Effect of Improving the Visibility of the Traffic Path on Vehicles Speeds and Safety at Work Zones

By

Mohammed N S Ahmed

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ABSTRACT

Because of the documented mobility issues and safety risks associated with work zones, extra attention is required when designing the layout of traffic control devices. Current traffic accommodation guidelines at work zones have certain limitations that potentially cause driver confusion and is often ineffective at reducing speeds. This study conducted a comprehensive review of frequent safety problems around work zones to identify common types of collisions and the major factors contributing to collision occurrences. The study then outlined different combinations of highly reflective and visible intervention materials from 3M Canada that were implemented at several work zones. These intervention materials, such as temporary reflective tape, removable black mask, and other fluorescent and highly reflective materials, were used to better demarcate the desired traffic paths for drivers as they passed through work zones. Finally, the impact of these interventions on traffic safety was evaluated in order to understand the relationship between improving the visibility of the traffic path and vehicle speed at work zones.

Prior studies indicate that speeding and inefficient traffic control devices are the main factors impacting safety around work zones. Therefore, a particular aim of this project was to evaluate the impact of 3M intervention materials in different combinations on vehicle speed through work zones. To do so, the study monitored before and after speeds at nine construction sites in the City of Edmonton (COE) during the summer months of 2019. These treatment sites were chosen in collaboration with COE's Traffic Operations group. Sites were also chosen as controls to account for confounding factors in the before and after analysis. This represents an experimental, observational study design to assess the effect of work zone interventions on driver speeds.

The results showed that increasing the visibility of the traffic path at work zones using the combinations of 3M high reflective and visible products led to significant vehicle speed reductions at the treatment sites that ranged between 4.7 to 11.6 km/h. The effectiveness of the interventions was either unidirectional or bidirectional, depending on the placement of the interventions. In addition, an improvement in drivers' speed limit compliance was observed in the 'after' period. Furthermore, the outcomes showed that observed vehicle speed reductions during working hours were higher than the values in non-working hours. A traffic conflict analysis revealed that there were no near misses or accidents during the test period, further indicating that the installed intervention materials did not cause any traffic issues or conflicts. Results found in this study can greatly assist traffic safety agencies to optimize the use of traffic intervention materials at work zones and provide more details about the effective use of the reflective control devices.

PREFACE

The work presented in this thesis has been submitted for presentation and publication at the 100th Annual Meeting of Transportation Research Board, Washington, DC, January 2021.

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CHAPTER 1: INTRODUCTION

1.1 Background

Work zones represent hazardous environments where workers are exposed to significant risks. This is particularly true for work zones on highways where traffic volumes and/or speeds are high. Work zone safety has received much recent attention, both by regulators and researchers, since numerous highway construction projects have resulted in work zone crashes. The highly dynamic environment and the limited space of work zones make workers at those locations vulnerable. Recent statistics in the US show that in 2015 alone, 96,626 collisions occurred at work zones, an increase of 7.8% and 42% from 2014 and 2013, respectively [1]. Severe crashes also represent a notable share of collisions at work zones. Statistics show that, in 2015, approximately seventy work zones recorded at least one traffic-related injury per day. Furthermore, twelve of the collisions that occurred in an average week involved at least one fatality [1]. In fact, research has shown that fatality rates are higher in work zone collisions than non-work zone ones [2].

Safety risks and mobility issues associated with work zones mean that extra attention is required when designing these areas, laying out traffic control devices, and placing signs around them. Countermeasures from Vision Zero fatality and serious injuries, such as dynamic message signs, mobile barrier systems, reduced speed limits, and orange pavement markings, have been implemented in many Canadian cities' work zone sites. However, since accident numbers are still problematic, innovative tools must be considered to help alleviate common safety problems. To minimize the risks around work zones on roadway safety, the possible contributing factors to crash severity must be investigated. In so doing, effective countermeasures can be identified and implemented to ensure motorist's safety.

Traffic control devices are used to facilitate safe and efficient movement of all road users. Theses devices are placed in key locations to guide and regulate traffic movement, control vehicle speeds, and warn of potentially hazardous conditions. When work activity is underway on a roadway that disrupts the normal flow of traffic, a traffic accommodation strategy of a traffic control devices based on the guidelines of traffic control accommodation of the city is required. The guidelines of the Traffic Accommodation Strategy assists in determining the most appropriate combination of traffic controls required to provide a safe, well-organized, and efficient flow of traffic through construction zones on all type roadways. However, the guidelines may not be explicit enough in providing more details on the exact installation of some traffic control devices. For instance, the Traffic Accommodation plan for Alberta's work zones recommend the use of traffic delineators, such as barriers, cones, pavement marking and signs, to guide drivers through work zone. However it does not specify the location where the traffic delineators should be placed, nor does it spell out the method or combination to be installed, especially for local roads [3]. Furthermore, the manual offers standard drawings of traffic accommodation layouts for highways only. However the traffic delineators that are recommended to use on highways such as cones, barricades, or barrels, are installed without making changes to the pavement markings or the edge of the path [3]. Therefore, a lack of clarity for drivers passing through work zones may cause driver confusion concerning the correct path and the required speed limits.

One significant area requiring attention is the lack of visibility of traffic control devices that may contribute to crashes at work zones. Visibility may be obstructed by physical objects or obscured in inclement weather conditions. Additionally, other objects at any given work zone may distract drivers' attention if the control devices are competing with other objects and movement in the area. All of these can result in riskier or more dangerous vehicle navigation. Providing sufficiently visible intervention materials offers one key avenue to collision prevention at these sites by facilitating drivers' advanced perception and understanding of upcoming work zones.

In this study, several different measures were undertaken to test their positive effects on traffic safety. The study included a comprehensive review of common safety problems at work zones, in particular common types of collisions and the major contributing factors. Moreover, different combinations of highly reflective and visible traffic devices were implemented along work zone routes especially where the existing layout causes drivers' confusion and the vehicles speed still increasing. Finally, the impact of these interventions on traffic safety was evaluated.

In terms of the practical contributions of this thesis, results found in this study can greatly assist traffic safety agencies to optimize the use of traffic interventions at work zone, and provide more details about the effective use of the reflective control devices in work zone which is not clearly defined and detailed in the Traffic Accommodation guidelines.

1.2 Research Problem Statement

Construction work zones (CWZs) are a major cause of concern for highway and safety engineers because of the increasing number of roadway accidents each year. Based on evidence from the literature, some researchers have indicated that speeding is the main contributing factor to collisions, and different countermeasures have been installed to minimize vehicles speed. Other researchers have suggested that the inefficient use and design of traffic control devices is the underlying cause of most work zone crashes. In addition to the guidelines' limitations regarding the installation of traffic delineators, a significant gap exists in the literature on the relationship between the driver speed through a work zone and its traffic interventions. There is widespread evidence to suggest that this is the reason why the number of crashes is still increasing despite the different countermeasures that have been used [2]. Government and transportation authorities are motivated, as a result, to develop effective safety countermeasures in work zones, with researchers keen to clarify the relationship between efficient interventions and speeding [1].

1. 3 Objectives

The initial focus of this thesis will be to provide a comprehensive literature review of studies that have investigated the risk factors impacting safety at work zones, common crash types, and current practical countermeasures to improve safety. The thesis will then outline the study design and implementation of combinations of highly reflective and visible materials and evaluate their impact on speed and safety around work zones. The objective is to demonstrate the relationship between improvements in the visibility of the intended roadway path to drivers and speed reductions.

1. 4 Scope and Limitations

This study will assess the impact of installing four new 3M intervention materials in nine work zone sites in the City of Edmonton. Those interventions are:

- 3M Stamark Wet Reflective Removable Tape, Series 710
- 3M Stamark Removable Black Line Mask 715
- Barrels applied with 3M Diamond Grade Flexible Work Zone Sheeting, Series 3910
- 3M Linear Delineation System 340

Data collection devices were used to record vehicles' speed passing through the test sites along with any accidents or near misses during the study period. The test sites were chosen in collaboration with the COE's Traffic Operations group.

1.5 Thesis Structure

What follows is the reporting of the research activity, which is divided into six sections. The first chapter introduces the study, includes background information on traffic safety issues at work zones, and provides details regarding the scope and milestones. Chapter 2 reviews the research literature on four key areas that form the basis of this study: the risk factors impacting safety at work zones, common crashes, elements of work zones, and best practice for improving work zone safety. The third chapter of this study outlines the data collection process used and also provides further detail regarding the test sites and intervention materials used for object and road layout demarcation. Chapter 4 explains in detail the methodology used for this study. The fifth chapter summarizes the data analysis and results before concluding with some additional discussion and areas for future investigation.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

With persistently significant accident rates at work zone areas around the world, identification of crash risk factors and enhancing safety is a major priority for many transportation agencies. In order to tackle this ongoing problem, there is a pressing need for collecting comprehensive data related to effective interventions at work zones that tangibly enhance the safety of both workers and drivers passing through. Numerous studies have laid important groundwork by evaluating driver behavior around work zones and investigating the factors that impact traffic safety. This study draws on this work as the basis for its proposed work zone interventions. The literature review presented here includes four related types of research around work zones that form the foundational knowledge for the current work: 1) risk factors impacting safety at work zones, 2) common collision types experienced at work zones, 3) design elements of traffic control work zones, and 4) present best practice for improving work zone safety.

2.2 Risk Factors Impacting Safety at Work Zones

Understanding the characteristics and major causes of highway work zone collisions is a critical step towards developing effective safety countermeasures in highway work zones. Identifying the different factors that may contribute to high-severity crashes and then alleviating their impact is a challenging task that traffic engineers and researchers have to confront. Certainly, work zone safety has been a research focus for decades, and many researchers have studied work zone crash characteristics and traffic control effectiveness. Additionally, a range of studies have focused on various types of non-work zone crashes in broader crash risk analyses. Yet, few in-depth analyses that assess the impact of individual risk factors on work zone crash severity based on injury and fatal crashes were identified. One study that has done so analyzed work zone crashes on Florida freeways using multiple and conditional logistic regression methods in an effort to identify risk factors in freeway work zones [4]. The outcomes indicated that factors, including roadway geometry, weather condition, age, gender, lighting condition, residence code, and influence of alcohol/drugs, could increase crash risk at freeway work zones. The key risk factors – speeding, insufficient traffic control devices, road conditions, and additional factors – are examined below.

2.2.1 Speeding

Where individual factors have been assessed, speeding has been identified as a primary cause of crashes at work zones [8, 9]. Statistics gathered in the United States in the 2005 and 2008 Traffic Safety Facts reported that excessive speed was the contributing factor in 30 and 31 percent of all traffic crashes, respectively [11, 12]. Furthermore, work zones on rural two-lane highways or urban highways with speed limits higher than 60 kph appear to increase the likelihood of fatalities in a severe crash [9]. Some crash characteristic studies indicated that other forms of human error coupled with speeding, including following too close, inattentive driving, and misjudging, appear to increase the risk of work zone crashes [5, 6, and 7].

Unfortunately, while traffic collisions overall have been declining, speed, as a contributing factor, has been trending positively. Across the United States, speed-related crashes claimed 11,767 lives in 2008 [12]. When considering the economic impact of these speed-related crashes, the most recent National Highway Traffic Safety Administration (NHTSA) figures estimate an annual cost of US$40.4 billion [12].

2.2.2 Visibility of the traffic path at work zone

As the need for higher-visibility traffic control devices has evolved, researchers have responded with improved materials and new technologies. A review of the literature indicates that the majority of that work has focused on nighttime visibility (retroreflectivity). Improving visibility for night drivers is critically important. National accident statistics indicate that 55 percent of fatalities occur at night, when only one third of the drivers are on the road [13, 14]. However, improving daytime conspicuity is also important. The vast majority of all traffic accidents, including the remaining 45 percent of

traffic fatalities, occur during daylight, when retroreflective performance plays no role. Of particular importance is the need to improve the daytime visibility of traffic control devices under low light (dawn and dusk) and adverse weather conditions.
One field study conducted by Burns DM et al. [15] compared the visibility performance of this fluorescent retroreflective sheeting with that of conventional fluorescent films and ordinary retroreflective materials. The results of the study indicated that fluorescent retroreflective sheeting provides better visibility for both day- and nighttime conditions than do ordinary signing materials [15].

2.2.3 Inefficient Traffic Control Devices

One of the means to minimize traffic-related hazards at work zones is the use of traffic control devices. Standard practices for traffic control at work zones are identified in the Manual on Uniform Traffic Control Devices for Canada, also known as the MUTCDC. However, even with the guidelines drawn from significant experience with work zone traffic control, work zone crashes have continued to increase [11]. As a result, transportation agencies at all levels have been actively searching for new traffic control devices, treatments, and practices that can improve safety in work zones for workers and road users.

Although the incorrect placement and distribution of those traffic control devices may lead to traffic safety issues, the majority of the research in this area focuses on evaluating the influence of interventions on speeding behavior [16, 17, 18, 19 and 20]. Different innovative temporary traffic control devices, treatments, and/or practices have been placed in work zones instead of other countermeasures without making changes in the layout, as a result, the safety and mobility advantages were lower than predictions [17,18 and 20]. Nonetheless, the effectiveness of different interventions cannot be truly compared in these studies since they are not subjected to the same conditions and study environment from these studies.

2.2.4 Road Conditions

The road conditions, such as physical factors and traffic conditions, can play a significant role in the probability of collisions to occur at work zones.

Physical factors of the roads themselves are key to understanding the number of severe crashes. For instance, one study used logistic regression techniques to assess the impact of work zone risk factors [10], demonstrating that a lack of good street lighting contributed to a significantly higher proportion of fatal collisions as compared to those resulting in injury alone.

Another significant factor, as identified in the literature, appears to be the geometric layout design of roads. A severe crash occurring in work zones on highways with unfavorable geometric alignment features was shown to have a higher probability of involving fatalities [21]. Furthermore, the findings indicated that severe collisions in work zones on asphalt-paved highways had a higher likelihood of involving fatalities. These results, however, need to be interpreted with caution and may require further exploration.

Another study showed that straight upgrades and downgrades may have lower crash risk at work zone settings compared to non-work zone settings [22]. This issue may be explained by the fact that drivers behave more cautiously on upgrades and downgrades, especially when road work is taking place [22].

Other road conditions that are significant factors are traffic conditions. The results of workers' injury data in work zones from California over a period of 10 years (1998–2007) indicate that the odds of more severe injuries are higher during nonpeak hours than during peak rush hours [23]. This result is arguably counterintuitive because fewer vehicles travel past the work zone during nonpeak hours. However, one possible explanation is that vehicles encounter less traffic during nonpeak hours, so they travel faster through the work zones, resulting in more severe worker injuries if a crash occurs [23].

2.2.5 Other Factors

Other elements can also contribute to collision numbers and severity levels. Regression models were estimated and analyzed to disclose the vehicle, driver, and environmental traits that contribute to freeway work zone crashes, highlighting that weather conditions are important [4]. Harb R et al.[4] indicate that cloudy weather, for instance, seems to be more hazardous for drivers passing through work areas than for drivers in non-work areas.

In terms of at-fault driver characteristics, driving under the influence is a significant risk factor contributing to crashes at work zones. The regression results produced by Yang H. et al. et al. [24] clearly showed that drivers under the influence of alcohol and/or drugs were 10.53 times more likely to cause crashes at work zones than sober drivers. Furthermore, both age and gender have an impact on the probability of causing fatalities when severe crashes occurred. A study by Li Y. and Bai Y. [10] found that male drivers almost double the odds of fatalities in severe crash cases.

As is evident in the available research, many factors can contribute to crashes and fatalities, all of which need to be considered when trying to address safety at work zones.

2.3 Common Collision Types Experienced at Work Zones

In general, collision types at work zones can vary according to different locations and times. However, the consensus of most studies is that rear-end collisions are the most frequent work zone collision types [5, 6, 8, 25, 26, 27 and 28]. Notably, the percentage of both rear-end and sideswipe collisions occurring at work zones are higher than the percentage of those same collisions in non-work zone crashes [29]. Another study conducted by Lindly JK et al. [30] used data from five work zones in Alabama and linked the increase in rear-end collisions to reduced speeds, reduced headways, and increased congestion. Some studies have suggested that that same-direction sideswipe collisions were the major type in work zone crashes [25, 26]. Other common types of work zone crashes involved angle collisions [25] and hitting-fixed-objects [5, 28 and 31]. A study conducted in Georgia, U.S. by Daniel J et al. [7] found that single-vehicle crashes, angle, and head-on collisions were the main types of fatal work zone crashes.

Some researchers, such as Hall JW and Rutman EW [32], have paid special attention to analyzing accident type because this variable reveals patterns of accidents and helps suggest possible countermeasures related to roadway design and traffic operation.

Table 1 provides the general accident types involved in construction zones taking into account environmental conditions such as weather, road condition, and road alignment.

Table 1: Types of crashes in environmental conditions and road alignment [32]

Collision type	Percentage %	Clear (%)	Dry (%)	Straight (%)
Read End	66.3	73	92	91
Sideswipe	20.4	91	89	86
Other	6.8	88	88	79
Fixed object	5.7	89	83	64
Front End	0.8	100	100	80

2.4 Design Elements of a Traffic Control Work Zone

Traffic control is required when traffic must move through or around highway or street construction, maintenance operations, or utility work on or adjacent to a roadway. The traffic control described and illustrated herein is generally the minimum required. No one standard sequence of signs or other control devices can be set up as an inflexible arrangement for all variations of conditions and locations. While the Traffic Control Manual for Work on Roadways contains mandatory language such as “shall,” there may be circumstances where strict compliance with such requirements is not reasonable, and deviation from the requirements is necessary.

When traffic is affected by construction, maintenance, utility, or similar operations, traffic control is needed to safely guide and protect both road users and workers in a work zone. The work zone is the area between the first advance warning sign and a point beyond the work where traffic is no longer affected. Most work zones can be divided into the following sections [**Figure 1**]:

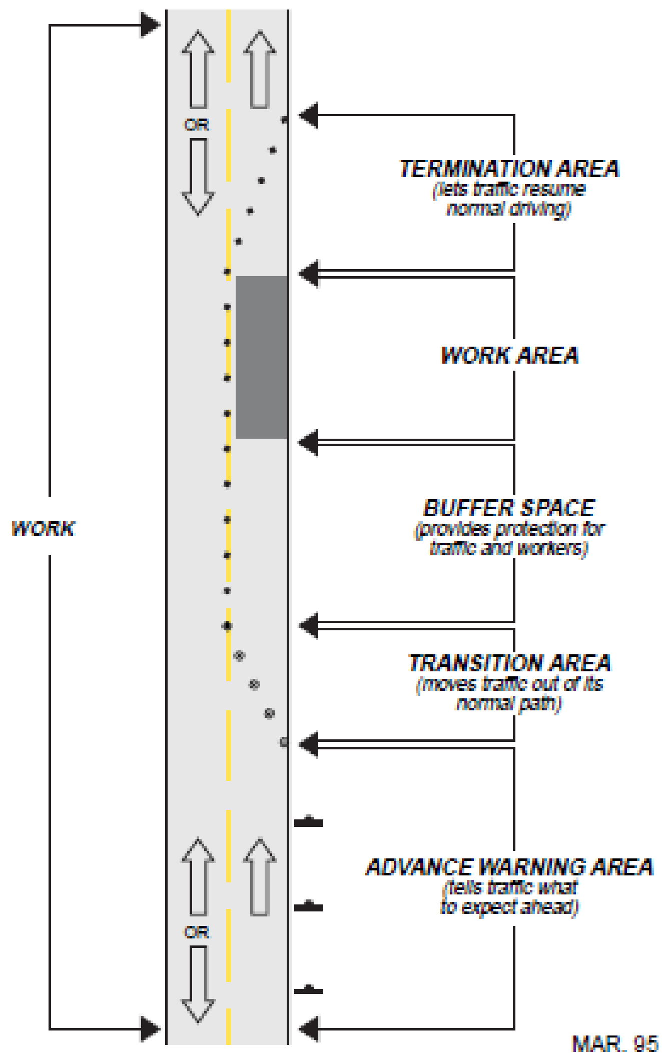


Figure 1: Elements of a traffic control work zone [33]

2.4.1 Advance Warning Area

An advance warning area is necessary for all traffic control zones to inform drivers of upcoming changes to road layouts, speed, patterns, etc. Before reaching the work area, drivers should have enough time to adjust their driving patterns. The advance warning area elements may vary from a series of signs starting 2 km in advance of the work area to a single sign or flashing lights on a vehicle.

Advance warning signs are not needed when the work area, including access to the work area, is entirely off the roadway and shoulder, and the work does not interfere with traffic. An advance warning sign or signs should be used when any problems or conflicts with the flow of traffic might possibly occur [3].

2.4.2 Transition Area

When work is undertaken within one or more traveled lanes, lane closure(s) is/are required. In the transition area, traffic is channeled from its normal highway lane(s) to another path in order to move traffic around the work area. The transition area contains tapers used to close lanes.

The transition area should be made obvious to drivers, with the correct path clearly demarcated by pavement markings and/or channeling devices that encourage drivers to follow the new path rather than the old one. For long duration work zones, existing pavement markings should be removed when they conflict with the transition, and new markings should be added where practical. Pavement marking arrows are also useful in transition areas [3].

2.4.3 Buffer Space

The buffer space is the open or unoccupied area between the transition and work areas. Where space permits, and it is considered desirable, a buffer zone should be included even though it may not be indicated on the typical sign layout or traffic control plan. With a moving operation, the buffer space is the space between the shadow vehicle, if one is used, and the work vehicle, providing a margin of safety for both traffic and workers. If a driver does not see the advance warning markers or fails to negotiate the transition, a buffer space provides room to stop before the work area. It is important that this area be free of equipment, workers, materials, and workers' vehicles, with the only exception being if a buffer vehicle is required. In that case, the vehicle would be parked upstream of the work zone [3].

2.4.4 Work Area

The work area is that portion of the roadway that contains the work activity, is closed to traffic, and is set aside for exclusive occupation by workers, equipment, and construction materials. Work areas may remain in fixed locations or may move as work progresses and are usually delineated by barricades or other channeling devices to exclude public traffic. In addition, an empty buffer space may be included at the upstream end at the end of the work area [3].

2.4.5 Termination Area

The termination area provides a short distance for traffic to clear the work area and return to the normal traffic lane or lanes. It extends from the downstream end of the work area and may include a short downstream taper.

There are occasions where the termination area could include a transition. For example, if a taper is used to shift traffic into an opposing lane of a multilane roadway, then the termination area should have a taper to shift traffic back to its normal path. This taper would then be in the transition area for the opposing direction of traffic. It is advisable to use a buffer space between the tapers for opposing traffic [3].

2.5 Best Practices for Improving Work Zone Safety

Best practices from various government agencies, transportation authorities, and researchers as identified by were reviewed for this study in order to identify newly developed and innovative temporary traffic control devices, treatments, and/or practices. Those examined for this study provided many potentially feasible options. Specifically, these sources identified several innovative treatments that are currently being used around the country with different applications on current roads.

The key objective of these new treatments across the board is to signal to drivers that they should reduce their speed before the work zone. Different forms of enforcement are perceived to be highly effective in reducing speeds and promoting safety in work zones, most notably traffic enforcement officers on site with speed detection equipment. However, limitations in funding and manpower often constrain agencies as to where and when such labour-intensive forms can be deployed. As a result, agencies have looked for alternative strategies and technologies that can be implemented in work zones to reduce speeds in lieu of enforcement. Theoretically, these alternatives accomplish their speed-reducing objectives in one of three ways:

- By implying enforcement presence at a work zone,
- By raising driver awareness that they are in a work zone and need to slow down
- By altering the driver's perception of the work zone environment to create a natural desire to reduce their speed.

A summary of the various studies on these strategies is outlined below [**Table 2**]:

Table 2: Summary of alternative enforcement to reduce speed

Alternative	**Test Conditions**	**Average Speed Reduction**	**Reference No.**
Changeable Message Sign	Rural Freeway	0-11.25 kph	[34]
	Rural Freeway Urban Freeway Urban Arterial	4.8-8 kph 0-3.2 kph 4.8 kph	[35]
Drone Radar	Rural Freeway	0-3.2 kph	[36]
	Rural Highway	0-4.8 kph	[37]
Rumble Strips	Two-Lane Highway	3.2 kph	[35]
	Two-Lane Highway	1.6-3.2 kph	[38]
Transverse Pavement Markings	Two-Lane Highway	0 kph	[35]
Narrowed Lanes	Urban Freeway	0-4.8 kph	[39]
	Rural Freeway	4.8-12.9 kph	[35]
	Rural Freeway Urban Freeway Two-Lane Highway Urban Arterial	3.2-8 kph 0 kph 6.4-12.9 kph 3.2-6.4 kph	[35]

One case study by Nnaji et al. used Work Zone Intrusion Alert Technology (WZIAT) to demonstrate the implementation of the proposed reduction framework [40].

Based on the case study results, the researchers selected Intellicone as the preferred alternative offering the best cost value, while the Traffic Guard Worker Alert System (WAS) was the preferred alternative in terms of the cumulative importance of advantages (IofA) value. The results from Nnaji et al. study also showed that, although the SonoBlaster was assigned as having a ‘paramount advantage’, it was considered the least value-generating technology based on the cost benefit analysis (CBA) evaluation. In the absence of paramount advantage, the SonoBlaster was not considered advantageous because of its complexity during implementation, inability to create a connected network, limited mobility, and the number of alert mediums.

Another study by Tymvios N and Gambatese J concentrated on the recent use of the mobile barrier system (MBS) that is transportable to work zones, providing positive protection to maintenance crews in a short time with minimum effort [41]. The research team investigated the barrier used in five cases implemented by the Ohio Department of Transportation maintenance activities, looking at various performance metrics such as time of setup, limitations/enhancements to work operations, worker safety and safety perception, worker productivity, and motorist safety perception. The same performance metrics were also investigated in similar maintenance operations without the MBS present. The results from Tymvios N and Gambatese showed that the MBS provides enhanced protection to the workers by reducing and eliminating hazards and providing a positive barrier between the work area and passing traffic. The barrier facilitates work operations by enhancing sites with additional lighting, noise protection, power capabilities, and storage compartments, although additional training is required for the work crews to fully harness the true potential of the barrier for efficiency [41].

Another recent intervention technique is the use of orange removable rumble strips, used for Highway Work Zones. These removable rumble strips were evaluated at a bridge repair site in rural Kansas by Meyer E [38]. Vehicle speeds were first recorded with the standard asphalt rumble strips in place. Then, the removable rumble strips were installed, and speed data collected. Despite being thinner than standard asphalt rumble strips, the orange removable rumble strips were found to have a significantly positive effect on vehicle speeds, attributable to their high visibility [38].

2.6 Concluding Remarks

Based on evidence gathered from the studies discussed, a number of researchers have indicated that speeding is the main contributing factor at crashes, with different countermeasures have been installed to minimize vehicles speed. Other researchers have indicated that the inefficient traffic control device design and use is the key underlying factor for most work zone collisions. Nevertheless, a significant gap exists in the literature regarding the relationship between the driver speed through work zones and the inefficient traffic interventions installed there. Certainly, testing and validating work zone interventions is crucial because, if poorly implemented, they could, at best, have no effect whatsoever or, at worst, cause a deterioration in traffic flow and safety. Arguably, this may be why the number of collisions continues to increase despite the different countermeasures have been used. Although the research presented here seeks to address this gap, perhaps the biggest advantage of this study is that aims to clearly prove the relationship between high visible and reflective traffic intervention use and substantial speed reductions at work zones.

CHAPTER 3: DATA COLLECTION

3.1 Background

Several work zone interventions were effected at different Edmonton locations in order to evaluate their impact on traffic safety, measured through observed changes in vehicle speeds and compliance to speed limits. The studied sites were clustered into two groups: 1) treatment groups and 2) control groups. No interventions were implemented at the control sites. What follows are the primary considerations in choosing the test sites, data collection devices, and 3M intervention materials used in this project.

3.2 Study Sites

This study focused on nine work zones situated within three COE construction sites (three work zones per site) in Summer 2019. The sites were chosen from construction projects across the city, based on specifications that fit the study purpose and in conjunction with advice from COE's Traffic Operation. Since the data collection process was to occur over a three-week span, it was necessary to ensure that each of the construction projects would continue for a minimum of three weeks with a consistent layout. The locations of the three construction sites chosen for testing were, 106 Avenue over Wayne Gretzky Dr., 122 St & White Mud Drive (WMD)-51 Ave., and 178 St & Stony Plain Rd.

Figure 2 shows the three work zones chosen from the construction site based at 106 Avenue over Wayne Gretzky Dr.

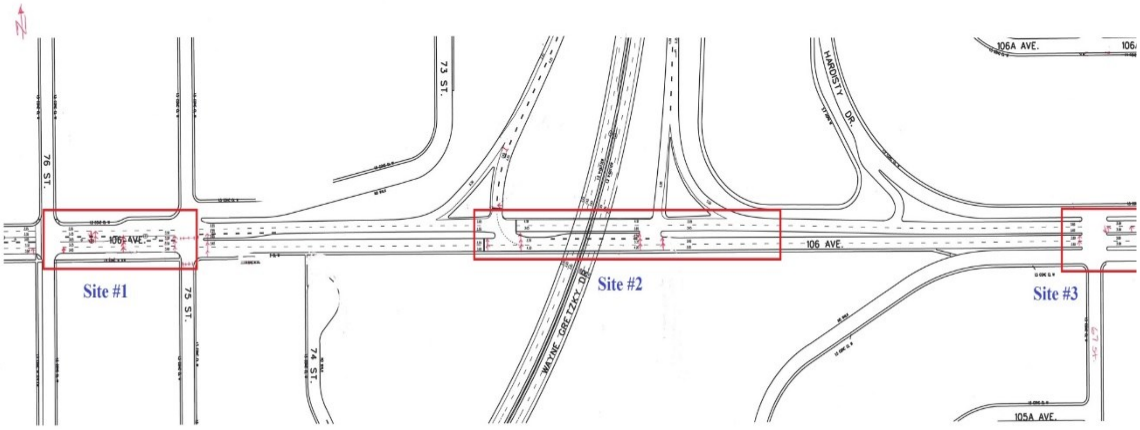


Figure 2: Work zones at 106 Ave. over Wayne Gretzky Dr

3.3 Data Collection Devices

As a first step, the work zone length was measured in order to determine the total required length of tape necessary as a part of the different intervention strategies. Additionally, the COE Traffic Monitoring team provided multiple Black Cat Radars to record the speed of vehicles at the test sites. These were particularly useful since they allowed for traffic data collection without the need for in-road traffic sensors. This newly developed radar product also can detect the lane position of vehicles, thus allowing the device to monitor two lanes of bi-directional traffic. Furthermore, improvements in the radar's on-board algorithms ensure that the vehicle length measurement is more accurate. **Table 3** numerically outlines the capabilities of the Black Cat Radar; the radar and its installation are shown in **Figure 3(a,b)** below.

Table 3: Characteristics of the Black Cat Radar

Black Cat RADAR	
Radar range	15 meters
Volume	98% accuracy with a 95% confidence
Speed	+/- 3.2 kph or 3% whichever is greater
Length	+/- 40cm or 5% whichever is greater with a 95% confidence

(a) (b)

Figure 3: (a) Black Cat Radar, (b) Radar installation

Furthermore, COE Traffic Safety and Traffic Monitoring teams provided street cameras to record videos during data collection. **Figure 4(a,b)** shows the camera and its installation.

(a) (b)

Figure 4: (a) Street camera, (b) Camera installation

3.4 Interventions

The intervention materials used in this study were provided by 3M for testing and include the following: 3M Stamark Wet Reflective Removable Tape, Series 710, 3M Stamark Removable Black Line Mask 715, barrels lined with 3M Diamond Grade Flexible Work Zone Sheeting, Series 3910, and 3M Linear Delineation System 340. Each product or material chosen offered an improvement to existing work zone demarcation materials as outlined below and were considered in terms of the overall intervention design.

3.4.1 3M Stamark Wet Reflective Removable Tape (Series 710).

3M Stamark Wet Reflective Removable Tape Series 710 [**Figure 5**] aims to improve work zone safety by demarcating temporary work zone lanes with removable, highly reflective, all-weather pavement markings. Its backing has a pressure-sensitive adhesive that eliminates the need for any other surface preparation adhesive. Its top surface is highly reflective in wet or dry conditions and possesses a raised pattern profile. The tape comes in white and yellow, both of which were used in this study [42].

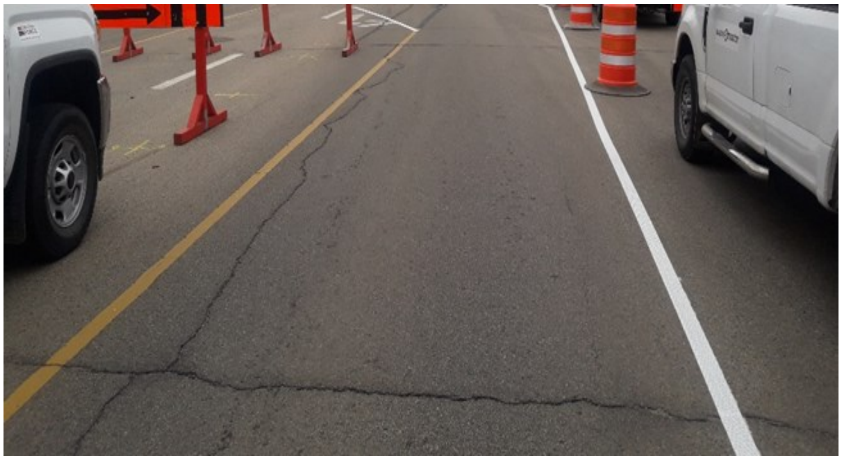


Figure 5: Installation of 3M Stamark Wet Reflective Removable Tape (Series 710)

3.4.2 3M Stamark Removable Black Line Mask 715

3M Stamark Removable Black Line Mask, A715 [**Figure 6**] is applied over existing pavement markings such as lane and edge lines, gore markings, crossovers, and skip lines. As with the 3M Stamark Wet Reflective Removable Tape (Series 710), its pressure-sensitive adhesive bonds the tape to pavement but removes easily. The black colour is intended to blend with existing pavement to minimize driver confusion and effectively mask existing pavement markings during both day and nighttime conditions [43].

Figure 6: 3M Stamark Removable Black Line Mask 715

3.4.3 3M Diamond Grade Flexible Work Zone Sheeting Series 3910

3M Diamond Grade Flexible Work Zone Sheeting Series 3910 [**Figure 7**] is a highly reflective, wide angle, prismatic lens sheeting with a pressure-sensitive adhesive backing. It is designed to be durable, flexible, and impact- and scratch-resistant, able to withstand rough handling. It can be applied to a variety of reboundable traffic control devices. In this project, Orange and White 3M Diamond Grade Flexible Work Zone Sheeting Series 3910 was installed on traffic barriers [44].

Figure 7: Barrels equipped with 3M Diamond Grade Flexible Work Zone Sheeting Series 3910

3.4.4 3M Linear Delineation System 340

3M™ Linear Delineation System 340 is made with durable 3M Diamond Grade Reflective Sheeting laminated onto a thin gauge of aluminum. It has bright colors that are highly visible during both day and night time lighting conditions. Its corrugated design aims to increase visibility across a wide range of entrance and observation angles and provide clear visual guidance to drivers navigating through work zones and challenging roadway conditions. It is manufactured in different colours for varying uses and locations in the work zone. In this study, orange was chosen and installed on concrete barriers, as shown in **Figure 8** [45].

Figure 8: 3M Linear Delineation System 340 on barriers

3.5 Data Processing

The study took three weeks for each project. In the first week, Black Cat Radars and cameras were installed by the COE Traffic Monitoring and Traffic Safety teams to enable the start of data collection. After seven days of data gathering, the devices were removed and recharged. In the second week, the COE Traffic Operations team installed the intervention materials as proposed by the University of Alberta research team and approved by COE. Finally, in the third week, Black Cat Radars and cameras were reinstalled in the same work zones to collect data for another seven days.

3.6 Concluding Remarks

Several highly visible and reflective traffic control materials (3M Products) to improve traffic layout in nine Edmonton work zones situated in three constructions sites (three work zones per site) were installed and tested. The products used were 3M Stamark Wet Reflective Removable Tape, Series 710, 3M Stamark Removable Black Line Mask 715, barrels lined with 3M Diamond Grade Flexible Work Zone Sheeting, Series 3910, and 3M Linear Delineation System 340. Black Cat Radars and street cameras were used for traffic data collection, and a questionnaire survey was used to capture workers' experience of the new materials at their work zones.

CHAPTER 4: METHODOLOGY

4.1 Background

Once the performance measures were set, the next step assessed the impact of the 3M intervention material combinations according to a set of surrogate safety performance metrics. The main method of this project was a before and after study, which is an experimental, observational study design used to assess the effect of an intervention based on the comparison of outcomes to its prior state. The aim was to compare changes in driver behaviour according to the predetermined performance measures as well as the differences in the control group work zones with installed surrogate safety measures and the treatment group with no additional interventions. The comparative study included assessing changes in driver compliance, average speed, and speed distributions. In addition, traffic conflicts were also compared across the two groups.

With all the safety performance metrics collected, correlations between design and safety performance were assessed to develop an understanding of how different work zone design alternatives compare from a safety perspective. This assessment provides insight into the value of the different measures that were introduced to the treatment groups to improve safety and mobility.

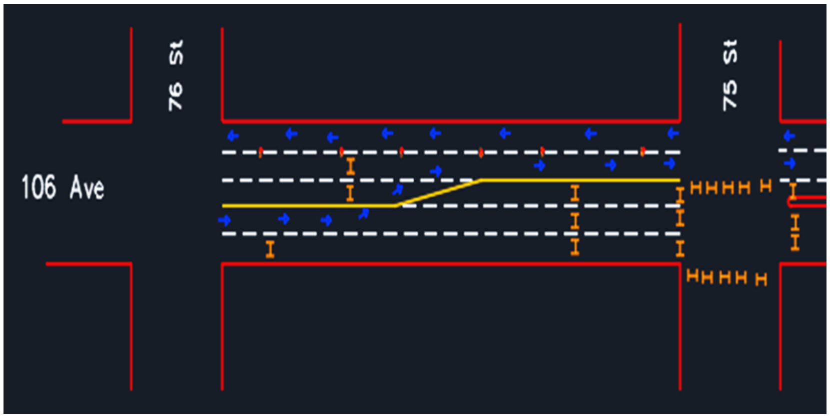
4.2 Before and After Study Design

The before-and-after study is an experimental study design commonly used in safety studies to evaluate and examine changes over time. In design terminology, “before” refers to a measurement being made before an intervention is introduced to a group, and “after” refers to a measurement being made after its introduction. Equivalent terms for “before” and “after” are “pre” and “post”.

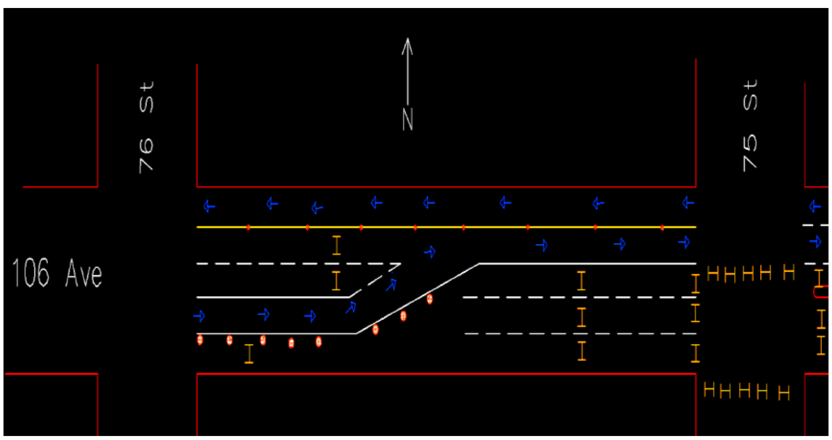
4.3 Treatment and Control Sites

4.3.1 Treatment Sites

The treatment group is comprised of the locations that were to be manipulated with newly introduced intervention materials as compared to the control group that maintained use of conventional work zone materials. After visiting the chosen sites, suggested designs for the layout of each work zone using 3M intervention materials was proposed based on the data and evidence gathered from the literature review and a consideration of the 3M materials available. This study included six treatment sites, labeled as Sites #1, #2, #4, #5, #7 and #8 as shown in **Figures 9, 10, 11, 12, 13,** and **14**. Photographs of the treatment sites are available in **Appendix F**.



Before



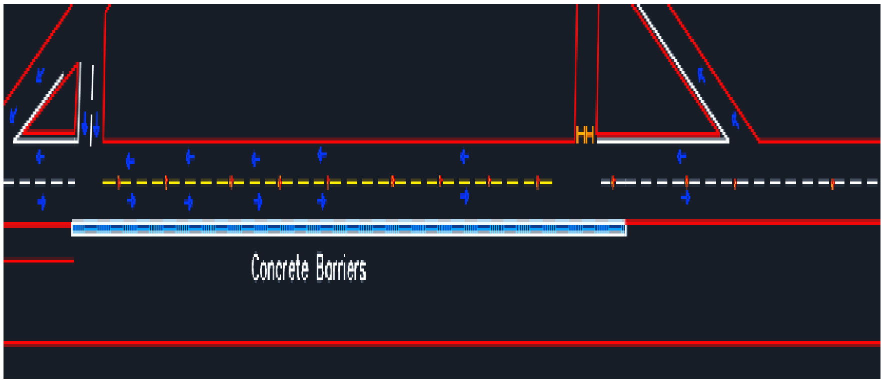
After

The broken white line (the first from the top) was replaced by installing solid yellow removable tape to separate Eastbound (EB) and Westbound (WB) movement.

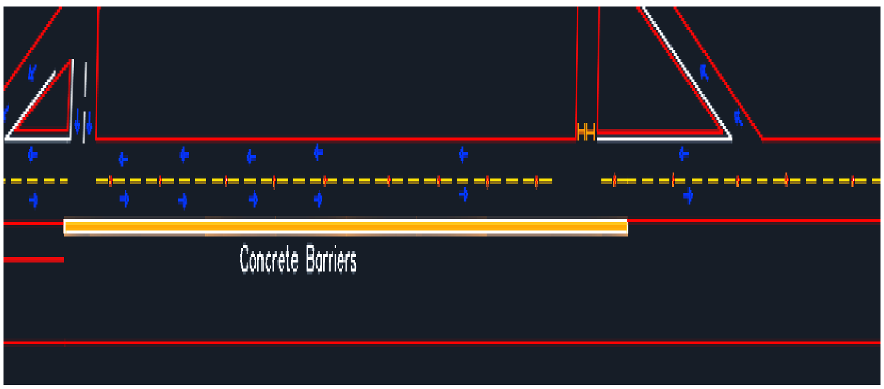
The solid yellow lane-marking line in the middle was hidden using removable black line mask. Then the solid white removable tape was installed in its place, which connected the fourth lane with a second lane.

Channelizer drums were installed on the side of the EB lane.

Figure 9:Implemented changes at Site #1



Before



After

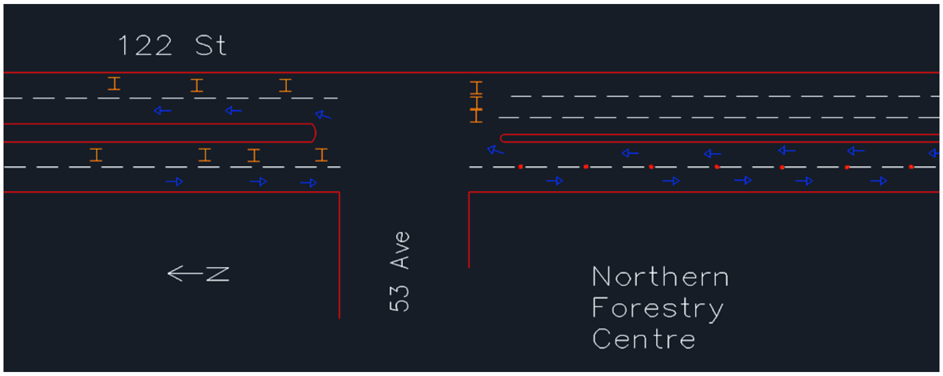
An orange linear delineation system was installed on the concrete barriers.

Solid yellow removable tape was installed on the bridge instead of the broken yellow line.

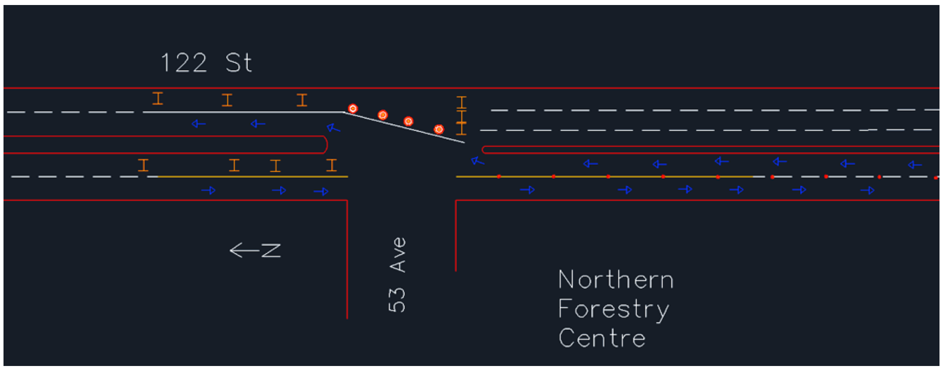
The broken white line was replaced by solid yellow removable tape on the east side of the bridge (to the trim line channelizers) and west side of the bridge (to about 10-15 meters downstream from end of curve of right turn).

A white stop line was installed using white removable tape on the west side of the bridge.

Figure 10: Implemented changes at Site #2



Before



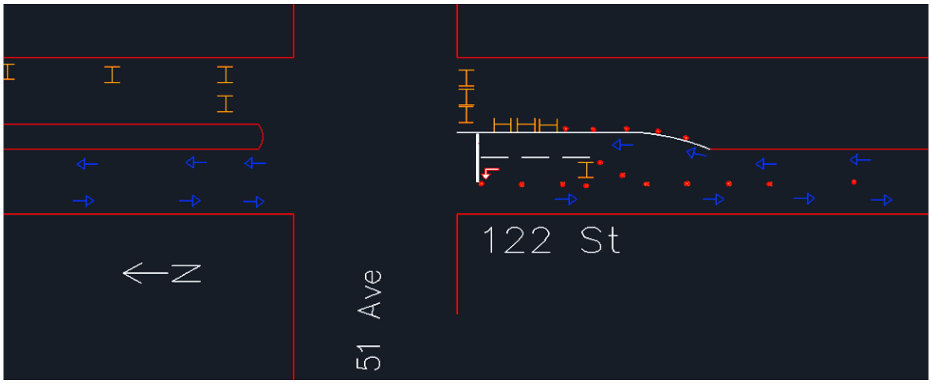
After

Four barrels with reflective sheeting were placed in the Northbound (NB) traffic lane.

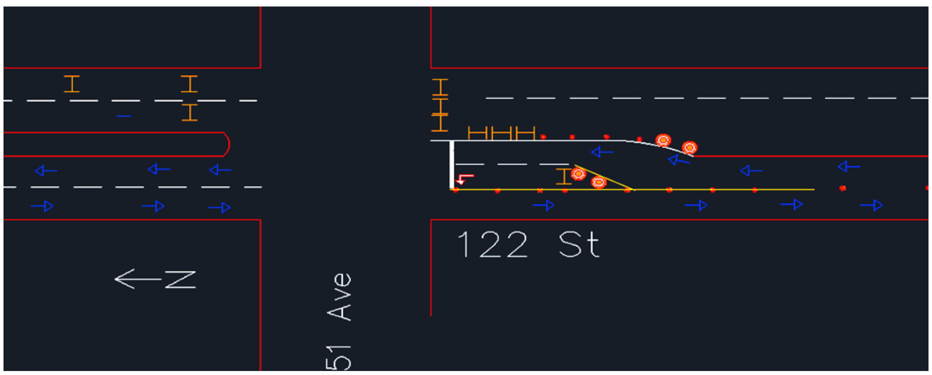
Solid white reflective tape was applied to the NB traffic lane.

Solid yellow reflective tape was laid between the NB and Southbound (SB) lanes. The tape was extended for 20m each side.

Figure 11: Implemented changes at Site #4



Before

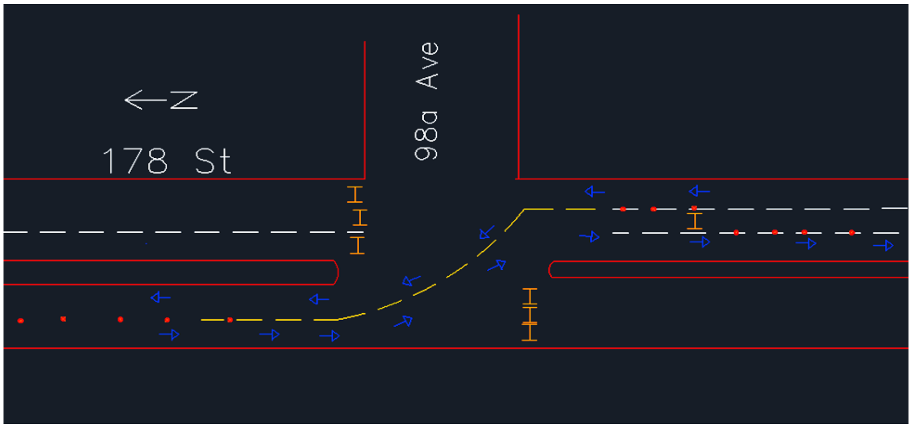


After

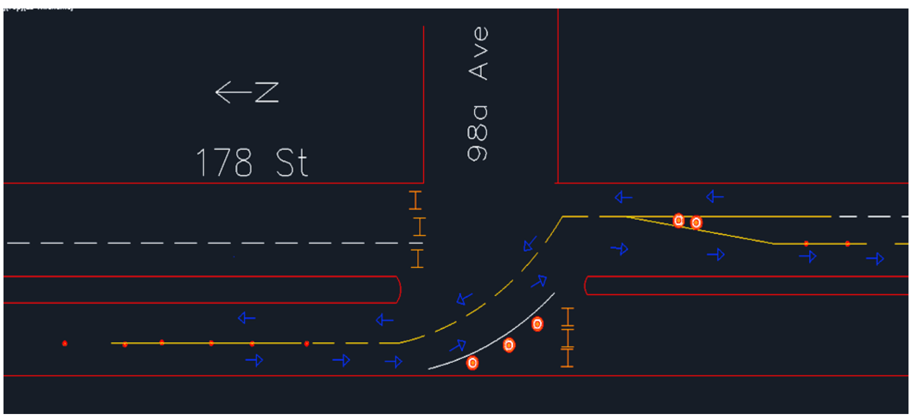
The traffic cones were replaced with two barrels on each side of the NB lane.

Solid yellow reflective tape was used between the NB and SB lanes. The tape extended for 20m each side.

Figure 12: Implemented changes at Site #5



Before



After

Solid yellow reflective tape was used between the NB and SB lanes. The tape was extended for 20m on each side of the intersection.

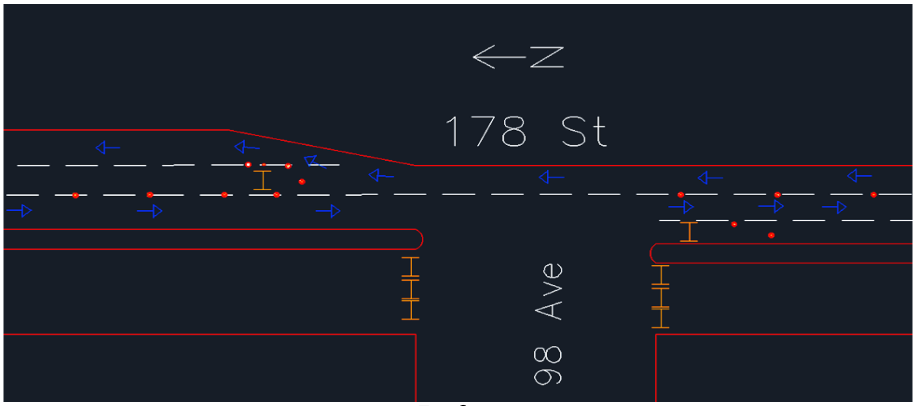
Three barrels with reflective sheeting were placed in SB traffic lane at the intersection.

Solid white reflective tape was used to guide the SB traffic lane at the intersection.

Two barrels with reflective sheeting were placed between the SB and NB lanes.

Black removable tape hid the previous broken white line.

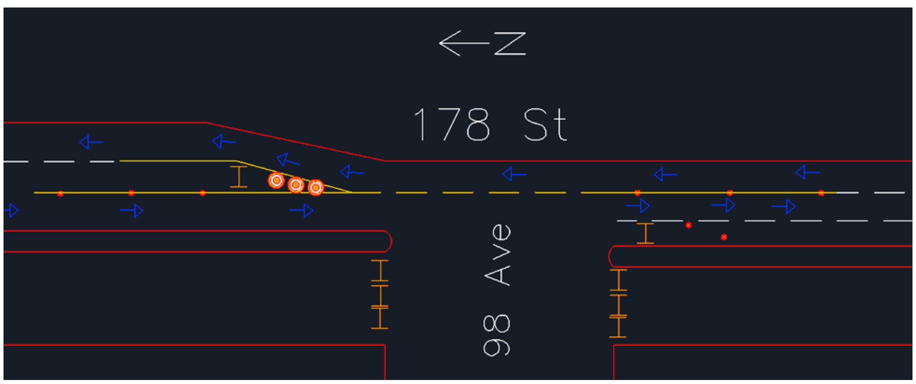
Figure 13: Implemented changes at Site #7



Before

Solid yellow reflective tape was applied between the NB and SB lanes. The tape extended for 20m on each side of the intersection.

Three barrels with reflective sheeting were installed.



After

Black removable tape hid the previous broken white lane.

Broken yellow reflective tape was applied between the NB and SB lanes in the middle of the intersection.

Figure 14: Implemented changes at Site #8

4.3.2 Control Sites

In a controlled before-and-after experimental design, a control group is often used as a baseline measure. The control group is identical to the test group in all respects, with the exception that it does not receive the treatment or the experimental manipulation that the test group receives. In this project, one control work zone was maintained in each of the three construction sites, giving a total of three control work zones, as shown in **Figure 15 (a,b,c)**.

(a) (c) (b)

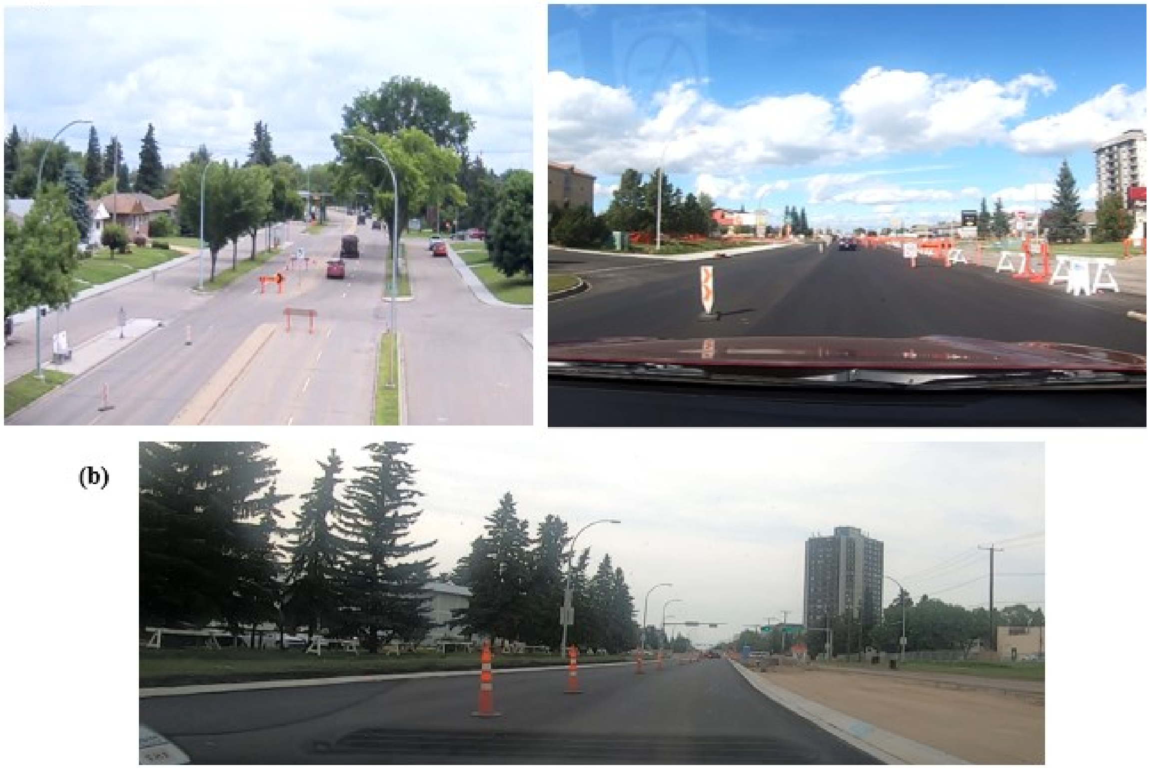


Figure 15: (a) Site #3, (b) Site #6, and (c) Site #9

4.4 Speed Analysis

Once the vehicles' speeds were collected, the next step was to assess the impact of the intervention materials on a set of surrogate safety performance metrics. The first step in this type of analysis is to remove the outliers, or the unusual values, in the dataset, as they can distort statistical analyses. In this study, a Histogram graph was done for each set of data to provide a visual interpretation of numerical data by indicating the number of data points that lie within a range of value, and to check if the data follows a normal distribution, so it will be then possible to remove the outliers using a boxplot, as shown in **Figure 16 (a,b)** [49].

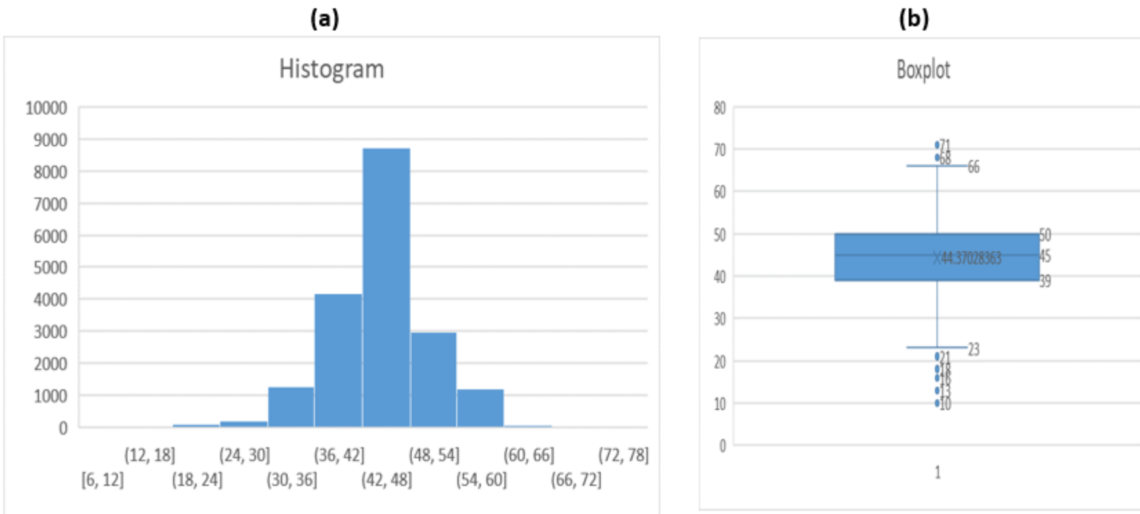


Figure 16: (a) Histogram graph, (b) Boxplot

The analysis of the data followed a specific algorithm in order to test the significance of installing the high reflective material in the traffic path on vehicles speed at work zones. The method of the analysis is summarized in **Figure 17.**

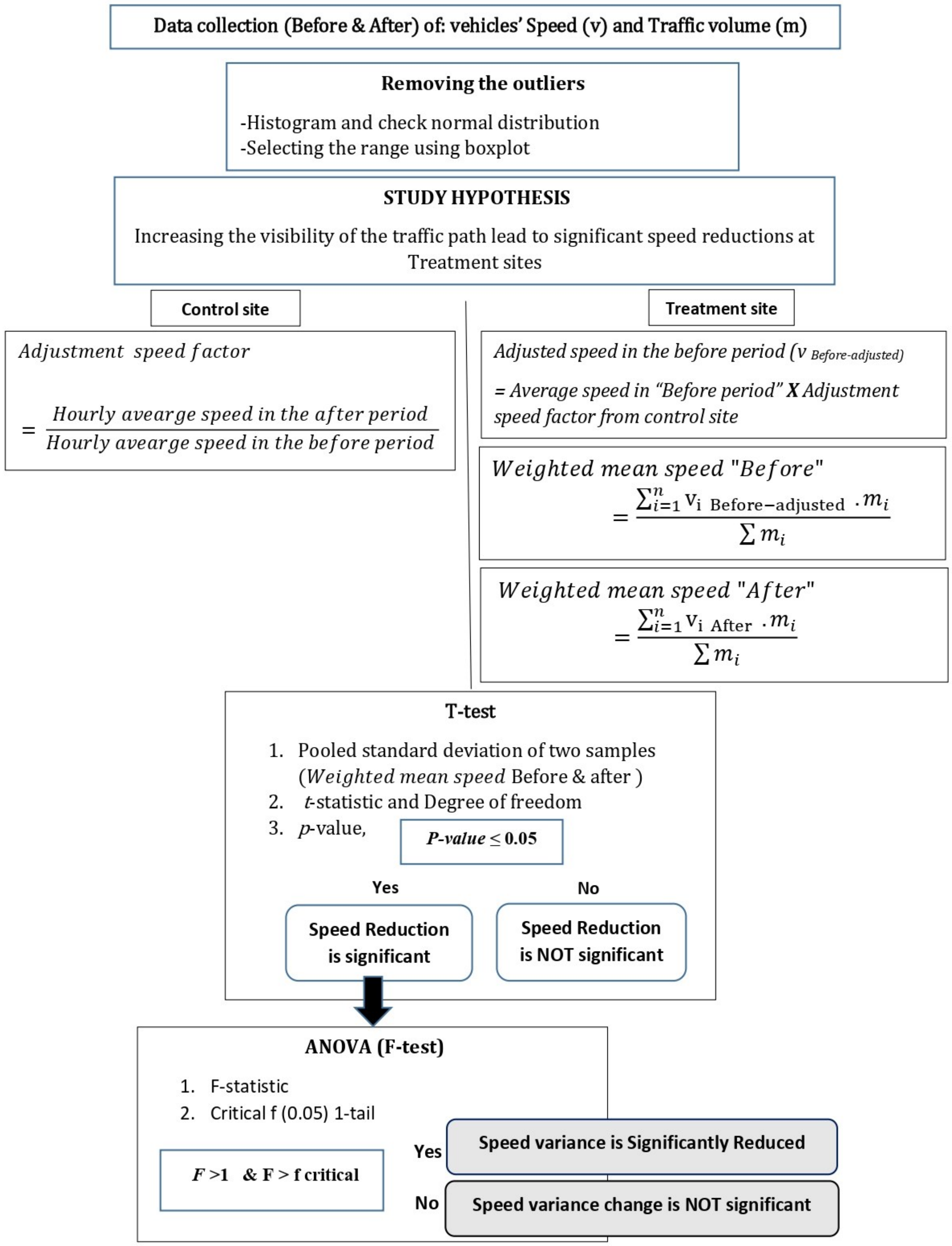


Figure 17: Data analysis algorithm

A two-sample *t*-test was used to examine the hypothesis that speed and speed limit compliance during the period after intervention installation would be significantly lower as compared to the same period before the installation. The null hypothesis is that the average speed during the 'after' period would not significantly differ from the average values in the 'before' period. The alternative hypothesis is that the values during the 'after' period would be significantly lower compared to the average during the 'before' period. To determine these values, the pooled standard deviation of two samples is estimated first, and then the *t*-statistic is calculated, as shown in equations (1) and (2). Finally, the *df* and *t*-statistic are used to determine the corresponding *p*-value, which represents the area under the curve of the *t*-distribution [46]. If the calculated *p*-value is lower than 0.05, then the alternative hypothesis is accepted, and the difference is considered significant at the 95% confidence level.

$$s_p = \sqrt{\frac{(n_1-1)s_1^2+(n_2-1)s_2^2}{n_1+n_2-2}} \tag{1}$$

$$t = \frac{\bar{x}_1-\bar{x}_2}{s_p\sqrt{\frac{1}{n_1}+\frac{1}{n_2}}} \tag{2}$$

$$df = n_1 + n_2 - 2 \tag{3}$$

where, n_1 and n_2 are the sample sizes; $\bar{x}_1$ and $\bar{x}_2$ are the samples' weighted means; s_1 and s_2 are the samples' weighted standard deviations; s_p is the pooled standard deviation of the two samples; t is the *t*-statistic; and *df* is the degree of freedom.

The reductions in speed and significance at the different work zones were used to make inferences about the effectiveness of the interventions. The normality assumption of the *t*-test was validated for the tested samples using the Anderson–Darling test, and the equal-variance assumption was met for the tested samples [46]. In order to account for the effect of traffic volume, the *t*-test was performed using the weighted mean (equation (4)) and weighted variance (equation (5)) for the tested parameter.

$$\bar{x}_{\mathrm{w}} = \frac{\sum_{i=1}^{n} \mathrm{x_i} m_i}{\sum m_i} \tag{4}$$

$$s_w^2 = \frac{\frac{\Sigma(m_i x_i^2)}{\overline{m}} - n\bar{x}_w^2}{n-1} \quad (5)$$

where $\bar{x}_\mathrm{w}$ is the weighted mean, s_w^2 is the weighted variance, X_i is the average value of a parameter in one hour, n is the number of testing hours, m_i is the traffic volume recorded in one hour (=weights), i indicates the ith value of a parameter in one hour, and $\overline{m}$ is the average volume per hour (Σm_i/n). To account for any confounding factors before attributing the reduction in speed at the work zones to the introduced interventions, the values of speed were corrected using data from the control sites during the same time period. Values of the 'before' period used in the *t*-test were corrected using equations 6 and 7 [47].

$$Adjustment\ factor = \frac{Parameter\ value\ in\ the\ after\ period\ at\ control\ sites}{Parameter\ value\ in\ the\ before\ period\ at\ control\ sites} \quad (6)$$

$$\bar{x}_1^* = \bar{x}_1 * Adjustment\ factor \quad (7)$$

where $\bar{x}_1$ is the parameter value at the test site, and $\bar{x}_1^*$ is the corrected parameter in the before period used in the *t*-test.

Finally, change in the variance of speed was tested using the *F*-test. The *F*-test is used to establish if the variance of two populations are equal or significantly different. The null hypothesis is that the variances of the two samples are not significantly different. The alternative hypothesis is that they are significantly different. The test statistic of the *F*-test is expressed in equation (8).

$$F = \frac{s_1^2}{s_2^2} \quad (8)$$

where s_1^2 and s_2^2 are the sample variances. The more this ratio deviates from 1, the stronger the evidence of unequal population variances. The hypothesis that the two variances are equal is rejected if ($F > F_{\alpha/2,N_1-1,N_2-1}$), where $F_{\alpha/2,N_1-1,N_2-1}$ is the critical value of the F distribution with $N_1 - 1$ and $N_2 - 1$ degrees of freedom and a significance level of α [48].

4.5 Concluding Remarks

The goal of the designed methodology was to compare changes in driver behaviour according to the predetermined performance measures as well as the differences in the control group work zones with installed surrogate safety measures and the treatment group with no additional interventions. The comparative study included assessing changes in driver compliance, average speed, and speed distributions. In addition, traffic conflicts were also compared across the two groups.

CHAPTER 5: DATA ANALYSIS AND RESULTS

5.1 Background

Once the data collection was complete, a comparative analysis was used to assess the effect of each intervention based on the before and after results. Those results show significant changes in the majority of the treatment sites. The analysis of the results for all the test sites are discussed in the following sections.

5.2 Speed Analysis Results

Analysing the radar speed data showed significant speed changes in the test sites. The treatment sites are Sites #1, #2, #4, #5, #7, and #8 while the control sites are Sites #3, #6 and # 9.

Table 4 (below) shows clear reductions in the weighted mean speed for most of the treatment sites in both directions while showing no significant change in the control sites. In addition, the weighted mean speed in the 'after' period for some control sites is higher than the 'before' period. This suggests that installing the intervention materials in the treatment sites would result in further reductions.

In some sites, the layout of the interventions resulted in vehicle speed reductions in one direction only. Additionally, in treatment Site #8, there was no clear change in vehicle speed, possibly because the speed was already low prior to the installation of the intervention materials. Furthermore, the outcomes showed that the effectiveness of the interventions could be unidirectional or bidirectional, depending on their distribution. The weighted mean speed for vehicles at each site is shown in **Table 4**.

Table 4: Weighted mean speed for the vehicles passing through the test sites

		Site#1	#2	#3	#4	#5	#6	#7	#8	#9
1st Direction	Before	43.46	45.74	33.75	41.32	46.72	38.74	33.74	32.04	37.48
	After	38.62	40.53	33.71	40.81	35.11	40.41	28.58	31.41	37.89
2nd Direction	Before	N/A	45.67	44.88	47.45	39.47	30.34	29.49	30.33	35.39
	After	N/A	40.89	45.54	36.64	32.77	29.44	28.63	29.31	35.67

To identify the significance of the reductions, a *t*-test was conducted whereby, for most treatment sites, the *p*-value < 0.05 at 95 % confidence level, **Table 5** shows more details for Site#1, #2, and #3 (for further details, see **Appendix A**).

Table 5: Weighted Mean Speed and Reductions for Sites #1, #2, and #3

Site No.			Nighttime		Daytime		Overall
			Weekend	**Weekday**	**Weekend**	**Weekday**	
Site #1	Weighted mean Speed (Km/h)	Before	46.94	42.63	44.13	41.25	43.46
		After	41.21	37.64	39.54	35.95	38.62
	Speed-Reduction (Km/h)		-5.73	-4.99	-4.59	-5.29	-4.84
	Degree of freedom		14941	10864	11908	16873	57592
	t-value		-7.65	-8.54	-8.36	-12.34	-9.88
	p-value		< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Site #2	Weighted mean Speed (Km/h)	Before	47.90	42.65	46.54	42.36	45.74
		After	41.97	38.01	41.64	37.11	40.53
	Speed-Reduction (Km/h)		-5.93	-4.65	-4.90	-5.24	-5.21
	Degree of freedom		30735	21088	25639	35163	112631
	t-value		-9.57	-15.69	-18.90	-22.54	-19.87
	p-value		< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Site #3 (Control Site)	Weighted mean Speed (Km/h)	Before	34.26	34.25	35.56	31.24	33.75
		After	34.94	34.89	35.49	31.55	33.71
	Adjustment factor		1.020	1.018	0.998	1.010	0.999
	Speed-Reduction (Km/h)		0.68	0.64	-0.07	0.31	-.04
	Degree of freedom		27571	21708	25669	35097	109535
	t-value		1.5	0.75	-1.42	0.97	-1.19
	p-value		0.066	0.226	0.078	0.166	0.117

Furthermore, an *F*-test was done to compare the speed variance in the before and after periods and test if the speed variance reduction was significant, **Table 6** shows F-test of Sites #1, site2 and site#3 (for further details, see **Appendix B**), while **Table 7** shows a summary of F-test for all the sites.

Table 6: F-test for Site #1, #2, and #3

Site No.		**Nighttime**				**Daytime**				**Overall**	
		Weekend		**Weekday**		**Weekend**		**Weekday**			
		Before	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
Site #1	**Variance**	3.9	2.659	4.28	2.994	2.06	1.2411	2.0682	1.6154	2.83	1.97
	DF	9280	8661	5439	5425	6719	5189	9560	7313	31001	26591
	F	1.46		1.42		1.659		1.28		1.43	
	Critical F(0.05) 1-tail	1.035		1.04		1.044		1.036		1.216	
Site #2	**Variance**	1.597	0.608	1.454	0.82	0.804	0.34	1.013	0.4	1.102	0.54
	DF	17089	13646	9428	11660	12964	12675	19446	15717	58930	53701
	F	2.627		1.773		2.365		2.533		2.041	
	Critical F(0.05) 1-tail	1.064		1.12		1.315		1.297		1.014	
Site #3 (Control)	**Variance**	2.18	5.075	2.96	4.62	1.24	2.555	1.44	3.22	1.95	3.5
	DF	16567	11004	9140	12052	12568	13101	18852	16245	57130	52405
	F	0.430		0.641		0.485		0.447		0.557	
	Critical F(0.05) 1-tail	1.33		1.08		1.104		1.297		1.054	

Table 7: Summary of F-test results

		Site #1	**Site #2**	**Site #3**	**Site #4**	**Site #5**	**Site #6**	**Site #7**	**Site #8**	**Site #9**
Are the speed variances significantly reduced?	***1st Direction***	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No
	2nd Direction	N/A	Yes	No	Yes	Yes	No	No	Yes	No

The hourly average speed graph for each site shows that the observable speed reduction was consistent throughout the day. **Figure 18** charts the hourly average speed for vehicles passing Site #1 (results for all other sites are provided in **Appendix C**).

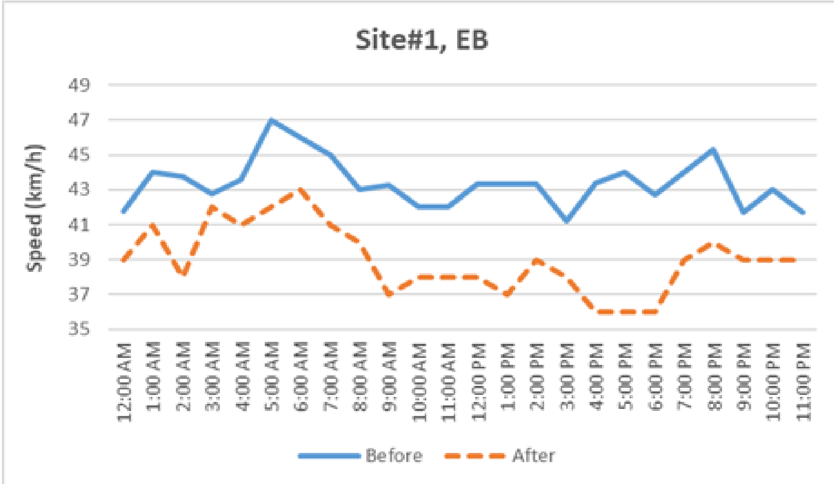


Figure 18: Hourly average speed for vehicles at Site #1

Similarly, the speed percentile profile for each site would show a shift in the S-curve with a reduction for the cumulative number of vehicles traversing each site. **Figure 19** shows speed percentile profile for Site #1 (results for all other sites are provided in **Appendix D**).

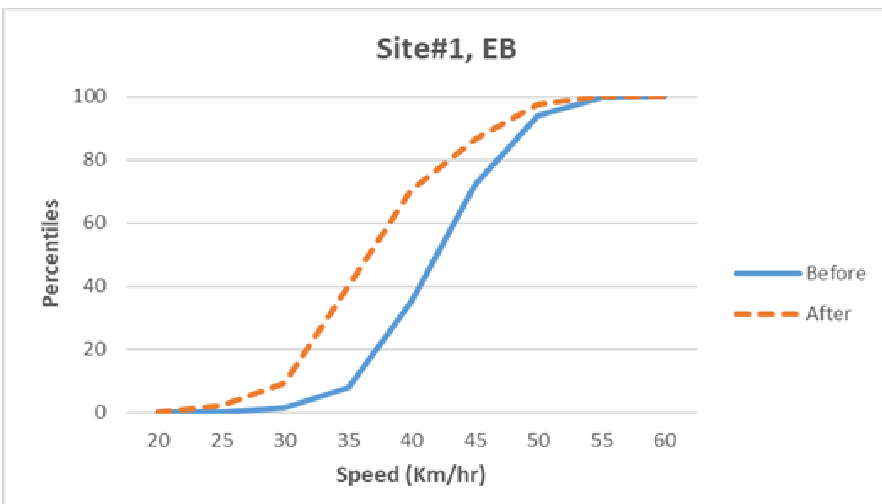


Figure 19: Speed percentile profile for vehicle at Site #1

The drivers' behavior changed according to the new interventions, with the speed limit compliance results as proof. The percentage of drivers driving above the speed limit

(50 Km/h) decreased after installing the new intervention materials. **Figure 20** shows the speed limit compliance comparison for Site #1 (results for all other sites are provided in **Appendix E**).

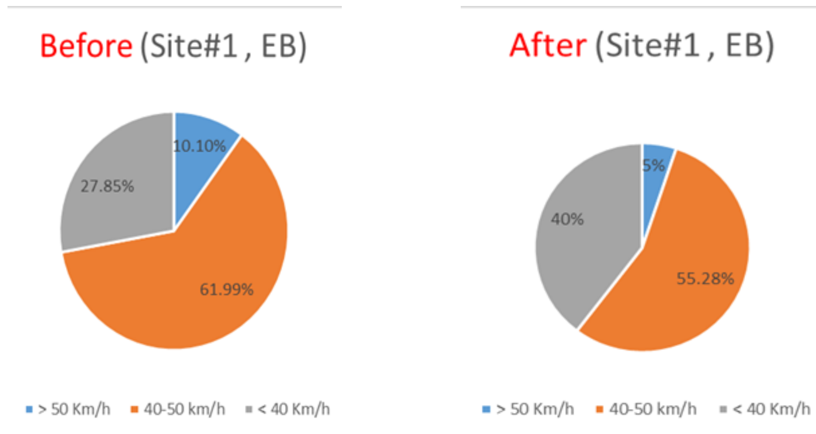


Figure 20: Speed limit compliance at Site #1

Furthe ıring working hours were more than non-working hours, as observed in Site #7 [**Figure 21**]. Although there was no reduction in the average daily speed for Site #8, a speed reduction was still observed during working hours, as shown in **Figure 22**.

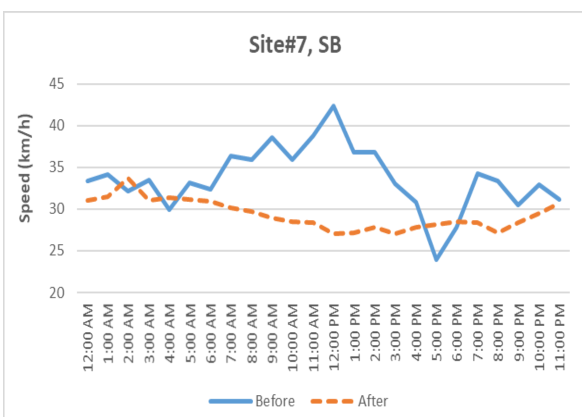


Figure 21: Hourly average speed at Site #7

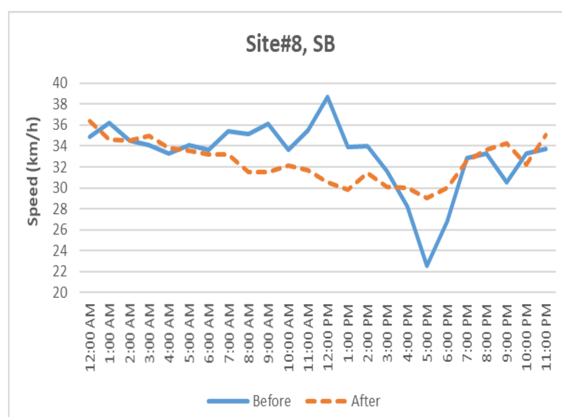


Figure 22: Hourly average speed at Site #8

5.3 Videos Analysis Results

Video analysis revealed that there were no critical cases that could have led to accidents in the test sites, either in the before or after periods. Indeed, the layout of the work zone that is extended in one directional line appeared to help reduce driver confusion, as observed in the video footage. As a result, a Time to Collision (TTC) analysis was unnecessary.

However, there were two rear-end near misses that occurred due to a left turn conflict in Site #1 during the before period, as shown in **Figure 23**. No near misses were recorded after installing the interventions. In this case, the speed was the primary basis upon which to test the efficiency of the installed interventions.

Figure 23: Left turn conflict at Site #1

5.4 Concluding Remarks

The outcomes in all of the test sites clearly indicate that the different combinations of 3M products improved the clarity of the intended path, which led to significant vehicle speed reductions unlike the previous studied where countermeasures have been installed without making changes in the traffic paths [17,18 and 20] . This was in contrast to vehicle speed at control sites, which showed no appreciable signs of change. In addition, an improvement in drivers' speed limit compliance was observed in the after period in the treatment sites.

The effectiveness of the interventions could be unidirectional or bidirectional, depending on the distribution of those intervention materials. The highly reflective material use led to speed reductions that ranged between 11.6 km/h and 4.7 km/h. By contrast, there were no significant vehicle speed reductions observed in the control sites.

CHAPTER 6: CONCLUSIONS

6.1 Research Conclusions

The majority of previous studies have shown that the main contributing factor to high-severity crashes in work zones is speeding. This study, aimed at addressing the safety issues caused when traffic flows past work zones, used combinations of highly reflective and visible intervention materials from 3M Canada installed in a set of test sites in order to assess their impact on work zone visibility and vehicle speed for drivers.

The study took place in nine work zones set within Edmonton city limits and were divided into two groups, treatment and control. Several combinations of 3M intervention materials were used in the treatment sites to clearly define the travel lanes, guide vehicles through the work zones to minimize driver confusion and, ultimately, to reduce vehicle speed. A before and after evaluation was conducted to analyze the impact of several highly visible and reflective traffic control devices (3M products) that were installed to improve work zone layout.

The results showed that the use of the chosen 3M products improved the clarity of the intended path at the treatment sites, leading to significant vehicle speed reductions that ranged between 11.6 km/h and 4.7 km/h in the treatment sites. By contrast, no reductions were recorded in the control sites. The effectiveness of the interventions could be unidirectional or bidirectional, depending on their distribution. In addition, an improvement in drivers' speed limit compliance was observed in the after period. The outcomes showed that vehicle speed reductions during working hours were more than in non-working hours.

From the video analysis, no near misses or accidents were observed during the test period, indicating that the installed interventions did not lead to any traffic issues or conflicts.

To sum up, improving the intended roadway path for drivers passing through work zone areas using intervention materials designed for improved visibility will influence driver behaviour, leading to vehicle speed reductions and a greater promotion of work zone safety.

6.2 Research Limitation

The extent of the study was limited to assessing the impact of installing new intervention materials as suggested by 3M Canada, such as 3M Wet Reflective removable tape, 3M Diamond Grade Flexible Work Zone Sheeting and 3M Linear Delineation System. Data collection devices were used to record vehicles' speed passing through the test sites along with any accidents or near misses during the study period. The nine test sites were chosen in collaboration with the COE's Traffic Operations group.

6.3 Research Contribution

This study provides a valuable contribution to the traffic safety literature. A significant gap exists in the literature regarding driver speeds at work zones in relation to the inefficient installation and design of traffic interventions. This may be a reason why the number of collisions continue to increase even though different countermeasures have been enacted. A key contributing result of this study is that it clearly proves that using highly visible and reflective intervention materials will reduce vehicle speed around work zones.

Validating the hypothesis of this study depended on an experimental, observational study design that included site visits, adequate intervention layout design, data collection, and data analysis, in order to assess the effect of work zone interventions on driver speeds. The relationship between the use and distribution of efficient, well-designed traffic intervention materials and the reductions in speed and speed limit adherence was studied, which was identified as another gap in previous research.

This thesis suggest some specifications for a better traffic path clarity at work zones. For instance, traffic delineators should be installed along the whole length of the work zone for both path sides alongside changes to pavement road marking, with previous road markings masked to avoid drivers' confusion. In addition, it's recommended to use high visibility and reflective delineators, and the distribution of delineators can be unidirectional or bidirectional depending on the work area and where there is a need to reduce the speed.

In terms of the practical contributions of this thesis, results found in this study can greatly assist traffic safety agencies to optimize the use of traffic interventions at work zones and provide more details about the effective use of the reflective control devices, which is currently not clearly defined and detailed in Alberta's Traffic Accommodation guidelines. This study can provide decision-makers with valuable information to help them estimate the safety benefits associated with traffic intervention materials at work zones.

6.4 Recommendations for Future Research

This research provided a significant understanding of traffic control intervention material use at work zones and their impact on vehicle speed reductions and, ultimately, on safety. Since speeding is such a pervasive and significant factor in work zones collisions, further research is required to provide solutions that help to enforce speed reduction at work zones. Future research should focus on effective countermeasures that have the ability to (i) manage speeding by alerting drivers to an upcoming work zone, (ii) reduce the number of rear-end collisions by alerting drivers who are following too closely, of slowing traffic, or of an upcoming queue, and (iii) avoid merge-related collisions by alerting drivers to the presence of surrounding vehicles. One possible technology is Automated Vehicles, with the advent of AVs, the construction experts and policymakers will need to work together to see how AVs can navigate through the work zone without limiting its ability to move in the construction work zone safely.

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APPENDICES

Appendix A: Weighted Mean Speed and Reductions

A1) 106 Avenue over Wayne Gretzky Drive (Eastbound)

Site No.			Nighttime		Daytime		Overall
			Weekend	Weekday	Weekend	Weekday	
Site #1	Weighted mean Speed (Km/h)	Before	46.94	42.63	44.13	41.25	43.46
		After	41.21	37.64	39.54	35.95	38.62
	Speed Reduction (Km/h)		-5.73	-4.99	-4.59	-5.29	-4.84
	Standard error		1.005	0.986	0.690	0.780	0.489
	Degree of freedom		14941	10864	11908	16873	57592
	t-value		-7.65	-8.54	-8.36	-12.34	-9.88
	p-value		< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Site No.		Nighttime		Daytime		Overall
		Weekend	Weekday	Weekend	Weekday	
Site #2,Radar #1	Weighted mean Speed (Km/h) Before& After	47.26	44.24	46.66	43.45	45.93
		37.01	35.99	37.43	34.44	36.79
	Speed Reduction (Km/h)	-10.25	-8.25	-9.23	-9.01	-9.19
	Standard error	0.422	0.395	0.417	0.388	0.411
	Degree of freedom	30735	21088	25639	35163	112631
	t-value	-16.45	-14.54	-12.33	-28.45	-22.35
	p-value	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Site No.			Nighttime		Daytime		Overall
			Weekend	Weekday	Weekend	Weekday	
Site #2,Radar #2	Weighted mean Speed (Km/h)	Before	47.90	42.65	46.54	42.36	45.74
		After	41.97	38.01	41.64	37.11	40.53
	Speed Reduction (Km/h)		-5.93	-4.65	-4.90	-5.24	-5.21
	Standard error		0.274	0.244	0.267	0.243	0.262
	Degree of freedom		26310	25213	15346	42754	109630
	t-value		-9.57	-15.69	-18.90	-22.54	-19.87
	p-value		< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Site No.			Nighttime		Daytime		Overall
			Weekend	Weekday	Weekend	Weekday	
Site #3 (Control Site)	Weighted mean Speed (Km/h)	Before	34.26	34.25	35.56	31.24	33.75
		After	34.94	34.89	35.49	31.55	33.71
	Adjustment factor		1.020	1.018	0.998	1.010	0.999
	Speed Reduction (Km/h)		0.68	0.64	-0.07	0.31	-.04
	Standard error		1.25	1.25	1.30	1.14	1.23
	Degree of freedom		27571	21708	25669	35097	109535
	t-value		1.5	0.75	-1.42	0.97	-1.19
	p-value		0.066	0.226	0.078	0.166	0.117

A2) 106 Avenue over Wayne Gretzky Drive (Westbound)

Site No.			Nighttime		Daytime		Overall
			Weekend	Weekday	Weekend	Weekday	
Site #2,Radar #1	Weighted mean Speed (Km/h)	Before	47.33	42.90	46.27	42.36	44.80
		After	41.24	37.24	40.25	37.53	39.85
	Speed Reduction (Km/h)		-6.09	-5.66	-6.01	-4.83	-4.95
	Standard error		0.261	0.237	0.255	0.234	0.247
	Degree of freedom		10237	9810	5971	16636	42660
	t-value		-13.055	-8.054	-12.4653	-23.454	-20.027
	p-value		< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Site No.			Nighttime		Daytime		Overall
			Weekend	Weekday	Weekend	Weekday	
Site #2, Radar #2	Weighted mean Speed (Km/h)	Before	47.65	43.66	46.53	41.65	45.67
		After	42.94	38.54	41.65	36.56	40.89
	Speed Reduction (Km/h)		-4.72	-5.12	-4.87	-5.09	-4.78
	Standard error		0.259	0.237	0.253	0.226	0.248
	Degree of freedom		5334	10356	3451	12239	31386
	t-value		-10.653	-12.51	-14.6536	-25.356	-19.284
	p-value		< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Site No.			Nighttime		Daytime		Overall
			Weekend	Weekday	Weekend	Weekday	
Site #3 (Control Site)	Weighted mean Speed (Km/h)	Before	46.33	45.26	46.36	41.25	44.88
		After	46.90	46.33	46.53	41.78	45.54
	Adjustment factor		1.01	1.02	1.00	1.01	1.01
	Speed Reduction (Km/h)		0.567	1.064	0.173	0.532	0.667
	Standard error		1.058	1.034	1.059	0.942	1.025
	Degree of freedom		18106	35148	11715	41539	106513
	t-value		1.32	1.49	1.739	1.548	1.184
	p-value		0.93	0.068	0.160	0.061	0.118

A3) 122 St & WMD-51 Ave (Southbound)

Site No.			Nighttime		Daytime		Overall
			Weekend	Weekday	Weekend	Weekday	
Site #4	Weighted mean Speed (Km/h)	Before	41.66	42.13	42.70	41.66	41.32
		After	40.68	40.93	40.98	40.76	40.81
	Speed Reduction (Km/h)		-0.98	-1.20	-1.72	-0.90	-0.50
	Standard error		0.49	0.6	0.86	0.45	0.327
	Degree of freedom		11658	22632	7543	26748	68587
	t-value		-1.36	-1.56	-1.63	-2.64	-1.54
	p-value		0.869	0.059	0.255	0.112	0.0617

Site No.			Nighttime		Daytime		Overall
			Weekend	Weekday	Weekend	Weekday	
Site #5	Weighted mean Speed (Km/h)	Before	47.46	44.66	47.63	43.22	46.72
		After	35.64	33.69	36.65	32.25	35.11
	Speed Reduction (Km/h)		-11.83	-10.97	-10.98	-10.97	-11.61
	Standard error		1.91	1.48	0.99	0.99	0.73
	Degree of freedom		10493	23987	9744	30734	74965
	t-value		-15.05	-14.67	-11.55	-20.65	-15.82
	p-value		< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Site No.			Nighttime		Daytime		Overall
			Weekend	Weekday	Weekend	Weekday	
Site #6 (Control Site)	Weighted mean Speed (Km/h)	Before	40.47	39.34	38.99	37.35	38.74
		After	41.27	41.10	40.61	38.24	40.41
	Adjustment factor		1.02	1.04	1.04	1.02	1.04
	Speed Reduction (Km/h)		0.807	1.761	1.626	0.89	1.665
	Standard error		0.99	0.68	0.87	0.77	0.43
	Degree of freedom		15145	14487	15145	21073	65856
	t-value		0.44	1.66	1.46	1.18	1.32
	p-value		0.329	0.048	0.072	0.119	0.093

A4) 122 St & WMD-51 Ave (Northbound)

Site No.		Nighttime		Daytime		Overall
		Weekend	Weekday	Weekend	Weekday	
Site #4	Weighted mean Speed (Km/h) Before & After	47.99	47.58	47.83	46.01	47.45
		37.16	37.23	36.92	36.16	36.64
	Speed Reduction (Km/h)	-10.83	-10.35	-10.91	-9.85	-10.81
	Standard error	5.415	5.175	5.455	4.9265	0.385
	Degree of freedom	7562	17287	7022	22149	54025
	t-value	-12.65	-8.66	-10.56	-30.54	-28.10
	p-value	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Site No.			Nighttime		Daytime		Overall
			Weekend	Weekday	Weekend	Weekday	
Site #5	Weighted mean Speed (Km/h)	Before	41.27	38.52	41.26	37.24	39.47
		After	33.25	31.64	33.65	30.23	32.77
	Speed Reduction (Km/h)		-8.02	-6.88	-7.60	-7.01	-6.70
	Standard error		2.11	1.243	1.04346	0.953	0.812
	Degree of freedom		13066	11977	12522	16878	54449
	t-value		-7.66	-8.65	-9.65	-10.23	-8.26
	p-value		< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Site No.			Nighttime		Daytime		Overall
			Weekend	Weekday	Weekend	Weekday	
Site #6 (Control Site)	Weighted mean Speed (Km/h)	Before	32.23	30.58	30.41	28.61	30.34
		After	30.17	29.56	29.13	28.14	29.44
	Adjustment factor		0.94	0.97	0.96	0.98	0.97
	Speed Reduction (Km/h)		-2.056	-1.02	-1.278	-0.476	-0.898
	Standard error		1.028	0.51	0.639	0.238	0.514
	Degree of freedom		14994	14342	14994	20863	65200
	t-value		-1.21	-1.49	-1.23	-2.56	-1.75
	p-value		0.083	0.0963	0.12156	0.0964	0.0875

A5) 178 St & Stony Plain Rd (Southbound)

Site No.			Nighttime		Daytime		Overall
			Weekend	Weekday	Weekend	Weekday	
Site #7	Weighted mean Speed (Km/h)	Before	34.53	32.57	33.74	32.98	33.74
		After	29.06	28.37	28.21	28.61	28.58
	Speed Reduction (Km/h)		-5.47	-4.20	-5.53	-4.37	-5.16
	Standard error		1.192	1.02	1.003	1.0045	1.007
	Degree of freedom		10492	16395	15083	23610	65587
	t-value		-6.34	-5.98	-4.22	-8.58	-5.123
	p-value		< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Site No.			Nighttime		Daytime		Overall
			Weekend	Weekday	Weekend	Weekday	
Site #8	Weighted mean Speed (Km/h)	Before	32.15	31.85	31.89	30.78	32.04
		After	31.79	30.99	31.17	30.65	31.41
	Speed Reduction (Km/h)		-0.36	-0.86	-0.72	-0.13	-0.63
	Standard error		1.008	1.002	0.997	0.972	0.956
	Degree of freedom		11440	13982	14618	23517	63563
	t-value		-0.667	-0.52	-0.63	-1.23	-0.657
	p-value		0.0921	0.653	0.354	0.213	0.5143

Site No.			Nighttime		Daytime		Overall
			Weekend	Weekday	Weekend	Weekday	
Site #9 (Control Site)	Weighted mean Speed (Km/h)	Before	38.12	36.52	37.92	32.32	37.48
		After	38.81	36.24	37.51	32.99	37.89
	Adjustment factor		1.02	0.99	0.99	1.02	1.01
	Speed Reduction (Km/h)		0.69	-0.28	-0.41	0.67	0.408
	Standard error		2.05	1.86	2.32	1.95	1.576
	Degree of freedom		11997	14663	15330	24662	66657
	t-value		0.22	-0.25	-0.48	0.92	0.259
	p-value		0.412	0.232	0.457	0.531	0.397

A6) 178 St & Stony Plain Rd (Northbound)

Site No.			Nighttime		Daytime		Overall
			Weekend	Weekday	Weekend	Weekday	
Site #7	Weighted mean Speed (Km/h)	Before	30.08	30.19	29.22	28.62	29.49
		After	29.45	28.96	28.03	27.87	28.63
	Speed Reduction (Km/h)		-0.63	-1.23	-1.19	-0.75	-0.87
	Standard error		0.654	0.875	0.685	0.752	0.616
	Degree of freedom		9825	15353	14124	22109	61417
	t-value		-1.785	-1.065	-1.324	-2.684	-1.413
	p-value		0.198	0.175	0.154	0.212	0.165

Site No.			Nighttime		Daytime		Overall
			Weekend	Weekday	Weekend	Weekday	
Site #8	Weighted mean Speed (Km/h)	Before	30.950	30.110	30.720	29.500	30.317
		After	30.180	29.230	29.110	28.620	29.311
	Speed Reduction (Km/h)		-0.770	-0.880	-1.610	-0.880	-1.010
	Standard error		0.999	0.956	0.896	0.724	0.630
	Degree of freedom		10514	14603	13435	19861	58419
	t-value		-0.13	-1.54	-1.00	-3.34	-1.60
	p-value		0.215	0.115	0.142	0.245	0.116

Site No.			Nighttime		Daytime		Overall
			Weekend	Weekday	Weekend	Weekday	
Site #9 (Control Site)	Weighted mean Speed (Km/h)	Before	34.96	31.54	36.89	30.77	35.39
		After	34.57	31.86	36.21	30.00	35.67
	Adjustment factor		0.99	1.01	0.98	0.97	1.01
	Speed Reduction (Km/h)		-0.39	0.32	-0.68	-0.77	0.279
	Standard error		3.78	2.99	3.25	2.98	2.46
	Degree of freedom		9912	14087	10956	17218	52179
	t-value		-0.116	0.126	-0.245	-0.354	0.113
	p-value		0.950	0.835	0.944	0.847	0.910

Appendix B: F-test results

B1) 106 Avenue over Wayne Gretzky Drive (Eastbound)

Site No.		Nighttime				Daytime				Overall	
		Weekend		Weekday		Weekend		Weekday			
		Before	After	Before	After	Before	After	Before	After	Before	After
Site #1	Variance	3.9	2.659	4.28	2.994	2.06	1.2411	2.0682	1.6154	2.83	1.97
	DF	9280	8661	5439	5425	6719	5189	9560	7313	31001	26591
	F	1.46		1.42		1.659		1.28		1.43	
	Critical F(0.05) 1-tail	1.035		1.04		1.044		1.036		1.216	

Site No.		Nighttime				Daytime				Overall	
		Weekend		Weekday		Weekend		Weekday			
		Before	After	Before	After	Before	After	Before	After	Before	After
Site #2, Radar #1	Variance	1.597	0.608	1.454	0.82	0.804	0.34	1.013	0.4	1.102	0.54
	DF	17089	13646	9428	11660	12964	12675	19446	15717	58930	53701
	F	2.627		1.773		2.365		2.533		2.041	
	Critical F(0.05) 1-tail	1.064		1.12		1.315		1.297		1.014	

Site No.		Nighttime				Daytime				Overall	
		Weekend		Weekday		Weekend		Weekday			
		Before	After	Before	After	Before	After	Before	After	Before	After
Site #2, Radar #2	Variance	1.597	0.608	1.454	0.82	0.804	0.34	1.013	0.4	1.102	0.54
	DF	17089	10646	9428	11660	12964	12675	19446	15717	58929	50701
	F	2.627		1.773		2.365		2.533		2.041	
	Critical F(0.05) 1-tail	1.64		1.12		1.22		1.297		1.014	

Site No.		Nighttime				Daytime				Overall	
		Weekend		Weekday		Weekend		Weekday			
		Before	After	Before	After	Before	After	Before	After	Before	After
Site #3 (Control Site)	Variance	2.18	5.075	2.96	4.62	1.24	2.555	1.44	3.22	1.95	3.5
	DF	16567	11004	9140	12052	12568	13101	18852	16245	57130	52405
	F	0.430		0.641		0.485		0.447		0.557	
	Critical F(0.05) 1-tail	1.33		1.08		1.104		1.297		1.054	

B2) 106 Avenue over Wayne Gretzky Drive (Westbound)

Site No.		Nighttime				Daytime				Overall	
		Weekend		Weekday		Weekend		Weekday			
		Before	After	Before	After	Before	After	Before	After	Before	After
Site #2, Radar #1	Variance	2.5085	2.016	2.2836	2.736	1.2629	1.152	1.5916	1.332	1.73	1.8
	DF	6686	4116	3688	4508	5072	4900	7608	6076	23057	19603
	F	1.24		0.83		1.10		1.19		0.96	
	Critical F(0.05) 1-tail	1.65		1.04		1.65		1.32		1.50	

Site No.		Nighttime				Daytime				Overall	
		Weekend		Weekday		Weekend		Weekday			
		Before	After	Before	After	Before	After	Before	After	Before	After
Site #2, Radar #2	Variance	1.28	0.75	1.444	0.82	0.59	0.399	0.779	0.39	0.95	0.74
	DF	5449	2644	3006	2896	4133	3148	6200	3904	18791	12595
	F	1.707		1.761		1.479		1.997		1.284	
	Critical F(0.05) 1-tail	1.44		1.335		1.024		0.894		1.01	

Site No.		Nighttime				Daytime				Overall	
		Weekend		Weekday		Weekend		Weekday			
		Before	After	Before	After	Before	After	Before	After	Before	After
Site #3 (Control Site)	Variance	4.731	4.59	2.32	2.75	2.208	2.84	1.874	1.94	1.505	1.56
	DF	16324	10546	9006	11550	12383	12555	18575	15568	56291	50222
	F	1.03		0.84		0.78		0.97		0.96	
	Critical F(0.05) 1-tail	1.44		1.33		1.02		0.89		1.014	

B3) 122 St & WMD-51 Ave (Southbound)

Site No.		Nighttime				Daytime				Overall	
		Weekend		Weekday		Weekend		Weekday			
		Before	After	Before	After	Before	After	Before	After	Before	After
Site #4	Variance	2.616	1.37	1.32	0.91	2.62	1.19	1.41	1.19	1.6	1.1
	DF	9754	6989	4036	8038	9418	8038	10427	11882	33637	34950
	F	1.909		1.451		2.202		1.185		1.455	
	Critical F(0.05) 1-tail	1.447		1.335		1.024		0.894		2.014	

Site No.		Nighttime				Daytime				Overall	
		Weekend		Weekday		Weekend		Weekday			
		Before	After	Before	After	Before	After	Before	After	Before	After
Site #5	Variance	7.64	6.36	3.59	2.63	5.86	4.63	7.38	4.20	6.03	5.68
	DF	9677	8318	4004	9566	9343	9566	10344	14141	33371	41594
	F	1.202		1.365		1.266		1.757		1.062	
	Critical F(0.05) 1-tail	1.648		1.529		1.628		1.297		1.014	

Site No.		Nighttime				Daytime				Overall	
		Weekend		Weekday		Weekend		Weekday			
		Before	After	Before	After	Before	After	Before	After	Before	After
Site #6 (Control Site)	Variance	2.27	3.09	2.07	4.19	1.14	1.76	1.44	2.04	1.57	2.76
	DF	9607	6544	3975	7526	9276	7526	10270	11126	33130	32726
	F	0.735		0.494		0.648		0.706		0.569	
	Critical F(0.05) 1-tail	1.652		1.322		1.447		1.3194		1.496	

B4) 122 St & WMD-51 Ave (Northbound)

Site No.		Nighttime				Daytime				Overall	
		Weekend		Weekday		Weekend		Weekday			
		Before	After	Before	After	Before	After	Before	After	Before	After
Site #4	Variance	2.176	0.860	3.800	2.170	2.100	1.490	2.640	0.960	2.880	1.77
	DF	9248	4426	3826	5090	8929	5090	9886	7525	31891	22134
	F	2.53		1.75		1.41		2.75		1.63	
	Critical F(0.05) 1-tail	1.648		1.52		1.0628		1.297		1.014	

Site No.		Nighttime				Daytime				Overall	
		Weekend		Weekday		Weekend		Weekday			
		Before	After	Before	After	Before	After	Before	After	Before	After
Site #5	Variance	4.380	3.890	2.439	1.840	3.910	2.014	5.090	3.210	4.521	2.921
	DF	9325	4458	3858	5127	9003	5127	9968	7579	32156	22293
	F	1.126		1.326		1.941		1.586		1.548	
	Critical F(0.05) 1-tail	0.96		0.821		1.498		1.22		1.0496	

Site No.		Nighttime				Daytime				Overall	
		Weekend		Weekday		Weekend		Weekday			
		Before	After	Before	After	Before	After	Before	After	Before	After
Site #6 (Control Site)	Variance	6.43	6.1	5.86	6.8	1.24	1.2	1.08	1.4	1.44	1.9
	DF	9395	6560	3887	7544	9071	7544	10043	11152	32398	32802
	F	1.05		0.86		1.03		0.77		0.76	
	Critical F(0.05) 1-tail	1.65		1.53		2.62		1.30		1.01	

B5) 178 St & Stony Plain Rd (Southbound)

Site No.		Nighttime				Daytime				Overall	
		Weekend		Weekday		Weekend		Weekday			
		Before	After	Before	After	Before	After	Before	After	Before	After
Site #7	Variance	1.35	1.02	1.52	1.12	0.63	0.54	0.82	0.54	1.213	0.854
	DF	7709	8969	3987	8969	7177	8969	7709	12090	26586	39001
	F	1.324		1.357		1.167		1.519		1.420	
	Critical F(0.05) 1-tail	0.85		1.06		1.08		1.23		0.96	

Site No.		Nighttime				Daytime				Overall	
		Weekend		Weekday		Weekend		Weekday			
		Before	After	Before	After	Before	After	Before	After	Before	After
Site #8	Variance	4.31	4.41	6.85	5.98	1.21	2.52	5.35	2.91	4.25	3.94
	DF	10375	8196	6439	6390	7513	5278	11448	7918	35778	27785
	F	0.977		1.145		0.480		1.838		1.079	
	Critical F(0.05) 1-tail	1.64		2.529		1.62		1.297		1014	

Site No.		Nighttime				Daytime				Overall	
		Weekend		Weekday		Weekend		Weekday			
		Before	After	Before	After	Before	After	Before	After	Before	After
Site #9 (Control Site)	Variance	4.66	4.83	3.429	6.2	10.38	11.1	6.905	7.5	5.81	5.98
	DF	7962	8623	4941	9015	6040	9800	8511	11760	27456	39201
	F	0.965		0.553		0.935		0.921		0.972	
	Critical F(0.05) 1-tail	0.4967		1.672		0.696		1.418		1.049	

B6) 178 St & Stony Plain Rd (Northbound)

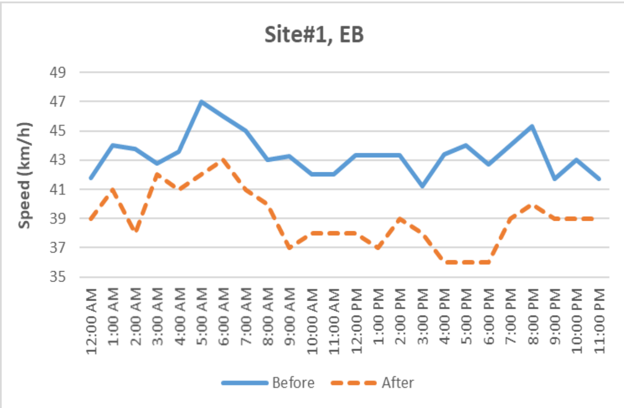
Site No.		Nighttime				Daytime				Overall	
		Weekend		Weekday		Weekend		Weekday			
		Before	After	Before	After	Before	After	Before	After	Before	After
Site #7	Variance	10.692	7.22	7.9	7.92	2.527	3.82	5.31	3.82	6.48	7.08
	DF	10124	5300	4189	6095	9775	6095	10823	9010	34914	26503
	F	1.481		0.997		0.662		1.390		0.915	
	Critical F(0.05) 1-tail	0.801		0.722		1.055		0.969		1.040	

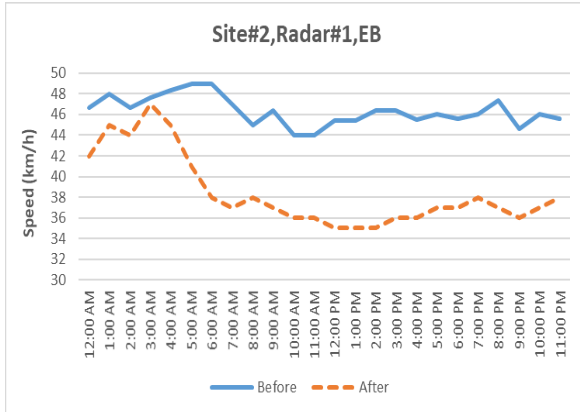
Site No.		Nighttime				Daytime				Overall	
		Weekend		Weekday		Weekend		Weekday			
		Before	After	Before	After	Before	After	Before	After	Before	After
Site #8	Variance	5.748	4.88	8.68	5.36	6.07	2.58	5.83	2.58	7.12	4.79
	DF	9475	5921	4900	5921	8821	5921	9475	7980	32674	25745
	F	1.18		1.62		2.35		2.26		1.49	
	Critical F(0.05) 1-tail	1.252		1.0932		2.22		1.498		1.014	

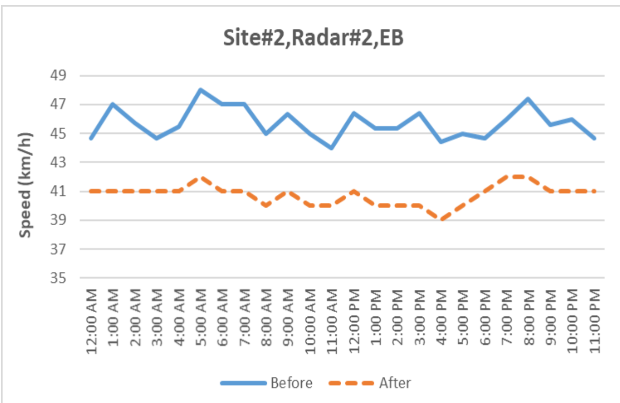
Site No.		Nighttime				Daytime				Overall	
		Weekend		Weekday		Weekend		Weekday			
		Before	After	Before	After	Before	After	Before	After	Before	After
Site #9 (Control Site)	Variance	8.93	6.5	10.06	117.4	4.8	5.4	2.77	3.157	5.23	6.24
	DF	6901	6243	4283	6527	5235	7095	7377	8514	23798	28381
	F	1.37		0.09		0.89		0.88		0.84	
	Critical F(0.05) 1-tail	1.65		1.62		1.32		0.919		0.84	

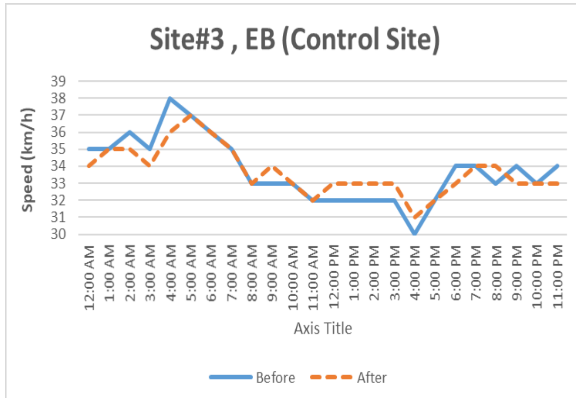
Appendix C: Hourly Average Speed (km/h)

C1) 106 Avenue over Wayne Gretzky Drive (Eastbound)

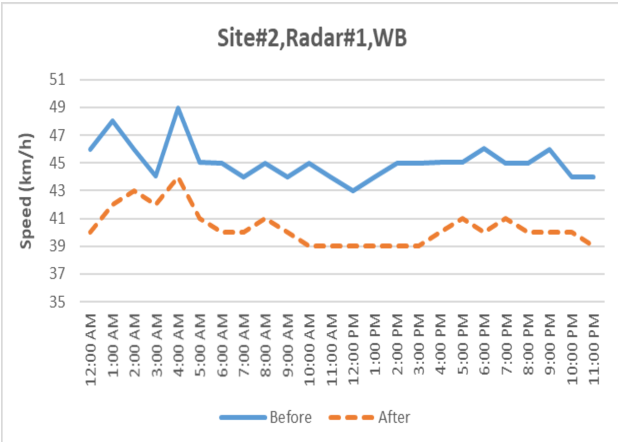


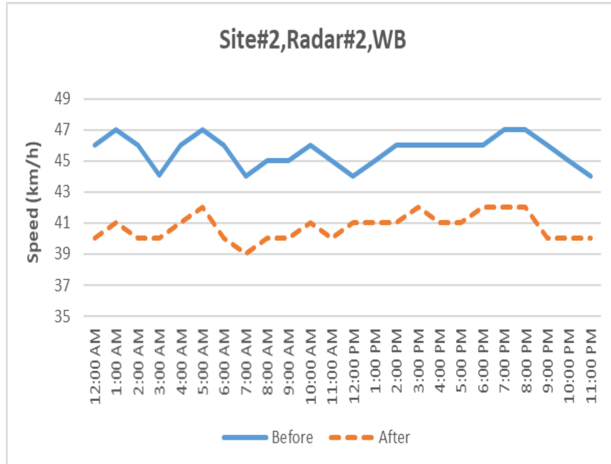


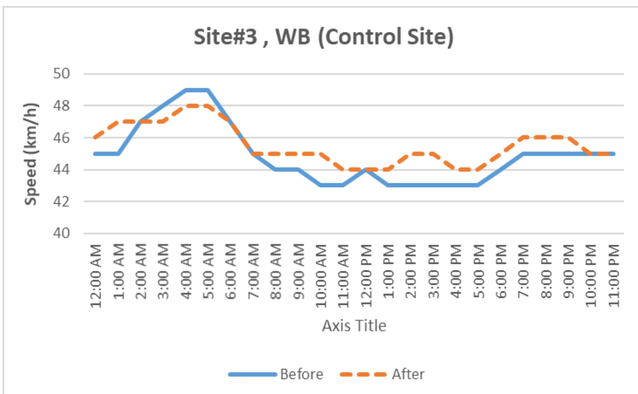




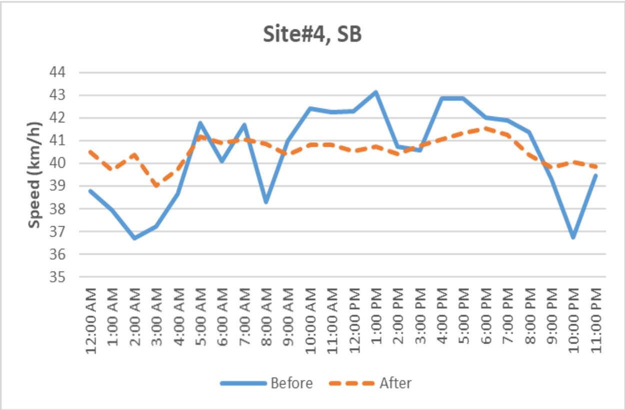
C2) 106 Avenue over Wayne Gretzky Drive (Westbound)

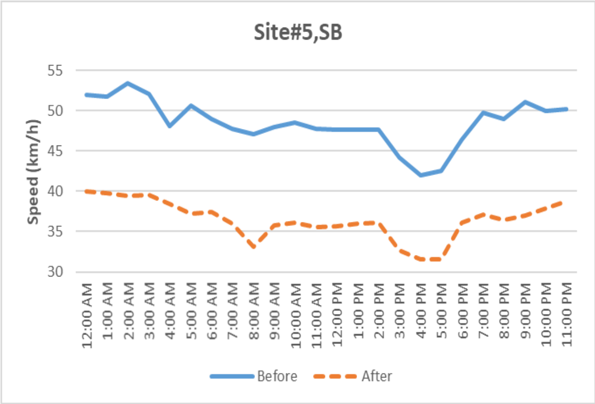


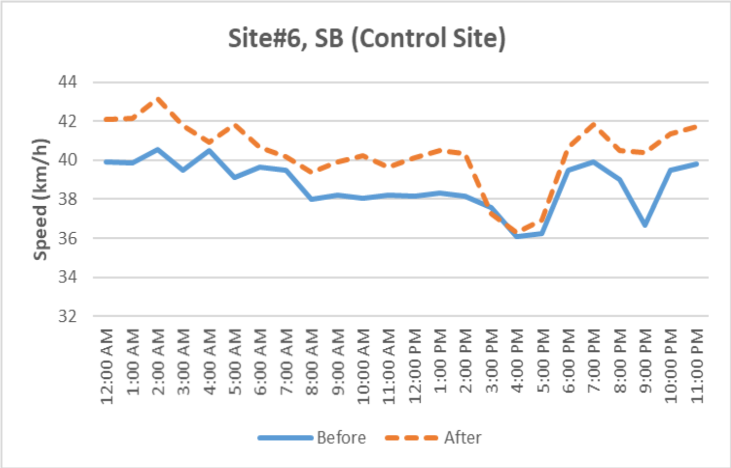




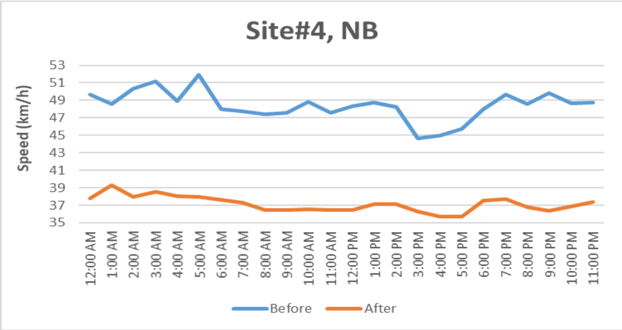
C3) 122 St & WMD-51 Ave (Southbound)

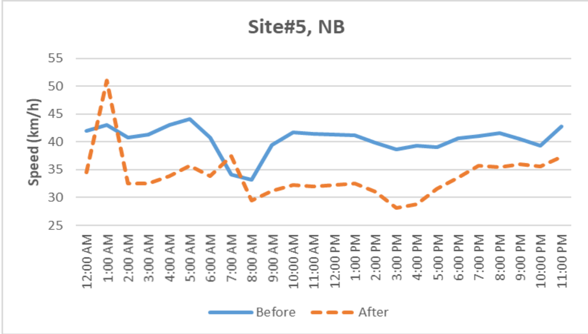


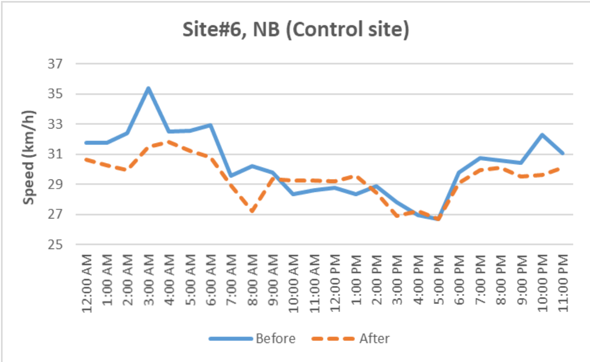




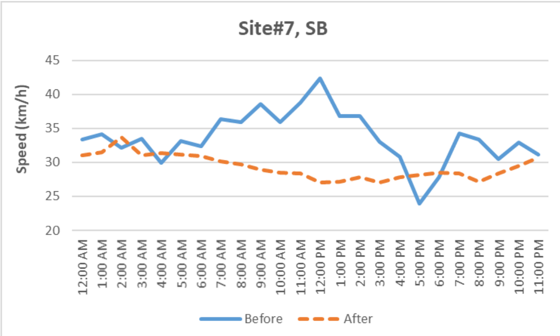
C4) 122 St & WMD-51 Ave (Northbound)

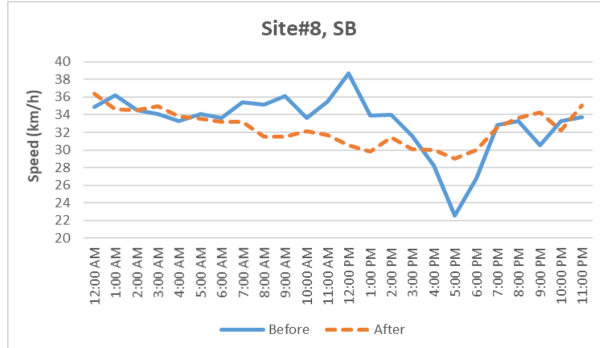


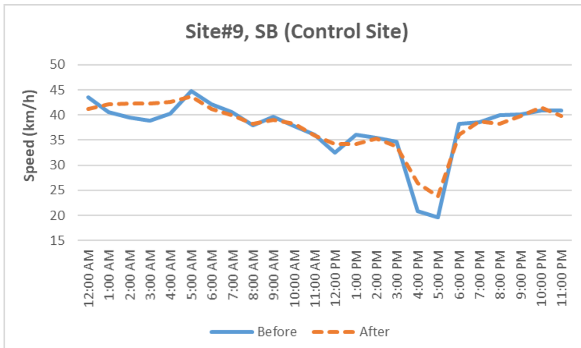




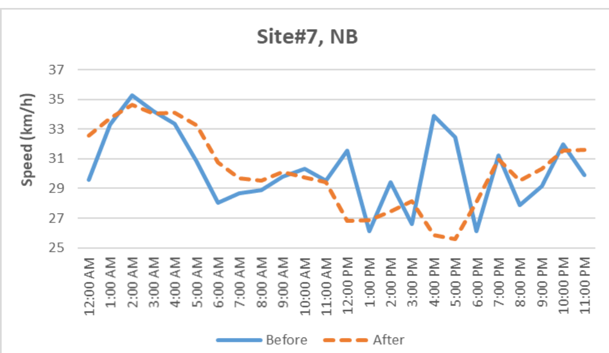
C5) 178 St & Stony Plain Rd (Southbound)

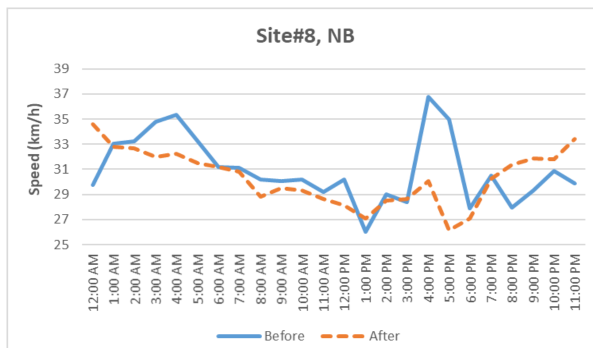


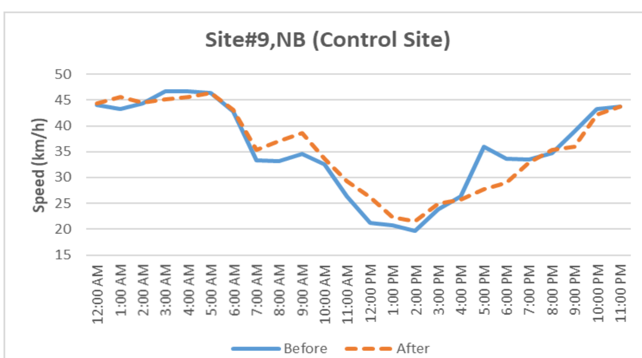




C6) 178 St & Stony Plain Rd (Northbound)

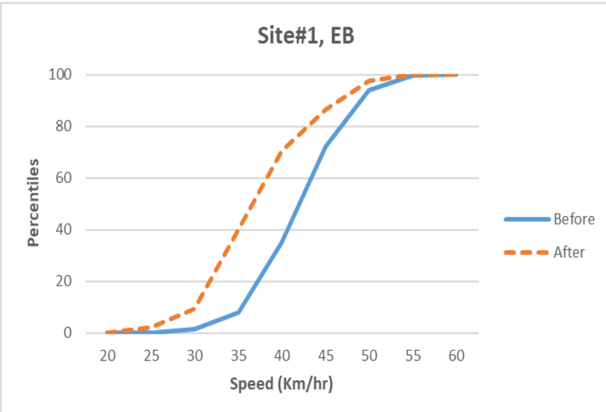


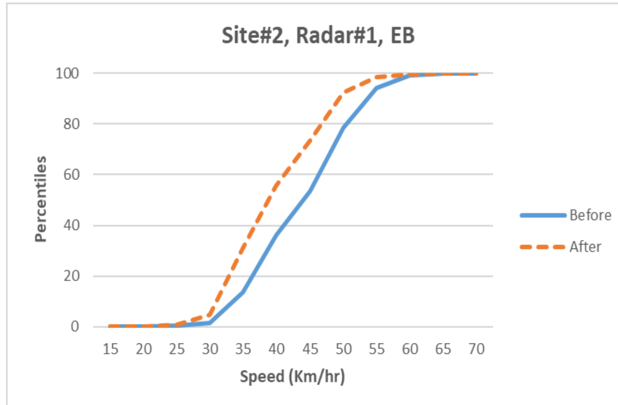


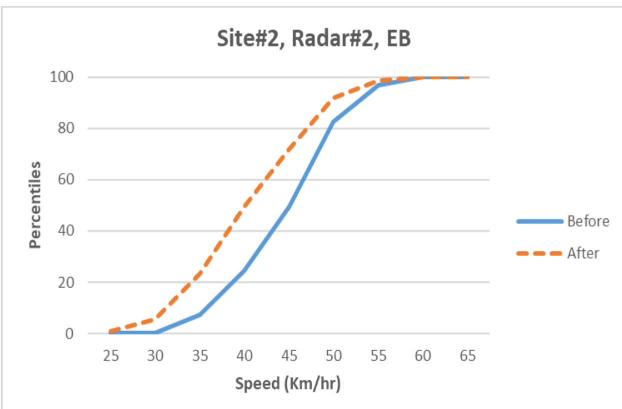


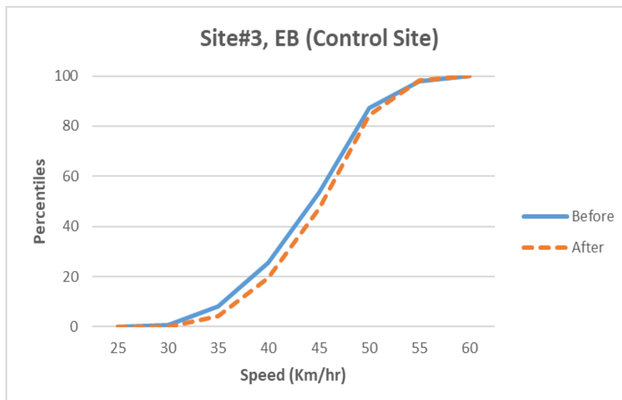
Appendix D: Percentile Speed Profiles

D1) 106 Avenue over Wayne Gretzky Drive (Eastbound)

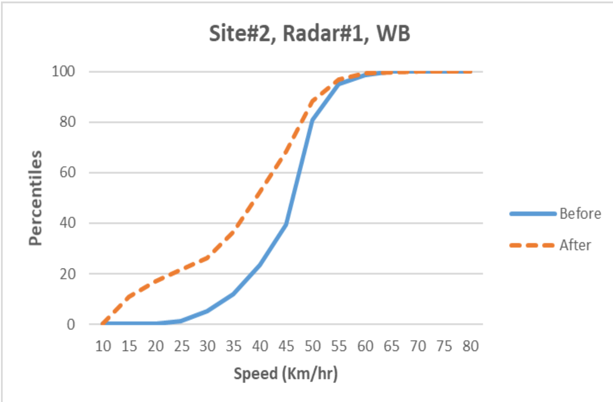


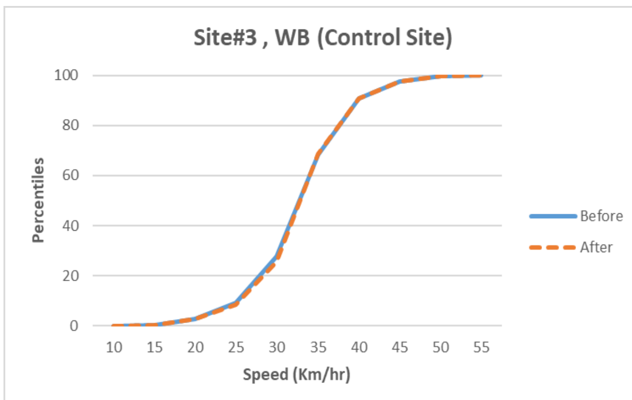




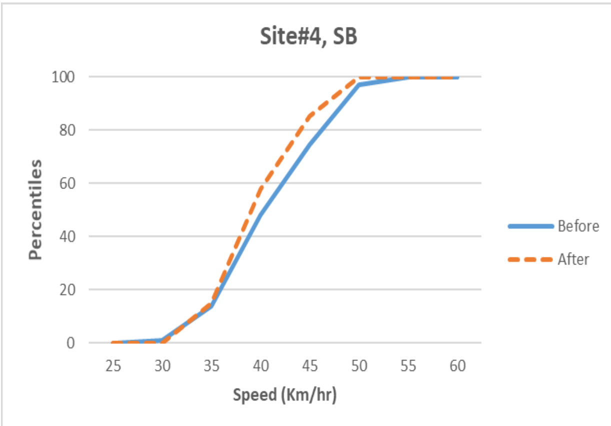


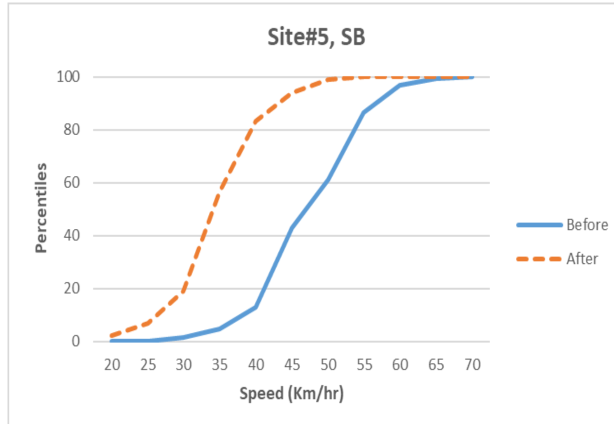
D2) 106 Avenue over Wayne Gretzky Drive (Westbound)

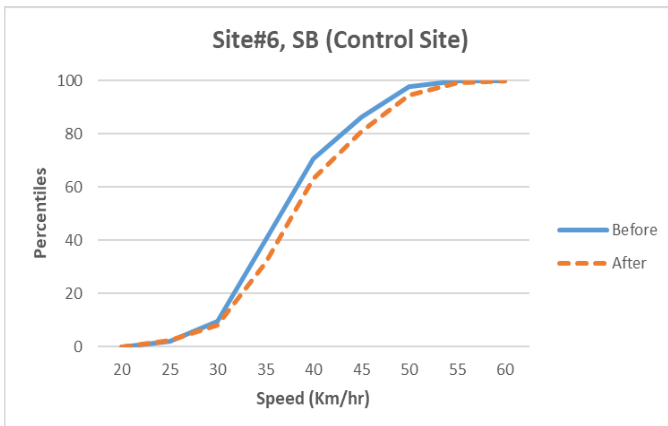




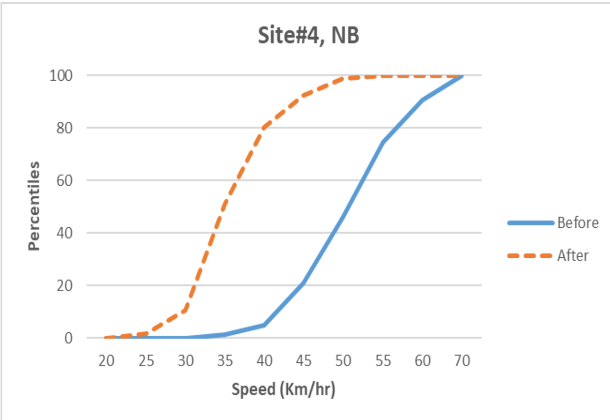
D3) 122 St & WMD-51 Ave (Southbound)

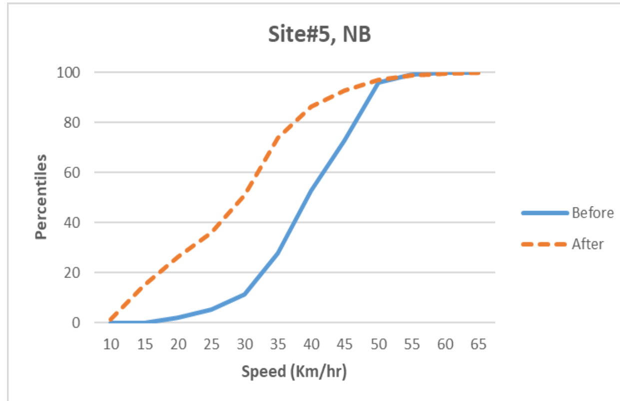


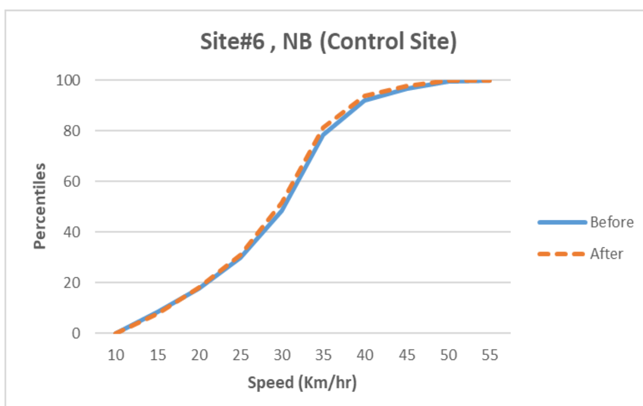




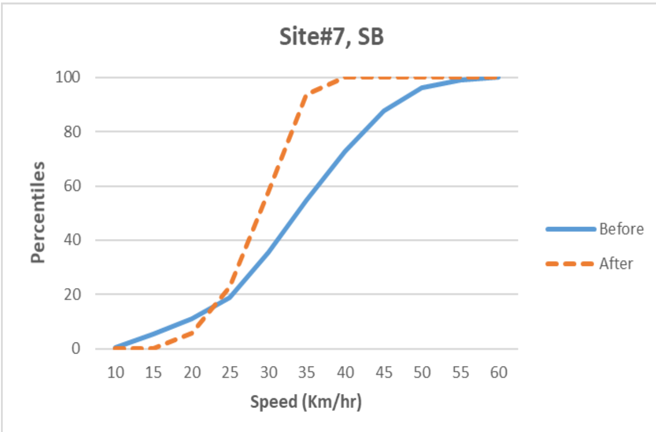
D4) 122 St & WMD-51 Ave (Northbound)

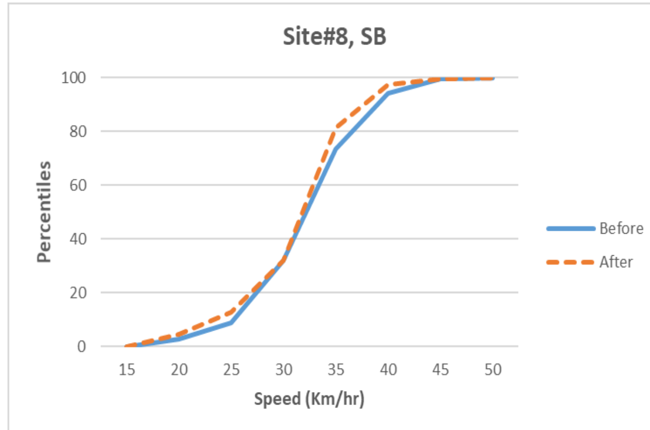


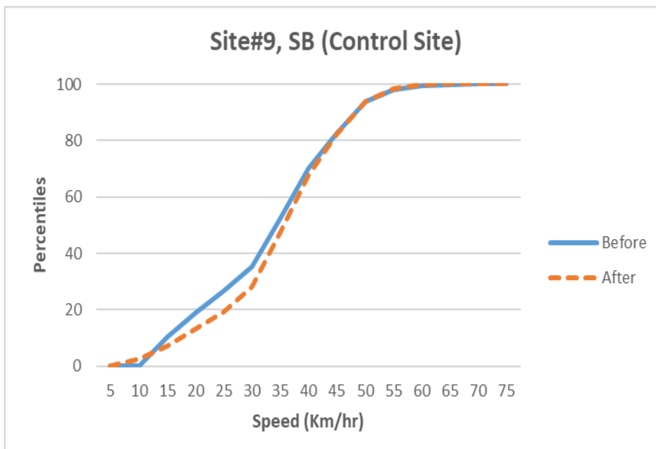




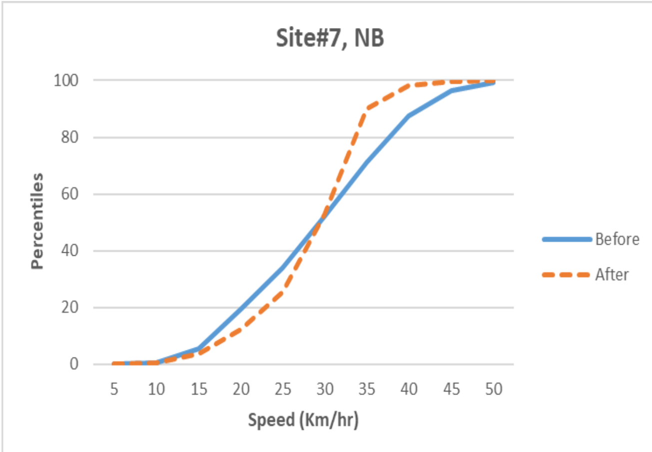
D5) 178 St & Stony Plain Rd (Southbound)

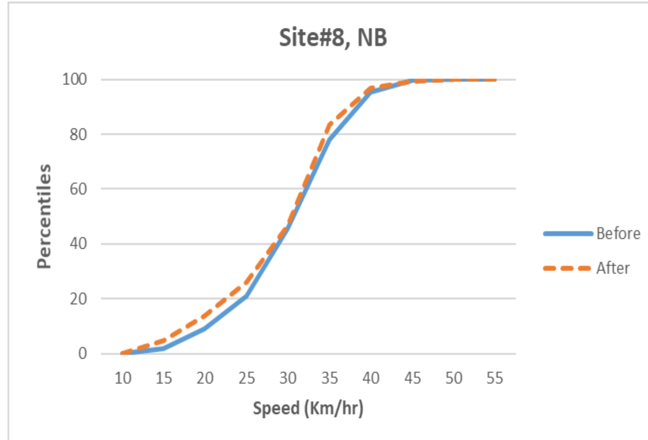


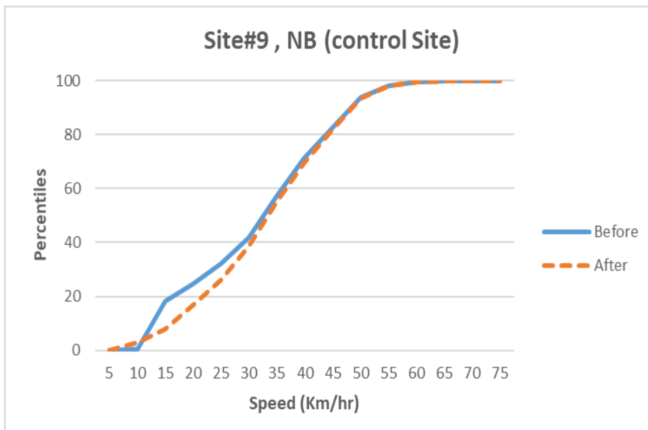




D6) 178 St & Stony Plain Rd (Northbound)

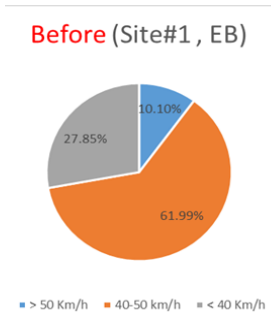


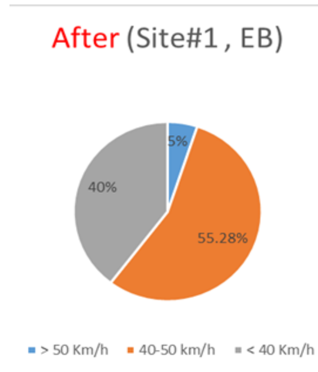


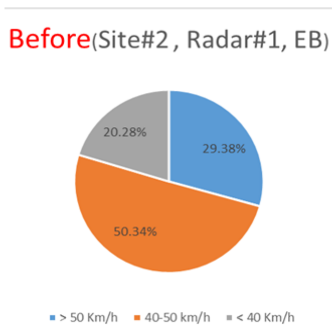


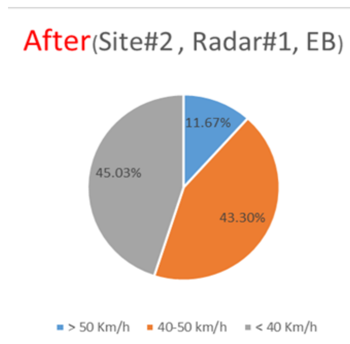
Appendix E: Speed Limit Compliance Comparison

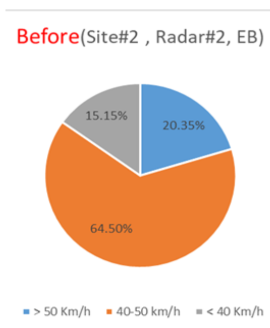
E1) 106 Avenue over Wayne Gretzky Drive (Eastbound)

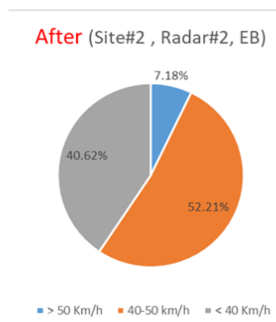


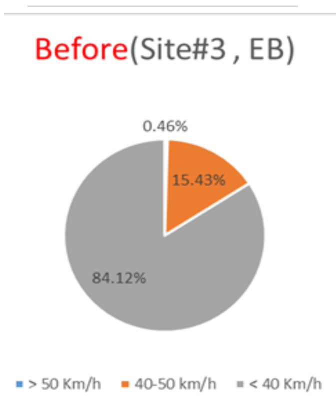


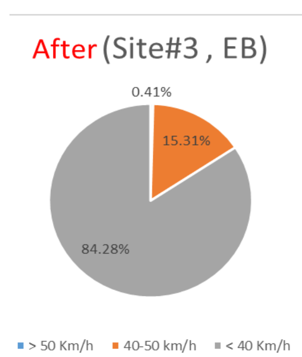




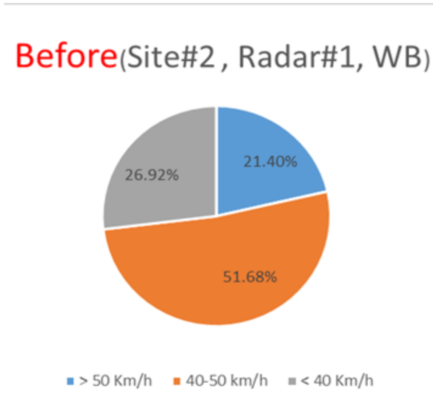


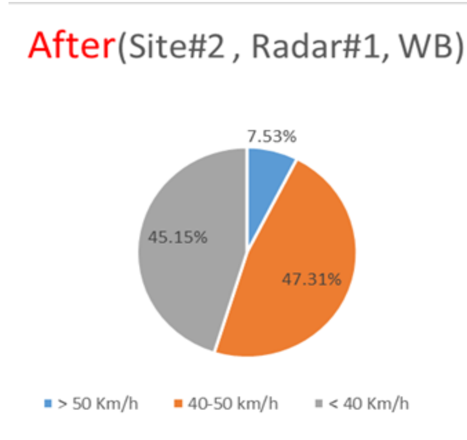


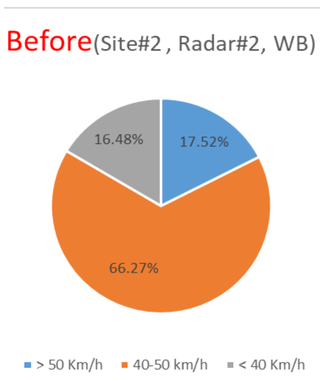


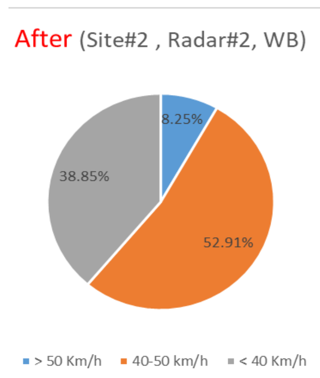


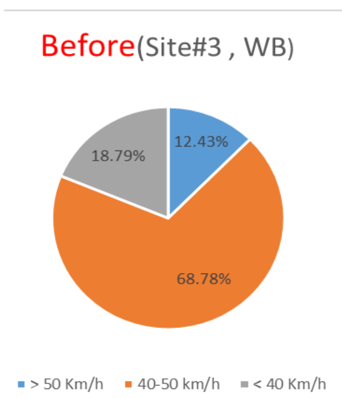
E2) 106 Avenue over Wayne Gretzky Drive (Westbound)

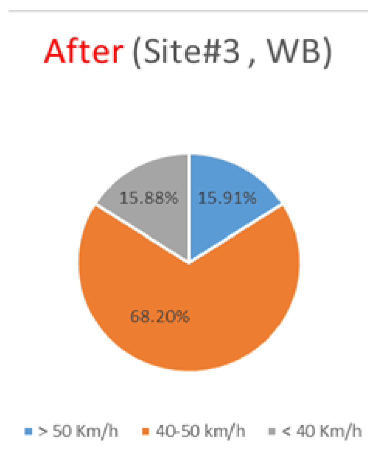




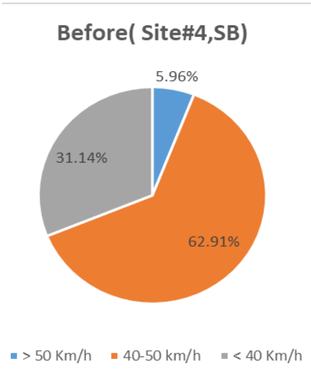


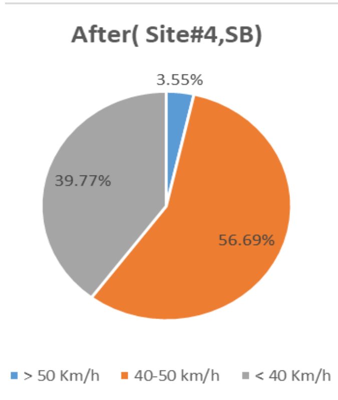


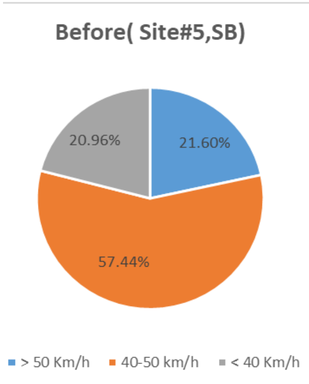


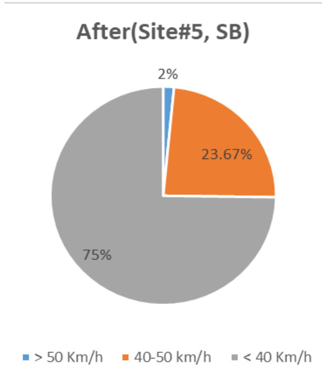


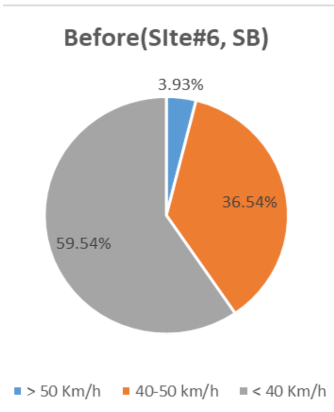
E3) 122 St & WMD-51 Ave (Southbound)

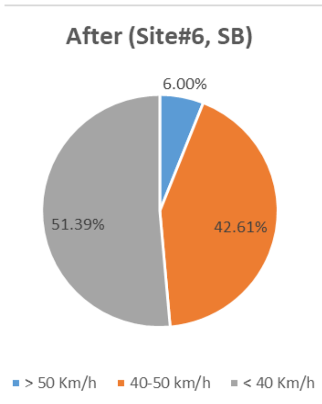




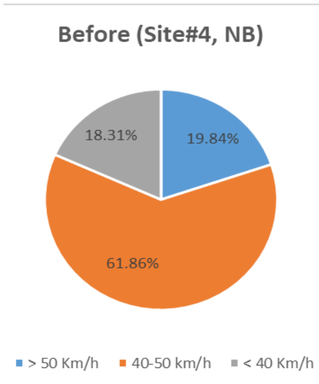


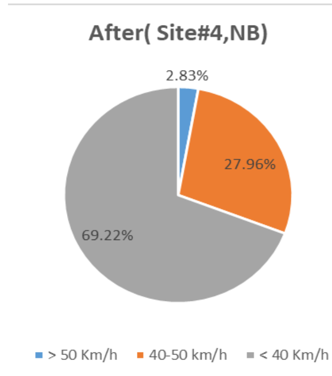


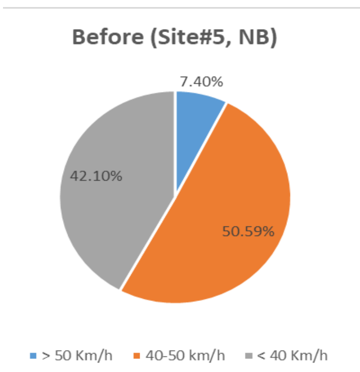


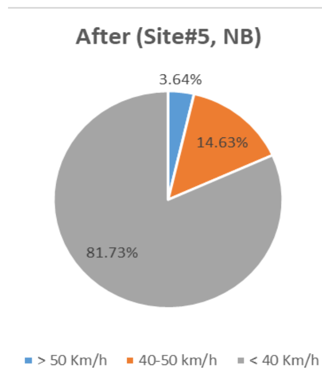


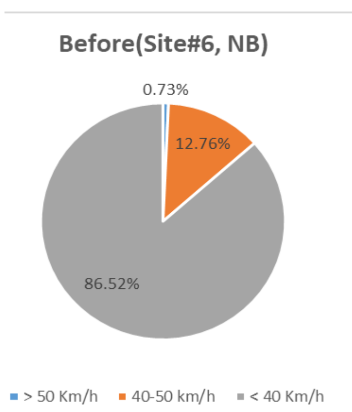
E4) 122 St & WMD-51 Ave (Northbound)

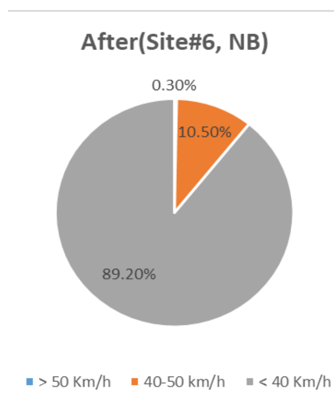




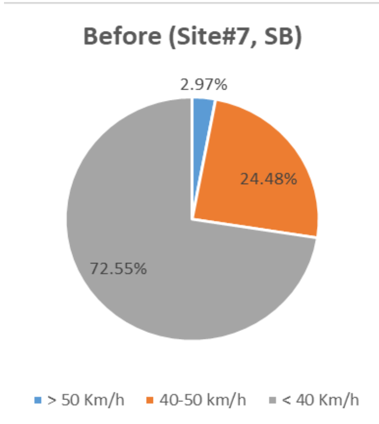


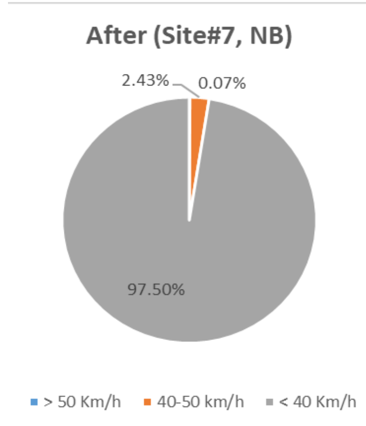


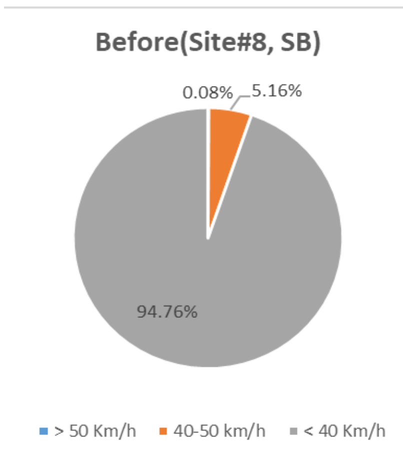


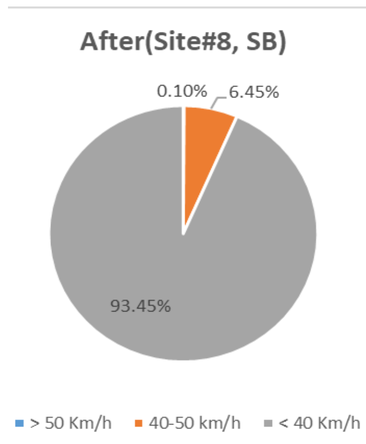


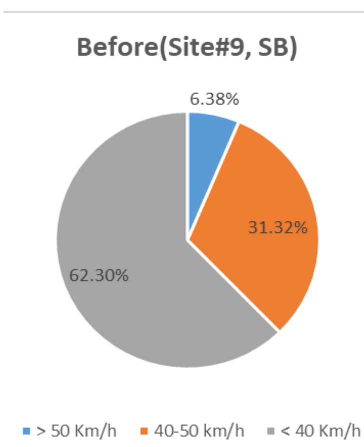
E5) 178 St & Stony Plain Rd (Southbound)

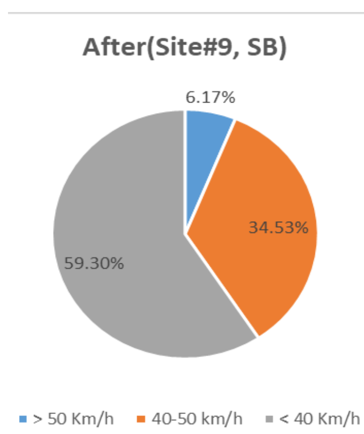




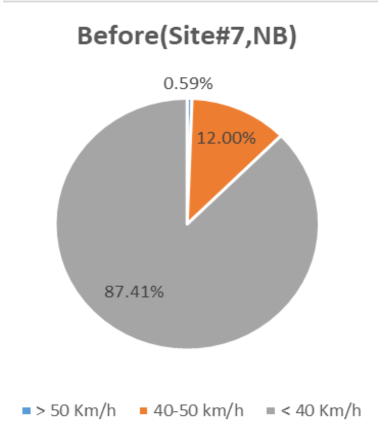


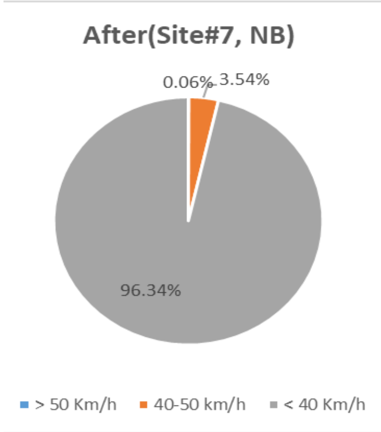


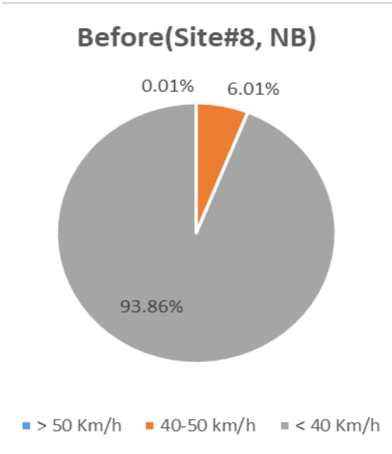


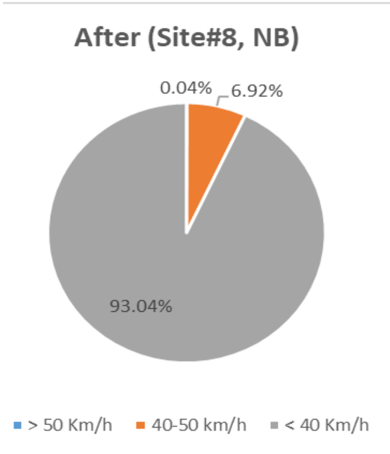


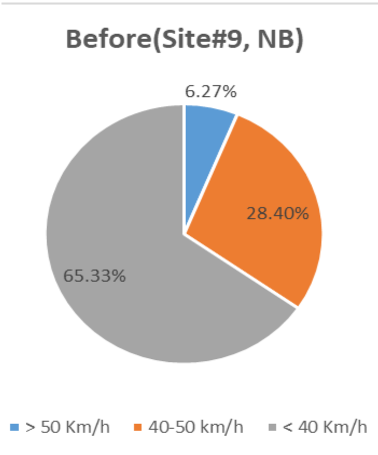
E6) 178 St & Stony Plain Rd (Northbound)

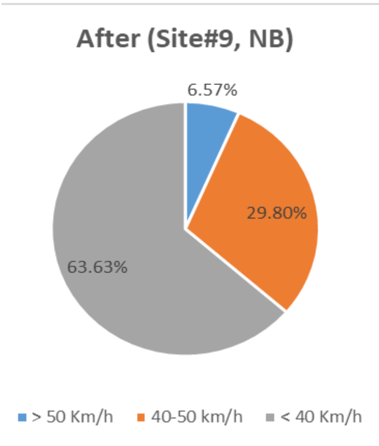












Appendix F: Implemented Changes on Treatment Sites

Site 1: 75 St -76 St & 106 Ave NW

Site 2: 106 Ave over Wayne Gretzky Dr

Site 4: 53 Ave & 122 St NW

Site 5: 51 Ave & 122 St NW

Site 7: 98a Ave & 178 St NW

Site 8: 98 Ave & 178 St NW