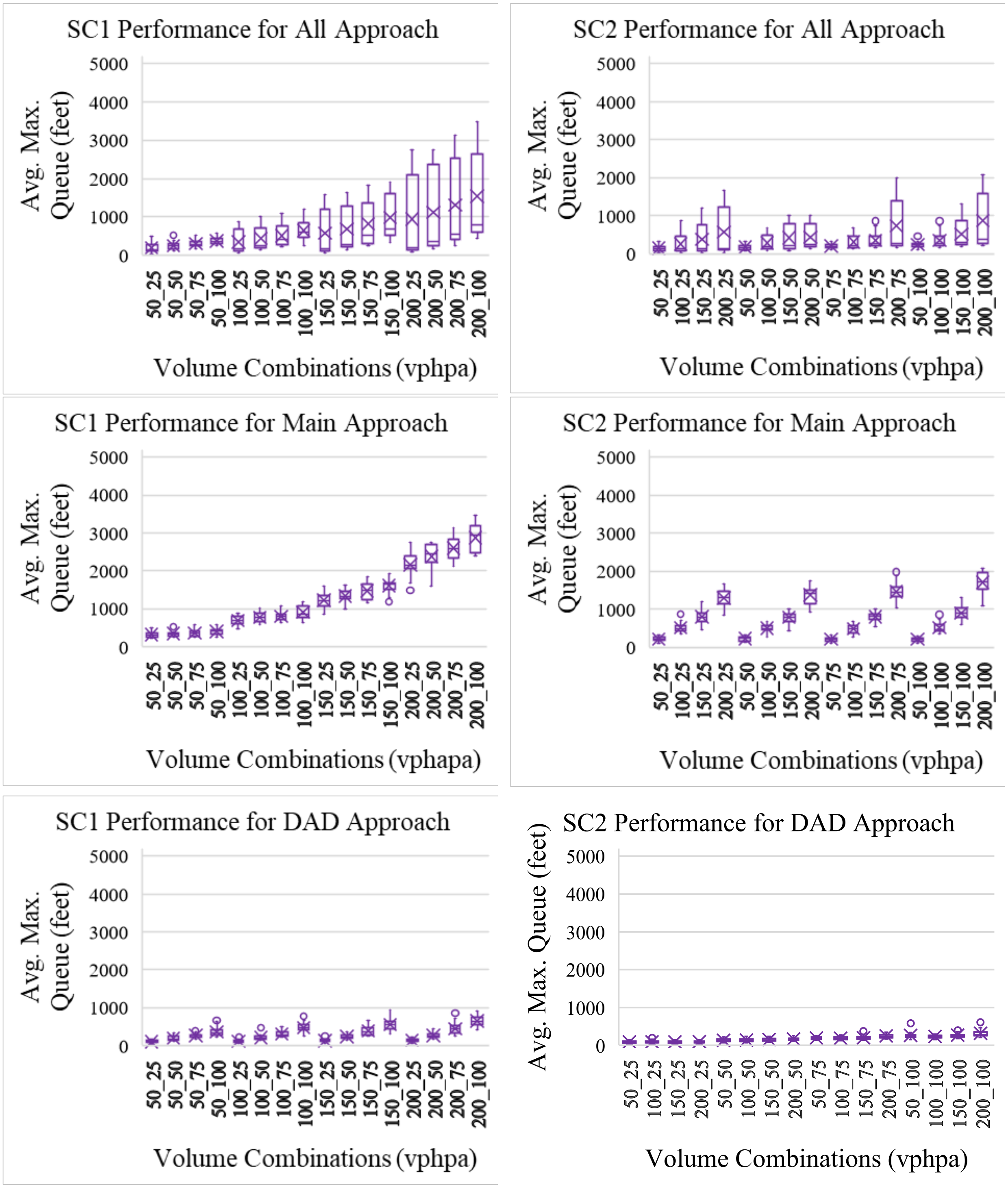

Figure B.5 Average maximum queue for All, Main and DAD approach under SC1 and SC2 for DAD approach volume increase for various levels of constant Main approach volume (WZL=1.1 mile, N_{DAD}=3, $T_{M\%}$=20, $T_{DAD\%}$=5)

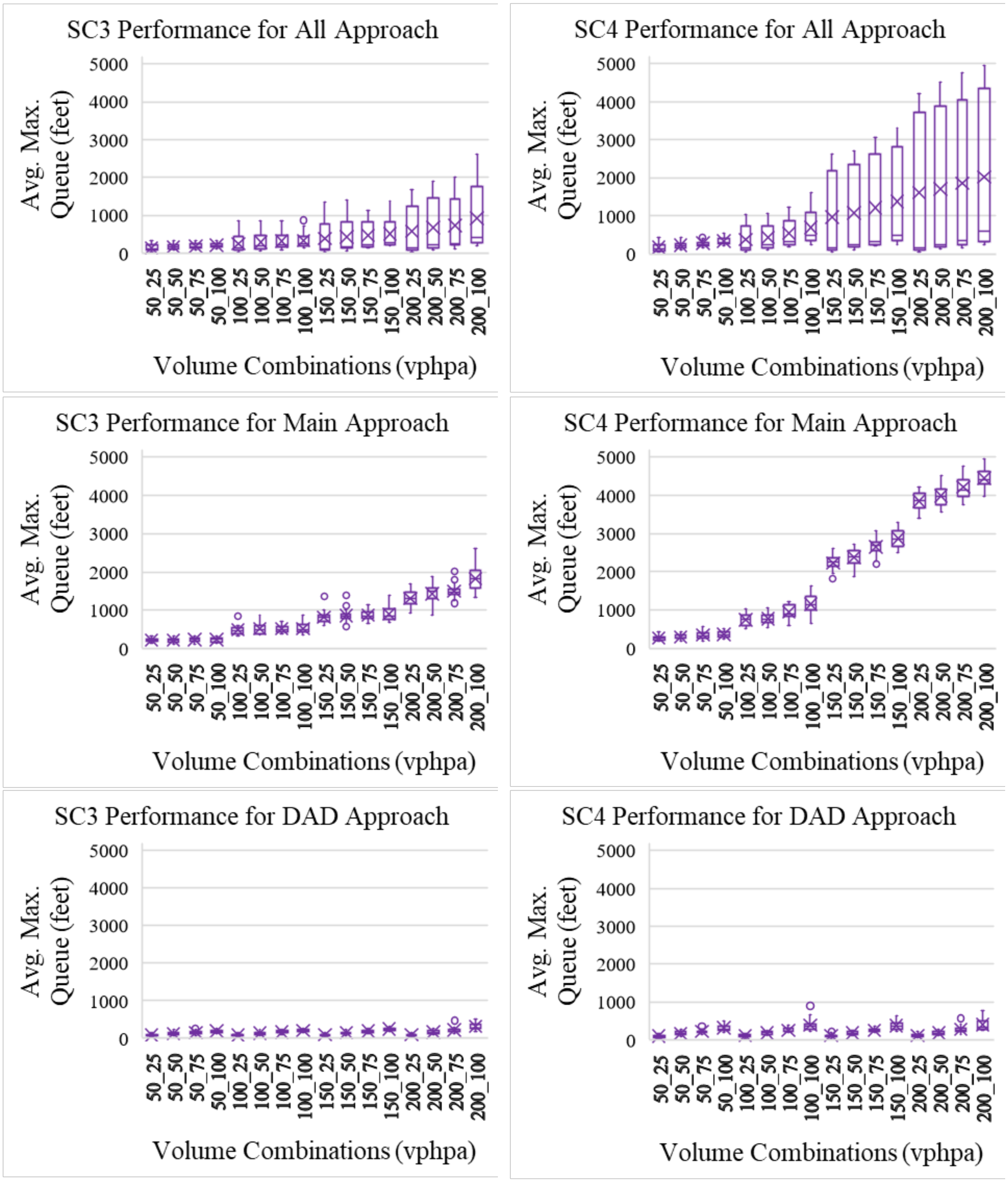

Figure B.6 Average maximum queue for All, Main and DAD approach under SC3 and SC4 for DAD approach volume increase for various levels of constant Main approach volume (WZL=1.1 mile, N_{DAD}=3, $T_{M\%}$=20, $T_{DAD\%}$=5)

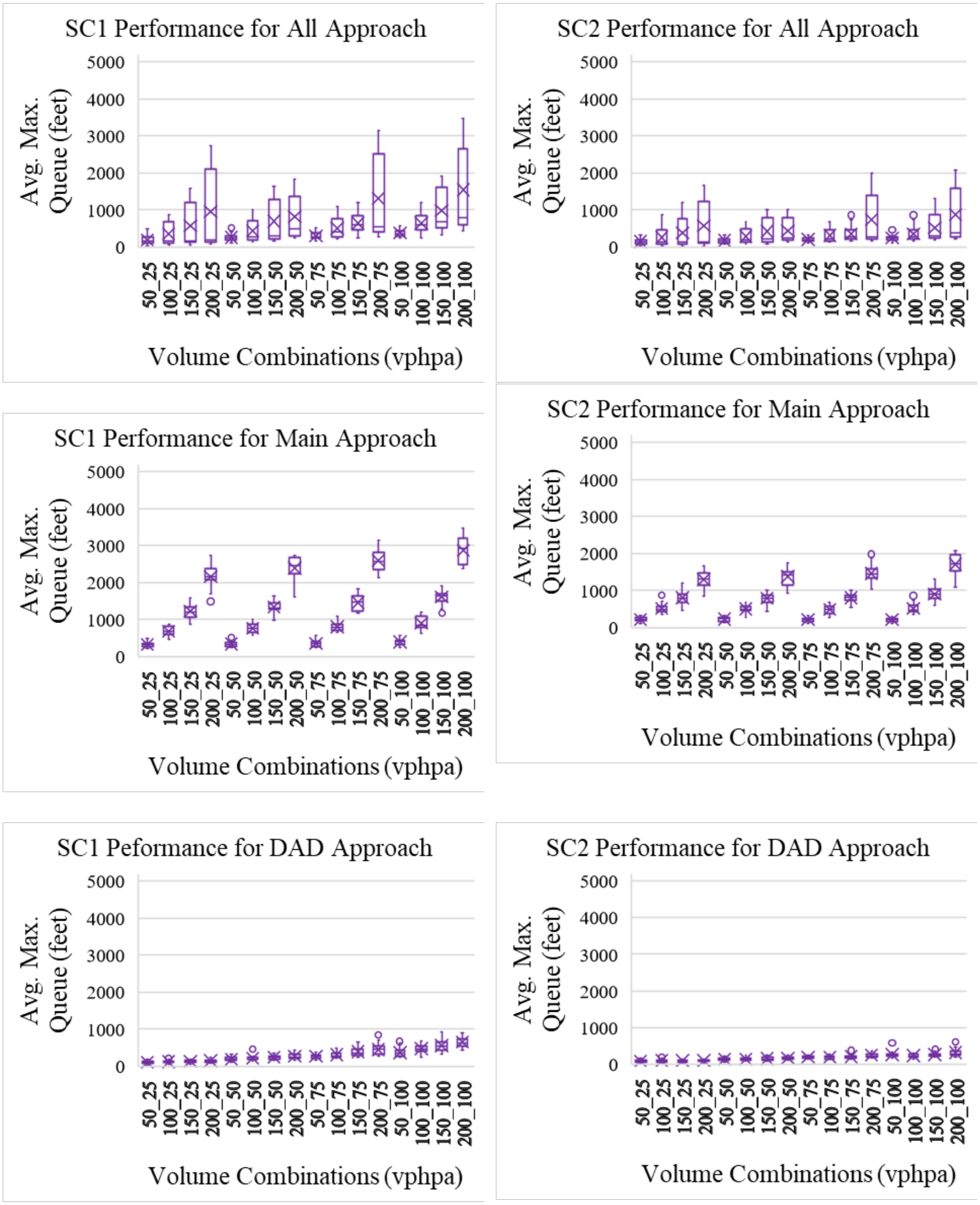

Figure B.7 Average maximum queue for All, Main and DAD approach under SC1 and SC2 for Main approach volume increase for various levels of constant DAD approach volume (WZL=1.1 mile, N_{DAD}=3, $T_{M\%}$=20, $T_{DAD\%}$=5)

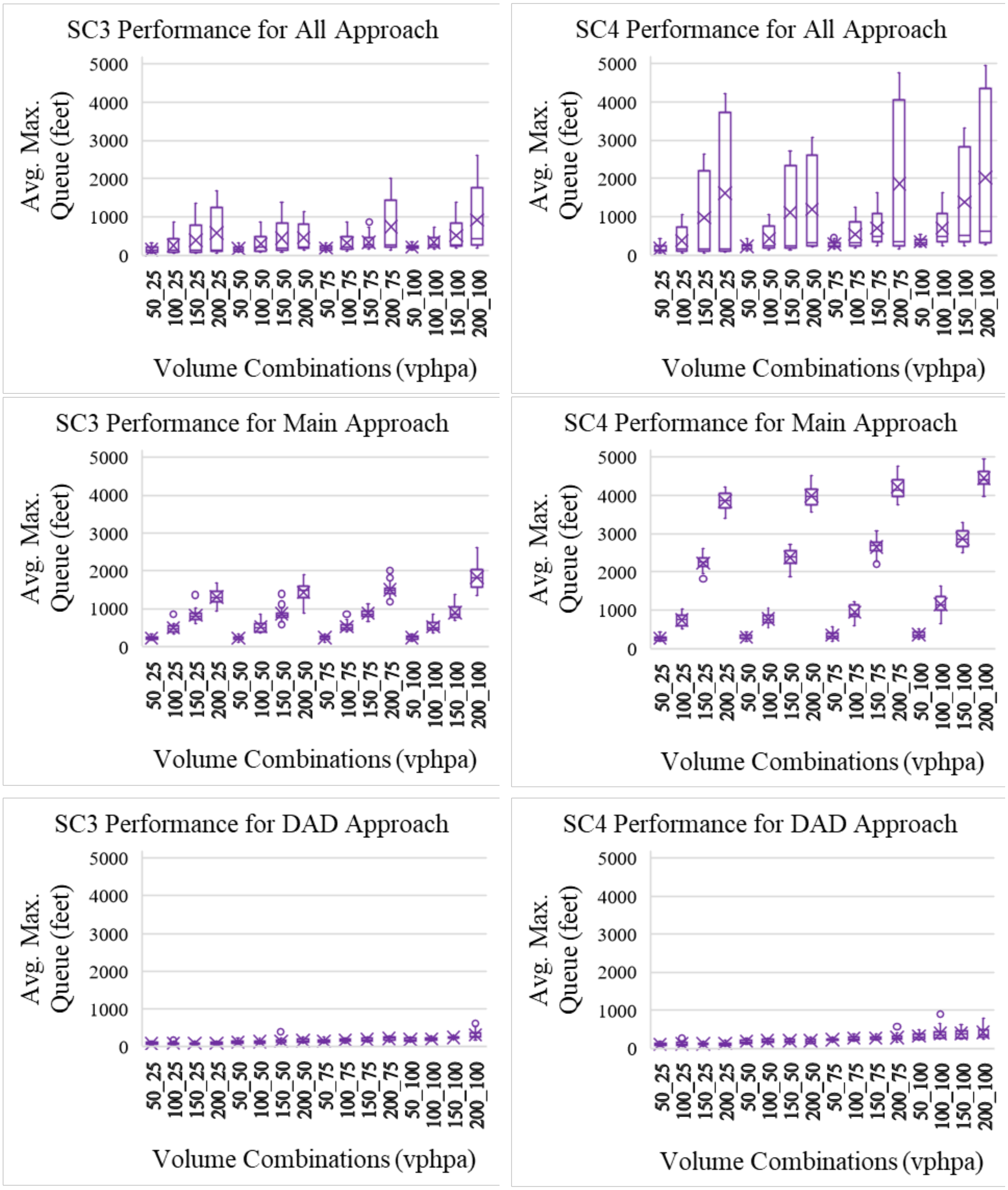

Figure B.8 Average maximum queue for All, Main and DAD approach under SC3 and SC4 for Main approach volume increase for various levels of constant DAD approach volume (WZL=1.1 mile, N_{DAD}=3, $T_{M\%}$=20, $T_{DAD\%}$=5)

B.3 Average Delay Reduction Comparisons

Table B.1 Performance analysis of SC2 and SC3 compared to SC1 in terms of average delay reduction (WZL=1.1 mile, N_{DAD}=3, $T_{M\%}$=20, $T_{DAD\%}$=5)

	SC2 and SC3 performance compared to SC1 in terms of avg. delay reduction in % (negative value means delay reduction)					
Volm	**Major**		**DAD**		**All**	
Comb	SC2	SC3	SC2	SC3	SC2	SC3
50_25	-56.5	-58.0	-60.0	-246.1	-57.8	-63.4
50_50	-62.6	-62.1	-59.2	-271.6	-60.6	-68.6
50_75	-62.9	-60.1	-49.2	-271.3	-53.0	-68.9
50_100	-63.7	-63.3	-31.4	-279.6	-39.4	-71.0
100_25	-53.4	-54.3	-60.6	-237.8	-55.6	-58.8
100_50	-60.5	-60.1	-61.8	-254.6	-61.0	-65.3
100_75	-62.7	-62.6	-64.3	-283.9	-63.4	-68.8
100_100	-67.7	-63.9	-62.1	-294.5	-64.3	-70.3
150_25	-54.5	-53.1	-67.6	-259.6	-57.3	-57.4
150_50	-57.4	-55.7	-68.7	-288.6	-61.8	-62.8
150_75	-64.3	-61.9	-68.3	-299.9	-66.1	-67.7
150_100	-65.9	-64.2	-66.2	-246.1	-66.0	-67.6
200_25	-64.0	-63.4	-70.1	-280.6	-64.9	-64.9
200_50	-67.5	-66.9	-65.7	-228.2	-67.0	-67.3
200_75	-67.4	-64.2	-62.4	-201.8	-65.2	-64.3
200_100	-61.2	-52.7	-58.1	-162.1	-58.7	-54.2

Table B.2 Performance analysis of SC2 and SC3 compared to SC4 in terms of average delay reduction (WZL=1.1 mile, N_{DAD}=3, $T_{M\%}$=20, $T_{DAD\%}$=5)

	SC2 and SC3 performance compared to SC4 in terms of avg. delay reduction in % (negative value means delay reduction)					
Volm	**Major**		**DAD**		**All**	
Comb	SC2	SC3	SC2	SC3	SC2	SC3
50_25	-49.4	-51.2	-48.2	-62.6	-48.9	-55.7
50_50	-51.7	-51.0	-49.3	-66.5	-50.2	-60.3
50_75	-57.5	-54.4	-38.1	-67.2	-44.0	-63.0
50_100	-61.4	-61.0	-24.8	-71.1	-34.1	-68.5
100_25	-66.4	-67.0	-51.1	-63.2	-63.9	-66.5
100_50	-71.2	-70.9	-51.6	-64.3	-65.0	-68.9
100_75	-78.4	-78.4	-54.8	-67.1	-69.3	-73.8
100_100	-83.2	-81.2	-59.1	-72.6	-72.3	-77.0
150_25	-86.3	-85.9	-45.1	-52.9	-83.1	-83.1
150_50	-86.8	-86.3	-49.1	-58.1	-80.9	-81.4
150_75	-87.8	-87.0	-48.3	-59.2	-78.8	-79.8
150_100	-87.3	-86.7	-51.1	-58.2	-75.5	-76.6
200_25	-87.5	-87.3	-40.7	-47.8	-84.6	-84.6
200_50	-86.9	-86.7	-39.8	-46.5	-81.1	-81.2
200_75	-85.9	-84.6	-34.8	-42.5	-75.6	-75.0
200_100	-82.3	-78.4	-38.0	-43.5	-67.4	-63.8

Table B.3 Performance analysis of SC2 and SC3 compared to SC1 in terms of standard deviation reduction of average delay (WZL=1.1 mile, N_{DAD}=3, $T_{M\%}$=20, $T_{DAD\%}$=5)

Volm Comb	SC2 and SC3 performance compared to SC1 in terms of SD (avg. delay) reduction in % (negative value means delay reduction)					
	Major		**DAD**		**All**	
	SC2	SC3	SC2	SC3	SC2	SC3
50_25	-49.4	-51.2	-48.2	-62.6	-48.9	-55.7
50_50	-51.7	-51.0	-49.3	-66.5	-50.2	-60.3
50_75	-57.5	-54.4	-38.1	-67.2	-44.0	-63.0
50_100	-61.4	-61.0	-24.8	-71.1	-34.1	-68.5
100_25	-66.4	-67.0	-51.1	-63.2	-63.9	-66.5
100_50	-71.2	-70.9	-51.6	-64.3	-65.0	-68.9
100_75	-78.4	-78.4	-54.8	-67.1	-69.3	-73.8
100_100	-83.2	-81.2	-59.1	-72.6	-72.3	-77.0
150_25	-86.3	-85.9	-45.1	-52.9	-83.1	-83.1
150_50	-86.8	-86.3	-49.1	-58.1	-80.9	-81.4
150_75	-87.8	-87.0	-48.3	-59.2	-78.8	-79.8
150_100	-87.3	-86.7	-51.1	-58.2	-75.5	-76.6
200_25	-87.5	-87.3	-40.7	-47.8	-84.6	-84.6
200_50	-86.9	-86.7	-39.8	-46.5	-81.1	-81.2
200_75	-85.9	-84.6	-34.8	-42.5	-75.6	-75.0
200_100	-82.3	-78.4	-38.0	-43.5	-67.4	-63.8

Table B.4 Performance analysis of SC2 and SC3 compared to SC4 in terms of standard deviation reduction of average delay (WZL=1.1 mile, N_{DAD}=3, $T_{M\%}$=20, $T_{DAD\%}$=5)

Volm Comb	SC2 and SC3 performance compared to SC4 in terms of SD (avg. delay) reduction in % (negative value means delay reduction)					
	Major		**DAD**		**All**	
	SC2	SC3	SC2	SC3	SC2	SC3
50_25	-51.4	-52.0	-38.5	-50.9	-64.0	-61.0
50_50	-51.7	-38.2	-30.8	-51.6	-30.2	-14.9
50_75	-60.1	-62.6	16.7	-29.6	-21.9	-62.1
50_100	-41.4	-50.5	32.9	-63.5	110.9	-75.7
100_25	-77.5	-80.5	-35.6	-51.9	-76.8	-73.9
100_50	-78.7	-78.8	-29.4	-44.0	-71.1	-80.4
100_75	-86.8	-85.0	-35.4	-45.0	-73.5	-76.6
100_100	-87.9	-88.6	-59.3	-71.0	-66.9	-76.3
150_25	-89.2	-86.3	-34.6	-38.3	-92.8	-79.7
150_50	-89.0	-86.4	-19.4	-30.4	-88.4	-82.1
150_75	-84.3	-89.1	-33.9	-39.2	-80.7	-87.2
150_100	-87.9	-85.0	-51.4	-52.5	-76.4	-87.0
200_25	-84.9	-78.5	-23.8	-35.1	-85.2	-80.8
200_50	-79.3	-77.2	-26.9	-40.0	-73.4	-65.3
200_75	-69.0	-73.0	-8.2	-10.9	-44.1	-48.4
200_100	-65.8	-57.6	-22.5	-29.6	-47.4	-44.7

B.4 Average Maximum Queue Reduction Comparisons

Table B.5 Performance analysis of SC2 and SC3 compared to SC1 in terms of average maximum queue reduction (WZL=1.1 mile, N_{DAD}=3, $T_{M\%}$=20, $T_{DAD\%}$=5)

Volm Comb	**SC2 and SC3 performance compared to SC1 in terms of avg. max. Queue reduction in %** (negative value means delay reduction)					
	Major		**DAD**		**All**	
	SC2	SC3	SC2	SC3	SC2	SC3
50_25	-29.4	-29.8	-17.3	-32.7	-26.3	-28.3
50_50	-31.5	-33.3	-31.4	-58.3	-32.4	-35.2
50_75	-35.6	-33.0	-27.2	-78.2	-32.2	-39.3
50_100	-43.8	-41.2	-28.0	-94.8	-35.1	-45.2
100_25	-23.6	-27.5	-23.7	-41.8	-24.5	-28.4
100_50	-34.9	-33.8	-35.1	-60.5	-34.4	-34.4
100_75	-39.9	-36.9	-39.4	-82.4	-39.4	-38.3
100_100	-41.7	-41.6	-50.4	-133.2	-46.0	-48.8
150_25	-33.8	-31.6	-31.3	-53.1	-33.8	-33.0
150_50	-40.5	-36.6	-36.3	-65.1	-40.1	-36.5
150_75	-45.2	-40.1	-47.6	-104.2	-45.5	-43.1
150_100	-43.7	-44.1	-51.9	-129.6	-46.7	-48.6
200_25	-39.1	-38.6	-31.2	-50.6	-39.2	-38.9
200_50	-40.2	-39.1	-38.7	-61.6	-41.7	-39.9
200_75	-43.5	-42.2	-45.0	-104.0	-44.0	-44.2
200_100	-39.8	-34.9	-51.1	-105.6	-43.2	-40.2

Table B.6 Performance analysis of SC2 and SC3 compared to SC4 in terms of average maximum queue reduction (WZL=1.1 mile, N_{DAD}=3, $T_{M\%}$=20, $T_{DAD\%}$=5)

Volm Comb	**SC2 and SC3 performance compared to SC4 in terms of avg. max. Queue reduction in %** (negative value means delay reduction)					
	Major		**DAD**		**All**	
	SC2	SC3	SC2	SC3	SC2	SC3
50_25	-18.4	-19.0	-8.7	-16.8	-15.2	-17.5
50_50	-21.4	-23.4	-23.4	-29.5	-23.5	-26.6
50_75	-32.9	-30.3	-13.9	-33.6	-24.8	-32.7
50_100	-39.3	-36.5	-16.7	-40.6	-27.3	-38.6
100_25	-30.8	-34.2	-18.4	-24.6	-28.5	-32.2
100_50	-34.5	-33.4	-28.4	-31.3	-32.7	-32.7
100_75	-48.3	-45.7	-27.5	-34.5	-42.7	-41.6
100_100	-54.4	-54.3	-39.2	-47.4	-49.8	-52.4
150_25	-63.7	-62.5	-19.1	-23.0	-60.7	-60.2
150_50	-66.2	-64.0	-19.9	-23.9	-61.9	-59.6
150_75	-69.0	-66.1	-21.3	-26.5	-63.2	-61.6
150_100	-67.9	-68.1	-29.9	-36.5	-62.0	-63.3
200_25	-65.3	-65.0	-16.8	-19.7	-64.2	-64.0
200_50	-64.0	-63.3	-12.3	-11.5	-61.9	-60.7
200_75	-64.6	-63.8	-10.6	-20.4	-60.3	-60.5
200_100	-61.2	-58.1	-22.4	-22.9	-56.8	-54.5

Table B.7 Performance analysis of SC2 and SC3 compared to SC1 in terms of standard deviation reduction of average maximum queue (WZL=1.1 mile, N_{DAD}=3, $T_{M\%}$=20, $T_{DAD\%}$=5)

Volm Comb	SC2 and SC3 performance compared to SC1 in terms of SD (avg. max. Queue) reduction in % (negative value means delay reduction)					
	Major		**DAD**		**All**	
	SC2	SC3	SC2	SC3	SC2	SC3
50_25	-30.0	-35.7	-9.2	-23.2	-34.8	-32.6
50_50	-31.3	-33.3	-25.0	-31.9	-32.5	-29.6
50_75	-31.3	-43.3	-34.8	-14.8	-40.6	-22.7
50_100	-35.8	-30.3	-29.0	-219.0	-27.7	-51.4
100_25	13.8	25.7	-15.0	-29.9	-21.8	-23.3
100_50	-27.0	-6.6	-32.0	-26.2	-33.0	-28.2
100_75	-9.2	-1.7	-43.9	-91.0	-36.6	-25.7
100_100	-23.4	-21.7	-53.5	-237.2	-34.5	-29.7
150_25	-17.0	-21.7	-19.1	-14.8	-33.5	-31.8
150_50	-12.5	2.3	3.6	11.6	-40.5	-32.9
150_75	-49.9	-44.4	-61.0	-141.8	-44.5	-37.0
150_100	-7.5	-4.7	-50.8	-216.6	-38.2	-37.1
200_25	-28.2	-39.1	-15.4	-32.9	-40.1	-39.8
200_50	-32.0	-21.6	-42.5	-37.0	-42.3	-39.6
200_75	-18.9	-34.5	-46.4	-122.1	-42.8	-40.6
200_100	-29.1	-11.9	-26.0	-22.6	-37.1	-31.0

Table B.8 Performance analysis of SC2 and SC3 compared to SC4 in terms of standard deviation reduction of average maximum queue (WZL=1.1 mile, N_{DAD}=3, $T_{M\%}$=20, $T_{DAD\%}$=5)

Volm Comb	SC2 and SC3 performance compared to SC4 in terms of SD (avg. max. Queue) reduction in % (negative value means delay reduction)					
	Major		**DAD**		**All**	
	SC2	SC3	SC2	SC3	SC2	SC3
50_25	-19.0	-25.6	-10.7	-20.1	-22.4	-19.7
50_50	-7.7	-10.3	-15.8	-15.0	-18.2	-14.6
50_75	-34.8	-46.2	-13.1	16.3	-44.7	-28.0
50_100	-36.4	-31.0	-2.0	-56.7	-12.8	-41.4
100_25	-10.2	-0.9	-26.4	-33.4	-31.0	-32.3
100_50	-27.5	-7.2	-25.7	-13.4	-35.1	-30.5
100_75	-34.6	-29.2	-28.6	-33.5	-54.1	-46.2
100_100	-43.3	-42.1	-56.9	-72.5	-59.9	-57.0
150_25	-20.7	-25.2	-20.5	-14.4	-65.1	-64.3
150_50	-33.9	-22.8	22.0	33.2	-69.9	-66.0
150_75	-49.2	-43.6	10.3	16.8	-73.9	-70.4
150_100	-28.8	-26.6	-40.6	-61.9	-72.9	-72.4
200_25	5.6	-10.5	-20.5	-29.3	-67.1	-66.9
200_50	-9.7	4.1	-16.5	6.0	-67.3	-65.7
200_75	-18.8	-34.5	-9.0	-23.5	-68.3	-67.1
200_100	0.1	24.4	-39.9	-33.8	-64.7	-61.2

Appendix C Performance Analysis of Different Signal Control Strategies (N_{DAD}=5)

C.1 Average Delay Analysis

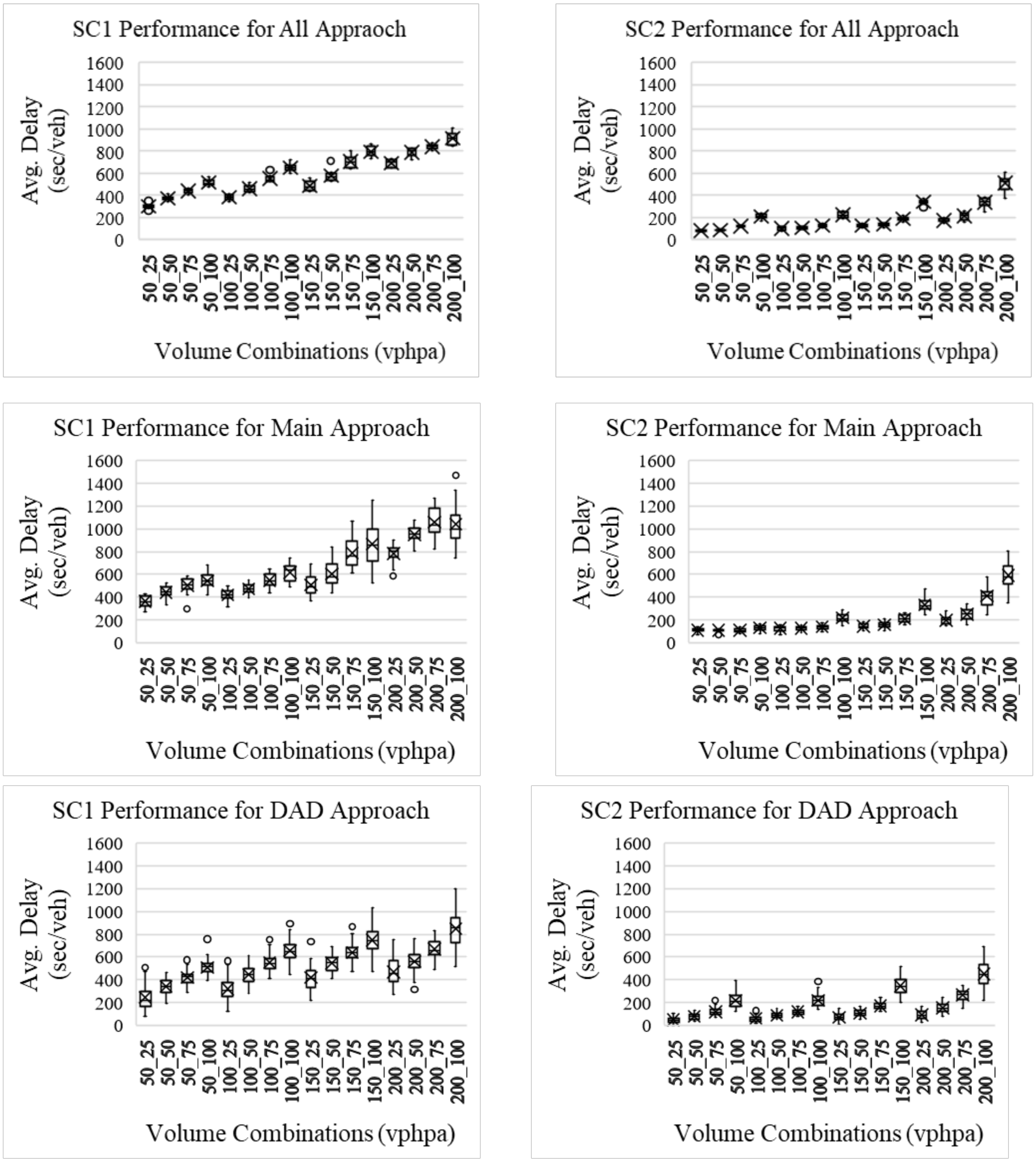

Figure C.1 Average delay for All, Main and DAD approach under SC1 and SC2 for DAD approach volume increase for various levels of constant Main approach volume (WZL=1.1 mile, N_{DAD}=5, $T_{M\%}$=20, $T_{DAD\%}$=5)

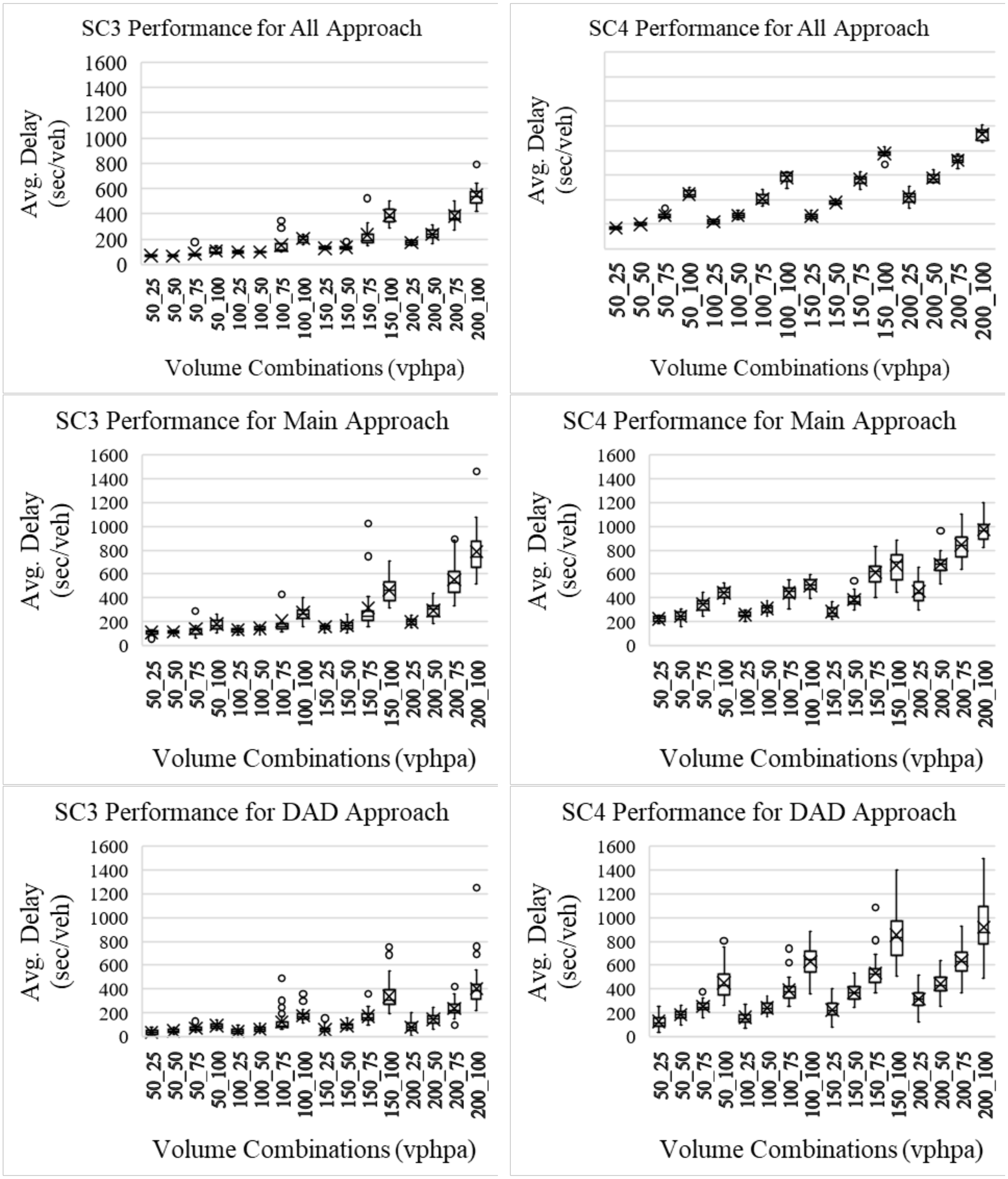

Figure C.2 Average delay for All, Main and DAD approach under SC3 and SC4 for DAD approach volume increase for various levels of constant Main approach volume (WZL=1.1 mile, N_{DAD}=5, $T_{M\%}$=20, $T_{DAD\%}$=5)

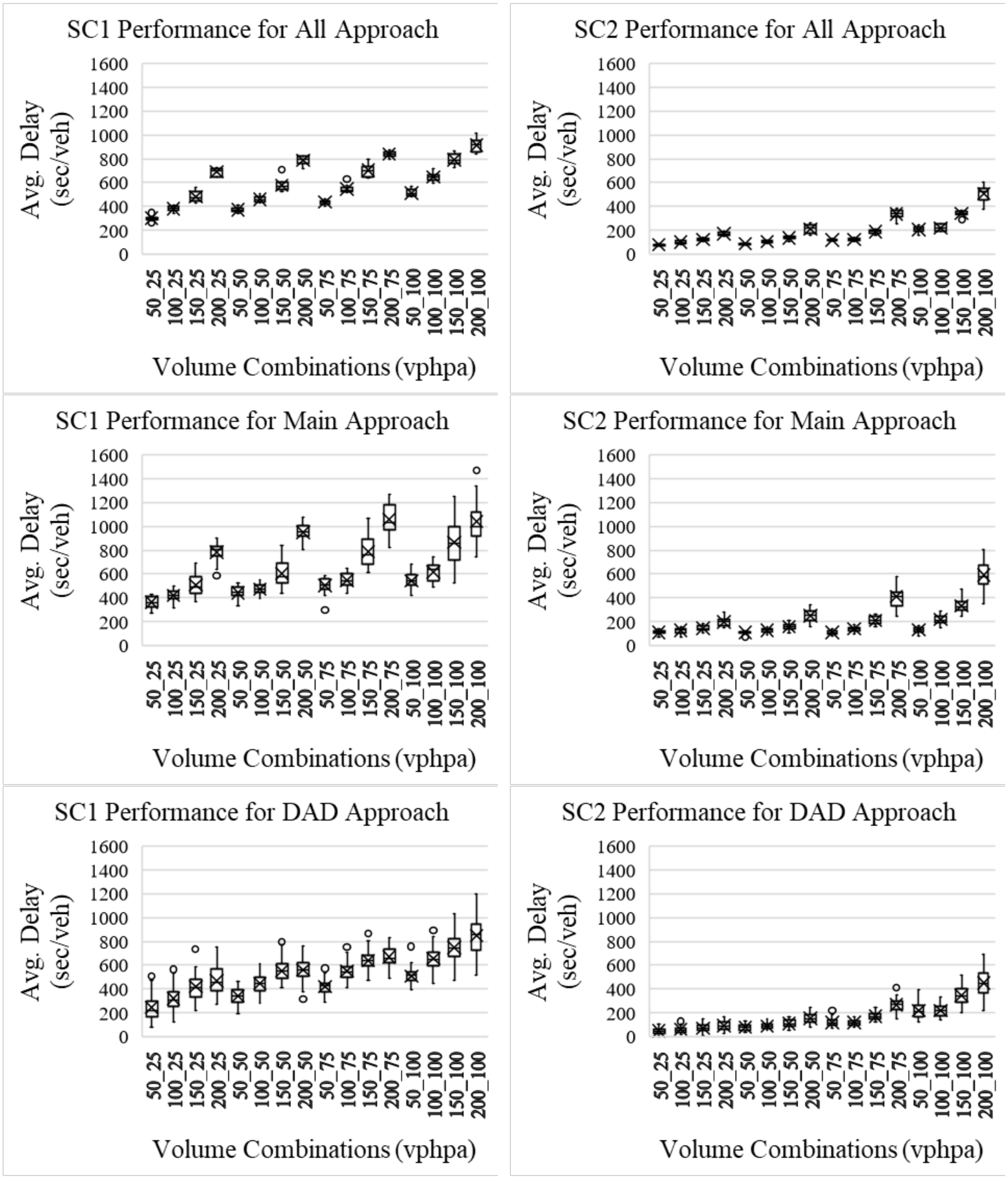

Figure C.3 Average delay for All, Main and DAD approach under SC1 and SC2 for Main approach volume increase for various levels of constant DAD approach volume (WZL=1.1 mile, N_{DAD}=5, $T_{M\%}$=20, $T_{DAD\%}$=5)

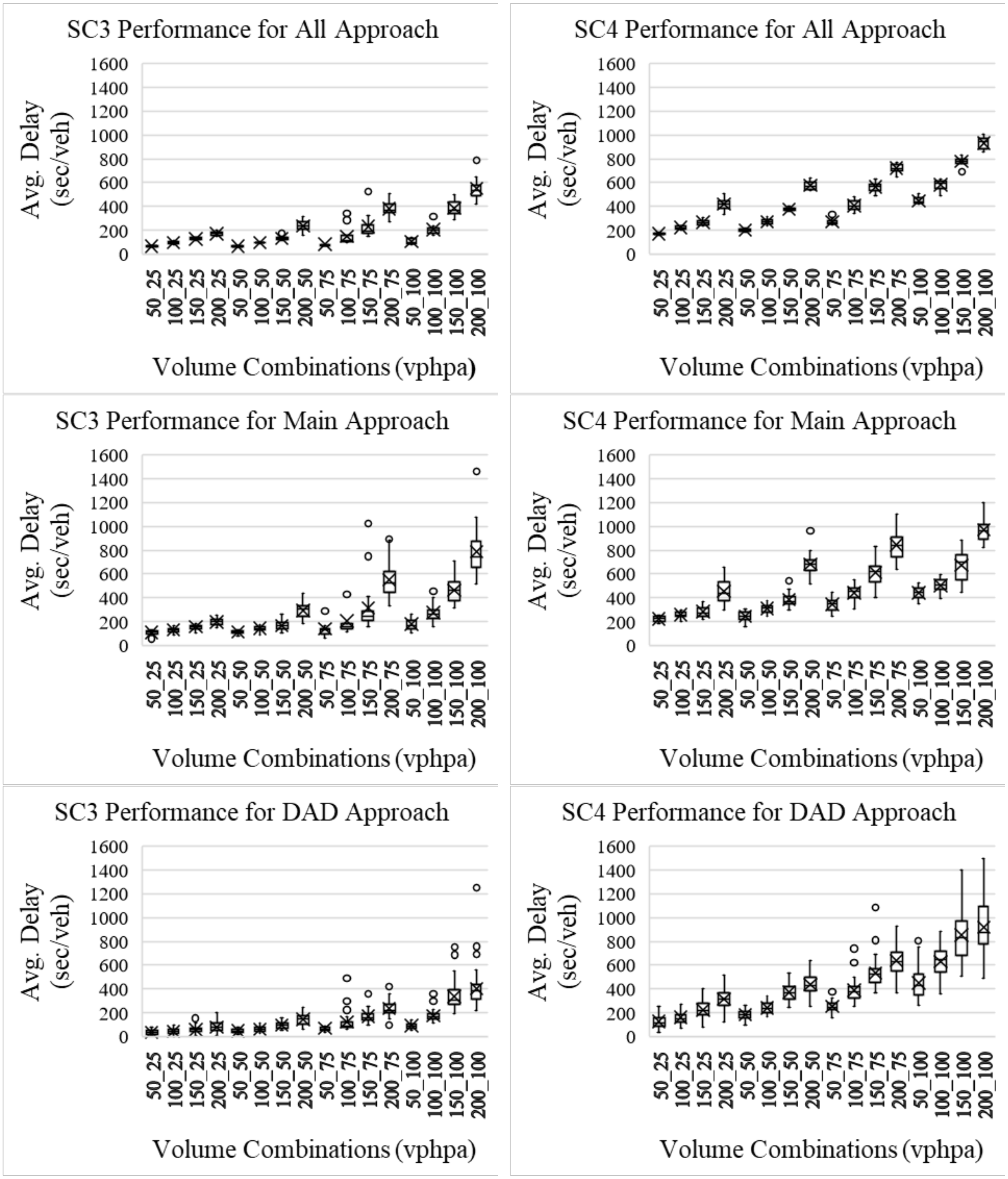

Figure C.4 Average delay for All, Main and DAD approach under SC3 and SC4 for Main approach volume increase for various levels of constant DAD approach volume (WZL=1.1 mile, N_{DAD}=5, $T_{M\%}$=20, $T_{DAD\%}$=5)

C.2 Average Maximum Queue Analysis

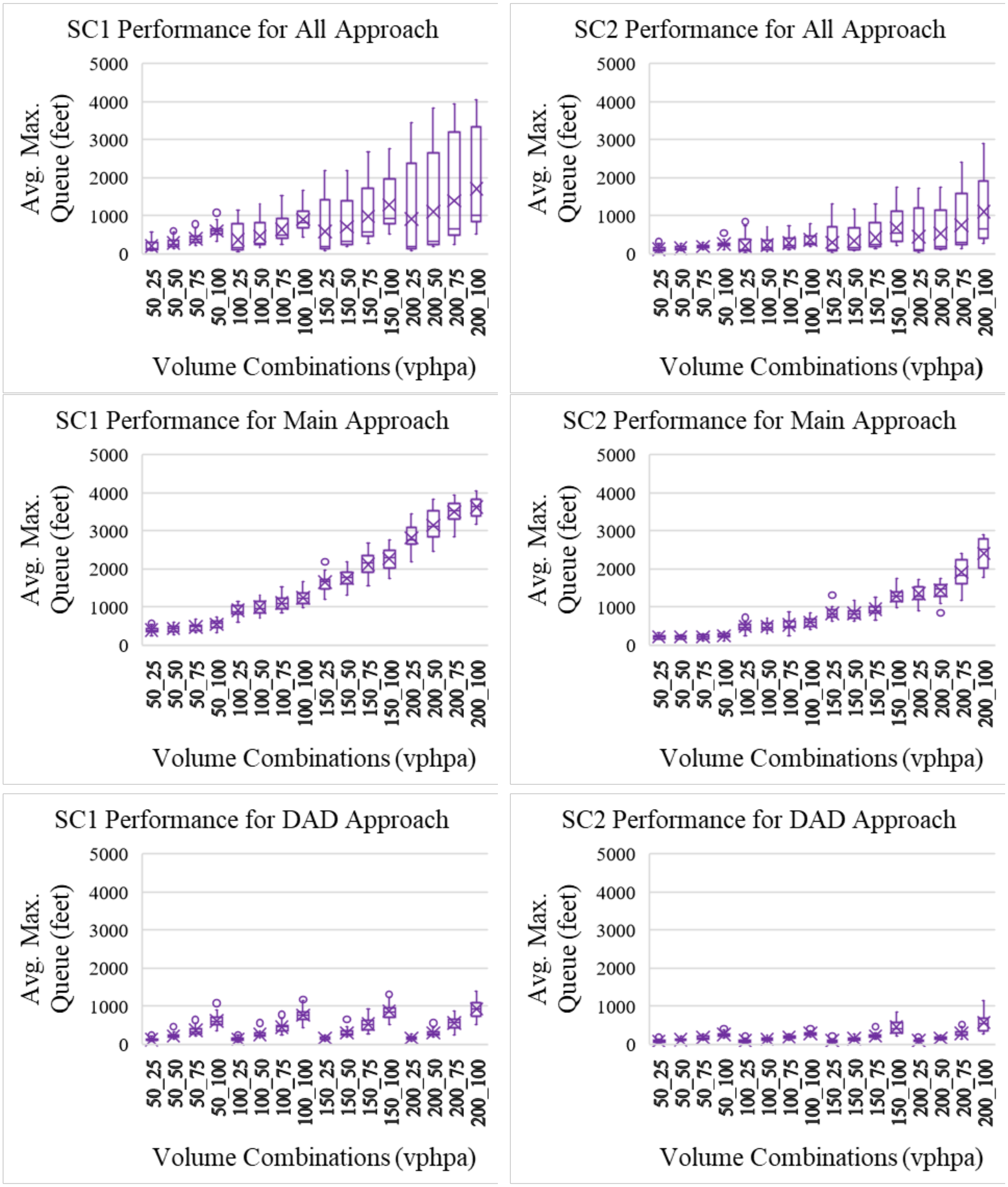

Figure C.5 Average maximum queue for All, Main and DAD approach under SC1 and SC2 for DAD approach volume increase for various levels of constant Main approach volume (WZL=1.1 mile, N_{DAD}=3, $T_{M\%}$=20, $T_{DAD\%}$=5)

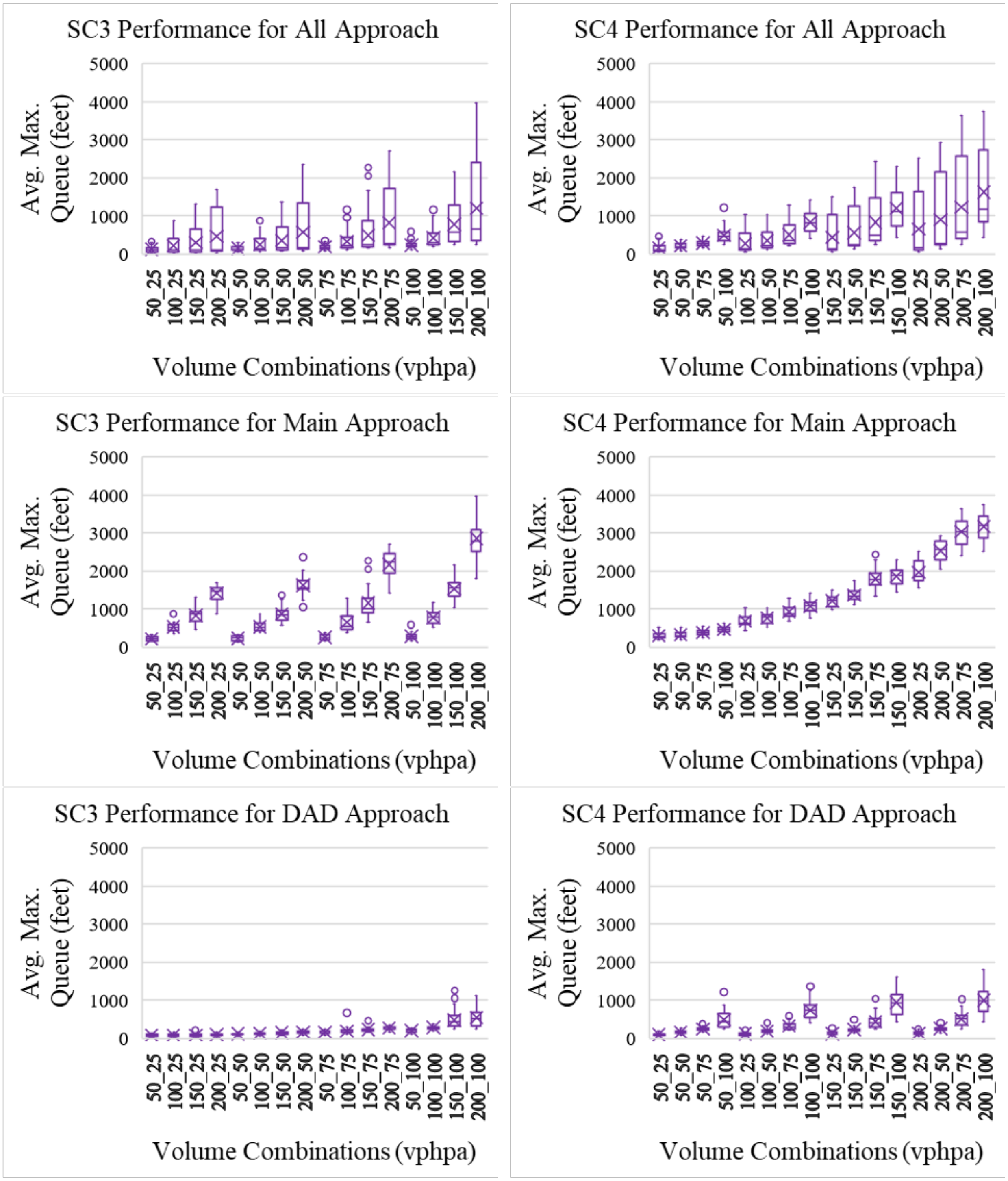

Figure C.6 Average maximum queue for All, Main and DAD approach under SC3 and SC4 for DAD approach volume increase for various levels of constant Main approach volume (WZL=1.1 mile, N_{DAD}=5, $T_{M\%}$=20, $T_{DAD\%}$=5)

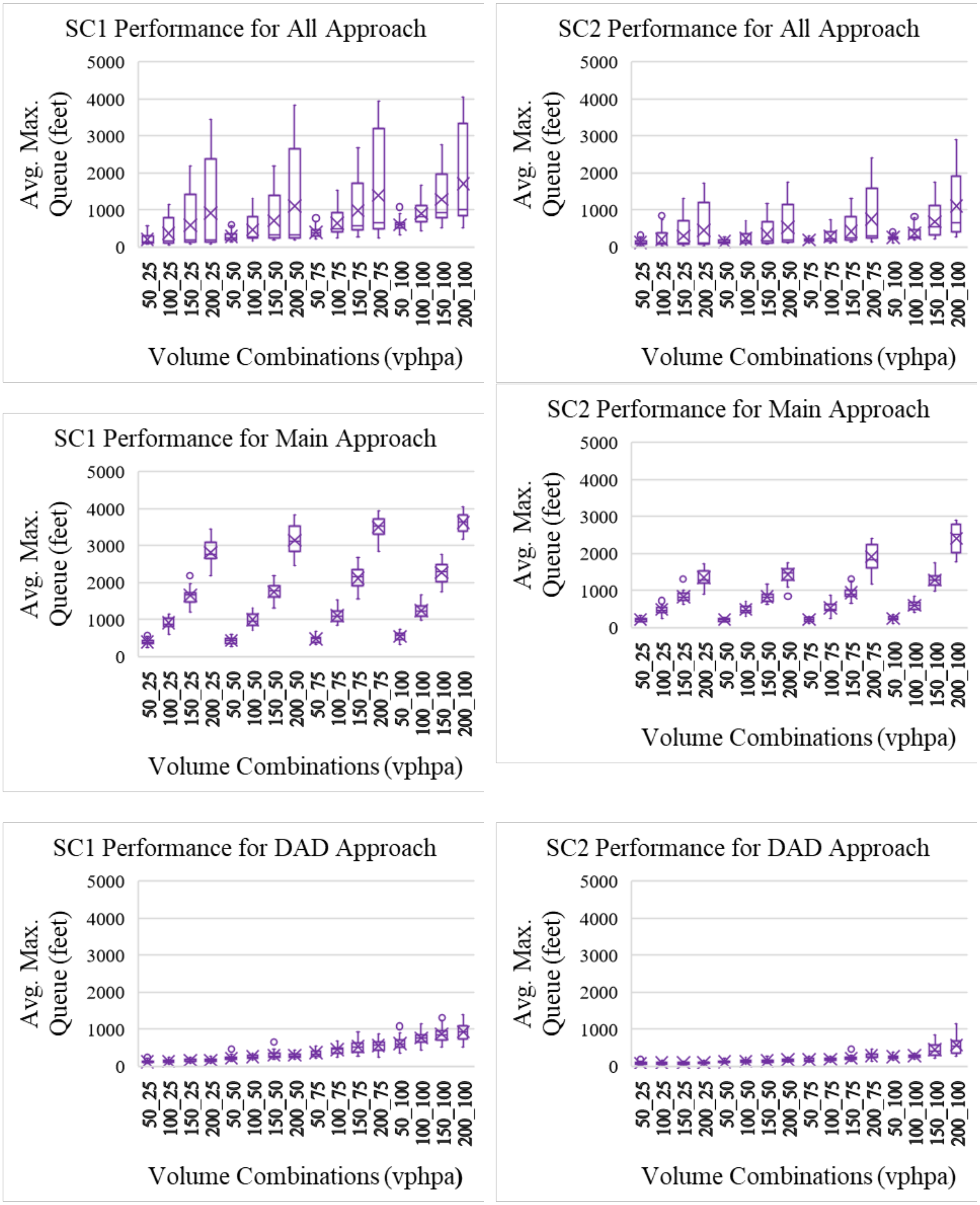

Figure C.7 Average maximum queue for All, Main and DAD approach under SC1 and SC2 for Main approach volume increase for various levels of constant DAD approach volume (WZL=1.1 mile, N_{DAD}=5, $T_{M\%}$=20, $T_{DAD\%}$=5)

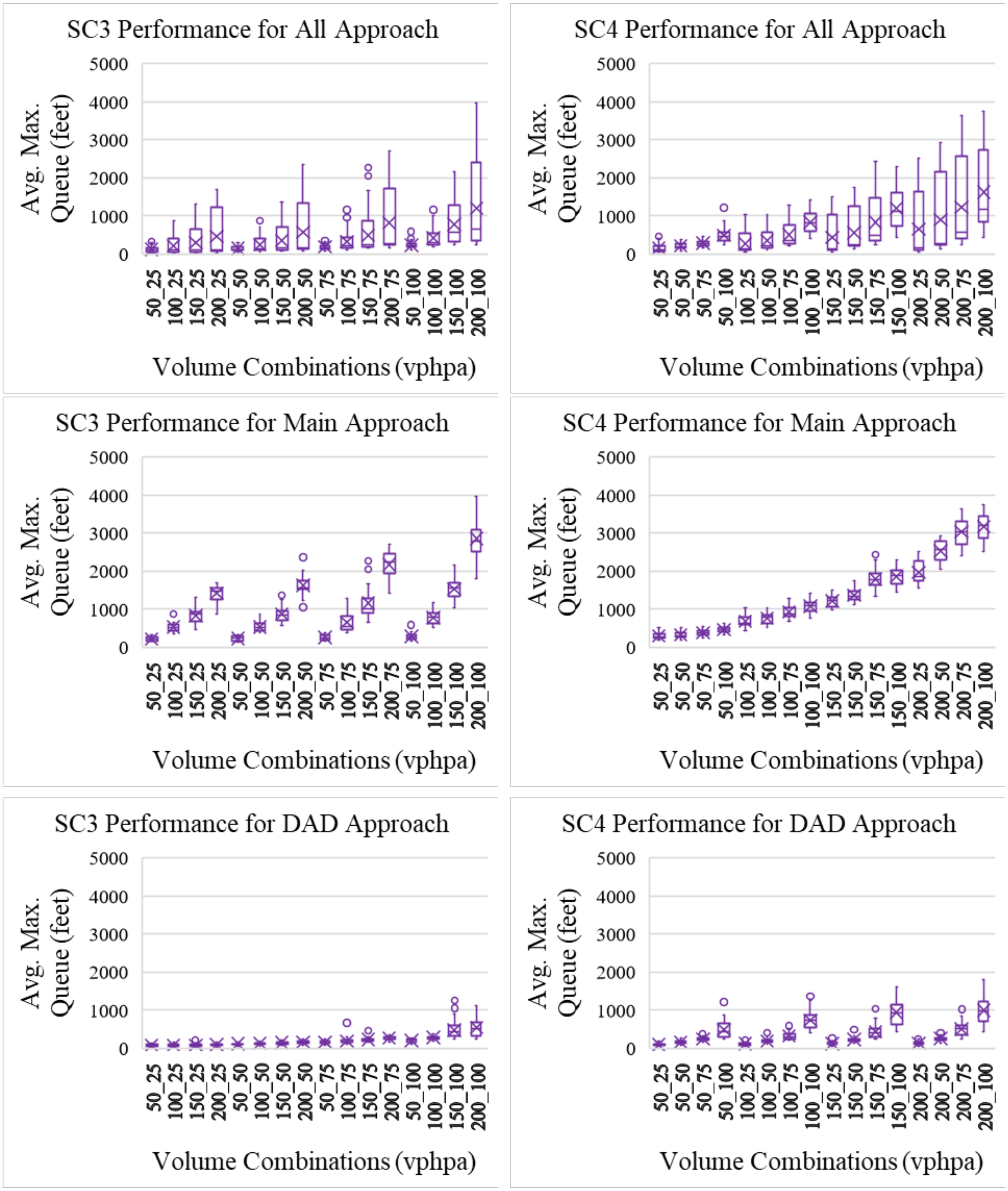

Figure C.8 Average maximum queue for All, Main and DAD approach under SC3 and SC4 for Main approach volume increase for various levels of constant DAD approach volume (WZL=1.1 mile, N_{DAD}=5, $T_{M\%}$=20, $T_{DAD\%}$=5)

C.3 Average Delay Reduction Comparisons

Table C.1 Performance analysis of SC2 and SC3 compared to SC1 in terms of average delay reduction (WZL=1.1 mile, N_{DAD}=5, $T_{M\%}$=20, $T_{DAD\%}$=5)

	SC2 and SC3 performance compared to SC1 in terms of avg. delay reduction in % (negative value means delay reduction)					
Volm	**Major**		**DAD**		**All**	
Comb	SC2	SC3	SC2	SC3	SC2	SC3
50_25	-69.5	-70.0	-79.8	-632.6	-74.5	-77.9
50_50	-75.6	-74.7	-77.7	-624.6	-77.0	-82.4
50_75	-78.6	-72.5	-71.5	-505.7	-73.0	-80.9
50_100	-75.9	-67.5	-57.0	-454.7	-59.9	-79.3
100_25	-70.5	-69.3	-81.5	-615.1	-74.0	-74.7
100_50	-73.7	-70.1	-80.5	-629.1	-77.4	-78.9
100_75	-74.6	-62.6	-79.0	-359.4	-77.5	-72.8
100_100	-64.8	-55.2	-66.4	-276.3	-66.0	-68.5
150_25	-71.7	-69.5	-82.9	-618.3	-74.5	-73.6
150_50	-73.7	-72.5	-80.7	-486.7	-76.7	-77.0
150_75	-73.6	-60.0	-73.1	-270.7	-73.3	-66.8
150_100	-61.7	-46.4	-54.2	-121.6	-57.1	-51.3
200_25	-74.9	-74.7	-80.9	-491.5	-75.2	-75.3
200_50	-73.9	-69.2	-72.5	-288.3	-73.1	-69.9
200_75	-61.3	-47.9	-60.3	-184.0	-60.0	-54.4
200_100	-43.2	-24.5	-47.3	-110.5	-44.4	-39.7

Table C.2 Performance analysis of SC2 and SC3 compared to SC4 in terms of average delay reduction (WZL=1.1 mile, N_{DAD}=5, $T_{M\%}$=20, $T_{DAD\%}$=5)

	SC2 and SC3 performance compared to SC4 in terms of avg. delay reduction in % (negative value means delay reduction)					
Volm	**Major**		**DAD**		**All**	
Comb	SC2	SC3	SC2	SC3	SC2	SC3
50_25	-50.5	-51.4	-60.3	-73.2	-54.8	-60.9
50_50	-55.5	-53.9	-58.1	-74.1	-57.4	-67.5
50_75	-68.8	-59.8	-52.4	-72.4	-56.5	-69.3
50_100	-70.3	-59.8	-51.3	-79.6	-53.7	-76.1
100_25	-51.6	-49.6	-63.0	-72.0	-55.2	-56.3
100_50	-59.6	-54.0	-64.1	-74.7	-62.1	-64.5
100_75	-68.7	-53.9	-70.3	-69.2	-69.6	-63.2
100_100	-56.8	-45.1	-65.1	-72.4	-62.2	-65.1
150_25	-48.9	-45.0	-68.1	-73.9	-53.8	-52.1
150_50	-58.5	-56.7	-71.3	-74.7	-64.2	-64.7
150_75	-66.0	-48.5	-67.8	-67.7	-66.7	-58.6
150_100	-50.7	-31.0	-59.7	-60.3	-56.2	-50.3
200_25	-56.9	-56.5	-71.4	-74.7	-59.1	-59.2
200_50	-63.7	-57.1	-65.0	-67.2	-63.3	-58.9
200_75	-51.6	-34.9	-58.4	-63.1	-53.6	-47.1
200_100	-39.2	-19.1	-51.3	-56.1	-45.7	-41.0

Table C.3 Performance analysis of SC2 and SC3 compared to SC1 in terms of standard deviation reduction of average delay (WZL=1.1 mile, N_{DAD}=5, $T_{M\%}$=20, $T_{DAD\%}$=5)

	SC2 and SC3 performance compared to SC1 in terms of SD (avg. delay) reduction in % (negative value means delay reduction)					
Volm	**Major**		**DAD**		**All**	
Comb	SC2	SC3	SC2	SC3	SC2	SC3
50_25	-65.8	-61.4	-73.8	-437.8	-73.7	-74.1
50_50	-73.5	-73.4	-65.7	-305.0	-75.7	-81.1
50_75	-76.1	-5.3	-47.3	-116.6	-63.3	95.0
50_100	-64.1	-40.5	-2.6	-167.3	-20.1	-23.6
100_25	-50.2	-55.9	-74.0	-323.5	-42.4	-57.7
100_50	-55.1	-47.2	-68.9	-307.3	-72.9	-77.7
100_75	-64.7	102.4	-64.9	14.5	-67.0	163.9
100_100	-51.4	3.4	-45.4	-103.8	-21.3	34.5
150_25	-73.9	-78.6	-71.0	-282.5	-72.8	-78.0
150_50	-78.5	-71.4	-63.8	-207.1	-75.8	-66.7
150_75	-76.5	57.9	-63.1	-30.5	-69.5	122.4
150_100	-72.4	-47.8	-38.6	-6.5	-53.7	42.9
200_25	-59.6	-62.6	-69.7	-222.1	-50.9	-48.5
200_50	-34.3	-17.8	-54.6	-123.7	-4.0	17.2
200_75	-24.0	27.0	-28.5	-37.0	78.3	176.9
200_100	-30.7	20.0	-33.2	0.4	17.8	77.5

Table C.4 Performance analysis of SC2 and SC3 compared to SC4 in terms of standard deviation reduction of average delay (WZL=1.1 mile, N_{DAD}=5, $T_{M\%}$=20, $T_{DAD\%}$=5)

	SC2 and SC3 performance compared to SC4 in terms of SD (avg. delay) reduction in % (negative value means delay reduction)					
Volm	**Major**		**DAD**		**All**	
Comb	SC2	SC3	SC2	SC3	SC2	SC3
50_25	-21.6	-11.7	-45.1	-61.0	-21.3	-22.4
50_50	-60.5	-60.3	-35.6	-53.7	-55.6	-65.4
50_75	-68.7	23.8	-31.5	-40.1	-75.4	31.1
50_100	-52.0	-20.5	-49.1	-80.4	-40.5	-43.1
100_25	-3.2	-14.3	-46.0	-50.9	-7.3	-31.9
100_50	-45.9	-36.4	-48.0	-58.9	-66.6	-72.5
100_75	-69.0	77.5	-73.7	-12.2	-73.5	112.0
100_100	-34.8	38.5	-59.1	-63.2	-37.5	6.7
150_25	-46.5	-56.1	-56.0	-60.3	-53.0	-62.0
150_50	-54.8	-39.9	-55.9	-60.4	-19.7	10.8
150_75	-68.3	113.2	-76.9	-52.1	-60.4	189.1
150_100	-53.0	-11.3	-66.7	-49.0	-42.6	77.2
200_25	-67.5	-69.9	-53.9	-52.7	-67.4	-65.9
200_50	-48.6	-35.7	-47.5	-48.3	1.3	23.7
200_75	-18.5	36.2	-59.9	-59.1	10.3	71.3
200_100	33.3	130.9	-50.5	-25.6	33.2	100.7

C.4 Average Maximum Queue Reduction Comparisons

Table C.5 Performance analysis of SC2 and SC3 compared to SC1 in terms of average maximum queue reduction (WZL=1.1 mile, N_{DAD}=5, $T_{M\%}$=20, $T_{DAD\%}$=5)

	SC2 and SC3 performance compared to SC1 in terms of avg. max. Queue reduction in % (negative value means delay reduction)					
Volm	**Major**		**DAD**		**All**	
Comb	SC2	SC3	SC2	SC3	SC2	SC3
50_25	-44.0	-43.8	-33.4	-63.1	-39.3	-41.5
50_50	-50.2	-46.8	-42.7	-92.9	-46.0	-47.5
50_75	-53.5	-45.3	-50.9	-130.5	-51.8	-52.7
50_100	-54.4	-47.2	-57.5	-199.3	-56.7	-61.5
100_25	-46.7	-41.8	-36.3	-72.6	-43.8	-41.9
100_50	-51.0	-46.0	-47.4	-98.6	-49.6	-47.4
100_75	-51.6	-40.4	-58.2	-134.9	-54.9	-49.0
100_100	-51.4	-37.4	-63.0	-172.6	-58.4	-53.1
150_25	-49.5	-49.5	-43.8	-85.0	-48.4	-48.9
150_50	-52.7	-50.5	-51.9	-110.1	-52.5	-51.1
150_75	-55.8	-45.7	-58.1	-127.1	-56.7	-49.6
150_100	-43.4	-32.6	-49.0	-84.1	-46.2	-39.0
200_25	-51.9	-49.6	-40.0	-79.3	-50.4	-49.0
200_50	-54.5	-48.5	-42.7	-88.6	-52.3	-48.2
200_75	-45.5	-37.9	-48.9	-99.1	-46.5	-41.2
200_100	-33.5	-21.2	-38.1	-71.6	-35.3	-29.2

Table C.6 Performance analysis of SC2 and SC3 compared to SC4 in terms of average maximum queue reduction (WZL=1.1 mile, N_{DAD}=5, $T_{M\%}$=20, $T_{DAD\%}$=5)

	SC2 and SC3 performance compared to SC4 in terms of avg. max. Queue reduction in % (negative value means delay reduction)					
Volm	**Major**		**DAD**		**All**	
Comb	SC2	SC3	SC2	SC3	SC2	SC3
50_25	-26.1	-25.9	-15.9	-22.6	-21.5	-24.4
50_50	-33.6	-29.0	-24.5	-31.8	-28.5	-30.5
50_75	-41.8	-31.4	-28.2	-36.5	-33.3	-34.6
50_100	-47.2	-38.9	-46.3	-57.8	-46.5	-52.5
100_25	-28.6	-22.1	-21.7	-28.7	-26.6	-24.1
100_50	-36.2	-29.6	-31.2	-34.2	-34.2	-31.4
100_75	-42.9	-29.6	-42.3	-41.3	-42.6	-35.0
100_100	-43.9	-27.8	-62.1	-62.4	-55.4	-49.7
150_25	-31.1	-31.2	-27.9	-30.6	-30.4	-31.1
150_50	-39.3	-36.5	-39.3	-39.9	-39.3	-37.5
150_75	-47.6	-35.7	-50.1	-47.5	-48.6	-40.2
150_100	-30.7	-17.4	-52.3	-49.1	-42.8	-35.1
200_25	-31.2	-27.9	-29.4	-34.3	-30.9	-28.9
200_50	-43.4	-35.8	-33.7	-38.7	-41.4	-36.4
200_75	-37.0	-28.2	-44.0	-44.9	-39.1	-33.2
200_100	-24.0	-9.9	-42.5	-45.8	-32.1	-25.8

Table C.7 Performance analysis of SC2 and SC3 compared to SC1 in terms of standard deviation reduction of average maximum queue (WZL=1.1 mile, N_{DAD}=5, $T_{M\%}$=20, $T_{DAD\%}$=5)

	SC2 and SC3 performance compared to SC1 in terms of SD (avg. max. Queue) reduction in % (negative value means delay reduction)					
Volm	**Major**		**DAD**		**All**	
Comb	SC2	SC3	SC2	SC3	SC2	SC3
50_25	-37.7	-37.4	-35.2	-64.2	-46.4	-44.6
50_50	-52.7	-35.6	-25.9	-75.9	-50.9	-43.1
50_75	-46.5	-33.9	-65.9	-194.6	-61.1	-45.5
50_100	-48.0	-12.0	-42.3	-218.9	-44.8	-47.3
100_25	-10.4	-19.2	-30.0	-72.0	-46.0	-40.6
100_50	-35.4	-25.6	-35.6	-56.7	-50.6	-43.1
100_75	-9.6	62.9	-67.2	-45.7	-45.0	-18.3
100_100	-25.0	1.3	-55.9	-168.5	-37.3	-10.0
150_25	-30.9	-15.7	-21.2	-12.9	-49.3	-48.5
150_50	-38.7	-20.9	-52.2	-72.1	-52.3	-48.7
150_75	-45.0	40.2	-66.8	-108.7	-54.8	-36.9
150_100	-35.9	-8.5	-22.6	-1.5	-38.3	-21.6
200_25	-38.2	-42.7	-18.4	-48.3	-52.2	-49.8
200_50	-45.1	-32.1	-46.2	-126.2	-55.4	-48.1
200_75	27.3	31.7	-47.5	-77.7	-43.5	-34.5
200_100	48.1	105.2	3.6	7.7	-29.3	-11.1

Table C.8 Performance analysis of SC2 and SC3 compared to SC4 in terms of standard deviation reduction of average maximum queue (WZL=1.1 mile, N_{DAD}=5, $T_{M\%}$=20, $T_{DAD\%}$=5)

	SC2 and SC3 performance compared to SC4 in terms of SD (avg. max. Queue) reduction in % (negative value means delay reduction)					
Volm	**Major**		**DAD**		**All**	
Comb	SC2	SC3	SC2	SC3	SC2	SC3
50_25	-38.1	-37.8	-1.7	-7.6	-30.1	-27.8
50_50	-39.9	-18.1	-4.9	-27.1	-35.0	-24.6
50_75	-29.6	-12.9	-24.5	-24.8	-43.3	-20.5
50_100	-22.8	30.7	-59.7	-78.1	-57.1	-59.0
100_25	-14.4	-22.8	-16.0	-30.2	-28.3	-21.1
100_50	-27.6	-16.5	-17.2	-18.0	-36.4	-26.7
100_75	-8.5	64.9	-60.8	-18.0	-40.7	-11.9
100_100	-16.1	13.3	-68.6	-73.5	-35.1	-6.8
150_25	1.8	24.4	-18.1	-8.0	-30.3	-29.2
150_50	2.8	32.6	-33.2	-18.8	-38.1	-33.4
150_75	-41.3	49.7	-68.7	-54.8	-47.3	-26.4
150_100	-23.1	9.9	-49.6	-35.8	-19.4	2.3
200_25	-27.9	-33.1	-8.3	-24.3	-31.1	-27.6
200_50	-16.5	3.4	-34.9	-46.5	-43.8	-34.6
200_75	-1.4	2.0	-56.0	-52.9	-34.8	-24.5
200_100	8.6	50.5	-30.3	-27.1	-15.6	6.1