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Analysis of Speed Profiles and Evaluation of Dynamic Signs in Kansas Work Zones

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16 Abstract

Work zones are essential for maintaining and improving roadways in the United States. Although reduced speed limits are used throughout work zones to increase worker and driver safety, motorists often do not obey these speed limits. From 2016 to 2017, 799 work zone fatalities occurred, an increase of 3%, with vehicle speed as a main contributing factor. These fatalities cost construction industries up to $3.5 billion a year. These expenses result from on-the-job crashes and cover property damage, medical/legal expenses, and loss of productivity (Douglas, 2018). The purpose of this study was to evaluate the effectiveness of dynamic speed signs that attempt to reduce vehicle speeds through work zones. A computer program was developed to trace vehicles through a work zone to determine the effectiveness of following vehicles through a work zone versus evaluating overall vehicle data when evaluating the dynamic speed signs. This study utilized three work zones: Work Zone 1 (computer program) and Work Zones 2 and 3 (dynamic speed signs). Results showed that overall data evaluation more effectively determined vehicle speed than vehicle evaluation via the computer program. While Work Zones 2 and 3 both showed reductions in vehicle speed after the dynamic speed signs were placed, reduced speeds in Work Zone 3 were closer to the posted speed limit than Work Zone 2. In addition, results showed that passenger cars were most likely to exceed work zone speed limits, followed by speeding tractor-trailer trucks.

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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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Abstract

Work zones are essential for maintaining and improving roadways in the United States. Although reduced speed limits are used throughout work zones to increase worker and driver safety, motorists often do not obey these speed limits. From 2016 to 2017, 799 work zone fatalities occurred, an increase of 3%, with vehicle speed as a main contributing factor. These fatalities cost construction industries up to $3.5 billion a year. These expenses result from on-the-job crashes and cover property damage, medical/legal expenses, and loss of productivity (Douglas, 2018). The purpose of this study was to evaluate the effectiveness of dynamic speed signs that attempt to reduce vehicle speeds through work zones. A computer program was developed to trace vehicles through a work zone to determine the effectiveness of following vehicles through a work zone versus evaluating overall vehicle data when evaluating the dynamic speed signs. This study utilized three work zones: Work Zone 1 (computer program) and Work Zones 2 and 3 (dynamic speed signs). Results showed that overall data evaluation more effectively determined vehicle speed than vehicle evaluation via the computer program. While Work Zones 2 and 3 both showed reductions in vehicle speed after the dynamic speed signs were placed, reduced speeds in Work Zone 3 were closer to the posted speed limit than Work Zone 2. In addition, results showed that passenger cars were most likely to exceed work zone speed limits, followed by speeding tractor-trailer trucks.

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The authors wish to thank the Kansas Department of Transportation for sponsorship of this research project through the Kansas Transportation Research and New-Developments (K-TRAN) Research Program. Thank you to the many KDOT project monitors who assisted with this project including Kristi Ericksen, Eric Kocher, Eric Nichol, and Garry Olson who are all passionate about work zone safety in Kansas.

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List of Definitions

85th percentile speed: the speed at or below which 85% of vehicles travel

Advisory speed: recommended, unenforceable speed displayed on warning signs for a section of highway (e.g., a sharp curve or exit ramp)

Designated design speed: speed established based on a roadway's geometric design given a specific segment

Operating speed: vehicle's speed while operating during free-flow conditions

Posted/regulatory speed limit: the legal maximum vehicle speed for a given location displayed on a regulatory sign as established by state legislature, city, or county

Speed limit: legal maximum for vehicle speed given a specific location: posted speed and statutory speed

Statutory speed limits: numerical speed limits established by state law and applied to various categories of roads in the absence of posted speed limits (i.e., 25 mph in residential/school districts, 55 mph on rural highways, 70 mph on rural interstate highways)

Work zone speed limits: part of the work zone's control plan to facilitate safe and efficient flow of traffic through work zones

Variable speed limits (VSL): displayed on changeable message signs where reduced speed is needed (i.e., 10 mph below the posted speed limit).

Source: Donnell, Hines, Mahoney, Porter, & McGee (2009)

Chapter 1: Introduction

Work zones are essential for maintaining and improving roadways in the United States and monitoring these work zones is vital to the safety of all roadway users, including motorists and work zone laborers. Although reduced speed limits are often used prior to and within work zones and after work zones to increase worker and driver safety, motorists are more likely to travel at speeds they deem appropriate given current conditions. For example, if a work zone is not fully operational, motorists often do not obey reduced speed limits, resulting in varying speeds among vehicles that can result in congestion, unsteady flow through the work zone, and increased crash risk.

Work zones are accountable for 10% of overall traffic congestion and 24% of freeway delays. From 2016 to 2017, 799 work zone fatalities occurred, an increase of 3%, with vehicle speed as a main contributing factor (FHWA, 2019a, 2019b). These fatalities cost civil engineering construction industries up to $3.5 billion per year (FHWA, 2016). These expenses are from on-the-job crashes and cover property damage, medical/legal expenses, and the loss of productivity (Douglas, 2018). The evaluation of vehicle speed profiles in work zones will increase highway agency understanding of work zone safety and provide solutions for safety improvements.

Chapter 2: Review of Literature

2.1 Background

Traffic congestion and roadway user safety are most efficiently managed using a variety of methods and technologies. This literature review highlights vehicle speed profile studies to determine which methods and/or technologies are most effective for roadway variables such as roadway type, roadway location, roadway conditions, and weather conditions. Possible methods include the use of law enforcement, work zone signage, automated enforcement, speed advisory systems, and variable speed limit (VSL) systems. This review focuses on vehicle speed profiles during both typical roadway conditions and work zone conditions for a variety of methods.

2.2 Vehicle Speed Profiles

2.2.1 Law Enforcement

Safety corridors are often implemented on roadway sections with increased numbers of fatal and/or injury-related crashes and are patrolled by police officers to ensure that citizens comply with driving laws. Safety corridors also utilize additional traffic signage to prevent vehicle crashes. As of 2018, 15 states had utilized safety corridors to decrease crash risks and increase driver compliance. A study from Washington reviewed safety corridor SR 14, a two-lane rural road. Speeding, crossing the centerline, and drinking and driving were the top three causes of crashes in this area. Countermeasures included installing rumble strips and corridor signs, as well as prevalent ticketing of drivers who committed traffic violations, leading to a 55% increase in driving under the influence (DUI) arrests, a 103% increase in speeding tickets, a 158% increase in total tickets, and a 110% increase in traffic warnings. This project lasted two years, with results showing a 65% decrease in fatal and injury crashes, a 57% decrease in DUI arrests, and a 37% decrease in speeding violations (Finley et al., 2019). This study proved that increased enforcement improves driver compliance, thereby decreasing collision risks.

2.2.2 Signage

One type of traffic signage is the dynamic speed feedback sign (DSFS), also known as a speed display sign or speed-activated sign. A DSFS, which activates when a driver exceeds the posted speed limit or a set speed by engineer or law enforcement, displays the vehicle's speed up to a certain point (mainly to not encourage 100 mph+ speeds). The Center for Transportation Research and Education at Iowa State University conducted a study to evaluate DSFSs on curves at 22 sites on rural two-lane roadways and analyze the signs' impacts on speeding and crash rates. Results showed that the mean speed of most sites decreased by approximately 10.9 mph on the point of curvature and the center of the curve, while the number of vehicles exceeding the speed limit decreased for all points on the curves (Hallmark, Hawkins, & Smadi, 2015). This study proved that DSFSs successfully reduce high-end, average, and 85th percentile speeds.

Another study evaluated the use of vehicle activated signs (VASs) and speed indicator devices (SIDs). VASs are roads signs that display messages conditional to a vehicle's speed. SIDs are also activated by a vehicle's speed, but they flash the speed limit if a vehicle exceeds that speed. A study from Dalarna University in Sweden evaluated the use of these signs on a highway and a local roadway. Results showed that SIDs, while requiring less operational and capital costs, more effectively reduced driver speeds on local roadways than VASs. Although both signs showed significant speed reductions when used on highways, further research is needed to evaluate which sign is more efficient on highways (Jomaa, Yella, & Dougherty, 2017).

2.2.3 Driving Simulator Studies

Morgan State University explored the effects of variable message signs (VMSs) given whether motorists deemed the signs reliable. VMS are electronic overhead traffic signs that display traffic messages. The study integrated a driving simulator and a traffic simulator so research subjects could experience VMSs in realistic traffic conditions. Results showed that, on a scale from 1 to 5 (5 being "most reliable"), drivers gave the VMSs a score of 4.12 for reliability. VMSs were also shown to improve route choice behavior (Jeihani, NarooieNezhad, & Kelarestaghi, 2017).

Another study utilized 100 subjects to analyze driver behavior with reduced visibility due to fog. A driving simulator used the Baltimore metro area for analysis, and drivers' speeds were measured before, during, and after fog conditions. Results showed no significant difference between average speed during and after fog conditions. However, the correlation test showed that gender, work status, age, and social status affected motorist's average speed, with women (of any class and/or age) demonstrating significant speed reductions due to fog (Jeihani & Banerjee, 2018).

2.2.4 Vehicle Speed Profiles

A study in India reviewed the factors that affect free-flowing traffic speeds. An 8-hour video (morning and evening hours) was used to collect data on urban two-lane roads. Results showed a linear relationship between the durability of a given roadway and free-flowing speeds (Sekhar, Nataraju, Velmurugan, Kumar, & Sitaramanjaneyulu, 2016).

A study in Iowa evaluated the effect of speed bumps on traffic given roadways with 25 mph and 30 mph speed limits in small rural cities. Results showed a reduction in vehicle speeds after speed bumps were removed and the average number of vehicles that exceeded the speed limit decreased. These speed reductions were results of the speed bumps that were previously emplaced on that roadway. However, the results did not show statistically significant speed reductions, proving that speed bumps do not successfully reduce traffic volumes (Smith, Hallmark, Knapp, & Thomas, 2002).

A study by the National Cooperative Highway Research Program (NCHRP) utilized a Kustom ProLaser 4 light detection and ranging (LiDAR) gun to measure vehicles' free-flowing speeds in seven cities (Little Rock, St. Louis, Nashville, Portland, Boston, College Station, and Houston). Data was collected during weekdays under normal weather conditions (no rain, sleet, snow, strong wind, etc.). According to the results, the posted speed limit and 85th percentile speed showed a statistically strong relationship, meaning that, as speed limit increases, the 85th percentile speed also increases. The strongest relationship was found between operating speed and posted speed limit. Researchers found that the road's geometric design had minimal effect on drivers' operating speeds, with the exception of a tight horizontal radius on a curve. On horizontal suburban curves, operating speeds were lower than the design speed (43.5 mph), and on rural two-lane roadways, operating speeds were greater than the designed speed (55.9 mph). Significant fluctuation in operating speeds was observed for a given design speed (expected speed limit) on a rural two-lane highway (Fitzpatrick, Carlson, Brewer, Wooldridge, & Miaou, 2003).

Because horizontal curves have been proven to negatively affect crash risks, a study from Iowa State University evaluated vehicle speed profiles on horizontal curves. Pneumatic tubes were used to collect data for 70 hours in the summer months. The first studied site was on a rural highway with a speed limit of 55 mph, and the second site was on an urban roadway with a speed limit of 45 mph. Results from the study revealed that weather conditions significantly affect vehicle speeds, especially conditions that lead to wet roads, which cause vehicles to decrease speed on curves. On the curves at both testing sites, motorcycles, passenger cars, and school buses drove at greater speeds than trucks, and vehicles in the inside lane traveled at higher speeds than vehicles in the outside lane. Vehicles speeds were higher during nighttime hours than during the day (Fitzsimmons, 2011).

Another study measured vehicle speed profiles at 15 sites, 12 of which were on horizontal curves and 3 of which were tangent approaches to stop-controlled intersections. An NC-97 detector gathered speed profiles during the daytime under typical traffic conditions, and speed profile regression lines were used to find the relationship between speed and distance. For vehicles traveling in normal traffic conditions, the regression lines revealed no significant effects on speed profiles, proving that heavy vehicles' speed profiles are higher on tangential roadways than horizontal curves. Results also showed that passenger vehicles have higher free-flowing speeds on tangential roads and horizontal curves than heavy vehicles, and passenger cars have greater deceleration (given normal traffic conditions) than heavy vehicles. The speed profiles were predicted at a 95% confidence level (Schurr, McCoy, Pesti, & Huff, 2002).

A study from the Science Applications International Corporation (SAIC) at the Turner-Fairbank Highway Research Center studied the impact of pavement markings on speeding. Transverse pavement markings (i.e., transverse bars or transverse chevron) were placed perpendicular to traffic on a roadway to give the illusion of vehicle acceleration. Data collection was taken before installation, directly after installation, and 6 months after installation at several sites in New York, Mississippi, and Texas. Results showed that the use of transverse pavement markings significantly reduced vehicle speeds, especially at sites in New York and Mississippi on interstate and arterial roads; however, the effects of these markings were not as significant on local roads in Texas (Katz, 2004). Similarly, another study found that the use of transverse pavement markings led to a decrease in speed of 3–5 mph and a decrease of 5–7 mph for the 85th percentile speed (Corkle, Giese, & Marti, 2001).

2.2.5 Variable Speed Limits

Current weather and traffic conditions can cause changes in VSLs, meaning the signs display increasingly accurate speed limits in accordance with the current time of day. In contrast to static speed limits, VSLs require traffic/speed detectors, microprocessors, communication, VSL signs, a station for logging changes, and environmental sensors (Warren, 2007). Depending on whether or not a state enforces changeable speeds, drivers can receive a speeding citation if they exceed the VSL's speed limit. VSLs are commonly used in harsh weather conditions. For example, when roads are icy, a VSL sign will display a decreased speed limit to reduce crash risks. Similarly, VSL signs can alert drivers of upcoming traffic and ultimately reduce traffic congestion.

A case-control study that analyzed drivers' opinions regarding VSL signs found that overhead signs were more noticeable than roadside signs. Driver compliance for a VSL of 65 mph was similar to compliance for a 65-mph static sign. Although no significant changes in driver behavior were observed for a reduced speed limit (from the VSL) drivers noted that their speeds would probably exceed the decreased VSL if weather and/or roadway conditions were normal (no harsh weather or traffic conditions). Similarly, study participants discussed the need for visual compliance to follow the VSL; most subjects agreed that an alert or message on the VSL that explains the reason for the speed reduction is the most crucial factor in driver compliance (Harrington, 2015).

2.3 Vehicle Speed Profiles in Work Zones

Statistics show that 710 fatal crashes and 799 fatalities, 132 of which were worker fatalities in work zones, occurred in 2017 (ARTBA, 2019). Speed has been shown to be a contributing factor in almost 29% of fatal work zone crashes (FHWA, 2019a, 2019b). Because excessive speeding increases crash frequency and severity, efficient management of vehicle speeds in work zones must be implemented. In order to improve work zone mobility, various methods and technologies must be evaluated to determine which has the most significant impact on speed compliance, traffic congestion, safety, and travel time. These methods and technologies include (but are not limited to) automated enforcement, law enforcement, speed advisory systems, and VSL systems.

Another study used the Global Positioning System (GPS) to evaluate vehicle speed profiles in relation to a road's geometric layout. Work zones with partial closure (closure of one lane in one direction) and crossover (closure of a roadway to maintain two-way traffic on another roadway) were used for data collection, including Indiana freeways at four partial-closure work zones and three crossover work zones. Results showed more speed variation in work zones than average speeds on freeways. The work zones caused significant traffic congestion, thereby decreasing vehicle speeds and increasing average deceleration (Jiang & Li, 2001). This study highlighted the significance of speed management in work zones, while the following studies address efficient, effective methods and technologies for reducing vehicle speeds.

2.3.1 Use of Law Enforcement

Reduced speed limits, speed advisories, and other signage are typically used in work zones to enforce speed reductions, with mixed results of success. Motorists usually reduce driving speeds based on individual perceptions about work zone conditions and enforcement levels. Thus, if workers are working near oncoming traffic, drivers are likely to reduce speed 5–10 mph based on worker proximity. However, combined use of traffic signage and law enforcement has been shown to reduce speeds up to 15 mph (ARTBA, 2010).

Many motorists identify the presence of law enforcement as the most effective method for increasing driver compliance in work zones. Law enforcement uses three main types of enforcement activities in work zones: stationary, traffic control, and mobile. Stationary enforcement utilizes a police car placed at a visible section in the work zone. Traffic control enforcement occurs when an officer engages with motorists by escorting motorists through the work zone, while mobile enforcement occurs when an officer drives through the work zone and pulls vehicles over if they violate work zone regulations. A survey showed that, although stationary enforcement is most common throughout the United States, mobile enforcement is more effective at reducing vehicle speeds (Brewer, Pesti, & Schneider, 2005). The Colorado Department of

Transportation determined that the most effective method for ensuring speed compliance through work zones is mobile enforcement (Outcalt, 2009).

In many states, speeding citation fines are doubled in work zones regardless of work zone activity level, and some states also require jail time and/or community service for speeding violations (KDOT, n.d.). Furthermore, if the use of law enforcement is not available for a given site, then other methods should be employed.

2.3.2 Managing Speeds

Federal law states that, unless an engineering study has proven that the geometric layout of the site requires further reduction, speed limit reductions in work zones cannot exceed 9 mph below the regulatory speed limit for that site (Forbes, Gardner, McGee, & Srinivasan, 2012). According to a study from the Federal Highway Administration (FHWA), one work zone fatality occurs for every 4 billion miles traveled and for every $112 million worth of work zone expenditures. Work zone crashes also significantly impact traffic congestion, accounting for 10% of overall congestion and 24% of freeway delays (FHWA, 2019a, 2019b).

Speed limit enforcement has been proven to effectively manage speed variability. A study from Illinois evaluated the effect of speed photo-radar enforcement (SPE) on vehicle speed profiles. Three work zone locations were tested on major interstate highways (I-64 near St. Louis and I-55 near Chicago), including two open travel lanes and a right-hand shoulder. Results from the study showed that SPE reduced speeding by 7%–57% in the shoulder lane and increased driver compliance to 83.05%–100%. Speeding in the median lane decreased 40%–51%, while driver compliance increased to 81.1%–99.05%. Overall, SPE was found to be as effective as law enforcement at reducing vehicle speeds through work zones (Benekohal, Hajbabaie, Medina, Wang, & Chitturi, 2010).

Similarly, a study from the Idaho Department of Transportation found that the use of SPE decreased speeding 8%–40% for passenger vehicles and 4%–17% for heavy vehicles (gross vehicle mass of more than 4.5 tonnes). Heavy vehicles include semi-trailers, B-double freight trucks, passenger busses, etc. Overall, average speeds decreased 3–8 mph (Scriba & Atkinson, 2014). An Illinois study found that SPE reduced speeds 3–8 mph and significantly reduced speeds at 55 mph speed limits (Tobias, 2011). A study from the Oregon Department of Transportation found that SPE reduced speeds by approximately 27.3%, but this speed reduction was not maintained past the photo-radar (Joerger, 2010). When the Maryland State Highway Administration initially enforced the use of SPE in 2001, approximately 7 out of 100 drivers exceeded work zone speed limits by 12 mph or more; however, in 2011, less than 2 out of 100 drivers exceeded speed limits in work zones, resulting in the state's lowest number of work zone fatalities (MDOT, 2012). Overall, the use of SPE has proven to be successful at enforcing speed compliance and reducing crash risks in work zones. For future use, states could beneficially use SPE in multiple areas throughout work zones to create consistent speed reductions.

A Variable Advisory Speed System (VASS) also reduces vehicle speeds by giving drivers a speed reduction warning prior to the work zone site. A study from the Utah Department of Transportation evaluated the use of VASS for reducing queues at work zone entrances. Data was collected on I-15 Beck Street using speed sensors and two VMSs. Results showed that, in conjunction with VMSs, VASS was most successful on the weekends during evening hours when minimal traffic was present (Saito & Wilson, 2011). No statistically significant difference was observed during the weekdays, leading to the conclusion that future research is needed.

Temporary transverse rumble strips are often used to increase driver compliance in work zones. In general, research has shown that rumble strips effectively reduce crash risks and overall vehicle speeds. However, studies have shown that rumble strips should not be used in areas with high volumes of traffic because the strips could cause accidents. Rumble strips also cause significant noise, disturbing nearby residents (Rathner, 2015).

Similar to DSFSs and speed display signs, speed feedback trailer signs are changeable signs that display an approaching vehicle's speed. These signs are commonly used in work zones and on highways. Multiple studies from the Iowa Department of Transportation have shown that speed feedback trailers effectively reduce speed limits in work zones, with typical speed reductions of 10–15 mph. Specifically, these signs are beneficial when a work zone laborer is close to an open lane with high volumes of traffic and/or vehicles traveling at high speeds and on sites with a horizontal curve (IDOT, 2017). Another study evaluated the effect of speed-activated signs, otherwise known as speed feedback trailer signs, on two-lane primary and secondary highways in

Southern California. Results showed that mean speeds decreased 3.3 mph and driving speeds of vehicles exceeding the posted speed limit prior to the speed-activated sign decreased 4.1 mph (Mattox, Sarasua, Ogle, Eckenrode, & Dunning, 2007). This study found that speed-activated signs are most beneficial for short-term work zones, mainly because the sign's long-term effects could not be determined. Overall, speed-activated signs (speed feedback trailer signs) were shown to be cost efficient and effective because they increase speed compliance and decrease crash risks.

2.3.3 Driving Simulator

Driving simulators can effectively and reliably test and measure variabilities. Studies in this review used driving simulators to test the effects of traffic signage on work zone conditions. Traffic signage has been shown to reduce work zone-related crash risks and decrease the cost of work zone damages. The following studies utilized dynamic speed display signs (DSDSs), VSLs, portable changeable message signs (PCMSs), and dynamic message signs (DMSs).

One study used a driving simulator to evaluate the effects of SPE, DSDSs, and reduced speed limit signs on the Baltimore-Washington Parkway (MD-295). Sixty-six subjects participated in a total of 264 driving simulations. Results showed that SPE reduced vehicle speeds by approximately 11 mph, and the use of additional signs led to greater speed reductions. DSDSs were shown to reduce vehicle speeds by approximately 8 mph. An ANOVA test determined that SPE signs most effectively reduce vehicle speeds in work zones (Banerjee, Jeihani, & Morris, 2019).

Another driving simulator study reviewed the effects of DMSs on driving behavior. Several DMS formats were tested to determine if sign length, type, and content uniquely affect drivers. Sixty-five subjects participated in 390 simulations of a road in Maryland. Results showed that one-word messages were most efficient because motorists could quickly comprehend the messages. Similarly, the simultaneous display of messages, of more than one word, on the DMS was ineffective and increased traffic congestion. Therefore, the study concluded that only two or three units should be used on DMSs to maintain constant vehicle speeds through work zones and decrease traffic congestion. Color-coded DMS messages, which are color-blind friendly, resulted in increased driver compliance rates because they successfully caught the attention of most drivers

(Jeihani, Banerjee, Ahangari, & Brown, 2018). A study from the University of Ohio compared the effects of DMSs on speed compliance and found that drivers were more compliant to "SLOW DOWN 45" signs than regulatory speed limit signs (McAvoy, 2011). Both of these studies proved that DMSs effectively improve driver speed compliance. A similar study from the U.S. Department of Transportation found that the use of message boards during periods of heavy congestion increased driver compliance and led to a 1%–20% decrease in traffic volume (FHWA, 2008).

Fifty-three participants took part in a driving simulator study to test the effects of certain work zone conditions on driving behavior. A work zone concrete barrier, a lateral barrier, and high/low work zone activity were used as factors to measure driver speed and lane position. Results showed that subjects drove faster with more constant average speeds when concrete barriers were utilized. Although the lateral barrier showed significant speed reductions, average speeds were more constant without the barrier, and increased variabilities in speeds and low average speeds were observed in areas with significant work zone activity (Reyes & Khan, 2011). Similarly, another study found that concrete barriers resulted in increased driving speeds in real work zone conditions and that drivers tended to drift from the center line, away from the concrete barrier (Banerjee, Jeihani, & Moghaddam, 2018). Overall, study results showed that buffers and high activity work zones cause speed variability, potentially increasing crash risks.

Radar speed displays, interactive signs constructed with LEDs, display approaching vehicle speeds. The Midwest Smart Work Zone Deployment Initiative evaluated the effectiveness of these signs for reducing speeds by collecting data from a site on a two-lane rural commuter route west of Lawrence, Kansas. Data were measured over an 8-week period for 1 hour each day; radar speed displays were used for five of the study weeks. Results showed statistically significant reductions in mean speeds and 85th percentile speeds, approximately 5 mph, and the number of drivers exceeding the speed limit decreased approximately 25% (Meyer, 2003).

2.3.4 Variable Speed Limits

VSLs are advantageous because they change relative to current time and current work zone and weather conditions. To study VSL control, one VSL study used a simulation of urban mobility (SUMO) of Interstate 15 (three-lane interstate with one lane closed for the work zone) in San

Bernardino County, California. Results showed that, in the studied conditions, VSL reduced travel time by 17%, reduced crash risks by 90%, and reduced hazardous pollutants (oxides of nitrogen and carbon dioxide) and fuel consumption by 6% (Du & Razavi, 2019).

A study from the Utah Department of Transportation tested the effects of VSL signs on driver compliance in a work zone on I-90 in Summit County near the Utah-Wyoming border. VSLs and traffic counters measured vehicle speed profiles before, during, and after the work zone. Results showed that VSLs decreased total average speeds, regardless of high or low work zone activity. Although traffic congestion due to lane closures increased speed variance, speed variation was still less with the use of VSL signs than with regulatory signs (Riffkin, McMurtry, Heath, & Saito, 2008).

The FHWA studied the effects of VSL on speed compliance at a work zone on I-96 southwest of Lansing, Michigan. VSLs were shown to increase traffic speed uniformity, thereby decreasing travel time and crash risks. In addition, the number of vehicles exceeding the speed limit decreased with the use of VSLs, proving that VSLs effectively convey realistic speeds to motorists (FHWA, 2004). Similarly, a study from the Virginia Department of Transportation proved that the use of VSLs, in relation to current conditions, increases driver compliance and reduces speed variance (Fudala & Fontaine, 2010).

The University of Minnesota-Duluth evaluated VSLs in a work zone on I-494 in the Twin Cities, Minnesota. The data showed a 25%–35% decrease in average speed at peak morning hours (6:00–8:00 a.m.) but an increase in traffic volume by approximately 7%; however, this increase was not statistically significant (Kwon, Brannan, Shouman, Isackson, & Arseneau, 2007). Overall, VSLs have been proven to efficiently and effectively reduce speeds and increase driver compliance in work zones throughout the United States.

2.4 Research Objectives

Despite the previously discussed literature, a limited number of studies have evaluated vehicle speed profiles using dynamic speed signs in a work zone. Therefore, the study for this paper used three work zone sites on a roadway with a speed limit of at least 55 mph, and four road tubes, separated so that multiple interchanges were located at two of these sites, to track vehicles and their speeds with and without dynamic speed signs. The data were analyzed via computer software. The objective of the study was to develop actual vehicle speed profiles for the three work zone sites using four counters that collected speed profiles, giving data for various points throughout the work zone. Additionally, the study sought to analyze which vehicle classes comprised the largest percentage of speeding vehicles passing through all three sites. One of the three sites did not use a dynamic speed sign, while the other two sites utilized the signs. The effects of the signs at the two sites were compared to verify effectiveness of the dynamic speed signs.

Chapter 3: Methodology

3.1 Work Zone 1

Work Zone 1 of the current study was located on northbound I-35, north of Ottawa, Kansas, beginning at mile marker 188. The work zone used standard signage throughout with no variable message signs (VMS). Two pneumatic roads tubes, spaced 2 ft apart from each counter, were used to collect speed, gap, time, and vehicle class information. Counter 1 was located at the beginning of the work zones, before the speed reduction sign and before the road began to narrow. Counter 2 was located where the road decreased from two lanes to one lane, and Counter 3 was located approximately halfway through the work zone. Counter 4 was located at the end of the work zone, after traffic returned to two lanes.

Counter 1 and Counter 2, which were located prior to the interchange of I-35 and US 59 (Figure 3.1), included data from vehicles that exited onto US 59. As shown in Figure 3.2, Counter 3, which was located after the US 59 exit on I-35, did not include data from vehicles that exited I-35, but included vehicles that entered from US 59. Counter 4 was located after the Tennessee Road exit off I-35 (Figure 3.3). The presence of these entrances and exits increased the difficulty of determining accurate free-flow speeds through the work zone; these entrances and exits caused significant variation in the number of vehicles from Counter 2 to Counter 4. Therefore, the conclusion was made that individual vehicles must be traced through a work zone to obtain accurate vehicle speeds through a work zone and to determine whether or not dynamic speed signs help reduce vehicle speeds. Locations of all the counters for Work Zone 1 are shown in Figure 3.4.

Figure 3.1: Locations of Counters 1 and 2 for Work Zone 1

Figure 3.2: Location of Counter 3 for Work Zone 1

Figure 3.3: Location of Counter 4 for Work Zone 1

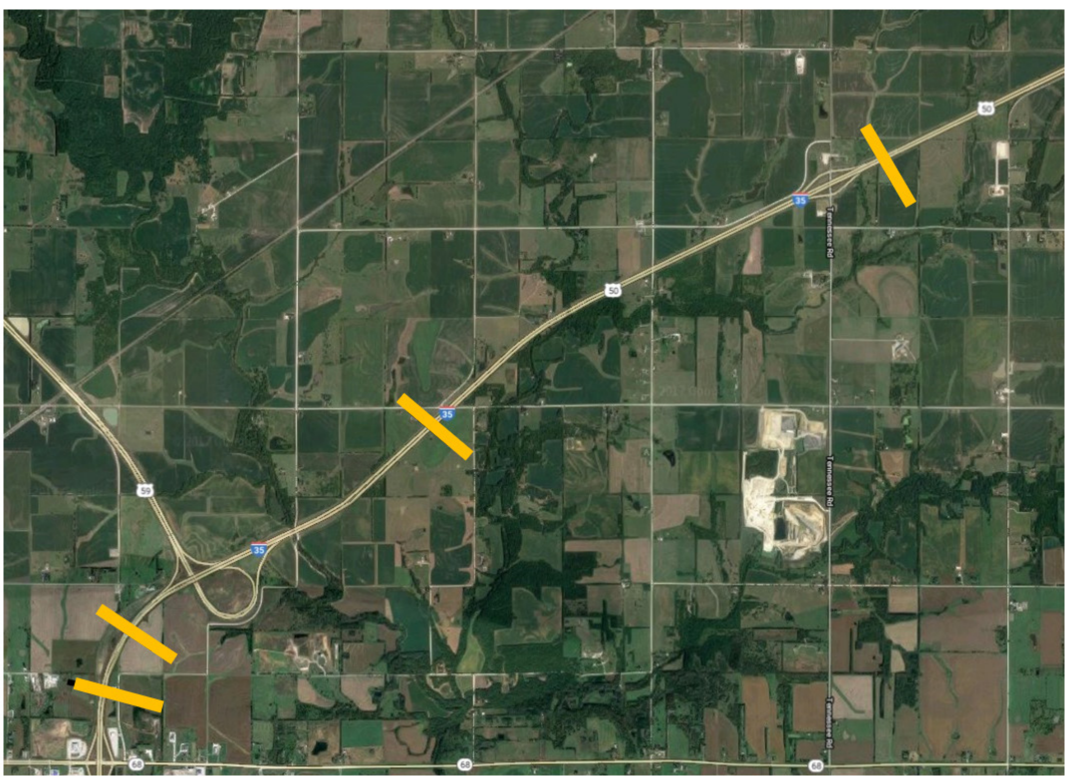


Figure 3.4: Locations of Counters 1, 2, 3, and 4 for Work Zone 1

To trace vehicles through Work Zone 1, the data were processed using standard JAMAR software and exported into Microsoft Excel; distances between the counters were determined using counter locations. Distances between the counters helped determine approximate travel times between the counters, meaning that, by synchronizing the counters before data collection, the research team used approximate travel times to trace each vehicle through the work zone. Although tube placement was maintained at 2 ft for each setup, variations occurred in captured vehicle lengths. By tracing each vehicle through the work zone, researchers could determine approximate variations in vehicle length between each pair of vehicles. Variations in length and travel time were then used to fully trace vehicles through Work Zone 1.

A novel computer program was developed to account for time and length between counters. The program took a vehicle hit on Counter 1, applied the calculated time to travel to Counter 2, and then used the calculated change in length at Counter 2 to find a match. The program then utilized the travel time from Counter 2 to Counter 3 and the length change calculated at Counter 3 to identify a match at Counter 3. Likewise, the program used the travel time from Counter 3 to Counter 4 and the calculated length change to find a match at Counter 4. To account for changes in speed and variances in length, the program searched for calculated time and length with a +/- 2% range.

When the program finished matching the vehicles, researchers then manually examined the data and verified the most accurate matches. Data were initially sorted by eliminating traffic with gap times less than 4 seconds to ensure that the traced vehicles moved at free-flow speeds. In order to accurately determine speed through the work zones, a determination was made to eliminate platooning vehicles. Platooning vehicles are those vehicles that are closer than 4 seconds from the vehicle in front of them. Platooning vehicles speeds are influenced by the speeds of the vehicles in front of them. By examining vehicles at free flow speeds, those vehicles with a separation greater than 4 seconds, we can get a true picture of vehicle speeds through the work zone. Because most vehicles demonstrated similar speeds and sizes, several vehicle hits from Counter 2 matched hits from Counter 1, requiring the research team to examine each set of matches and eliminate the ones that were most correct. Researchers closely examined the matching hits and used speed and length information to verify the match.

3.2 Work Zone 2

Work Zone 2 was located on northbound I-35, north of Ottawa, Kansas, beginning at mile marker 193. The work zone contained standard signage and a VMS. Data were collected using road tubes that were placed 2 ft apart, and four counters were placed at each of the tubes to collect speed, gap, time, and vehicle class information. Counters were placed on September 5, 2017, and collected on September 7, 2017. Counter 1 was located before the work zone at the point of speed reduction (VMS location), and Counter 2 was located at the point where the road decreased from two lanes to one lane. Counter 3 was located approximately halfway through the work zone, while Counter 4 was located at the end of the work zone after traffic returned to two lanes. Specifically, Counter 1 and Counter 2 were located before and after, respectively, the I-35 exit ramp onto Tennessee Road, approximately 1,500 ft from each other (Figure 3.5). As shown in Figure 3.6, Counter 3 was located before the crossover of Shawnee Road, approximately 16,000 ft from Counter 2, while Counter 4 was located after the crossover of Strafford Road, approximately 17,000 ft from Counter 3 (Figure 3.7).

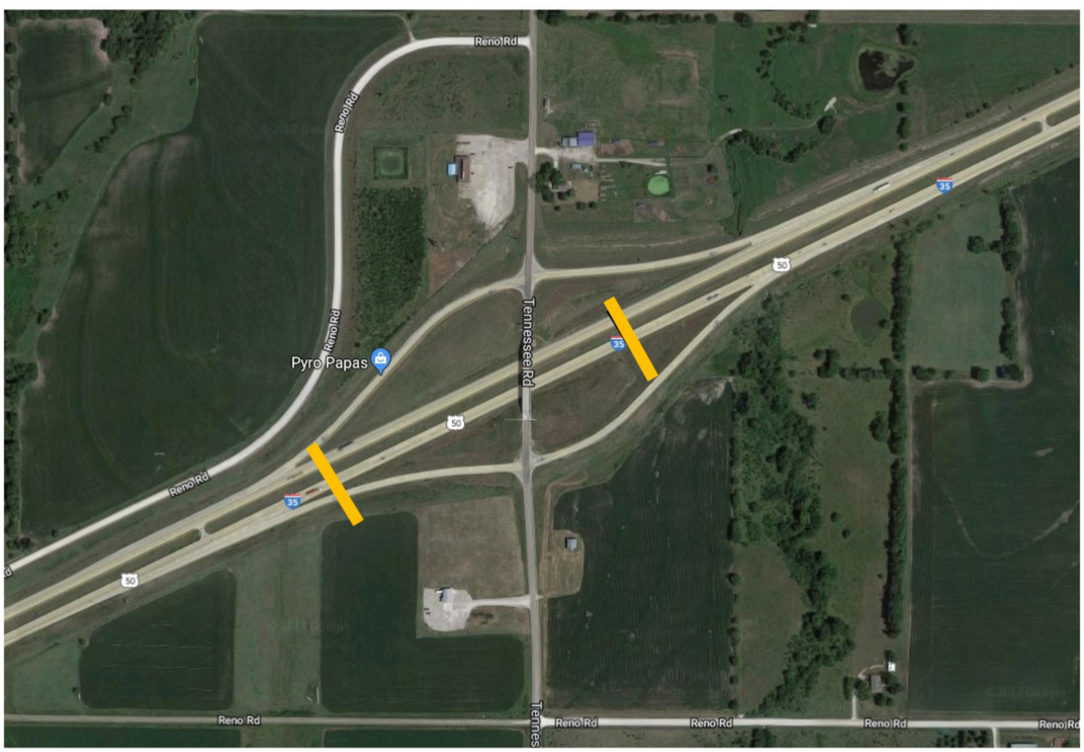


Figure 3.5: Locations of Counters 1 and 2 for Work Zone 2

Figure 3.6: Location of Counter 3 for Work Zone 2

Figure 3.7: Location of Counter 4 for Work Zone 2

The data for Work Zone 2 were processed using the standard JAMAR software and then exported to Microsoft Excel, where the data were sorted and vehicles with less than 4 seconds of gap time were removed to identify only free-flowing traffic. A 24-hr time period from before VMS placement (Monday) and after VMS placement (Thursday) was used for analysis. Average and 85th percentile speeds were calculated for all four counters, and before and after speeds were compared to identify differences. For deeper analysis, pivot tables were created from significant variables in the data, and vehicle class was compared to vehicle speed profiles to determine which vehicle classes were most likely to travel above the speed limit and identify safety risks associated with the number and types of vehicles exceeding the speed limit.

3.3 Work Zone 3

Work Zone 3 was located on southbound US-75, a two-lane divided highway with a speed limit of 70 mph, between mile marker 166 and 165. The work zone, which had a speed limit of 55 mph, was centered on a bridge that crossed NW 46th Street. One exit and no entrances were present in the area. Counter 1 and Counter 2 were located before the exit, and Counter 3 and Counter 4 were located on either side of the bridge after the exit. Data were collected using two roads tubes spaced 2 ft apart to collect speed, gap, time, and vehicle class information. As shown in Figure 3.8, Counter 1 was located at the beginning of the work zones, before the speed reduction sign and before the beginning of the road narrowing. Counter 2 was located where the roadway decreased from two lanes to one lane (Figure 3.9), and Counter 3 was located about halfway through the work zone at the beginning of the bridge immediately after the exit (Figure 3.10). As shown in Figure 3.11, Counter 4 was located at the end of the work zone after the traffic returned to two lanes but before traffic entering from the freeway entrance merged with the through traffic.

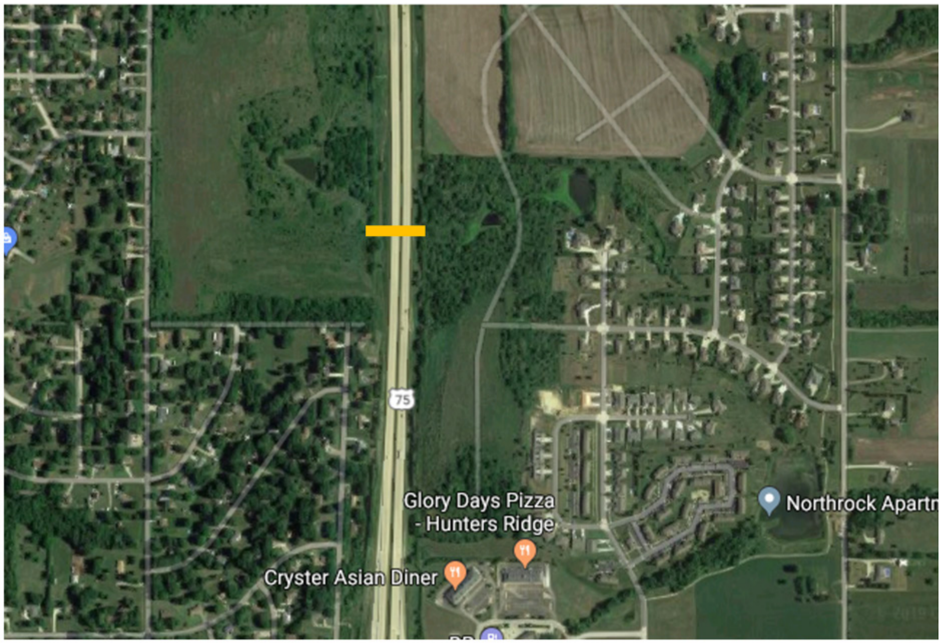


Figure 3.8: Location of Counter 1 for Work Zone 3

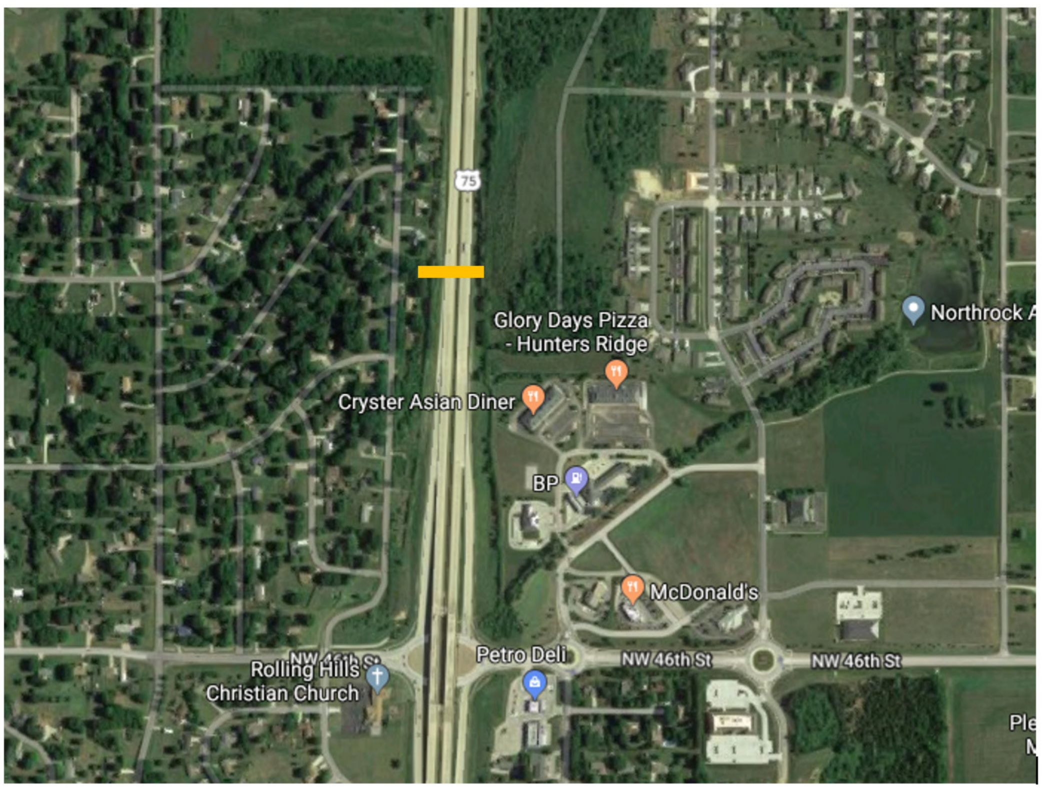


Figure 3.9: Location of Counter 2 for Work Zone 3

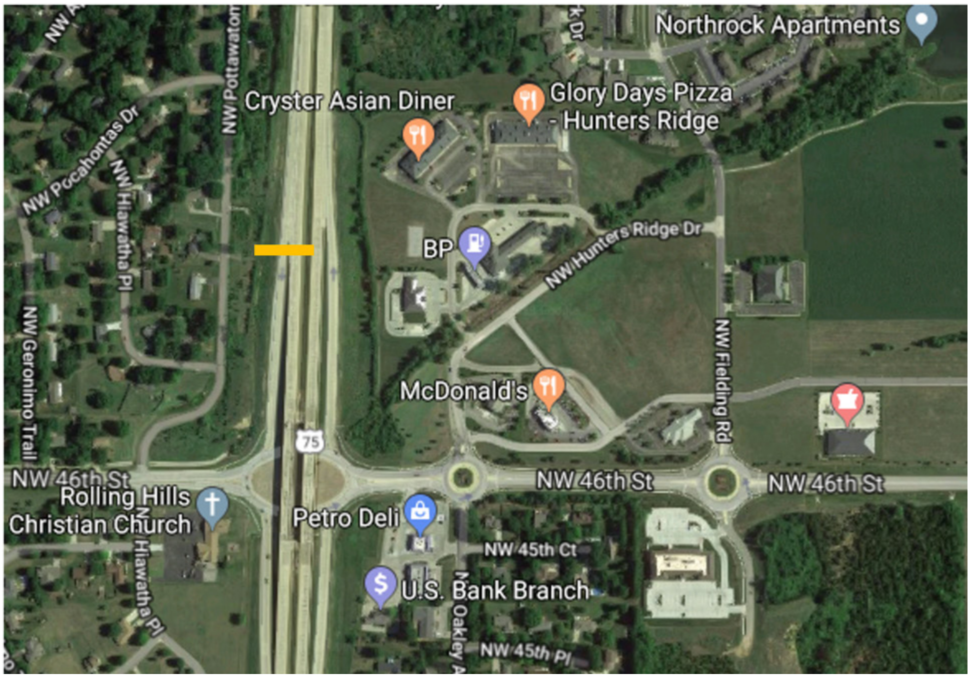


Figure 3.10: Location of Counter 3 for Work Zone 3

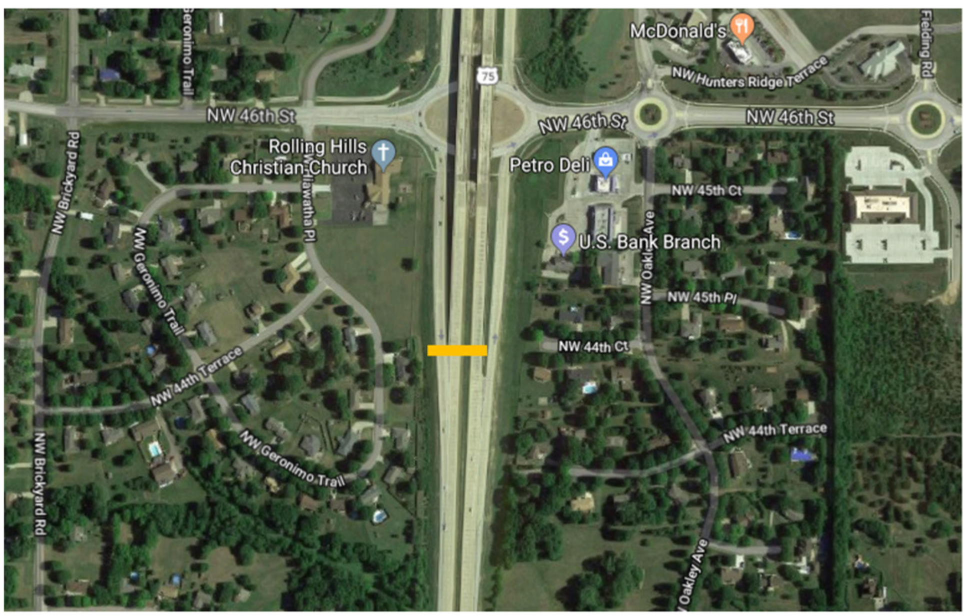


Figure 3.11: Location of Counter 4 for Work Zone 3

The countermeasure in Work Zone 3 was a speed limit sign with a radar speed display to inform oncoming motorists of their driving speed. However, the radar was not working when the dynamic speed sign was in place. The dynamic speed sign was placed between Counter 1 and Counter 2 from Wednesday (approximately 1:00 p.m.) until Friday (approximately 1:00 p.m.).

Data from Work Zone 3 were processed using the standard JAMAR software and exported to Microsoft Excel. The data were then sorted, removing vehicles with less than 4 seconds of gap time to identify only free-flowing traffic. A 24-hr time period from before the placement of the dynamic speed sign (Monday) and after placement of the sign (Thursday) was used for further analysis. Average and 85th percentile speeds were calculated for all four counters, and before and after speeds were compared to determine differences.

3.4 Pivot Table

Pivot tables were used to compare variables associated with vehicle speed profiles in Work Zone 1, Work Zone 2, and Work Zone 3 based on the time of day. These speeds were compared before and after vehicles approached the reduced speed limit sign. Data from Work Zone 1 were sorted by daytime and nighttime vehicle speeds, while data from Work Zone 2 data were sorted according to before and after driver encounters with the reduced speed limit sign and the VMS during daytime hours and nighttime hours. Data from Work Zone 3 were sorted according to before and after installation of the dynamic speed sign and during daytime hours and nighttime hours (6:00 a.m. to 6:00 p.m.).

Counters were used to collect variables such as date, time, lane, axles, class, and speed. Time, vehicle class, and speed were the most essential variables for understanding individual vehicle speed profiles. Times were converted into a 24-hr period and coded as

$$= trunc(time * 24,0)$$

Vehicle speeds were then sorted into increments of 5 mph to analyze vehicles that exceeded the reduced speed limit. For the given data, 45 mph was the minimum speed, 55 mph was the reduced speed limit, and 85 mph was the maximum speed. According to the following equation, vehicles exceeding "3," or 55 mph, were speeding:

$= IF(speed <= 45, "1", IF(speed <= 50, "2", IF(speed <= 55, "3", IF(speed <= 60, "4", IF(speed <= 65, "5", IF(speed <= 70, "6", IF(speed <= 75, "7", IF(speed <= 80, "8", IF(speed <= 85, "9", "10")))))))))$

FHWA designates vehicle classes as 1–13. A numbered vehicle class, however, may represent a basic vehicle class and several variations of the same vehicle. For example, as shown in Figure 3.12, a Class 2 vehicle is a passenger car, but variations such as a convertible, sedan, car with a small trailer, or car with a towed recreational vehicle are also possible. These classifications include every configuration of current vehicles. The JAMAR counter uses the distances between axles, number of wheel hits detected, and other factors to determine each vehicle's class. These classification numbers help increase analysis accuracy of the relationship between vehicle speed profiles and vehicle class given the time of day.

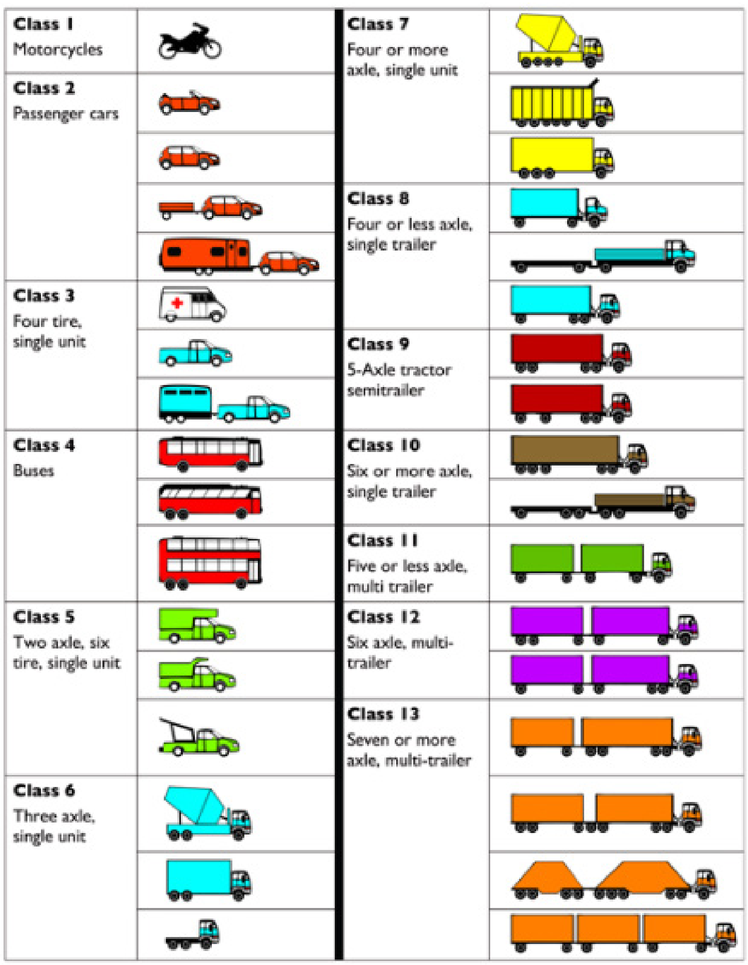


Figure 3.12: Vehicle Classifications (FHWA, 2014)

Once the vehicle classification codes were identified, this study created pivot tables, similar to Table 3.1, in which the x-axis of the pivot table is vehicle speed in increments of 5 mph (1–10), the y-axis is vehicle class (1–13), and the remaining values represent frequency.

Table 3.1: Work Zone 1, Counter 1 (Day)

	≤45 mph	46–50 mph	51–55 mph	56–60 mph	61–65 mph	66–70 mph	71–75 mph	76–80 mph	81–85 mph	≥86 mph	Grand Total
1	1		1	1	3	1	4	5	1		17
2	1	3	8	78	420	11	414	579	182	47	1743
3	2	1	13	28	149	18	209	238	97	37	792
4			5	17	21		11	40	4		98
5		2	10	29	96	1	97	138	43	26	442
6	3	26	29	11	22		5	19	2		117
7			1								1
8			4	24	68		30	70	6		202
9		1	13	31	166		25	129	5		370
10			1	2	6		1	2			12
11				2	3			3			8
12				1	2			2			5
13					4		2	5			11
Grand Total	**7**	**33**	**85**	**224**	**960**	**31**	**798**	**1230**	**340**	**110**	**3818**

As shown in Table 3.1, many vehicles from various classes exceeded the speed limit of 55 mph in Work Zone 1, with passenger cars and pickup trucks/vans (one- and two-axle trailers) most frequently exceeding the speed limit. In addition, most vehicles traveled at 65–70 mph when they exceeded the reduced speed limit of 55 mph. Three-axle single-unit trucks most commonly traveled between 45 and 55 mph. Using data in the pivot table, a line graph was created to illustrate relationships between significant variables (Figure 3.13).

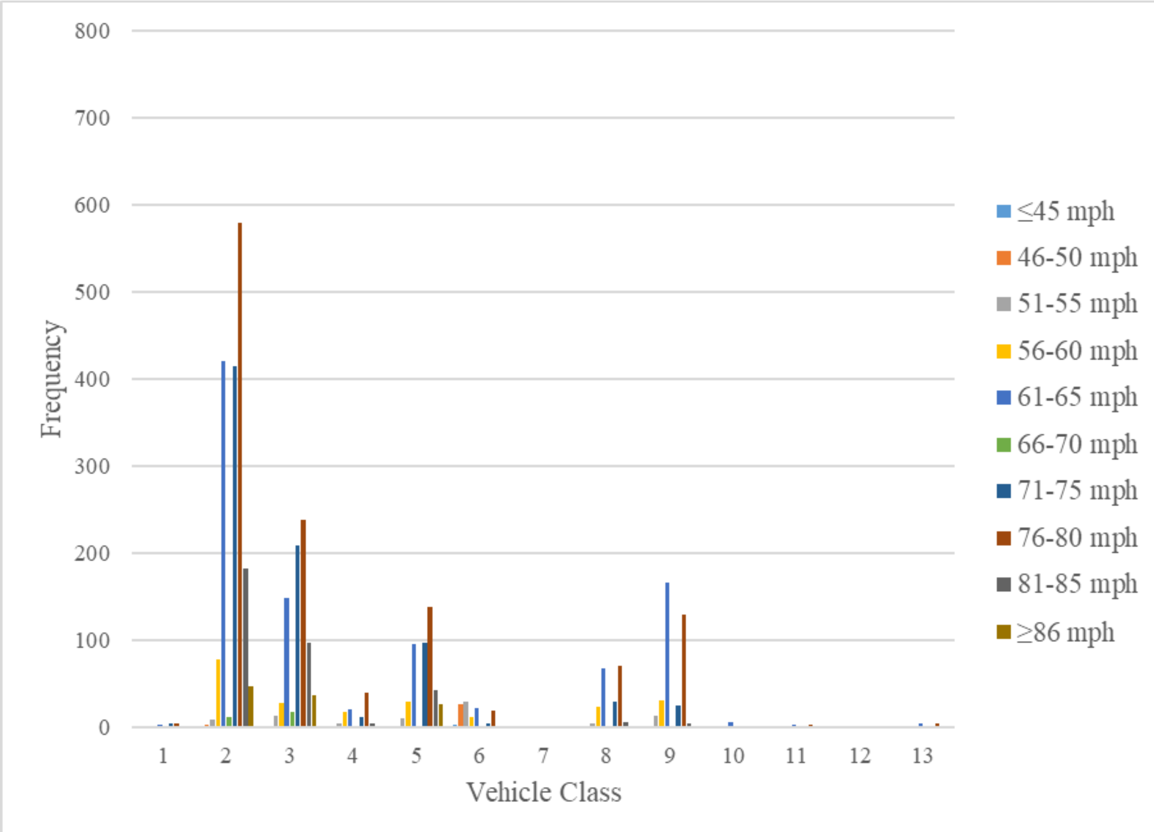


Figure 3.13: Work Zone 1, Counter 1 (Day)

Chapter 4: Significant Findings and Recommendations

Data from all work zones was sorted to determine average and 85th percentile speeds. Data from Work Zone 1 were processed manually using a computer program. Because Work Zone 2 and Work Zone 3 contained dynamic speed signs, data for these work zones were processed before and after sign deployment to determine their effectiveness at reducing speeds through the work zone.

4.1 Work Zone 1

Collected data from Work Zone 1 was first sorted manually. Figure 4.1 shows the average and 85th percentile speeds in Work Zone 1 for all four counters. The speed limit for this work zone was 55 mph, as demonstrated by the dashed red line in the figure. Although vehicle speeds decreased from Counter 1 to Counter 2 as the vehicles moved through the taper, a drastic drop (i.e., 11 mph) in average and 85th percentile speeds occurred by Counter 3, the midpoint of the work zone. Both speeds then increased by 6 mph as they encountered Counter 4 at the end of the work zone.

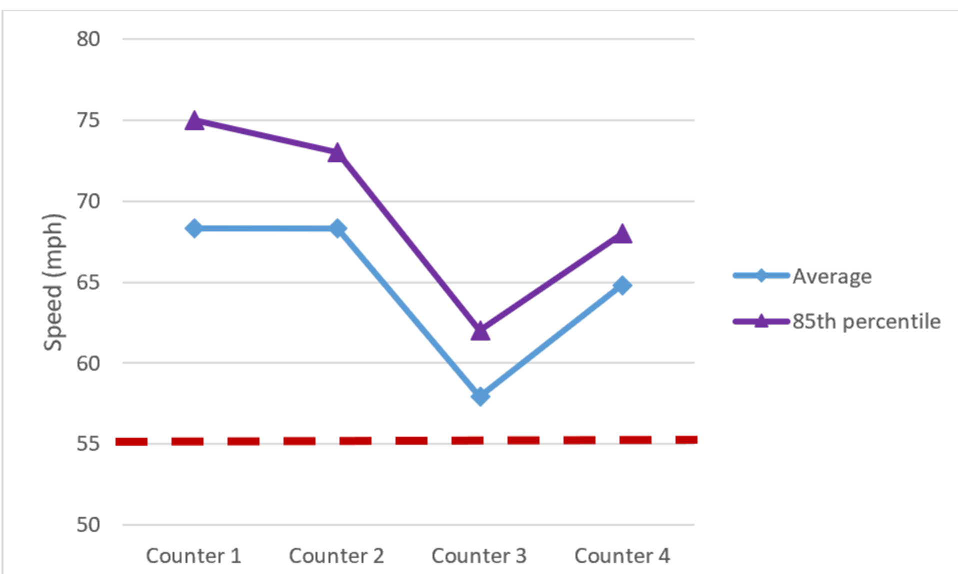


Figure 4.1: Work Zone 1 (Manual)

A computer program was then used to process data from Work Zone 1. The resulting speed profile can be seen in Figure 4.2. As shown in the figure, vehicle speeds drastically dropped (i.e., 10 mph) between Counter 2 and Counter 3 and then increased by 6 mph at Counter 4. The most significant difference between manual and computer sorting results is that, in the computer-sorted figure, Figure 4.2, the lines representing average speed and the 85th percentile speed begin drawing close to each other at Counter 2 and merge at Counter 3 through Counter 4. The reason for this merging is most likely sample size. The computer sorting resulted in multiple hits because Counter 2 was linked to each Counter 1, meaning the research team examined the hits and kept the most accurate one. Since two exit and entrance ramps were located between Counter 1 and Counter 4, many vehicles did not go through the entire work zone. In addition, many hits on Counter 1 and Counter 2 were eliminated due to no corresponding hits on Counter 3 and Counter 4. Consequently, the total sample size was 440 traces through the entire work zone. Manual data sorting resulted in 9495 hits on Counter 1 to 5918 hits on Counter 4.

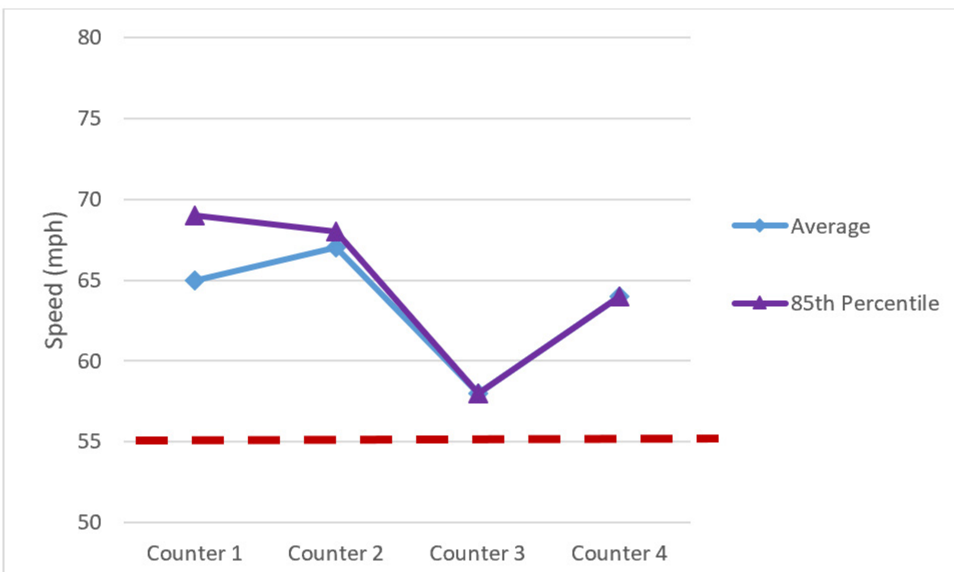


Figure 4.2: Work Zone 1 (Computer)

Further examination of the data from Work Zone 1 included comparing daytime (6:00 a.m. to 6:00 p.m.) and nighttime (6:00 p.m. to 6:00 a.m.) speeds. As shown in Figure 4.3, daytime speeds decreased from 75 mph at Counter 1 to 61 mph at Counter 3, the midpoint of the work zone. However, this reduced speed was 6 mph over the posted work zone speed limit of 55 mph and slightly less than the 85th percentile speed at Counter 3 for the entire day.

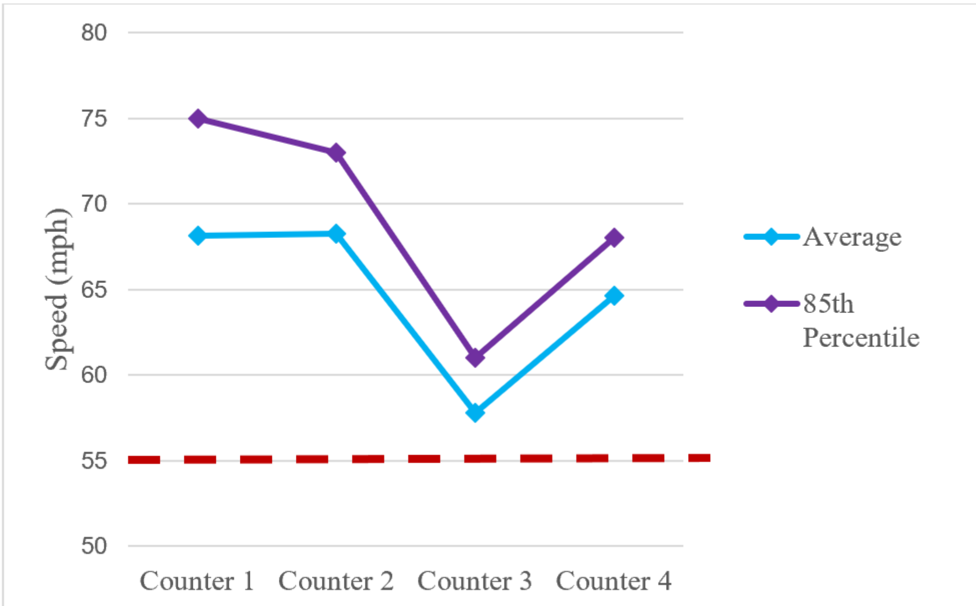


Figure 4.3: Work Zone 1 (Daytime)

Results of the nighttime data were similar to the daytime data. Nighttime speeds, as shown in Figure 4.4, were only 2 mph faster than daytime speeds, which contrasted with the study's initial assumptions.

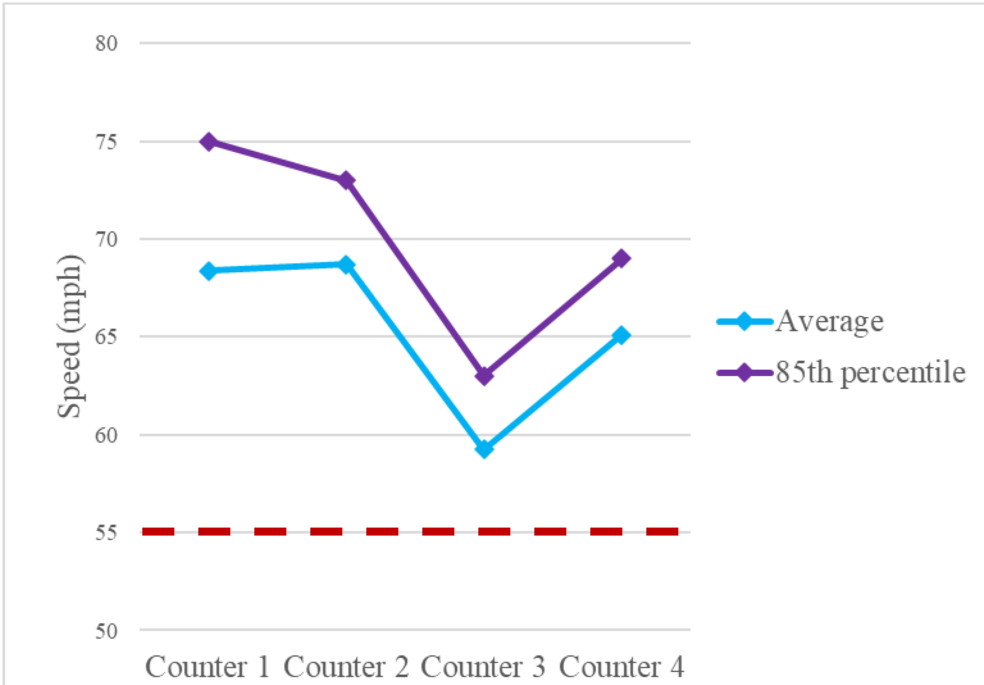


Figure 4.4: Work Zone 1 (Nighttime)

The research team then examined vehicle speed counts by class because knowing which vehicles are most likely to speed can help determine appropriate countermeasures and enforcement strategies to reduce speeds in work zones. This research primarily focused on Class 2 (passenger cars) and Class 9 (five-axle tractor semitrailers or tractor trailers) as defined in Figure 3.12. Passenger cars, with typical widths of approximately 7 ft, are the most common class of vehicles currently in use on roadways in the United States. Likewise, tractor trailers, which typically have widths of 8.5 ft, are also commonly used to transport goods throughout the United States. This additional width, however, can be a risk in work zones where lanes are often narrower than the typical lane width of 12 ft. Vehicle speeds were divided into increments, or bins, of 5 mph, with the top speed in each bin ending in 5 or 10 to allow rapid identification of speeds exceeding the speed limit and compare their frequency to other bins.

In Figure 4.5, the speed bin of 56–60 mph, the first bin that exceeded the speed limit, is the yellow line, which is the largest line for nearly every group. The lines in the figure are arranged left to right from lowest speed to highest speed; therefore, every line to the right of and including the yellow line are speeds that exceed the posted speed limit of 55 mph. Figure 4.5 shows that Class 2 and Class 9 were the largest classes of vehicles, but they also demonstrated the greatest number of speeding vehicles. Class 2 represents approximately 48% of all vehicles tracked in Work Zone 1, and Class 9 represents 20% of the vehicles. According to the data, 83% of Class 2 vehicles and 74% of Class 9 vehicles exceeded the speed limit. Overall, 80% of all vehicles exceeded the speed limit at free-flow speed.

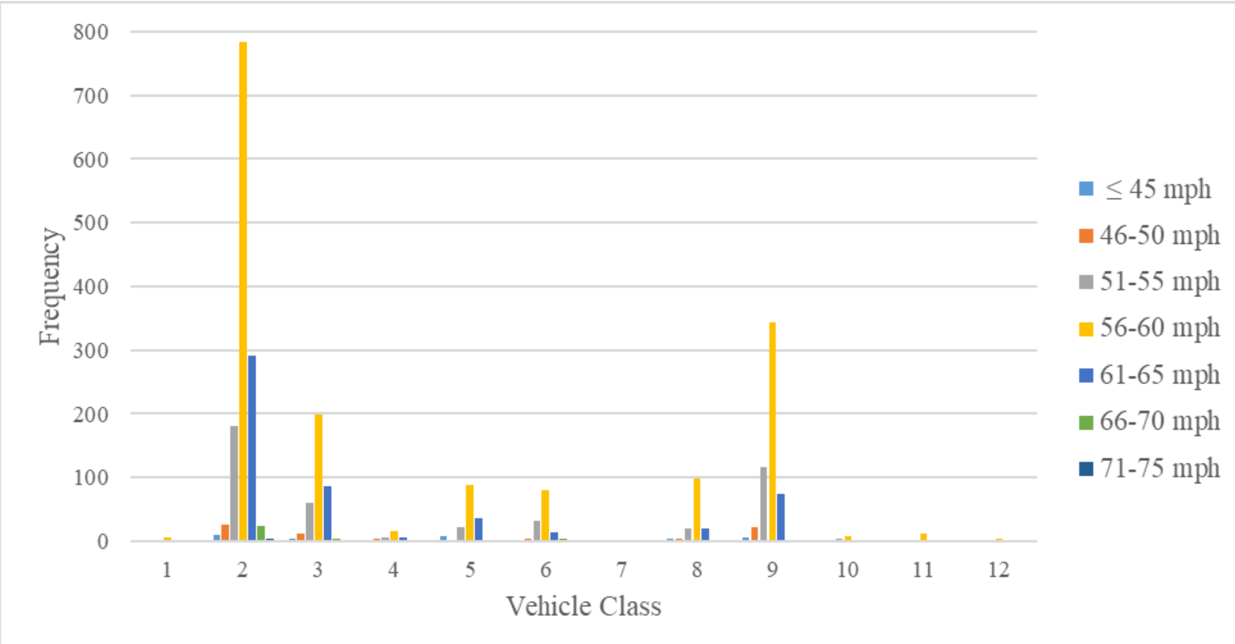


Figure 4.5: Work Zone 1, Counter 3, Before/After (Daytime)

4.2 Work Zone 2

Work Zone 2 contained a mobile dynamic speed sign that visibly displayed the work zone speed limit and the speed of passing vehicles, giving immediate feedback to drivers. Data from Work Zone 2 were analyzed based on before and after sign installation and categorized by daytime (6:00 a.m. to 6:00 p.m.) and nighttime (6:00 p.m. to 6:00 a.m.) to identify speed differences based on the likely presence of workers. Figure 4.6 shows the daytime average (blue line) and 85th percentile (purple line) speeds for each counter. Data from before sign installation is represented by the solid line, data after sign installation is represented by the dashed line, and the posted speed limit is denoted by the dashed red line in the figure.

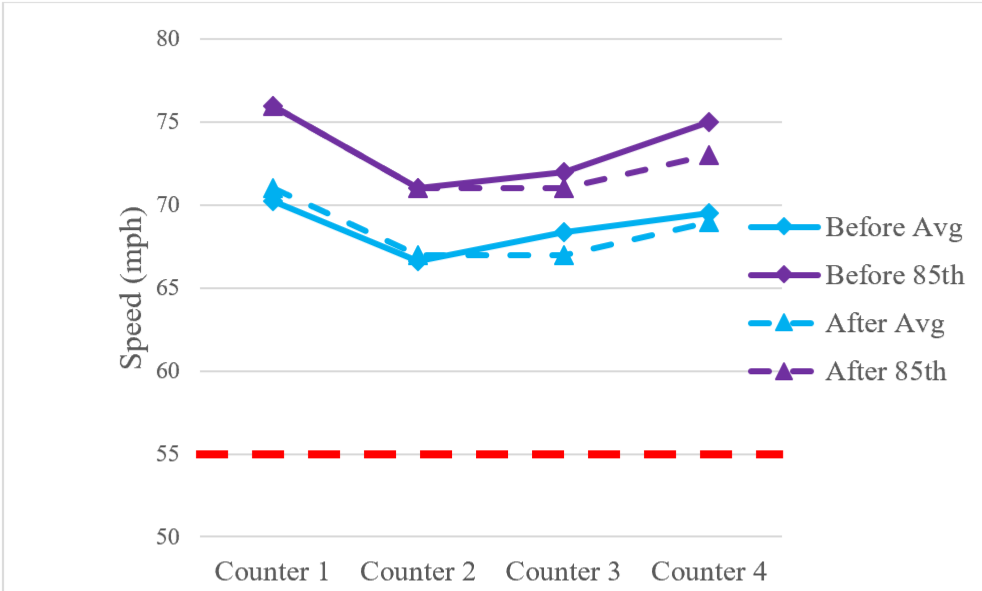


Figure 4.6: Work Zone 2, Before/After (Daytime)

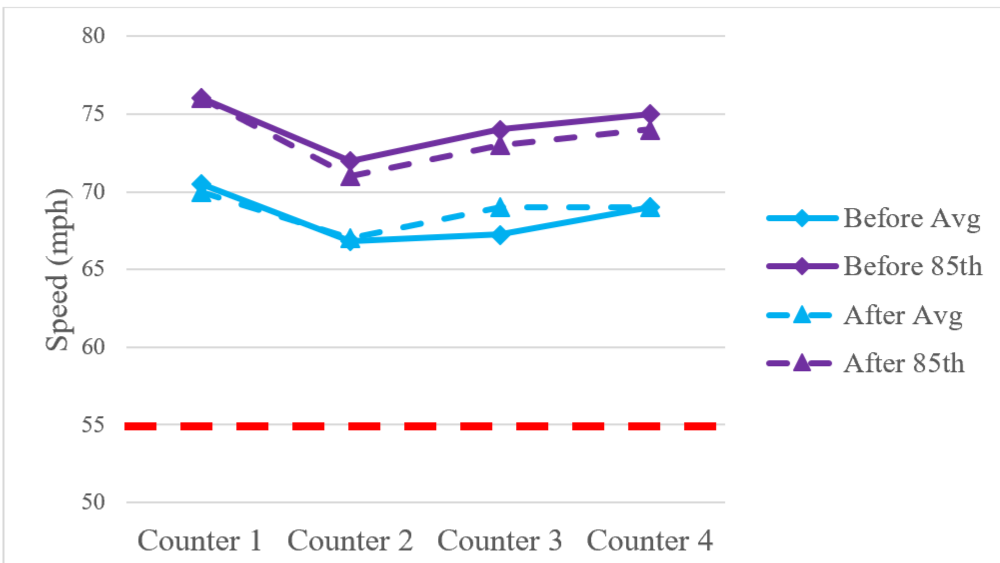


Figure 4.7: Work Zone 2, Before/After (Nighttime)

Figure 4.6 shows that the 85th percentile speeds never dropped below 70 mph throughout the work zone before or after the sign installation. In fact, vehicle speed increased from 71 mph to 72 mph from Counter 2 to Counter 3, and once the dynamic speed sign was installed, vehicle speed from Counter 2 to Counter 3 did not change at all. Both the before-installation and after-installation lines in the figure show increased vehicle speed from Counter 3 to Counter 4. Similarly, the daytime speeds and nighttime speeds exhibited many similarities, as shown in Figure 4.7.

Although nighttime speeds at Counter 3 were higher after sign installation, the figure shows similar results for the two conditions. When looking at the data in the pivot table, a different picture emerges.

According to Figure 4.8, vehicle Class 2 and Class 9 had the most vehicles before the dynamic speed sign was installed, as in Work Zone 1. However, in Work Zone 2, the 66–70 mph bin contained the most vehicles, which was slightly less than the 72–74 mph 85th percentile speeds for Counter 3 before installation during daytime and nighttime hours. These results prove that the graphs from the pivot tables were weighted enough to the right of 66–70 mph bin that, although this is the largest group, the 85th percentile speed still fell within the 71–75 mph bin. Class 2 vehicles in the 66–70 mph bin accounted for 18% of all vehicles crossing Counter 3, while Class 9 vehicles in the same bin accounted for 12.5% of all vehicles that crossed Counter 3. Alarmingly, the 66–70 mph speed bin contained 52% of all vehicle hits at Counter 3, and the three speed bins at 55 mph and lower contained only 0.4% of all vehicles hits before the sign was installed.

Figure 4.9 shows Counter 3 after the dynamic speed sign was installed. According to the figure, Class 2 and Class 9 still had the most vehicles in the most significant speed bin spike (i.e., 66–70 mph), but the number of speeding vehicles increased after the sign was installed. For example, in the 66–70 mph bin, Class 2 vehicles accounted for 19.5% of all vehicles after the sign was installed, which was an increase from 18% before sign installation; Class 9 vehicles accounted for 14% of all vehicles, up from 12.5%. The total number of vehicles in this bin increased to 56% of all vehicles, and the number of vehicles that adhered to the posted speed limit increased from 0.4% to 1.2%.

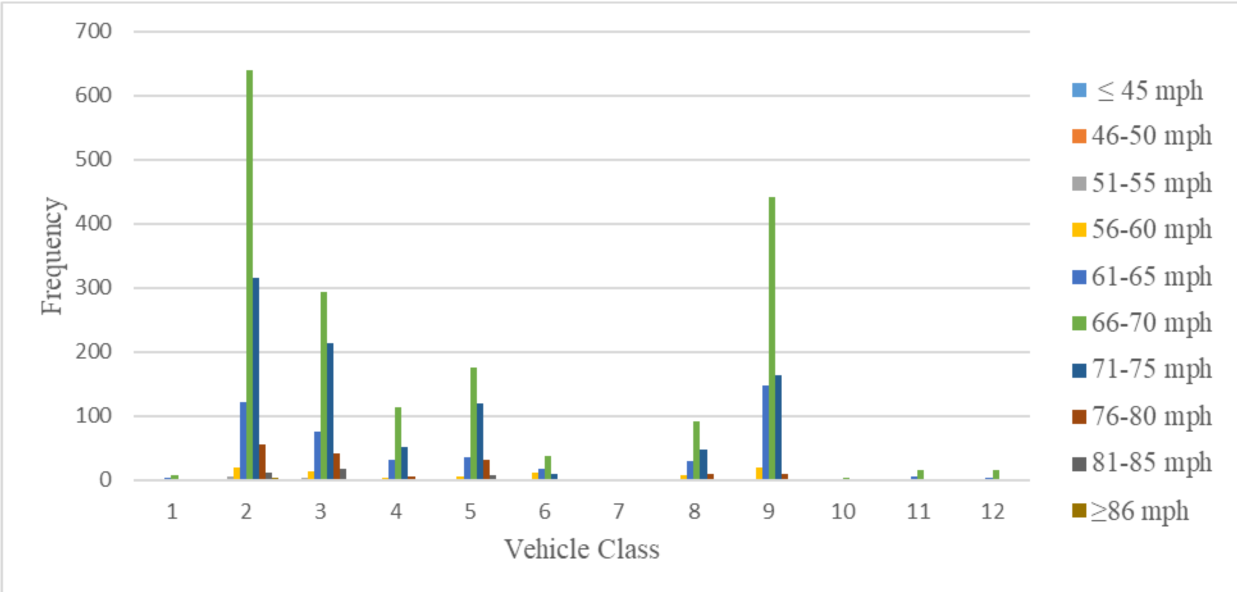


Figure 4.8: Work Zone 2, Counter 3 (Before)

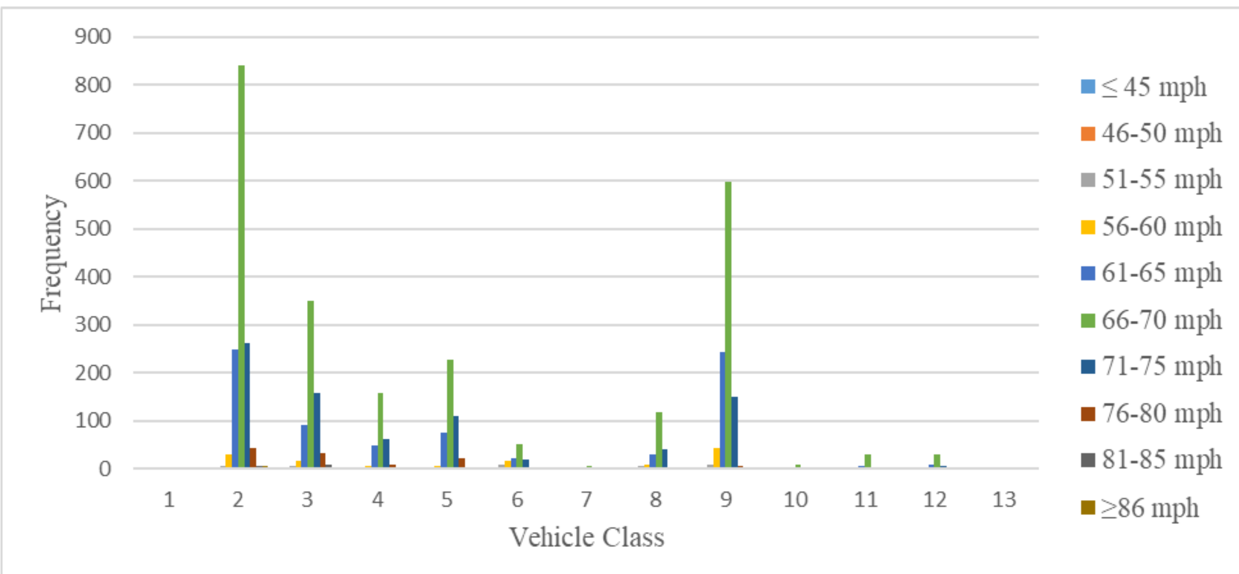


Figure 4.9: Work Zone 2, Counter 3 (After)

4.3 Work Zone 3

Although Work Zone 3 also utilized a dynamic speed sign, this work zone was much shorter than the other two work zones and contained only one exit and no entrances. The sign visibly displayed the work zone speed limit and was intended to flash oncoming vehicle speed, but the flashing function was not working on the sign at the time of testing. Data for Work Zone 3 were processed before and after the sign installation and categorized as daytime (6:00 a.m. to 6:00 p.m.) and nighttime (6:00 p.m. to 6:00 a.m.). Figure 4.10 shows the daytime average (blue line) and 85th percentile (purple line) speeds for each counter. The before-installation data is represented by the solid line, the after-installation data is represented by the dashed line, and the posted speed limit is denoted by the dashed red line in the figure. Although the daytime data in Figure 4.10 seems to show very little variation (1 mph or less) between the before and after data for the first two counters, the after-installation data were consistently lower than the before-installation data. In fact, for Counter 3, the midpoint, the average dropped to slightly above the posted speed limit; the average was the speed limit at Counter 4. The 85th percentile speed was approximately 5 mph higher than the average speed.

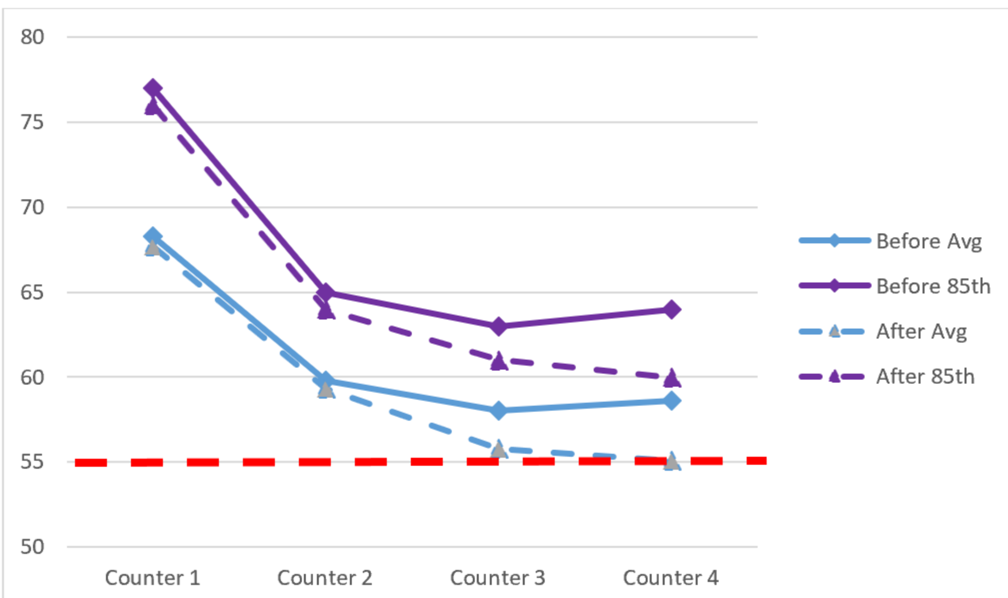


Figure 4.10: Work Zone 3, Before/After (Daytime)

Figure 4.11 shows nighttime data before and after the sign was installed. Except for a slight increase in speed, the nighttime data demonstrated a similar shape to the daytime data. In fact, Counter 1 and Counter 2 showed minimal difference in before- and after-installation data. Figure 4.11 also shows that, although vehicle speed leveled off for both sets of data, speeds decreased by approximately 2 mph after the sign was installed.

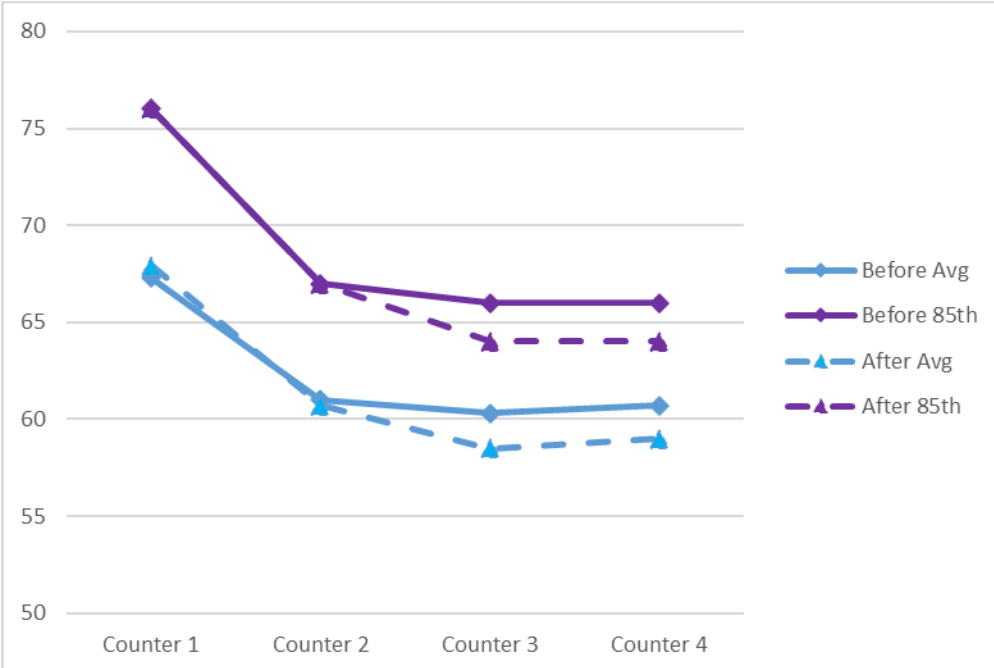


Figure 4.11: Work Zone 3, Before/After (Nighttime)

As shown in Figure 4.12, vehicle Class 2 and Class 3 comprised the largest percentage of motorists in Work Zone 3. Overall, vehicle speed was slightly above the posted speed limit, with most motorists traveling at the 56–60 mph speed bin for all classes, which was a significant reduction from Work Zone 2 where most vehicles traveled at the 66–70 mph speed bin before the dynamic speed sign was installed. Figure 4.12 shows that the 66–70 mph speed bin of Work Zone 3 had one of the lowest percentages of vehicles for all classes.

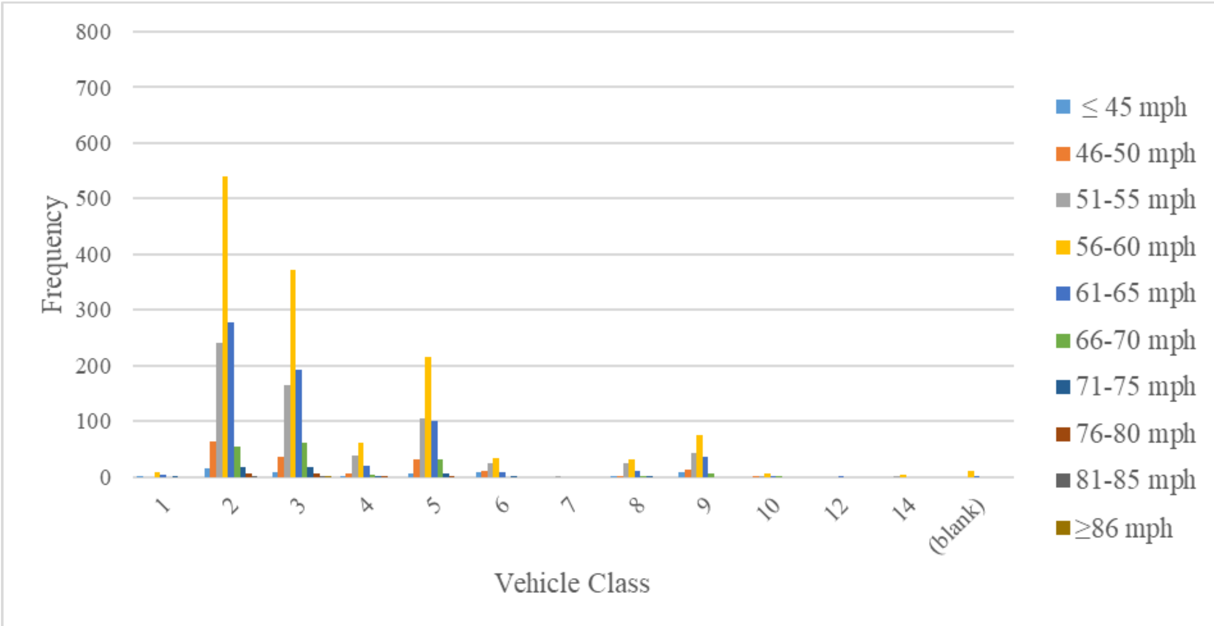


Figure 4.12: Work Zone 3, Counter 3, Before (Day)

As shown in Figure 4.13, after the dynamic speed sign was installed, most vehicles traveled at the 56–60 mph speed bin, followed closely by 51–55 mph for all classes, proving that the dynamic speed sign significantly reduced vehicle speeds for all classes. Compared to Figure 4.12, the 61–65 mph speed bin decreased significantly after the sign was installed (Figure 4.13).

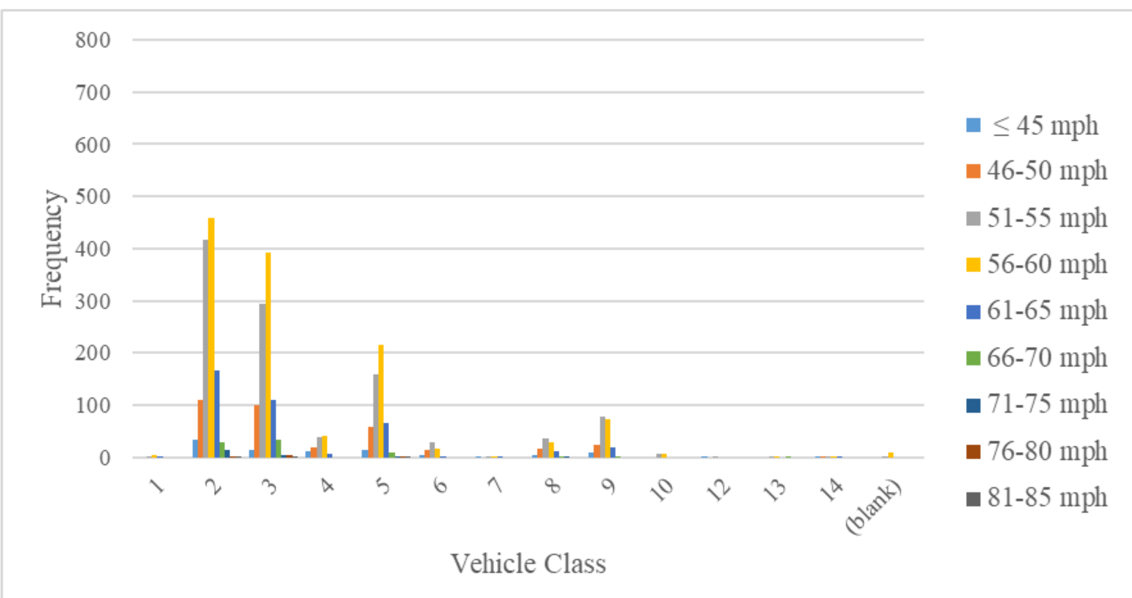


Figure 4.13: Work Zone 3, Counter 3, After (Day)

Chapter 5: Conclusions

5.1 Discussion

The purpose of this study was to evaluate vehicle speed profiles in work zones. This research is vital to state highway agencies because vehicle speeds directly impact traffic and work zone safety. Previous studies have shown that significant discrepancies in vehicle speeds can increase traffic congestion and delay time, as well as contribute to an increased number of rear-end collisions, and fatal/injury crashes between motorists and/or work zone laborers.

This study utilized three work zone sites to evaluate vehicle speed profiles at four counters. Work Zone 1 was used to validate a computer program and compare its output to statistical analysis. The limited number of traces through the work zone resulted in nearly identical average and 85th percentile speeds. In Work Zone 2, the dynamic speed sign did not significantly reduce vehicle speeds, while data from Work Zone 3 showed that the dynamic speed sign consistently decreased vehicle speed, with the 85th percentile speed occurring 5 mph over the average speed.

Overall, Work Zone 3 most consistently reduced vehicle speeds from Counter 1 to Counter 4. In Work Zone 1 and Work Zone 2, vehicle speeds decreased from Counter 1 to Counter 3 and then increased from Counter 3 to Counter 4. However, Work Zone 3 was the shortest work zone, and it was the only work zone located on a bridge, which offers the impression of narrowing, leading to motorists naturally reducing their driving speeds. Vehicle speeds in Work Zone 2 were not significantly less than Work Zone 3, where the 85th percentile speed began at approximately 75 mph and decreased to approximately 60 mph (after the dynamic speed sign was installed).

Passenger vehicles and tractor-trailers comprised the largest percentage of speeding vehicles. In Work Zone 2, a large percentage of these vehicles traveled at the 66–70 mph speed bin before and after the dynamic speed sign was installed. In fact, the number of speeding vehicles actually increased after the dynamic speed sign was installed. Passenger cars and four-tire, single-unit vehicles comprised the majority of vehicles in Work Zone 3. However, the highest speed bins for these vehicles were 56–60 mph and 51–55 mph, which were the highest speeds for every class after the dynamic speed sign was installed.

5.2 Effectiveness

Although the results from this speed study showed that dynamic speed signs were slightly effective, inconsistences between the work zones rendered the results inconclusive. Work Zone 2 showed a slight reduction in speed after the dynamic speed sign was installed, while Work Zone 3 showed better results after the dynamic speed sign was installed. However, Work Zone 2 was a longer site and contained exit and entrance ramps within the work zone, while Work Zone 3 was centered on a bridge, which could have caused naturally lowering speeds.

5.3 Limitations

The limited number of work zones studied in this research reduced the amount of data available for analysis. In addition, future studies should include work zones of similar length with the same number of exit and entrance ramps and the same type of dynamic speed signs.

References

American Road & Transportation Builders Association (ARTBA). (2010). *Guidelines on managing speeds in work zones*. ARTBA Work Zone Safety Consortium.

American Road & Transportation Builders Association (ARTBA). (2019). *2017 National work zone fatal crashes and fatalities*. Retrieved Nov. 4, 2019 from https://www.workzonesafety.org/crash-information/work-zone-fatal-crashes-fatalities/#national

Banerjee, S., Jeihani, M., & Moghaddam, Z. R. (2018). Impact of mobile work zone barriers on driving behavior on arterial roads. *Journal of Traffic and Logistics Engineering, 6*(2), 37–42.

Banerjee, S., Jeihani, M., & Morris, D. (2019). *Impact of work zone signage on driver speeding behavior: A driving simulator study*. Paper presented at Transportation Research Board 98th Annual Meeting, January 13–17, 2019, Washington, DC.

Benekohal, R. F., Hajbabaie, A., Medina, J. C., Wang, M., & Chitturi, M. V. (2010). *Speed photo-radar enforcement evaluation in Illinois work zones* (Report No. FHWA-ICT-10-064). Urbana, IL: Illinois Center for Transportation.

Brewer, M. A., Pesti, G., & Schneider, W. H., IV. (2005). *Identification and testing of measures to improve work zone speed limit compliance* (Report No. FHWA/TX-06/0-4707-1). Austin, TX: Texas Department of Transportation.

Corkle, J., Giese, J. L., & Marti, M. M. (2001). *Investigating the effectiveness of traffic calming strategies on driver behavior, traffic flow and speed* (Report No. MN/RC–2002-02). St. Paul, MN: Minnesota Local Road Research Board.

Donnell, E. T., Hines, S. C., Mahoney, K. M., Porter, R. J., & McGee, H. (2009). *Speed concepts: Informational guide* (Report No. FHWA-SA-10-001). Washington, DC: Federal Highway Administration.

Douglas, T. (2018). *The cost of on-the-job driving crashes*. Retrieved from http://www.constructionexec.com/article/the-cost-of-on-the-job-driving-crashes

Du, S., & Razavi, S. (2019). Variable speed limit for freeway work zone with capacity drop using discrete-time sliding mode control. *Journal of Computing in Civil Engineering, 33*(2).

Federal Highway Administration (FHWA). (2004). *A field test and evaluation of variable speed limits in work zones*. Retrieved from https://safety.fhwa.dot.gov/speedmgt/vslimits/docs/michiganvsl.pdf

Federal Highway Administration (FHWA). (2008). *Benefits of using intelligent transportation systems in work zones*. Washington, DC: Author.

Federal Highway Administration (FHWA). (2014). *Traffic monitoring guide, Appendix C. Vehicle types*. Retrieved from https://www.fhwa.dot.gov/policyinformation/tmguide/tmg_2013/vehicle-types.cfm

Federal Highway Administration (FHWA). (2016). *National work zone awareness week*. Retrieved from https://ops.fhwa.dot.gov/wz/outreach/nwzaw_factsheet/nwzaw_2016.htm

Federal Highway Administration (FHWA). (2019a). *FHWA work zone facts and statistics*. Retrieved Nov. 4, 2019, from https://ops.fhwa.dot.gov/wz/resources/facts_stats.htm

Federal Highway Administration (FHWA). (2019b). *Work zone safety: Drive like you work here* [pamphlet]. Retrieved Nov. 12, 2019, from https://ops.fhwa.dot.gov/publications/fhwahop19027/fhwahop19027.pdf

Finley, M. D., Pike, A. M., Park, E. S., Wu, L., Theiss, L., Brewer, M. A.,…Barrette, T. P. (2019). *Traffic control device analysis, testing, and evaluation program: FY2018 activities* (Report No. FHWA/TX-18/0-6969-R1). College Station, TX: Texas A&M Transportation Institute.

Fitzpatrick, K., Carlson, P., Brewer, M. A., Wooldridge, M. D., & Miaou, S.-P. (2003). *Design speed, operating speed, and posted speed practices* (NCHRP Report 504). Washington, DC: Transportation Research Board.

Fitzsimmons, E. J. (2011). *Development and analysis of vehicle trajectories and speed profiles along horizontal curves* (Doctoral dissertation, 12127). Iowa State University, Ames, IA.

Forbes, G. J., Gardner, T., McGee, H., & Srinivasan, R. (2012). *Methods and practices for setting speed limits: An informational report* (Report No. FHWA-SA-12-004). Washington, DC: Federal Highway Administration.

Fudala, N. J., & Fontaine, M. D. (2010). *Work zone variable speed limit systems: Effectiveness and system design issues* (Report No. FHWA/VTRC 10-R20). Richmond, VA: Virginia Department of Transportation.

Hallmark, S. L., Hawkins, N., & Smadi, O. (2015). *Evaluation of dynamic speed feedback signs on curves: A national demonstration project* (Report No. FHWA-HRT-14-020). McLean, VA: Federal Highway Administration.

Harrington, C. P. (2015). *Driver behavior evaluation of variable speed limits and a conceptual framework for optimal VSL location identification* (Master's thesis, 154). University of Massachusetts Amherst, Amherst, MA.

Iowa Department of Transportation (IDOT). (2017). *Guidelines for the application of speed feedback trailers*. Ames, IA: Author.

Jeihani, M., & Banerjee, S. (2018). Drivers' behavior analysis under reduced visibility conditions using a driving simulator. *Journal of Traffic and Logistics Engineering, 6*(2), 48–52. doi: 10.18178/jtle.6.2.48-52

Jeihani, M., Banerjee, S., Ahangari, S., & Brown, D. D. (2018). *The potential effects of composition and structure of dynamic message sign messages on driver behavior using a driving simulator* (Report No. MD-18-SHA/MSU/4-14). Baltimore, MD: Maryland Department of Transportation.

Jeihani, M., NarooieNezhad, S., & Kelarestaghi, K. B. (2017). Integration of a driving simulator and a traffic simulator case study: Exploring drivers' behavior in response to variable message signs. *IATSS Research*, *41*(4), 164–71.

Jiang, Y., & Li, S. (2001). Measuring and analyzing vehicle position and speed data at work zones using global positioning system. *Transportation Research Board 80th Annual Meeting Preprint CD-ROM*. Washington, DC: Transportation Research Board.

Joerger, M. (2010). *Photo radar speed enforcement in a state highway work zone* (Report No. OR-RD-10-17). Salem, OR: Oregon Department of Transportation.

Jomaa, D., Yella, S., & Dougherty, M. (2017). A comparative study between vehicle activated signs and speed indicator devices. *Transportation Research Procedia, 22*, 115–123.

Kansas Department of Transportation (KDOT). (n.d.). *Safety pays on expressways*. Retrieved Nov. 4, 2019, from http://www.ksdot.org/burTrafficSaf/sns/Presentation/expressway.asp

Katz, B. J. (2004). *Pavement markings for speed reduction* (Traffic control devices Pooled Fund Study TPF-5(065)). McLean, VA: Turner-Fairbank Highway Research Center.

Kwon, E., Brannan, D., Shouman, K., Isackson, C., & Arseneau, B. (2007). Development and field evaluation of variable speed limit system for work zones. *Transportation Research Record, 2015*, 12–18.

Maryland Department of Transportation (MDOT). (2012). *Maryland work zone fatalities at lowest level in more than a decade*. Retrieved from https://www.roads.maryland.gov/mdotsha/pages/pressreleasedetails.aspx?newsId=1240&PageId=818

Mattox, J. H., Sarasua, W. A., Ogle, J. H., Eckenrode, R. T., & Dunning, A. (2007). Development and evaluation of speed-activated sign to reduce speeds in work zones. *Transportation Research Record, 2015*, 3–11.

McAvoy, D. (2011). *Work zone speed reduction utilizing dynamic speed signs*. Athens, OH: Ohio University.

Meyer, E. (2003). *Radar speed display*. Midwest Smart Work Zone Deployment Initiative.

Outcalt, W. (2009). *Work zone speed control* (Report No. CDOT-2009-3). Denver, CO: Colorado Department of Transportation.

Rathner, J. L. (2015). Temporary rumble strips address work zone safety. *Laborers' Health & Safety Fund of North America, Lifelines, 11*(10).

Reyes, M. L., & Khan, S. A. (2011). *Examining driver behavior in response to work zone interventions: A driving simulator study*. Ames, IA: Smart Work Zone Deployment Initiative, Iowa State University.

Riffkin, M., McMurtry, T., Heath, S., & Saito, M. (2008). *Variable speed limit sign effects on speed and speed variation in work zones* (Report No. UT-08-01). Salt Lake City, UT: Utah Department of Transportation.

Saito, M., & Wilson, A. B. (2011). *Evaluation of the effectiveness of a variable advisory speed system on queue mitigation in work zones* (Report No. UT-11.04). Salt Lake City, UT: Utah Department of Transportation.

Schurr, K. S., McCoy, P. T., Pesti, G., & Huff, R. (2002). Relationship of design, operating, and posted speeds on horizontal curves of rural two-lane highways in Nebraska. *Transportation Research Record, 1796*, 60–71.

Scriba, T., & Atkinson, J. (2014). Creating smarter work zones. *Public Roads, 77*(5).

Sekhar, C., Nataraju, J., Velmurugan, S., Kumar, P., & Sitaramanjaneyulu, K. (2016). Free flow speed analysis of two lane inter urban highways. *Transportation Research Procedia, 17*, 664–673.

Smith, D., Hallmark, S., Knapp, K., & Thomas, G. (2002). *Temporary speed hump impact evaluation*. Ames, IA: Center for Transportation Research and Education, Iowa State University.

Tobias, P. (2011). Automated speed enforcement slows down drivers in work zones. *TR News, 277*, 29–31.

Warren, D. (2007, January 21). *Human factors workshop on work zone safety: Problems and countermeasures*. Transportation Research Board 86th Annual Meeting, Washington, DC.

Appendix A: Complete Pivot Tables

Pivot Tables for Work Zone 1

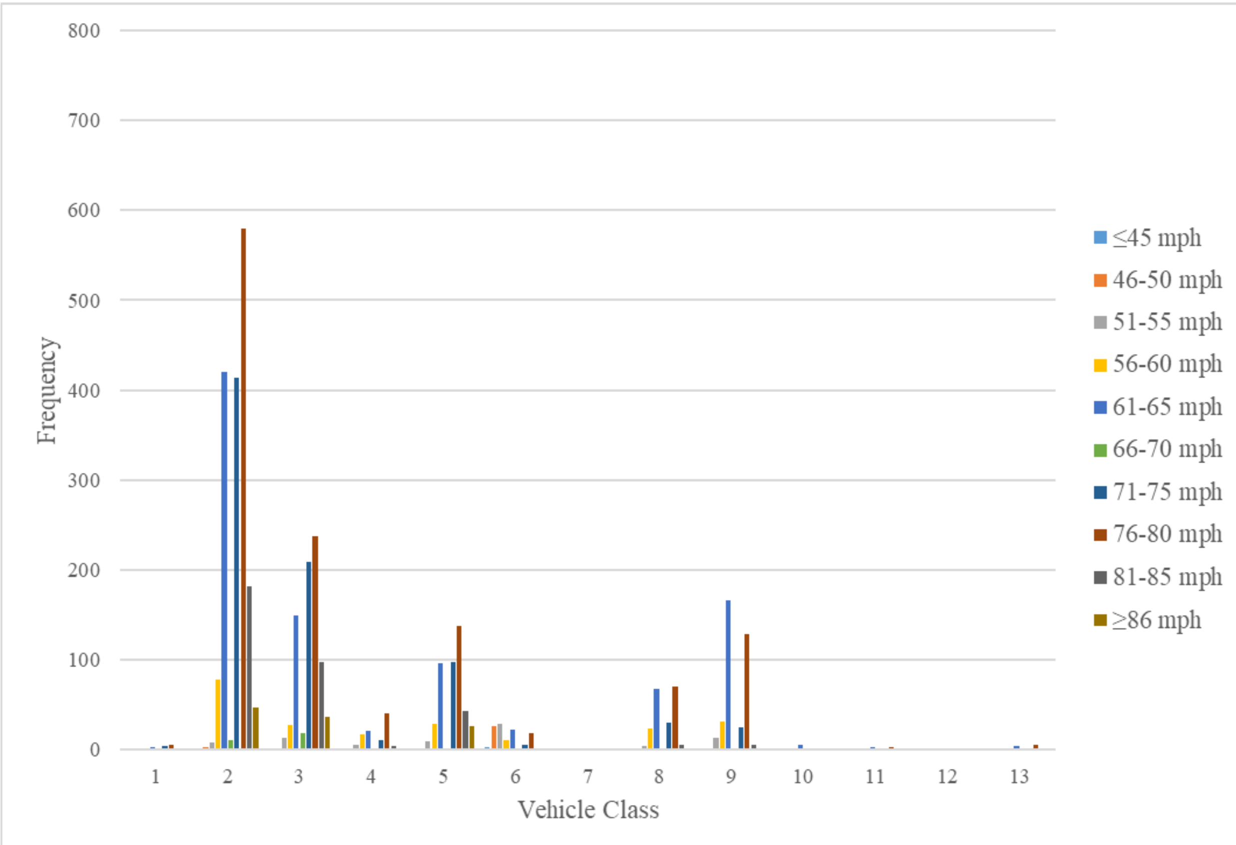


Figure A.1: Work Zone 1 Counter 1 (Day)

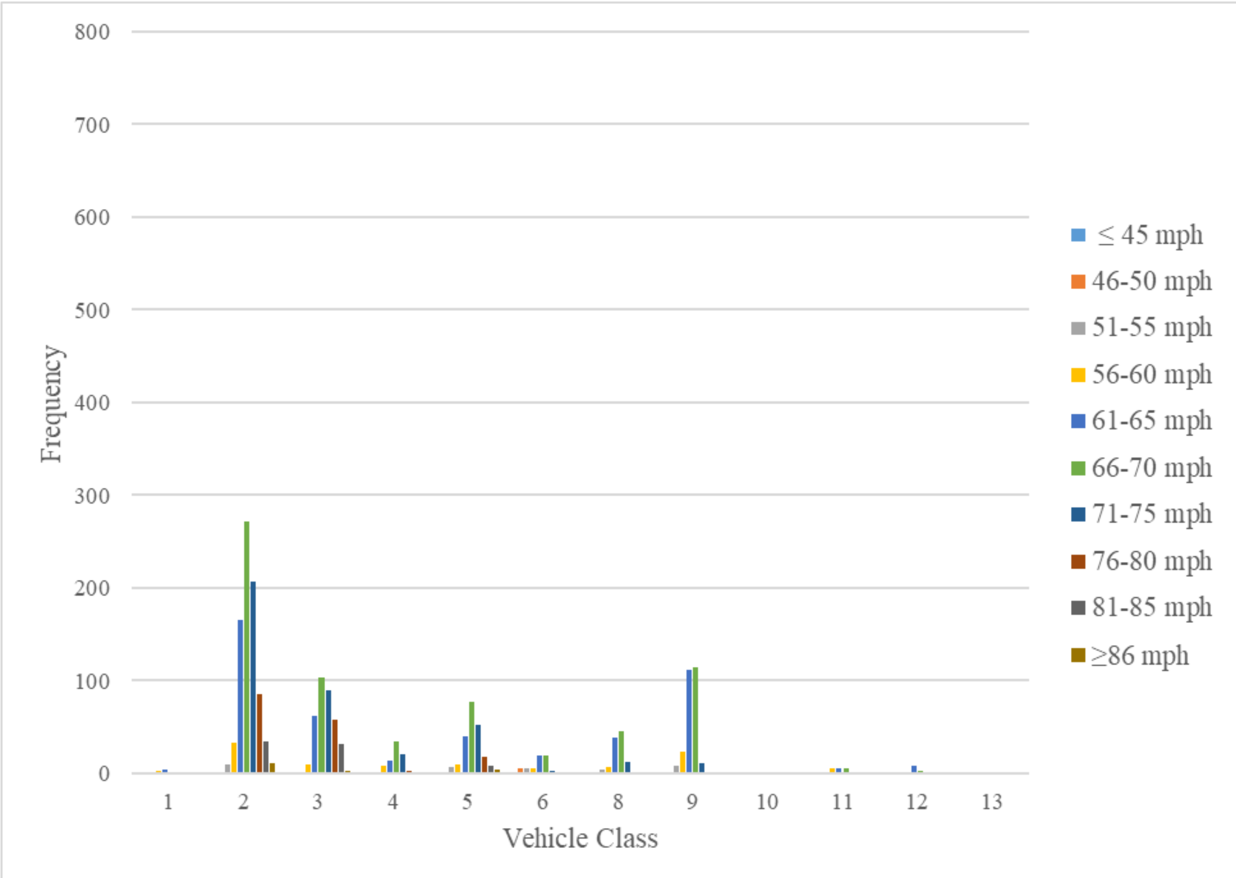


Figure A.2: Work Zone 1 Counter 1 (Night)

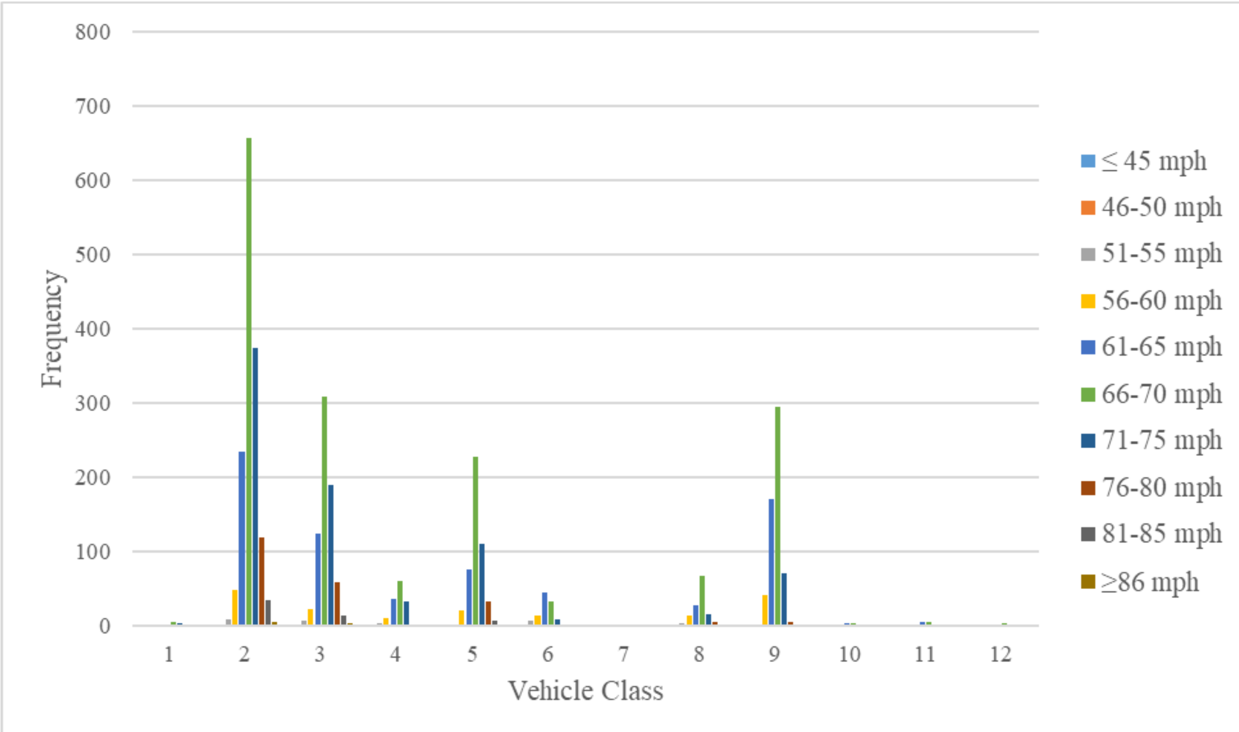


Figure A.3: Work Zone 1, Counter 2 (Day)

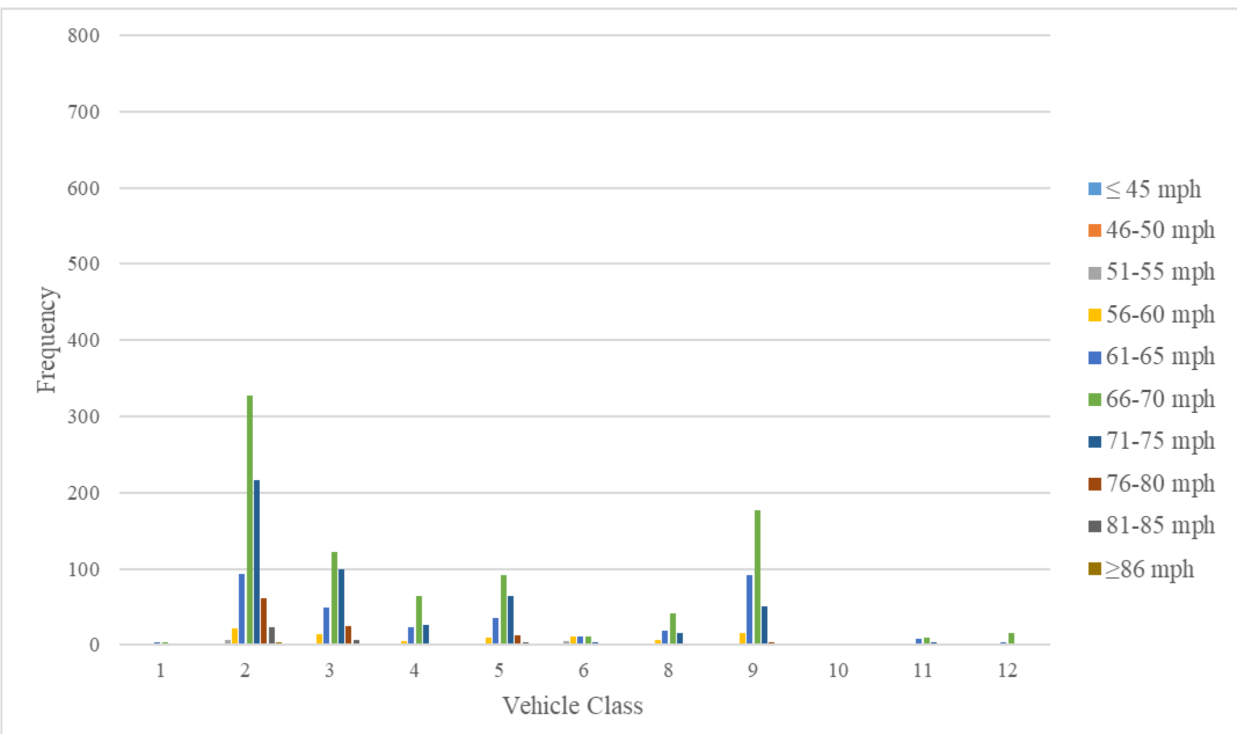


Figure A.4: Work Zone 1 Counter 2 (Night)

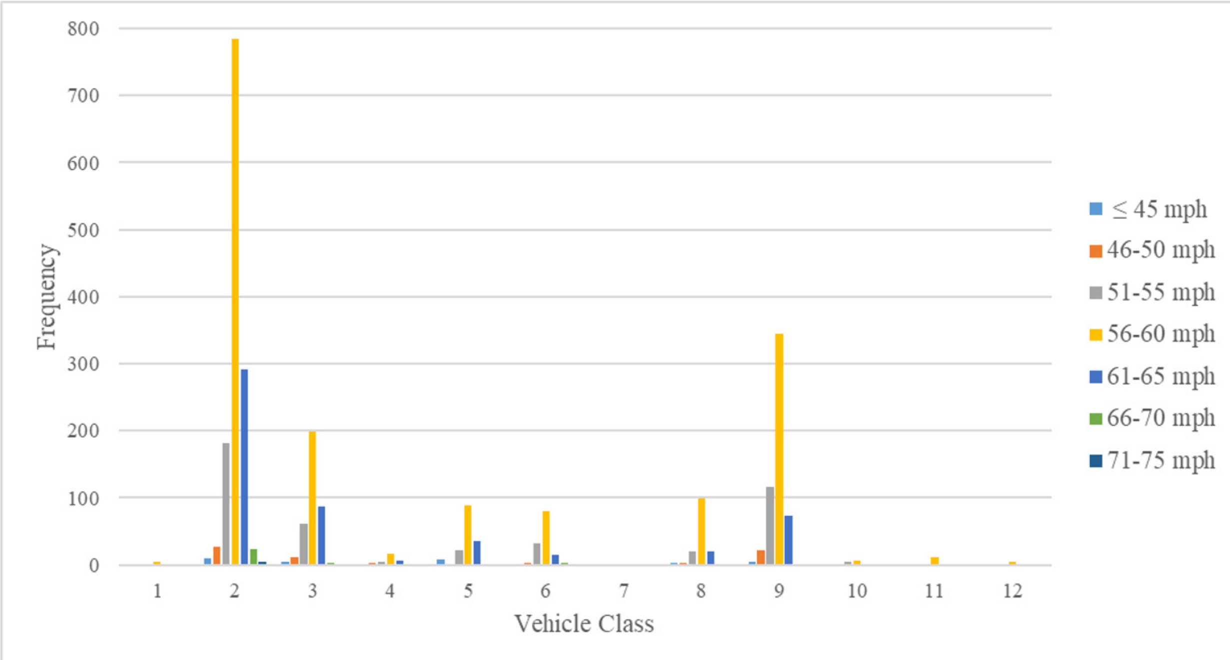


Figure A.5: Work Zone 1 Counter 3 (Day)

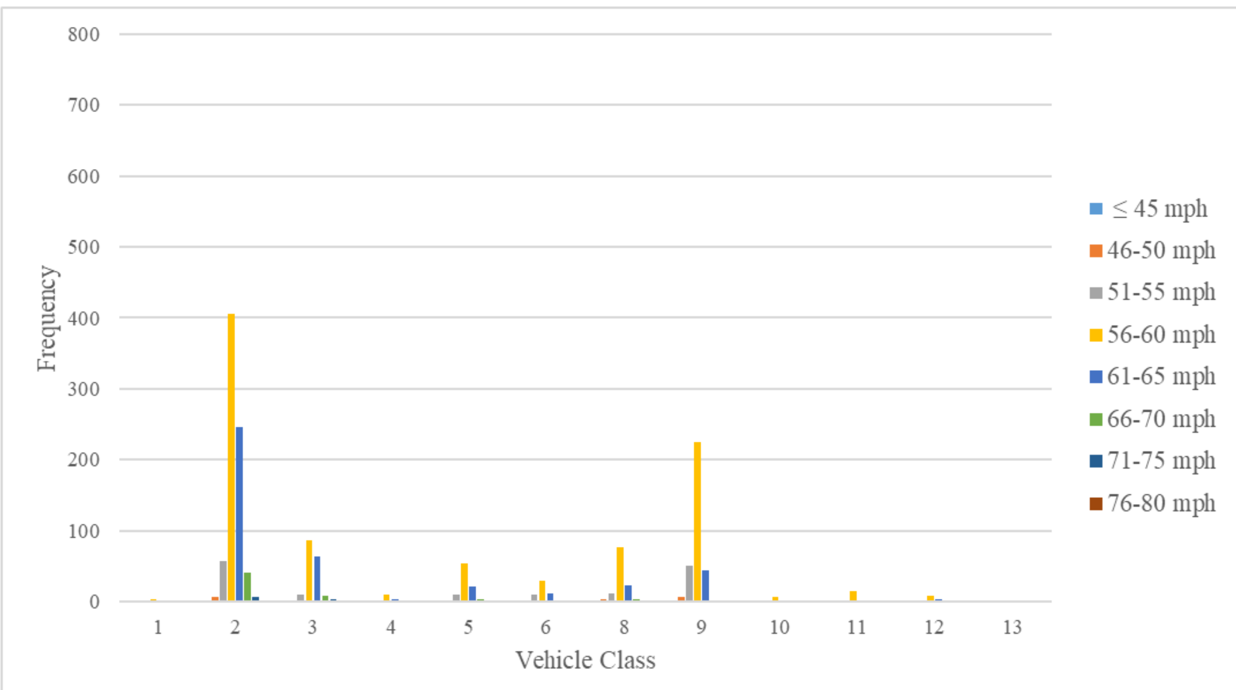


Figure A.6: Work Zone 1 Counter 3 (Night)

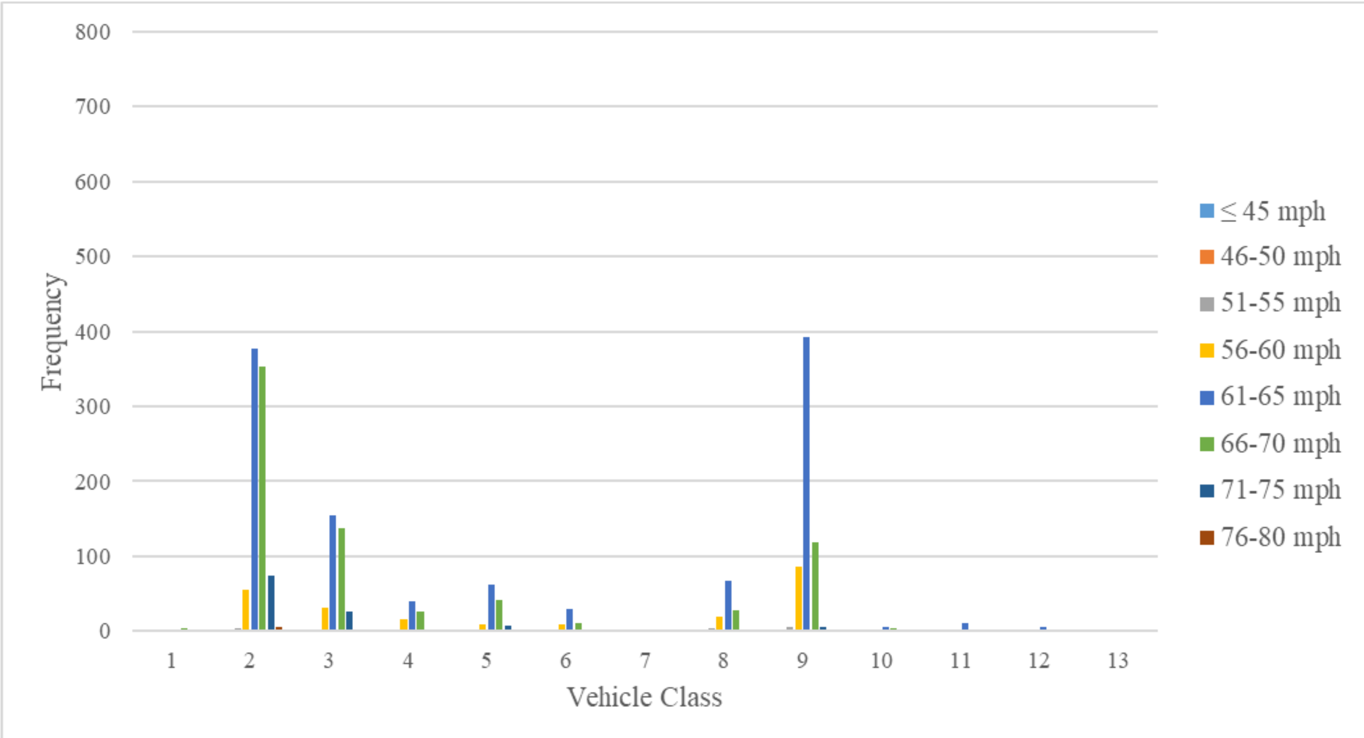


Figure A.7: Work Zone 1 Counter 4 (Day)

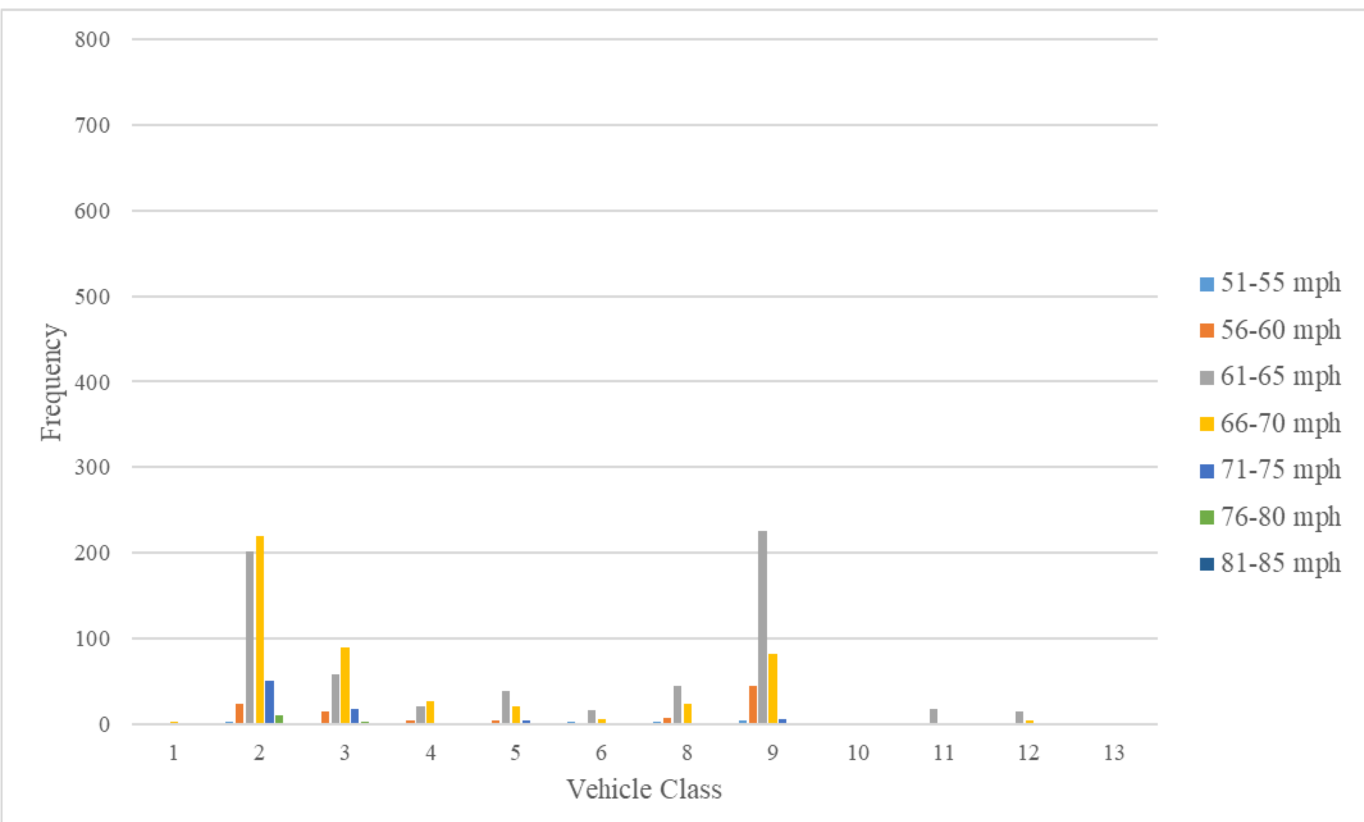


Figure A.8: Work Zone 1 Counter 4 (Night)

Pivot Tables for Work Zone 2

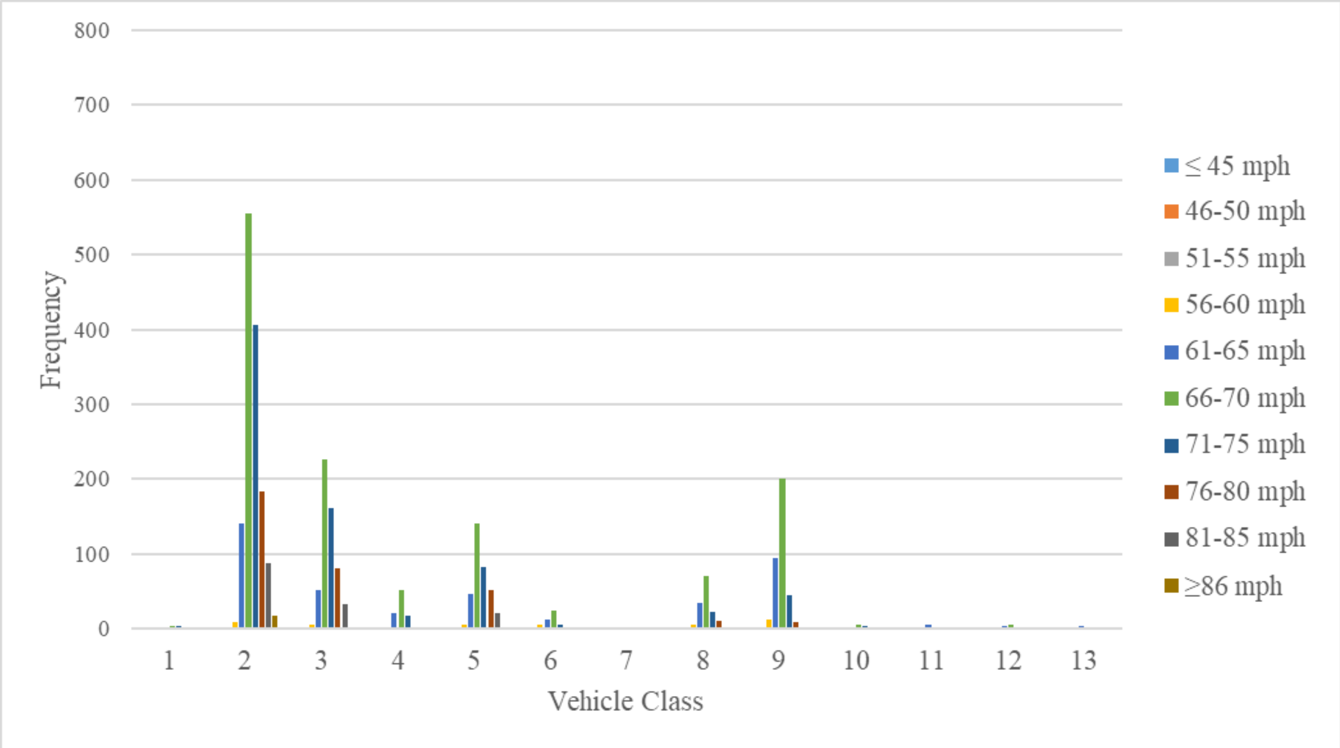


Figure A.9: Work Zone 2 Counter 1 -Before (Day)

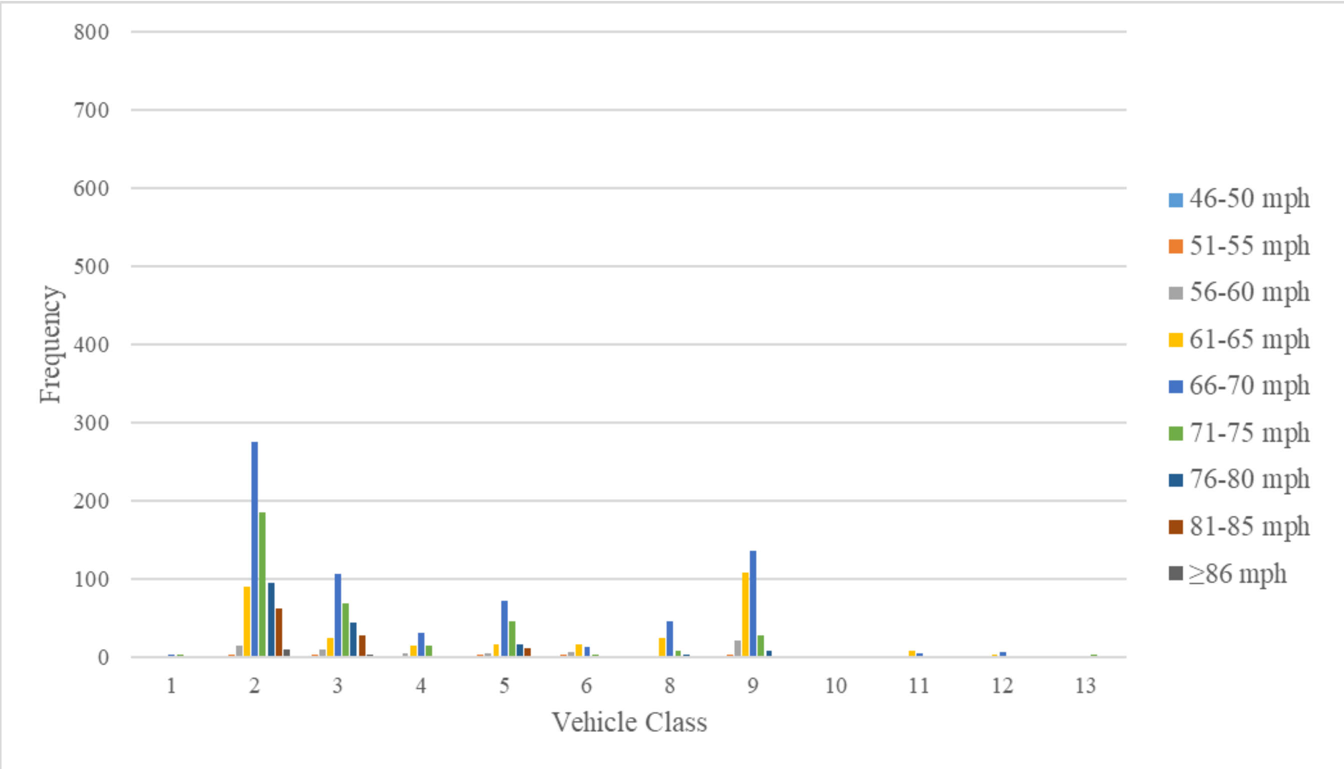


Figure A.10: Work Zone 2 Counter 1 -Before (Night)

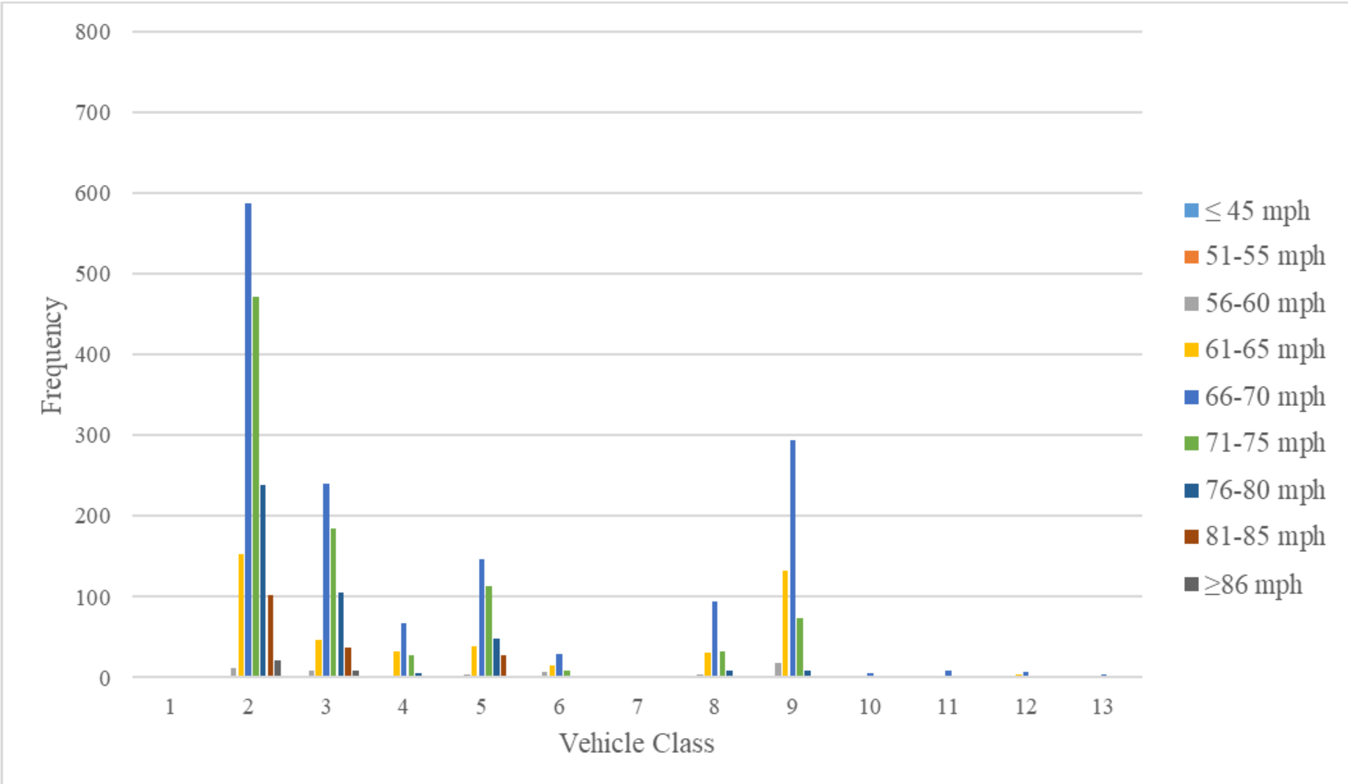


Figure A.11: Work Zone 2 Counter 1 -After (Day)

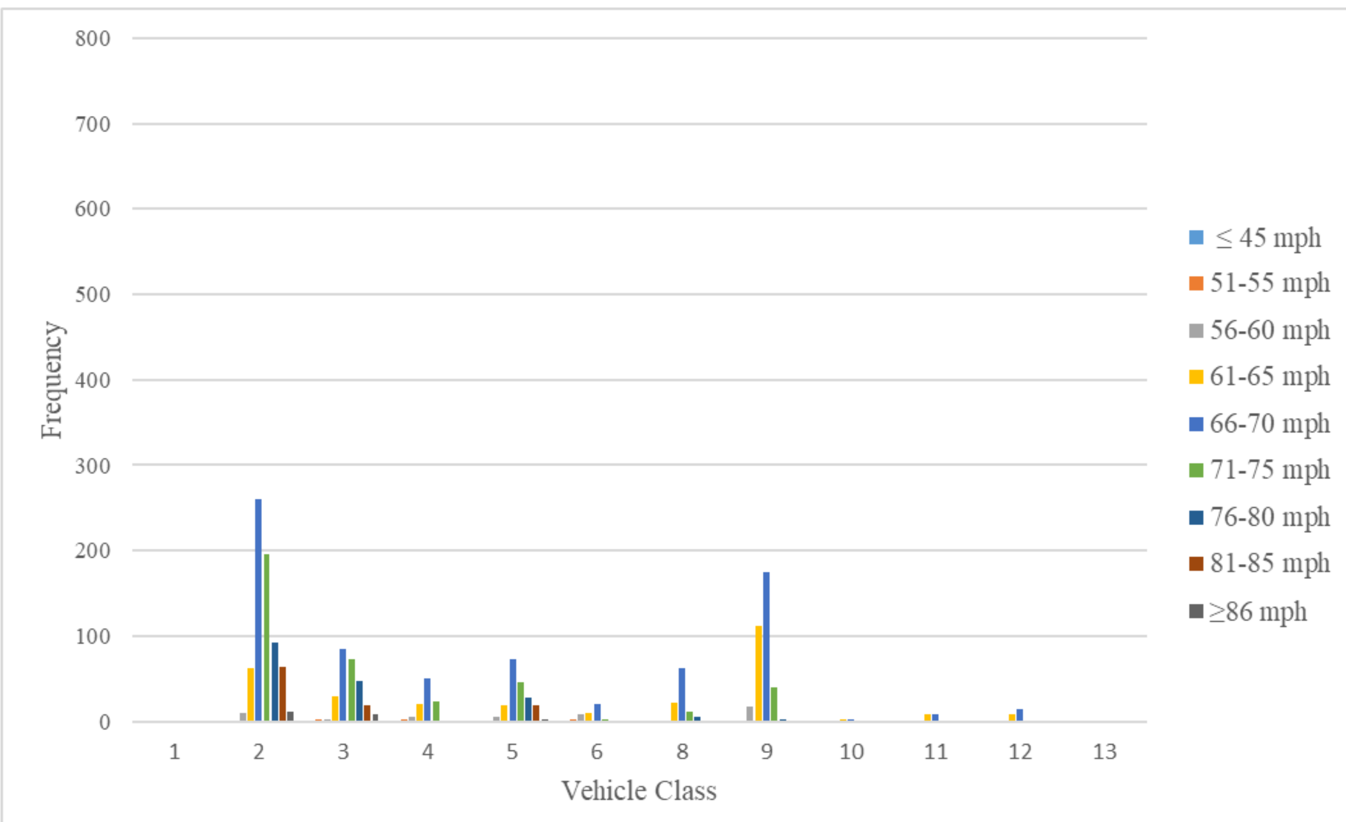


Figure A.12: Work Zone 2 Counter 1 -After (Night)

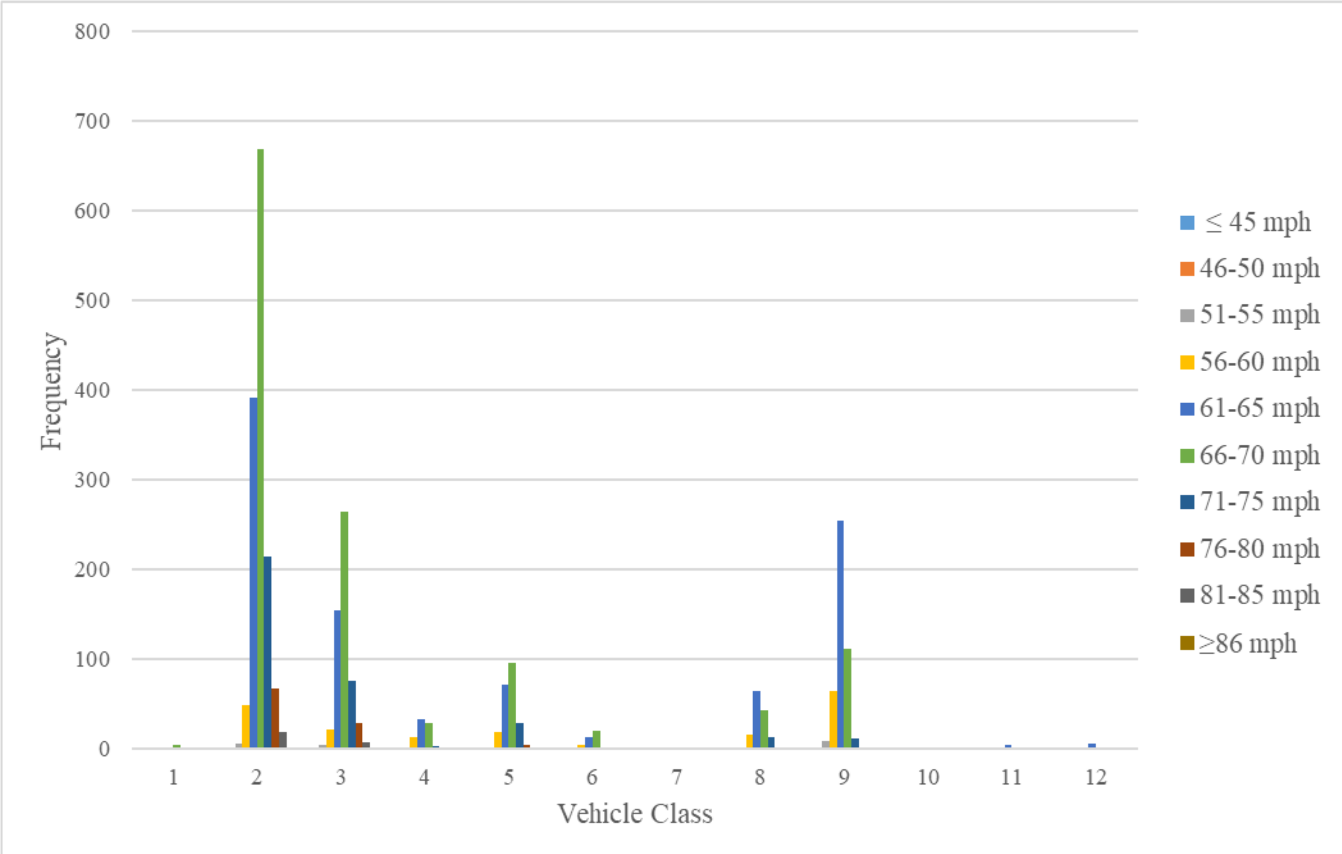
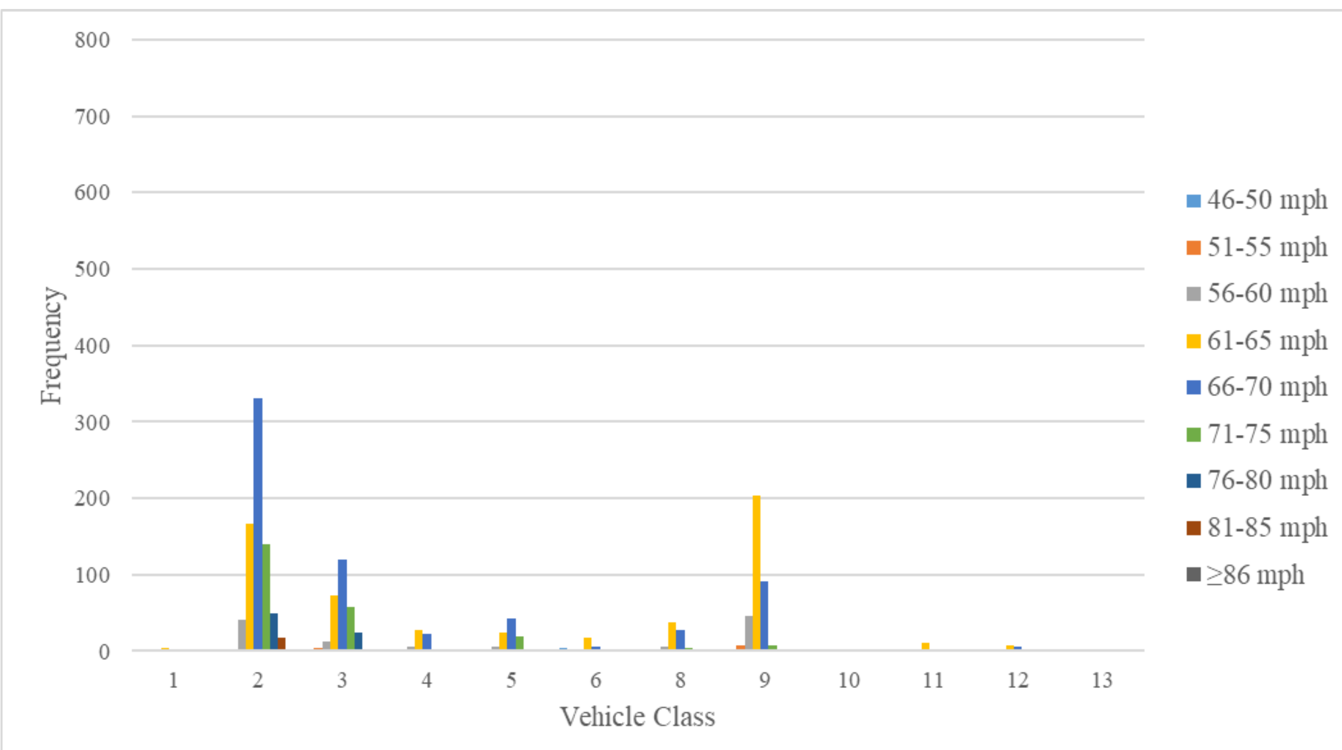


Figure A.13: Work Zone 2 Counter 2 -Before (Day)



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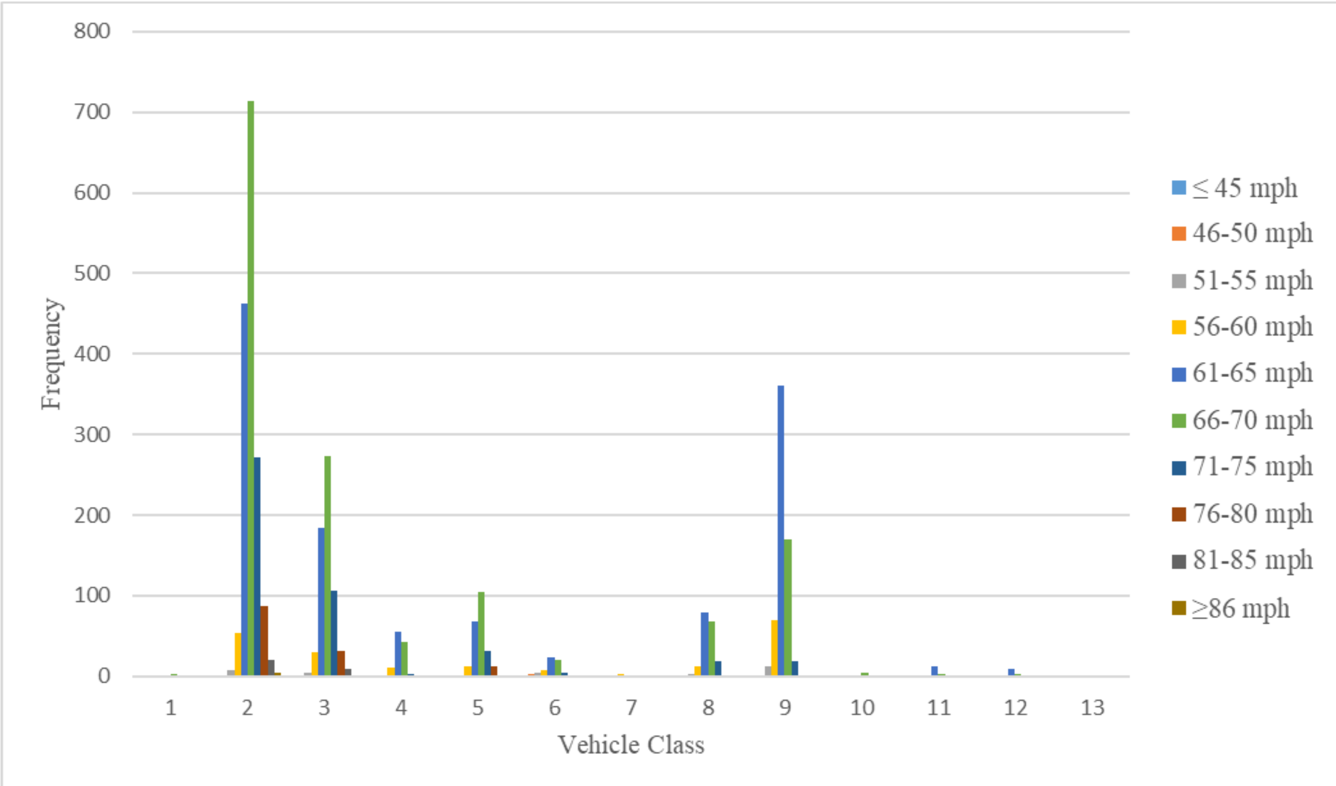


Figure A.15: Work Zone 2 Counter 2 -After (Day)

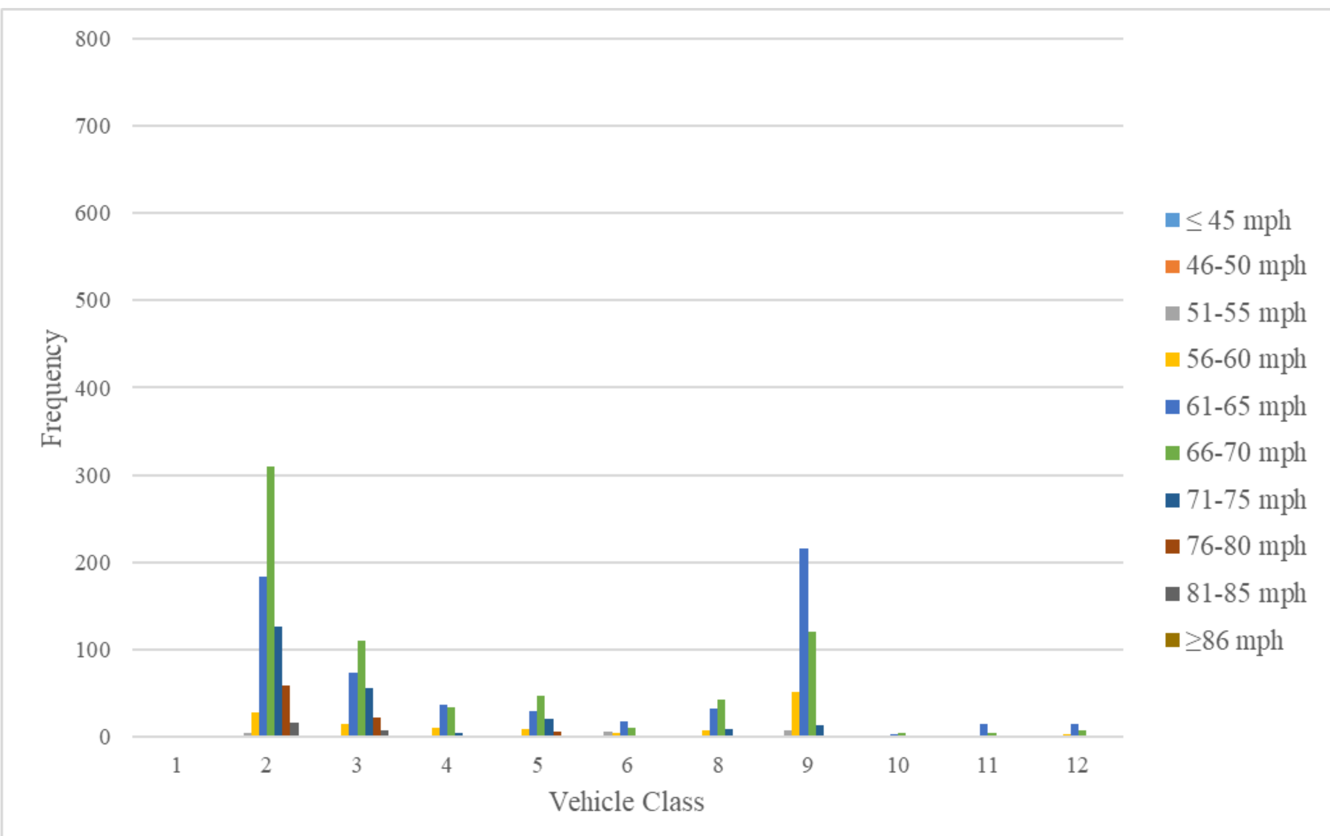


Figure A.16: Work Zone 2 Counter 2 -After (Night)

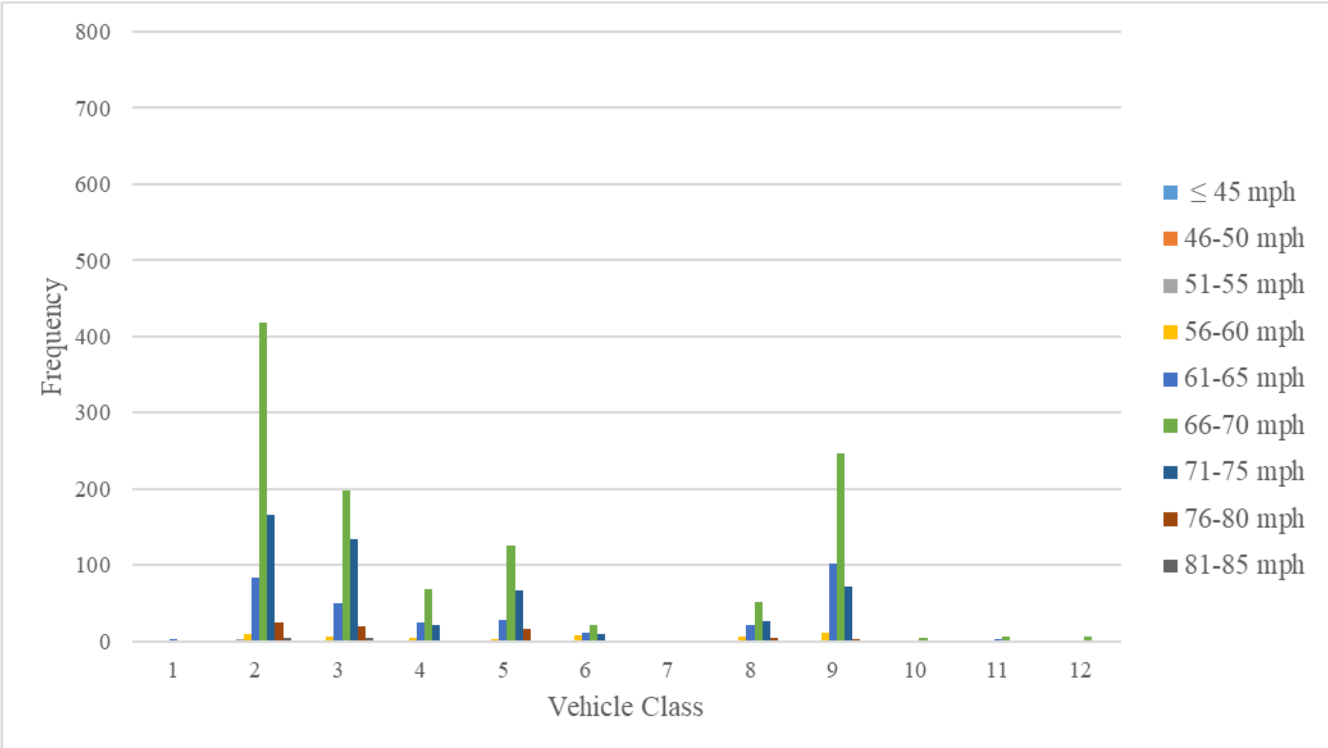


Figure A.17: Work Zone 2 Counter 3 -Before (Day)

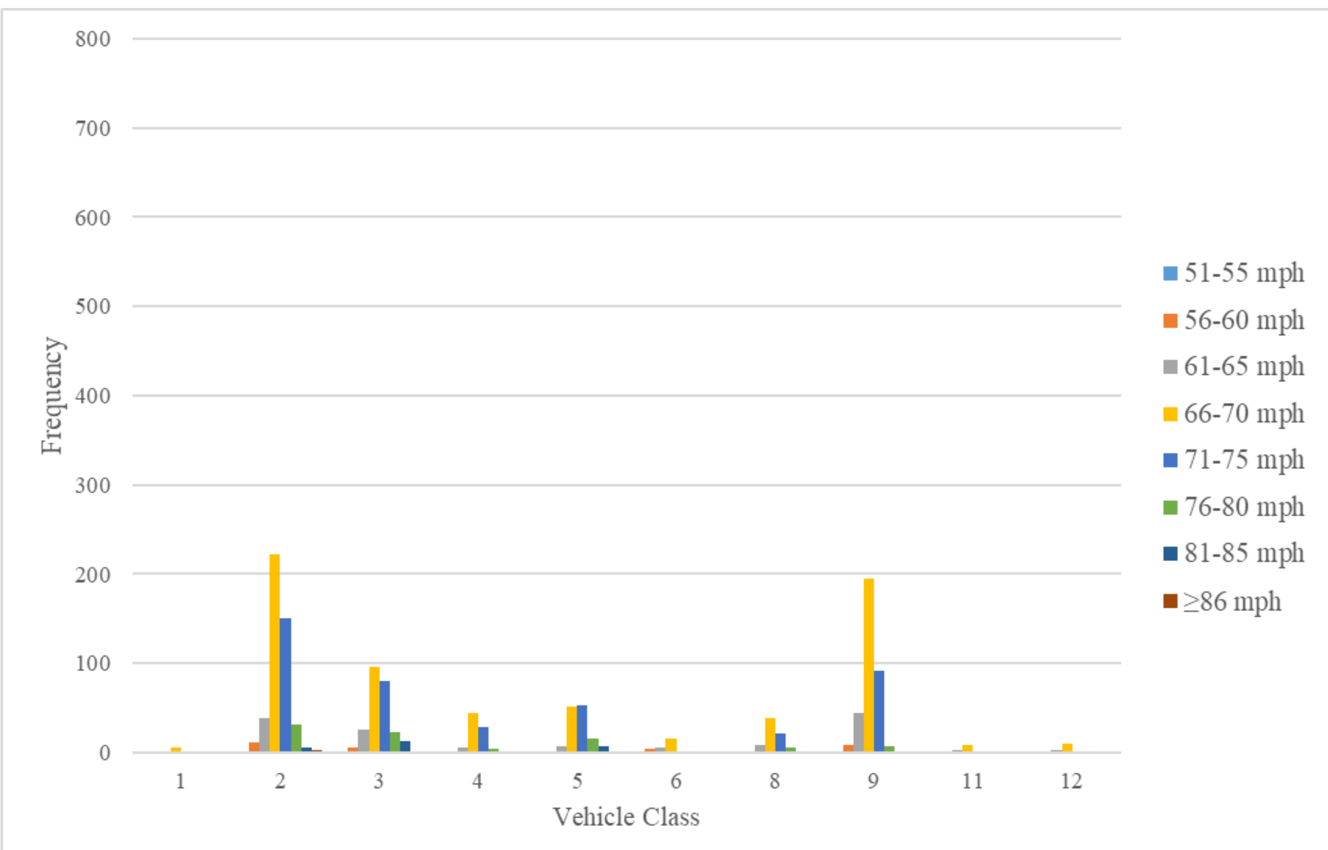


Figure A.18: Work Zone 2 Counter 3 -Before (Night)

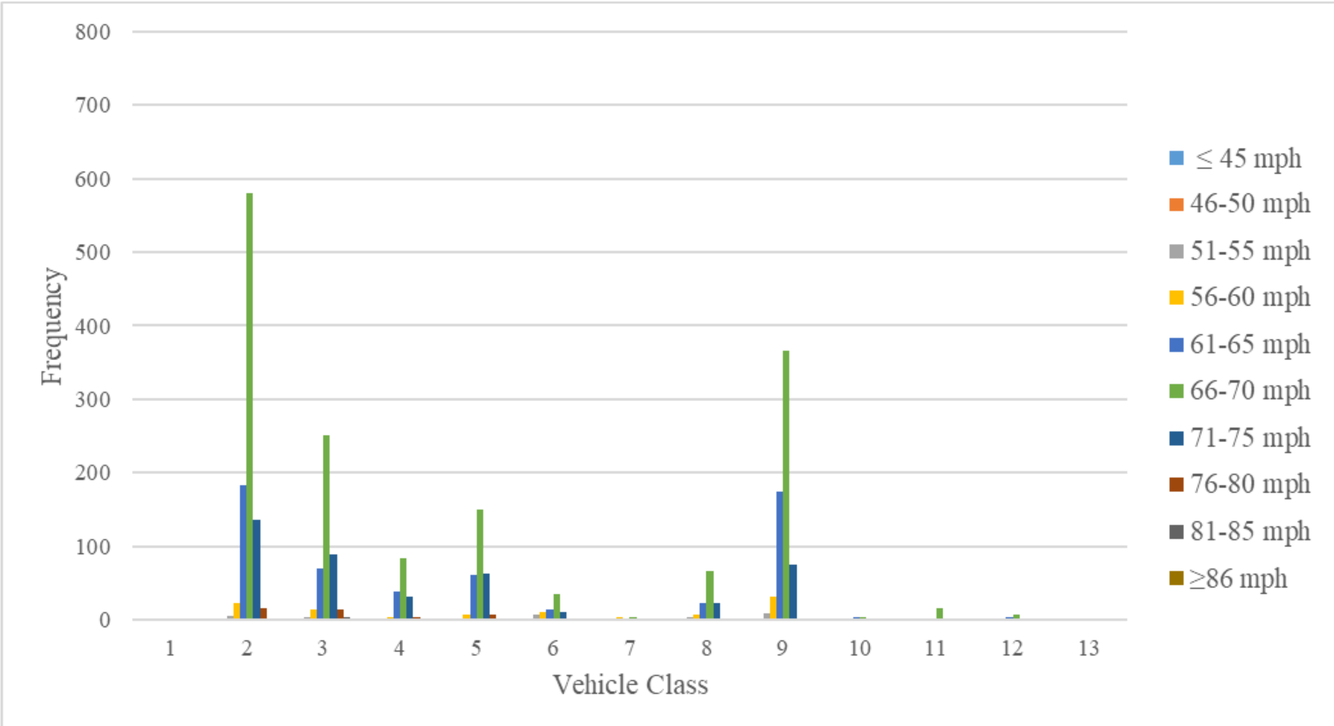


Figure A.19: Work Zone 2 Counter 3 -After (Day)

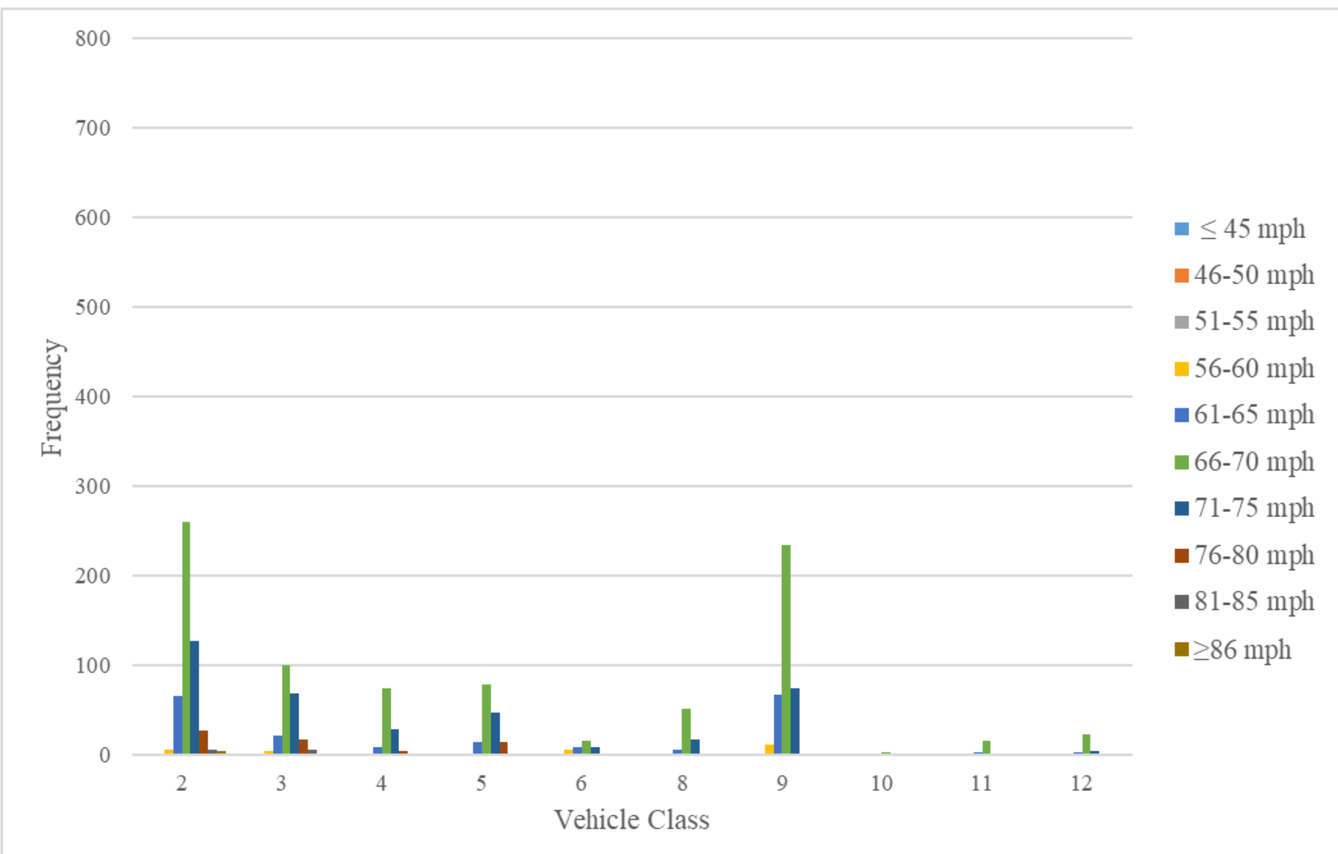


Figure A.20: Work Zone 2 Counter 3 -After (Night)

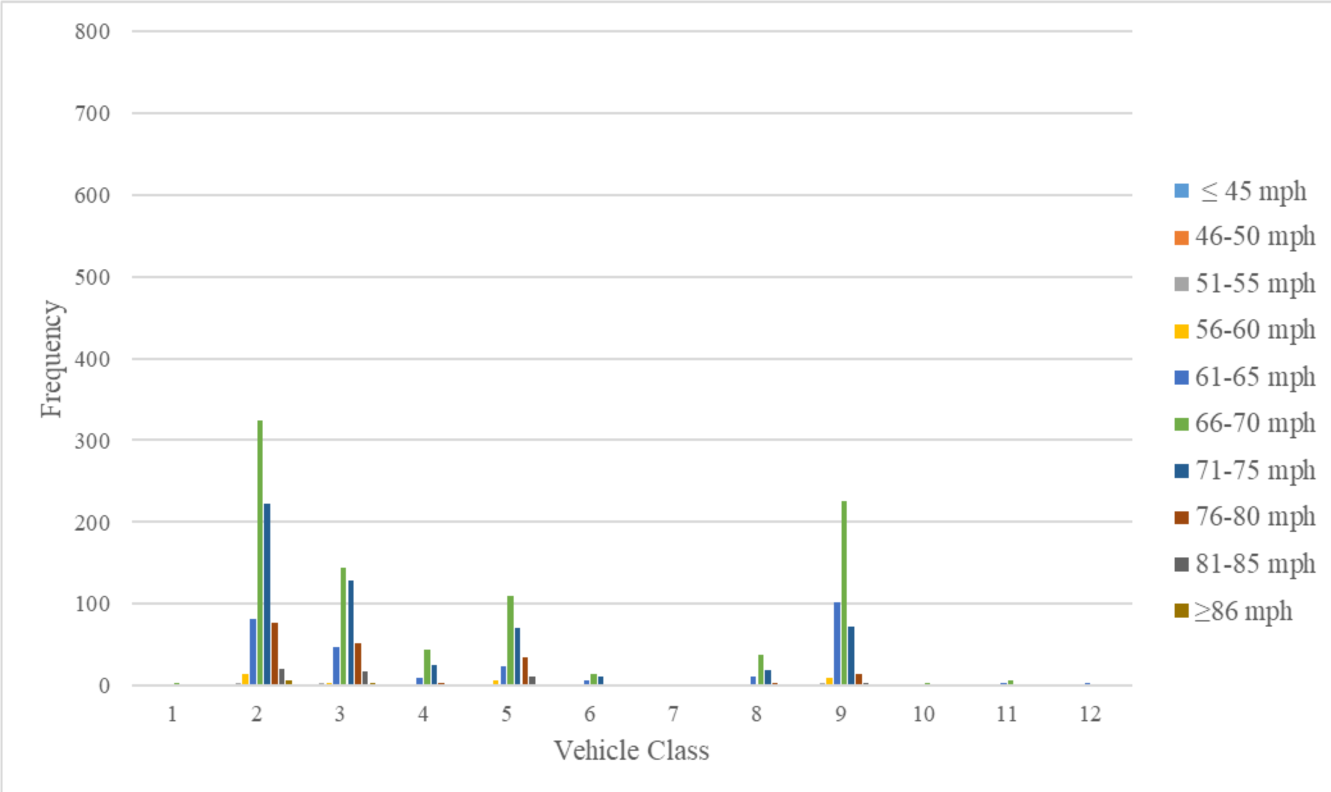


Figure A.21: Work Zone 2 Counter 4 -Before (Day)

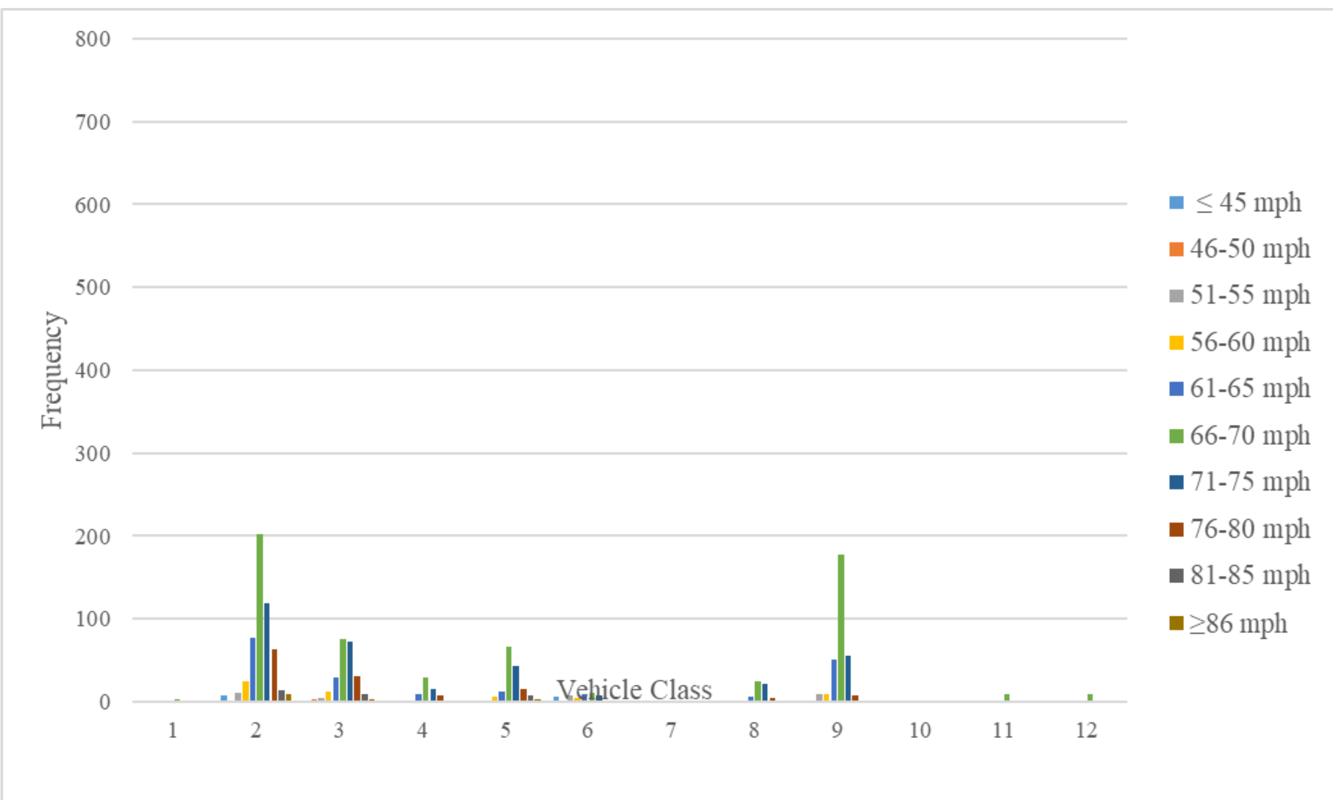


Figure A.22: Work Zone 2 Counter 4 -Before (Night)

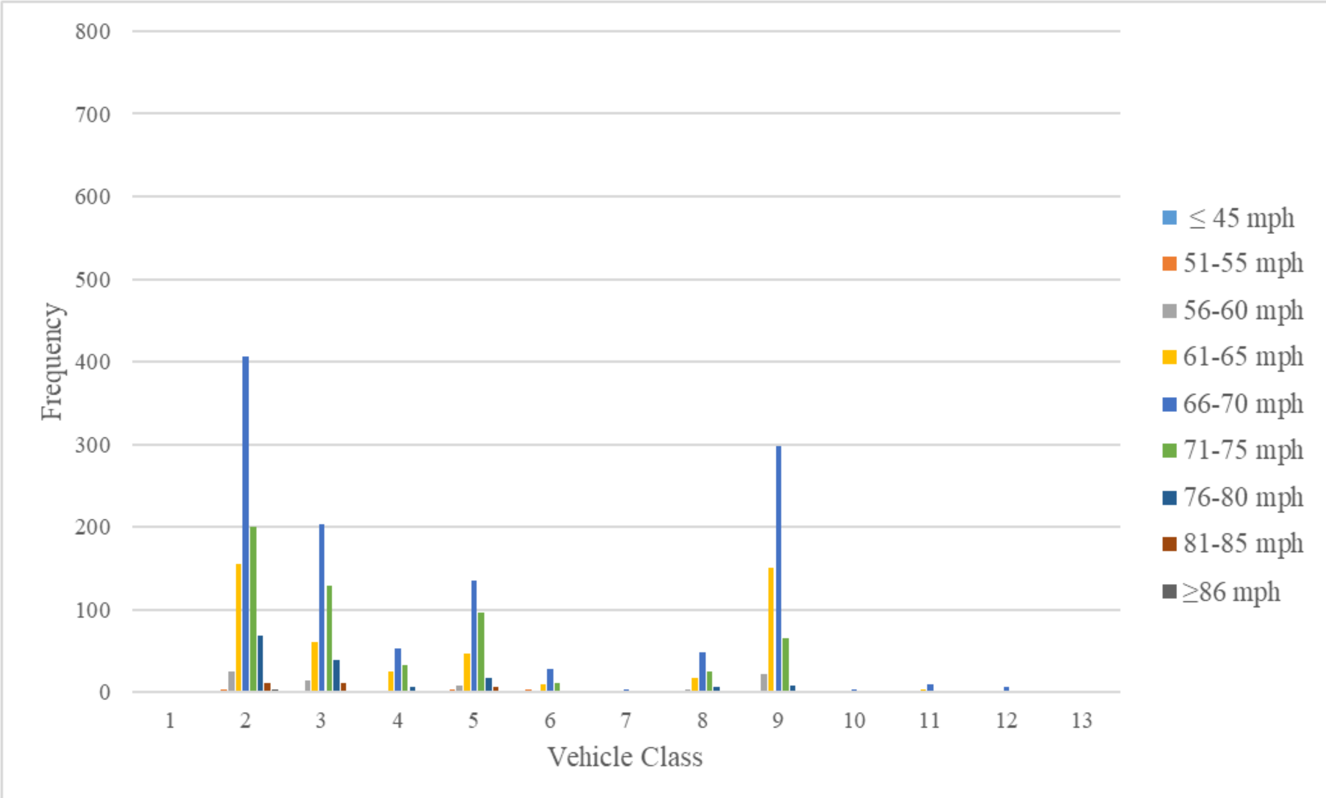


Figure A.23: Work Zone 2 Counter 4 -After (Day)

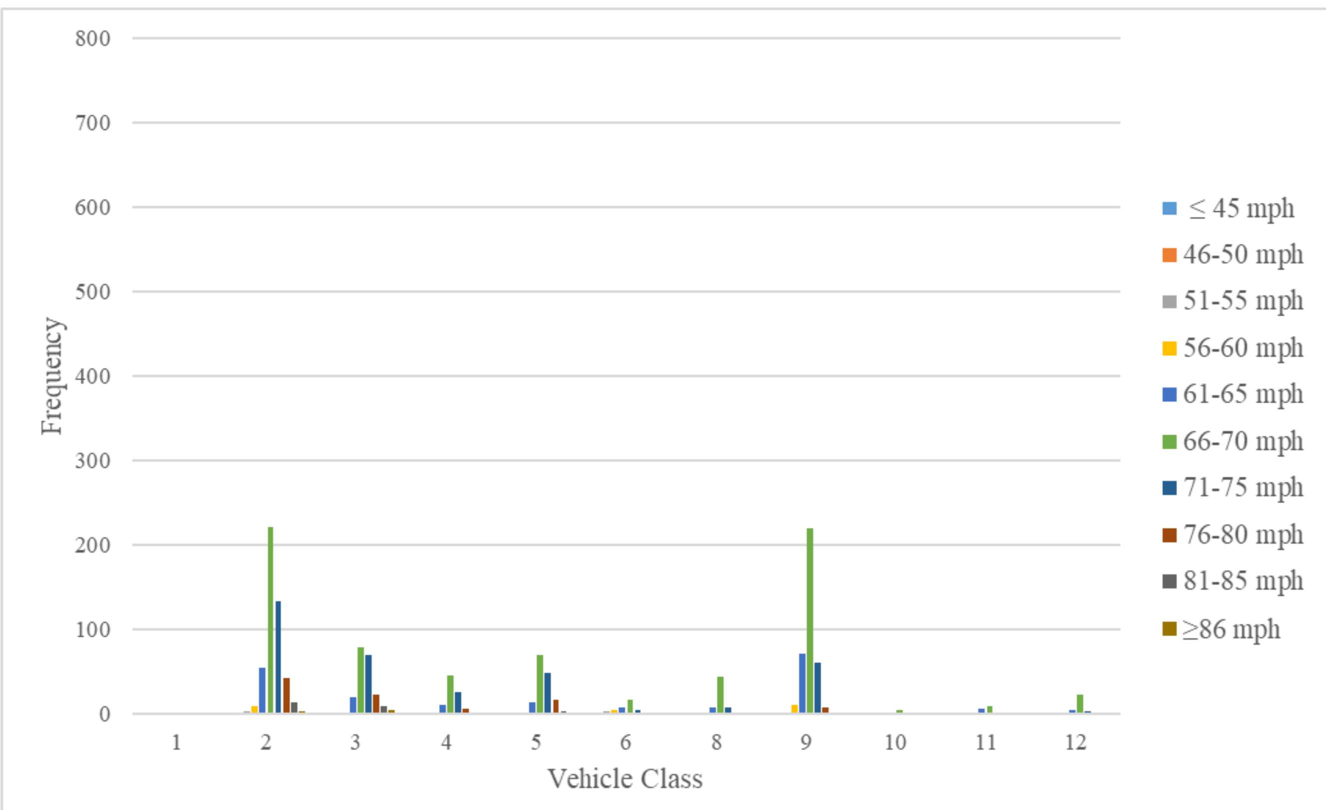


Figure A.24: Work Zone 2 Counter 4 -After (Night)

Pivot Tables for Work Zone 3

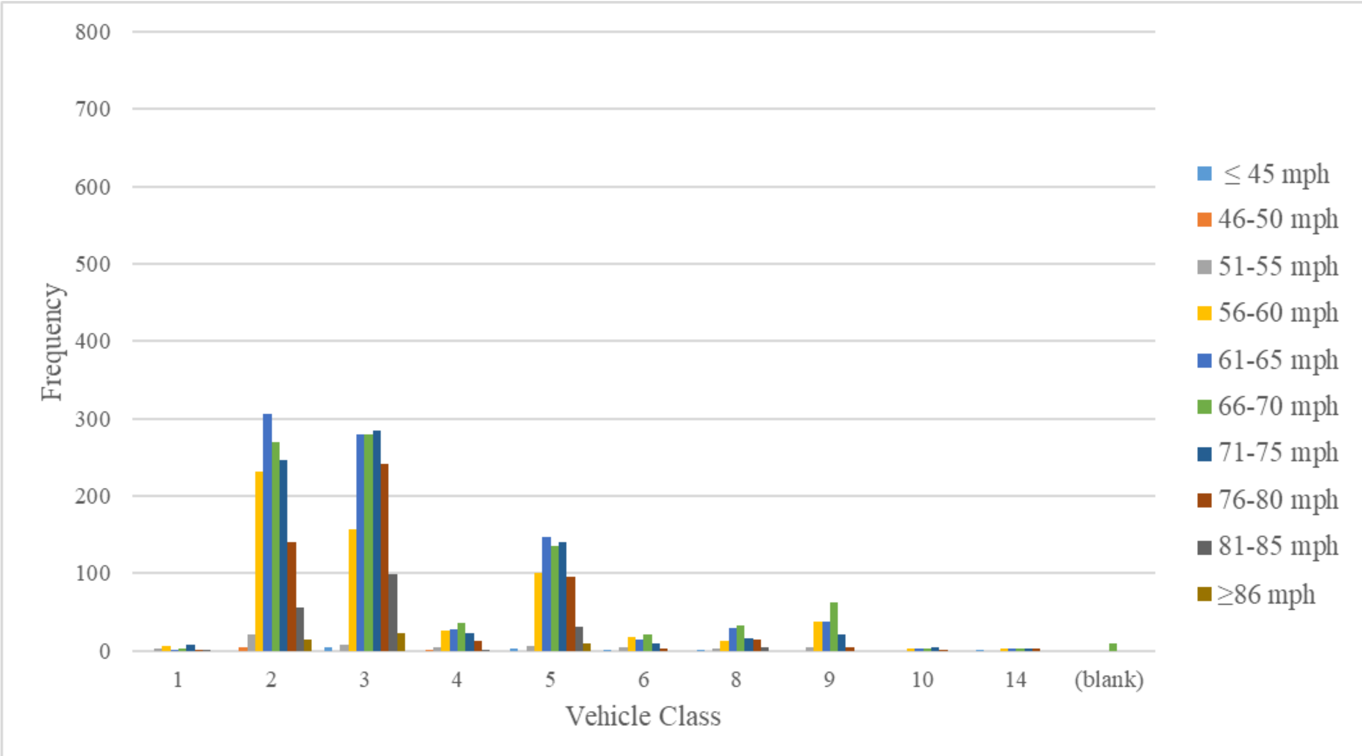


Figure A.25: Work Zone 3 Counter 1 -Before (Day)

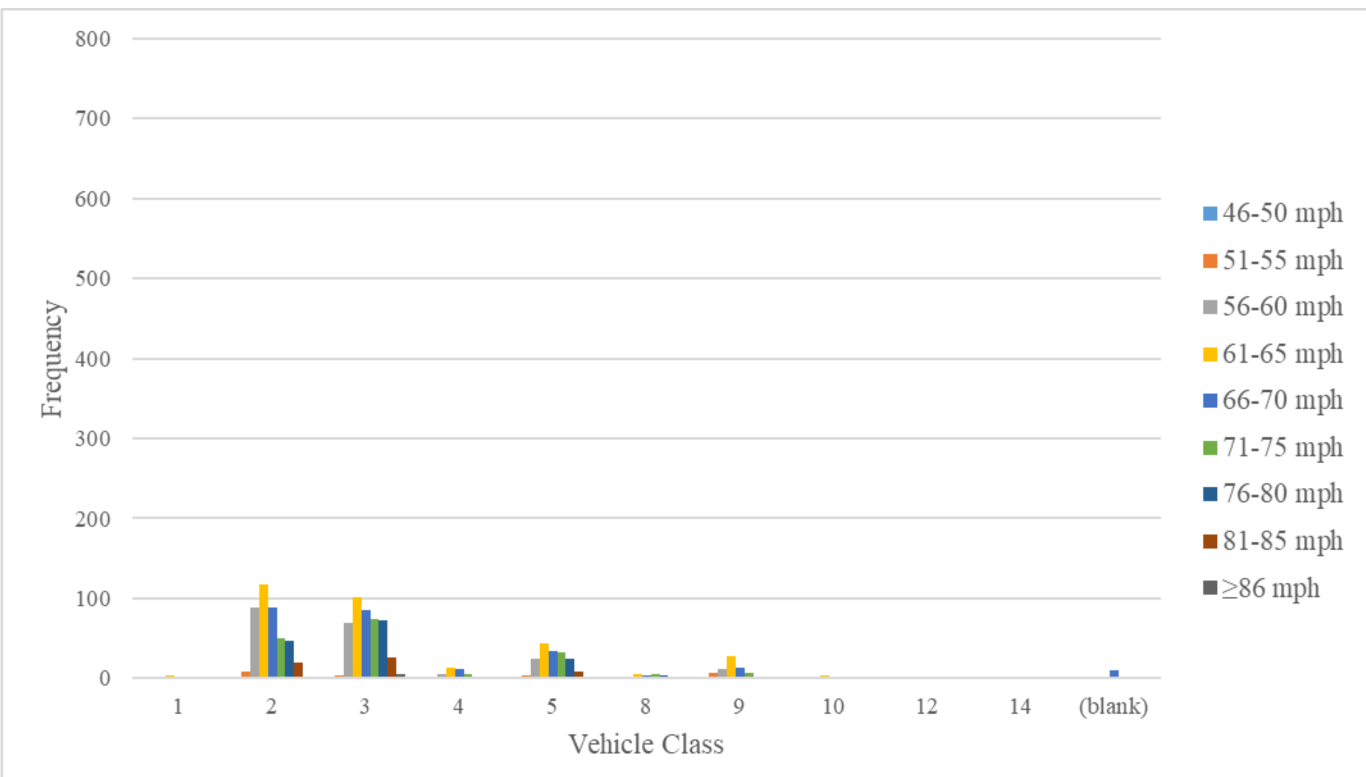


Figure A.26: Work Zone 3 Counter 1 -Before (Night)

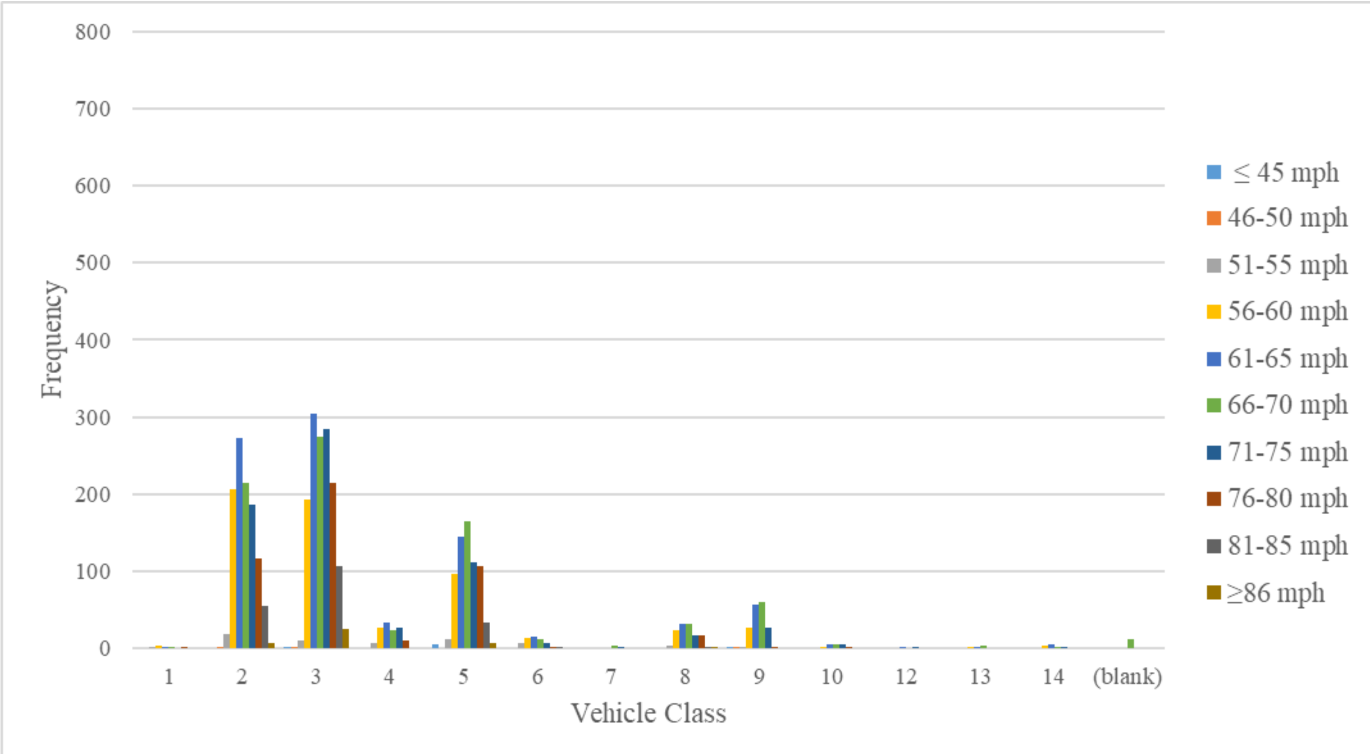


Figure A.27: Work Zone 3 Counter 1 -After (Day)

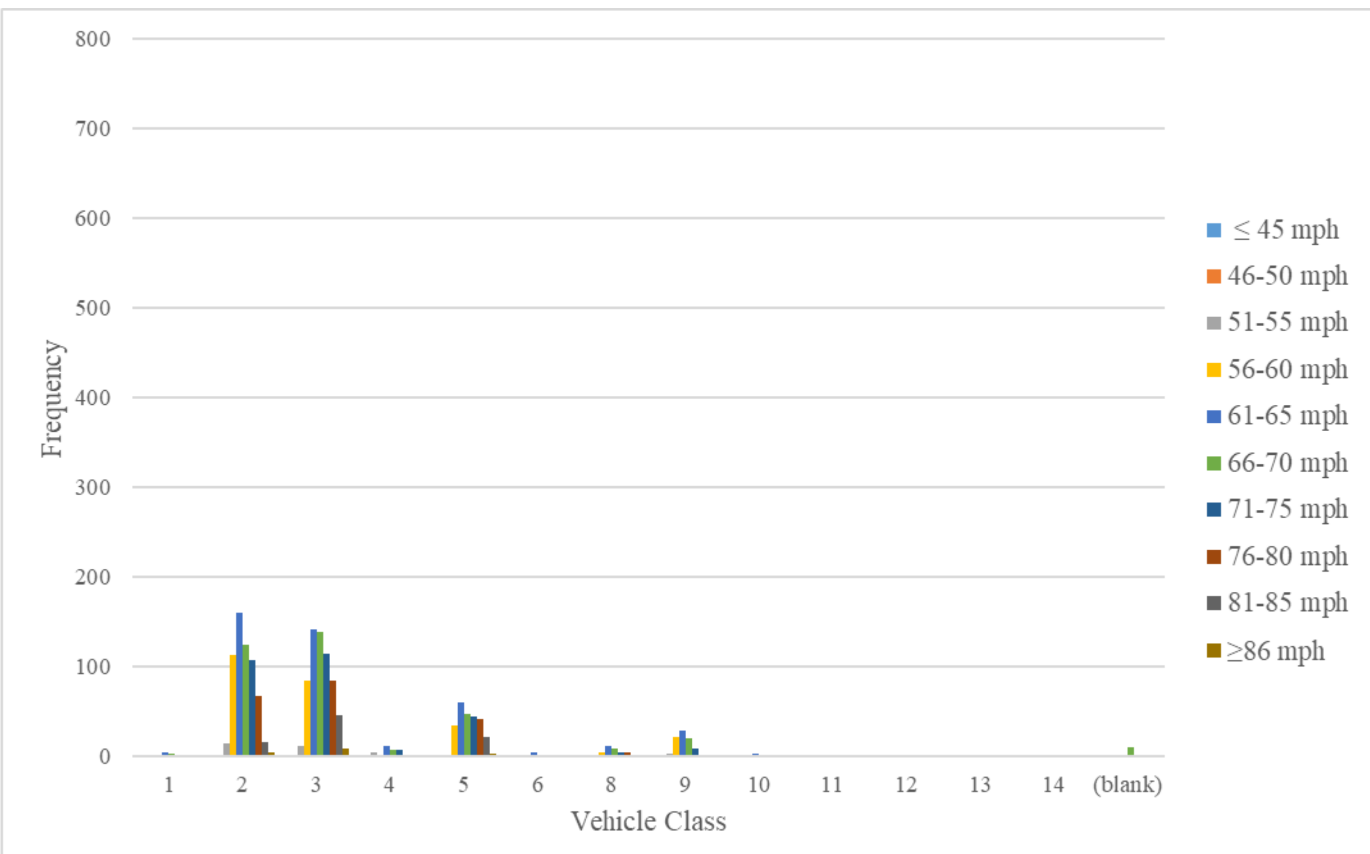


Figure A.28: Work Zone 3 Counter 1 -After (Night)

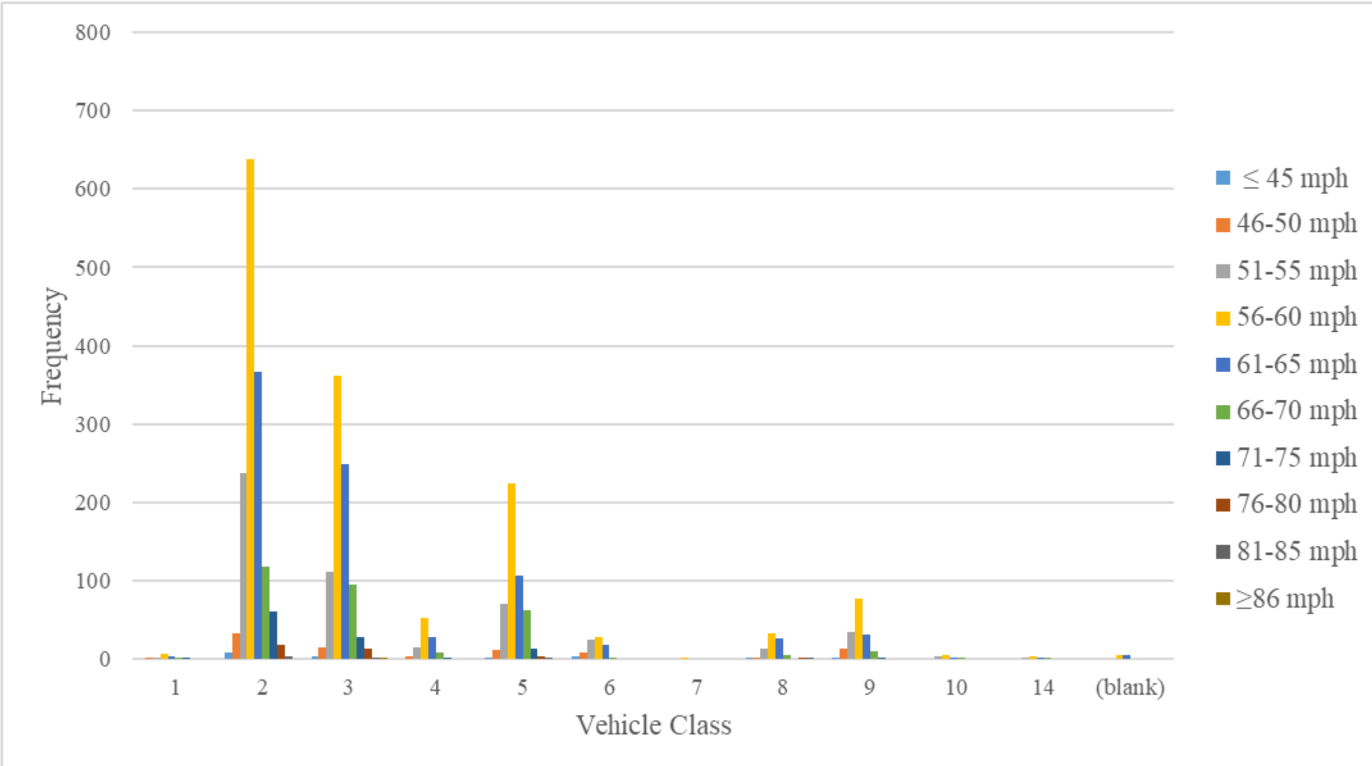


Figure A.29: Work Zone 3 Counter 2 -Before (Day)

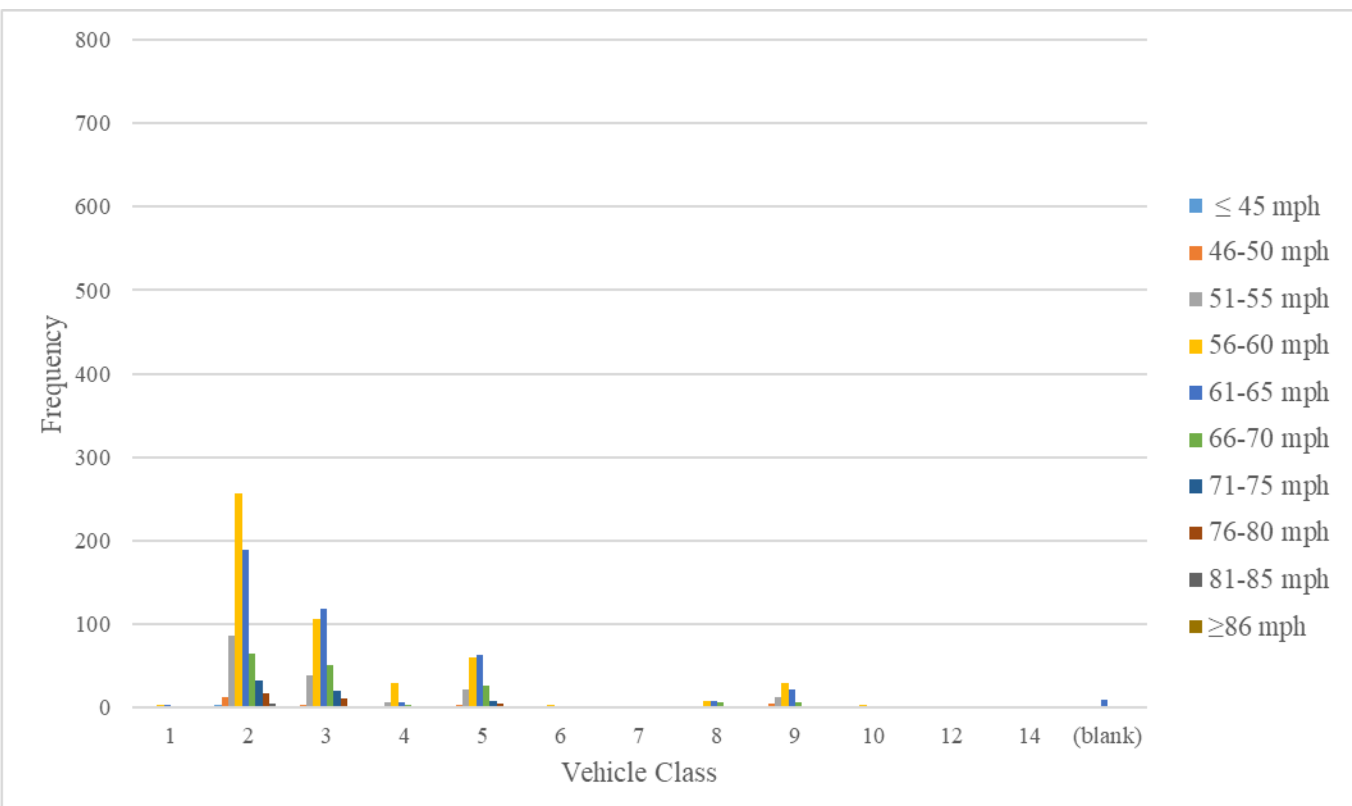


Figure A.30: Work Zone 3 Counter 2 -Before (Night)

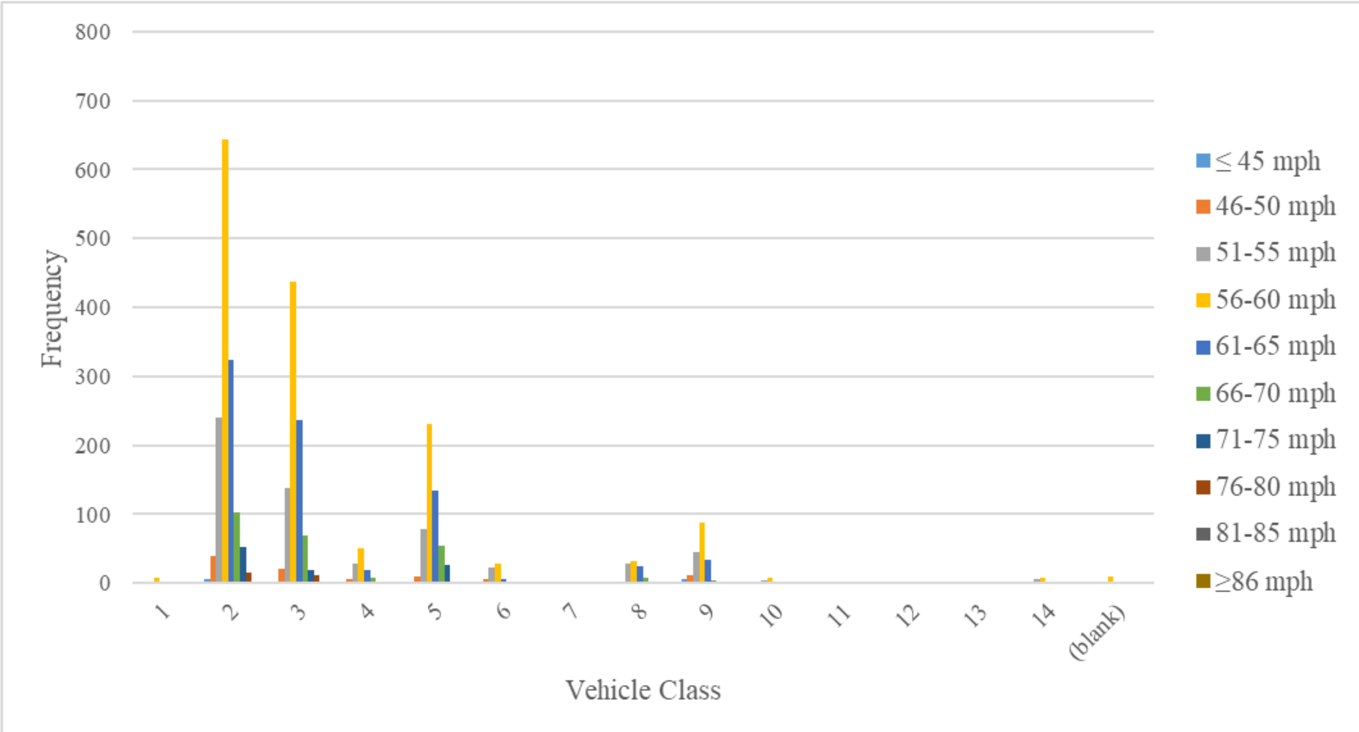


Figure A.31: Work Zone 3 Counter 2 -After (Day)

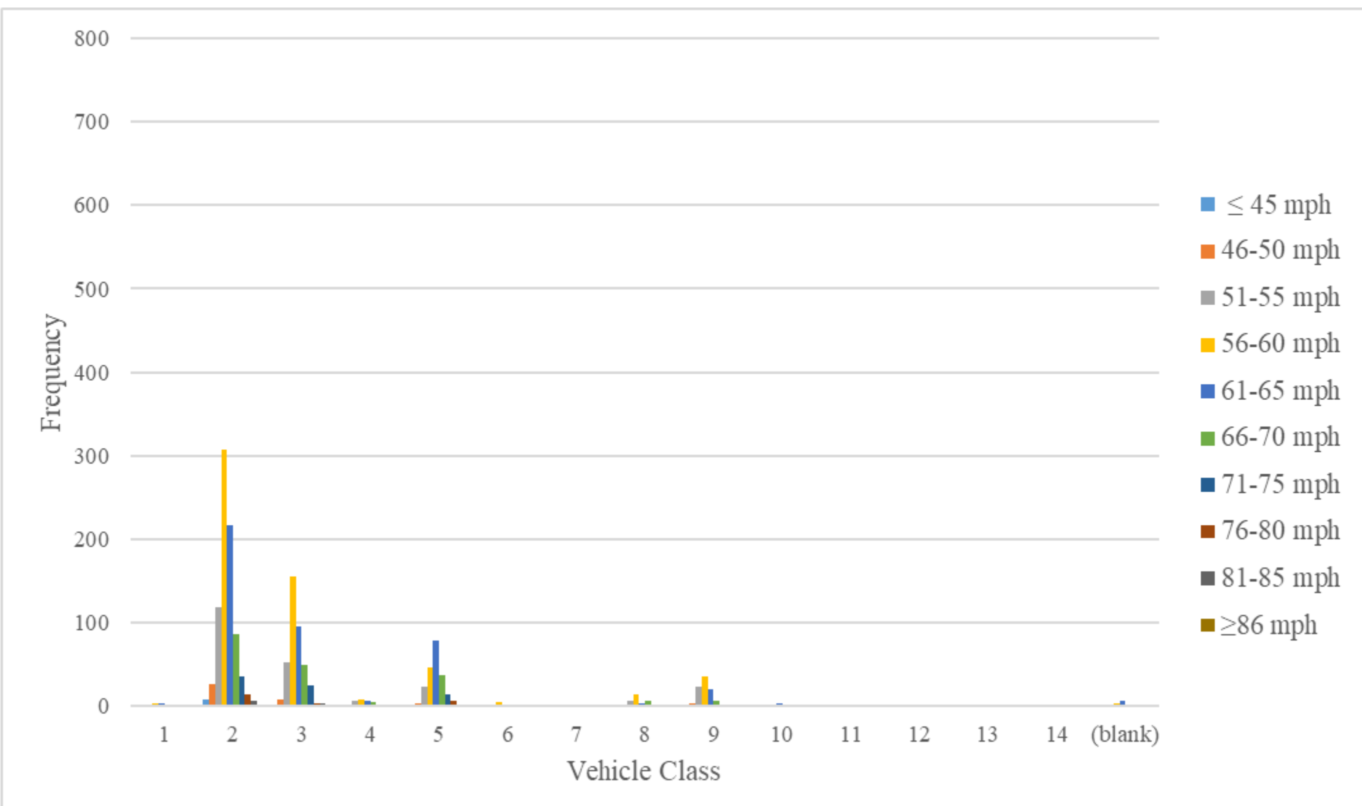


Figure A.32: Work Zone 3 Counter 2 -After (Night)

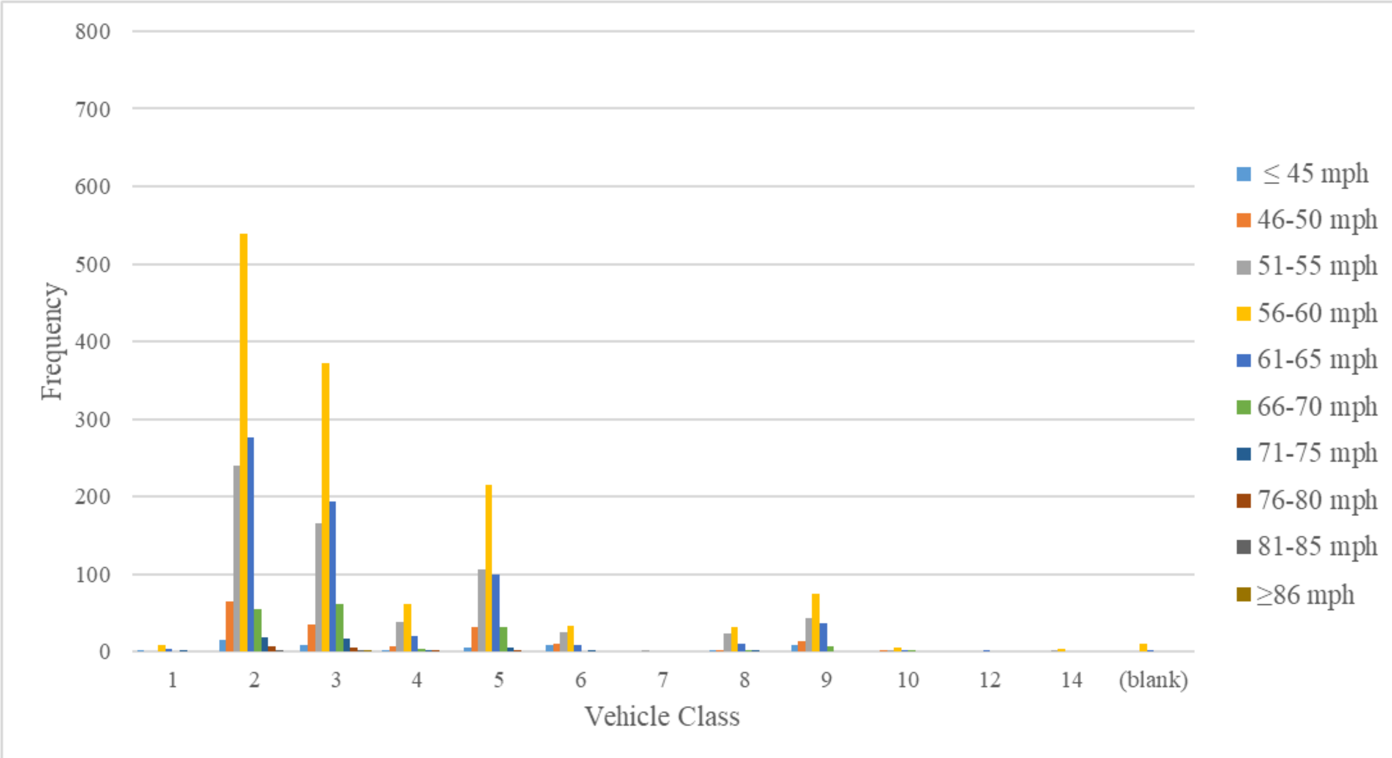
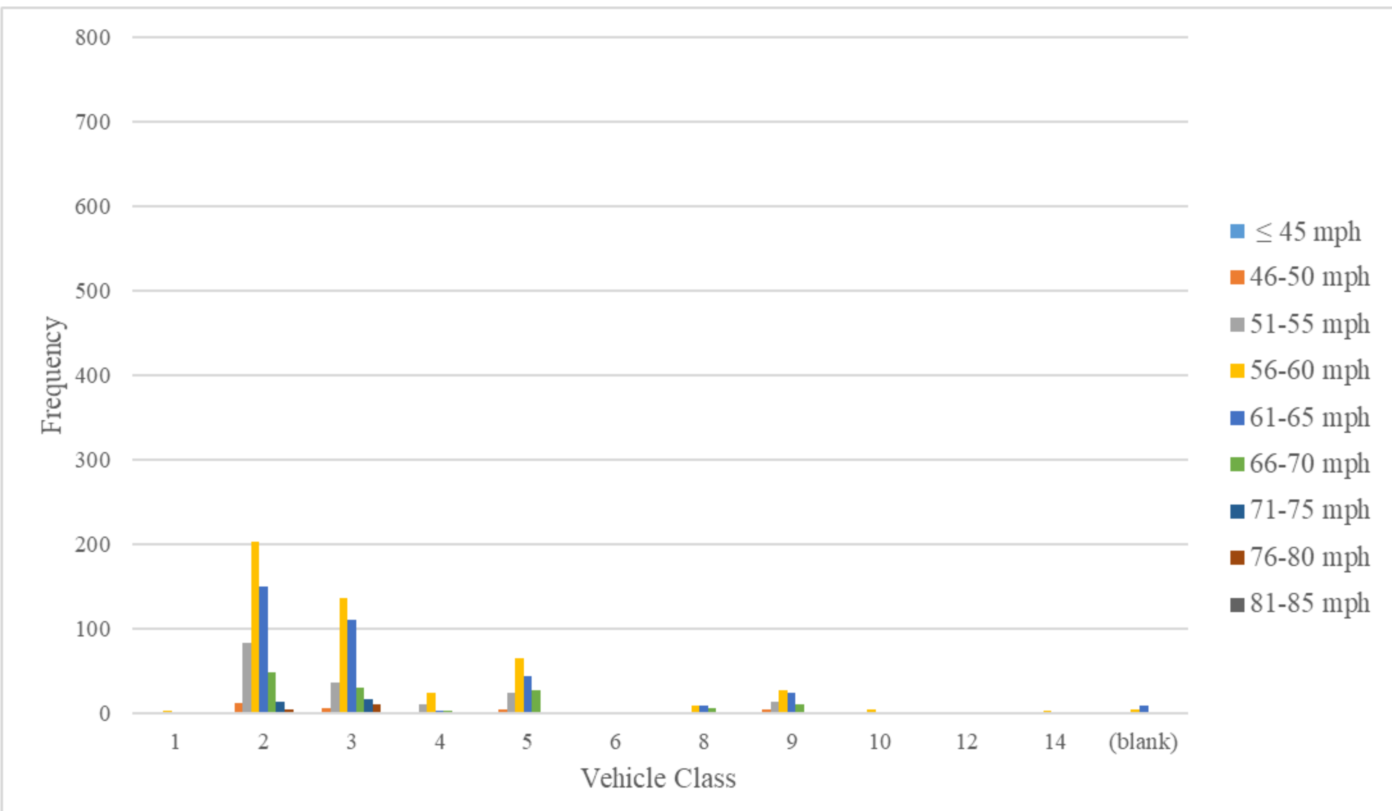


Figure A.33: Work Zone 3 Counter 3 -Before (Day)



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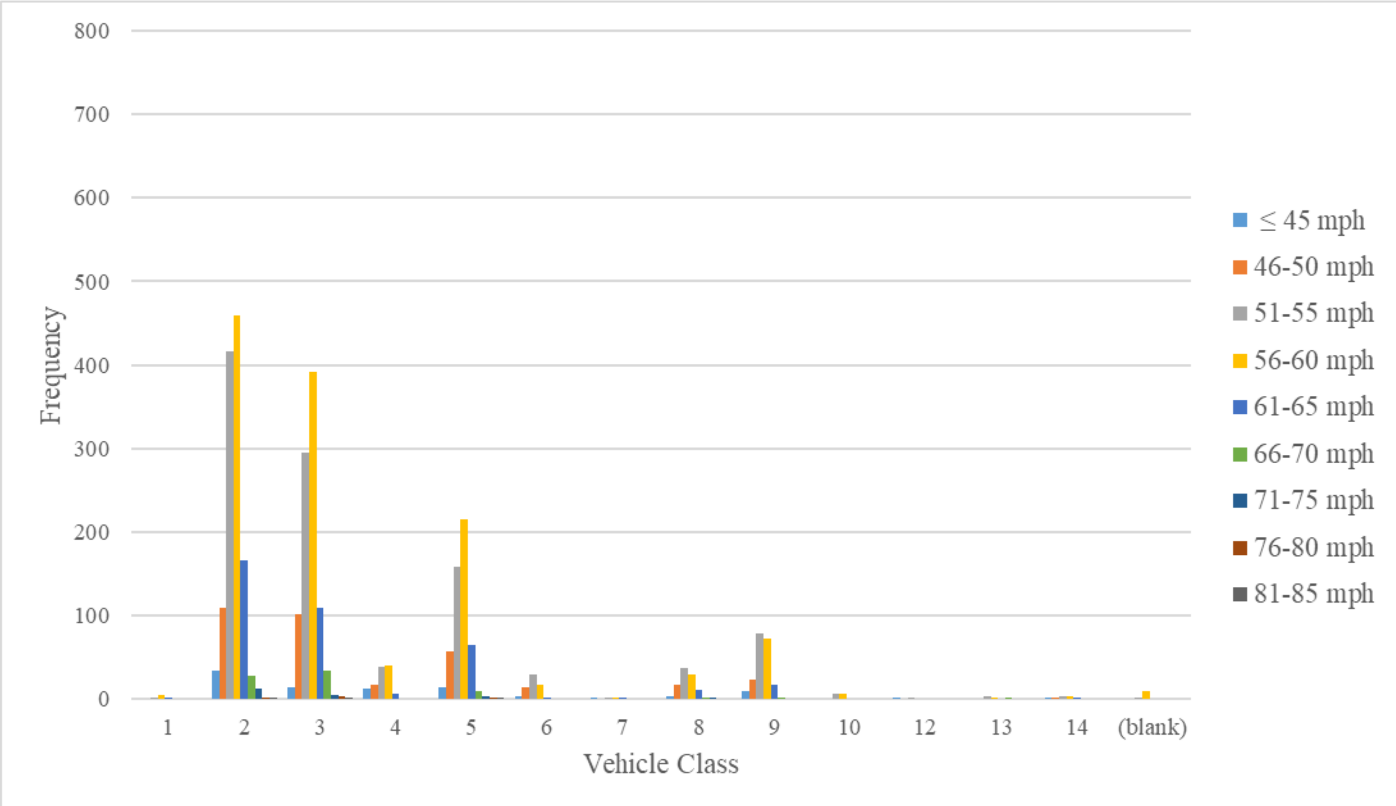

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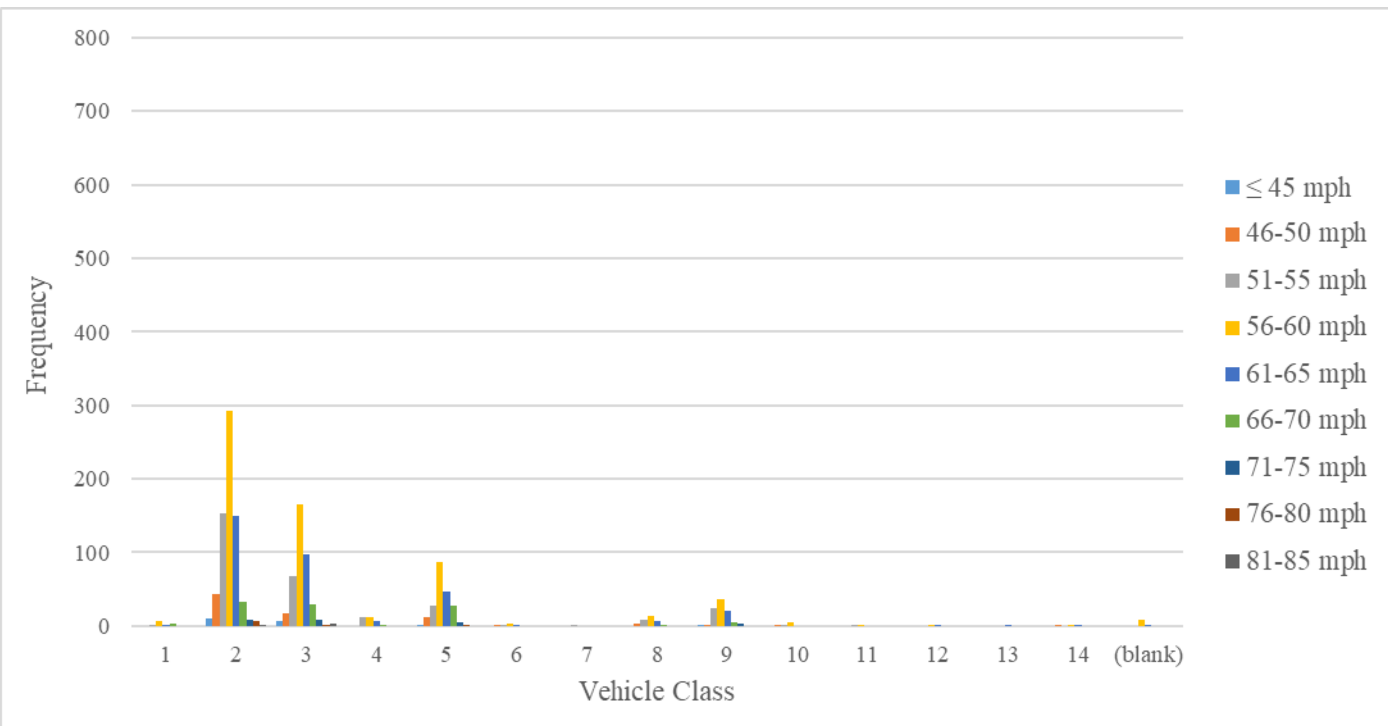

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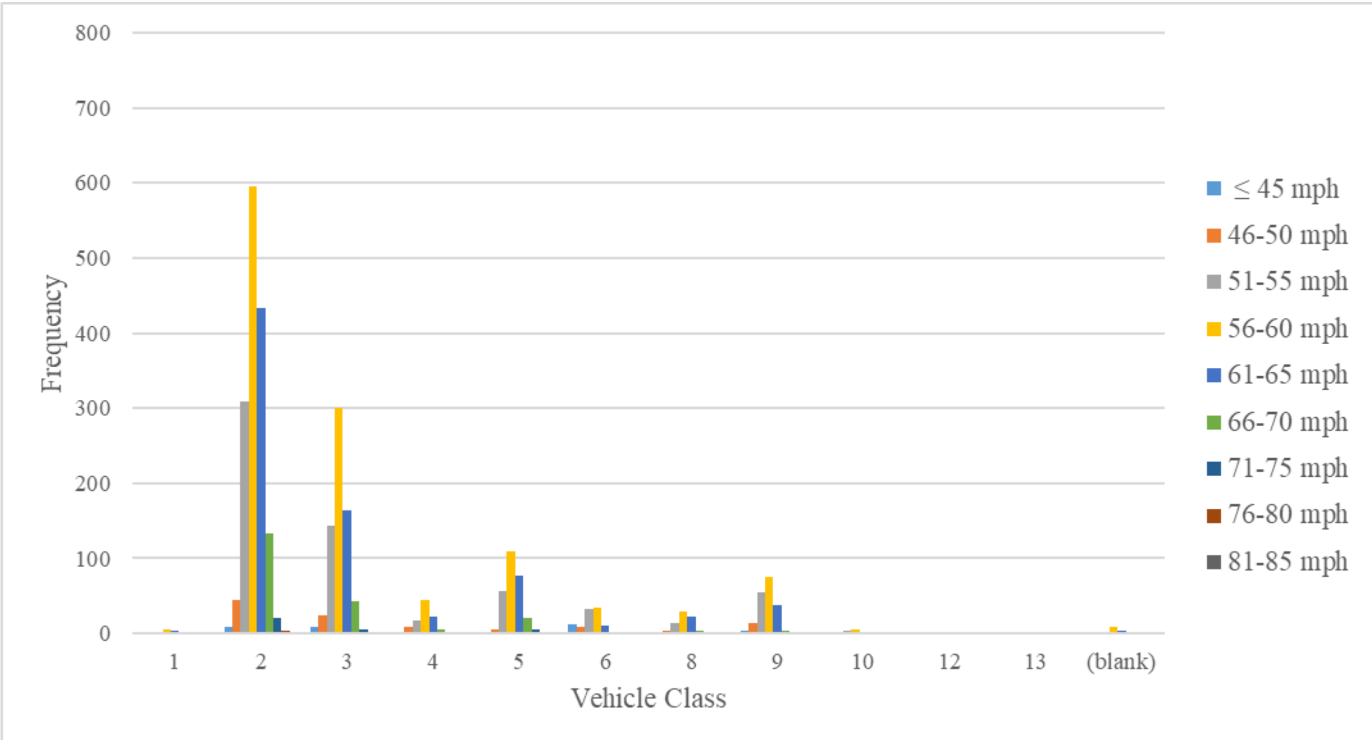


Figure A.37: Work Zone 3 Counter 4 -Before (Day)

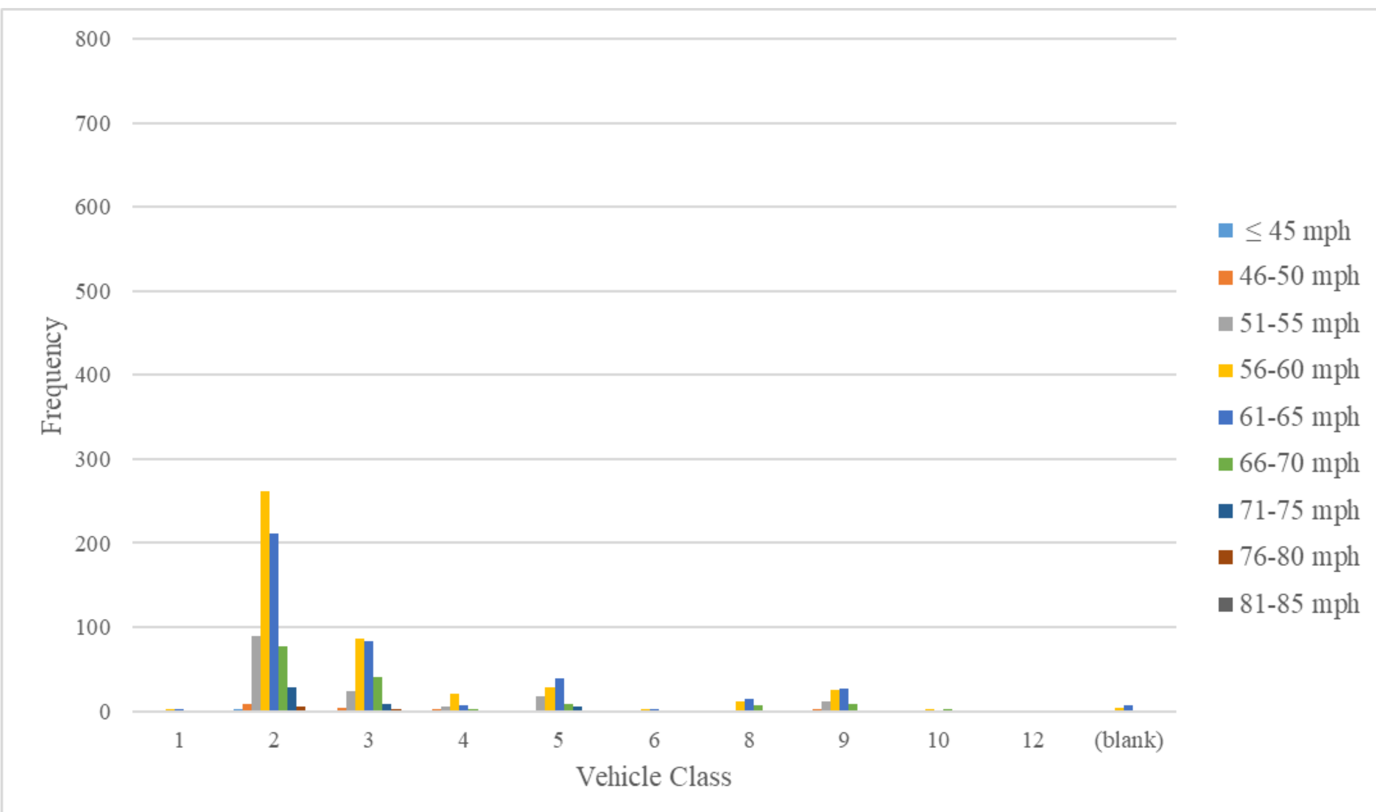
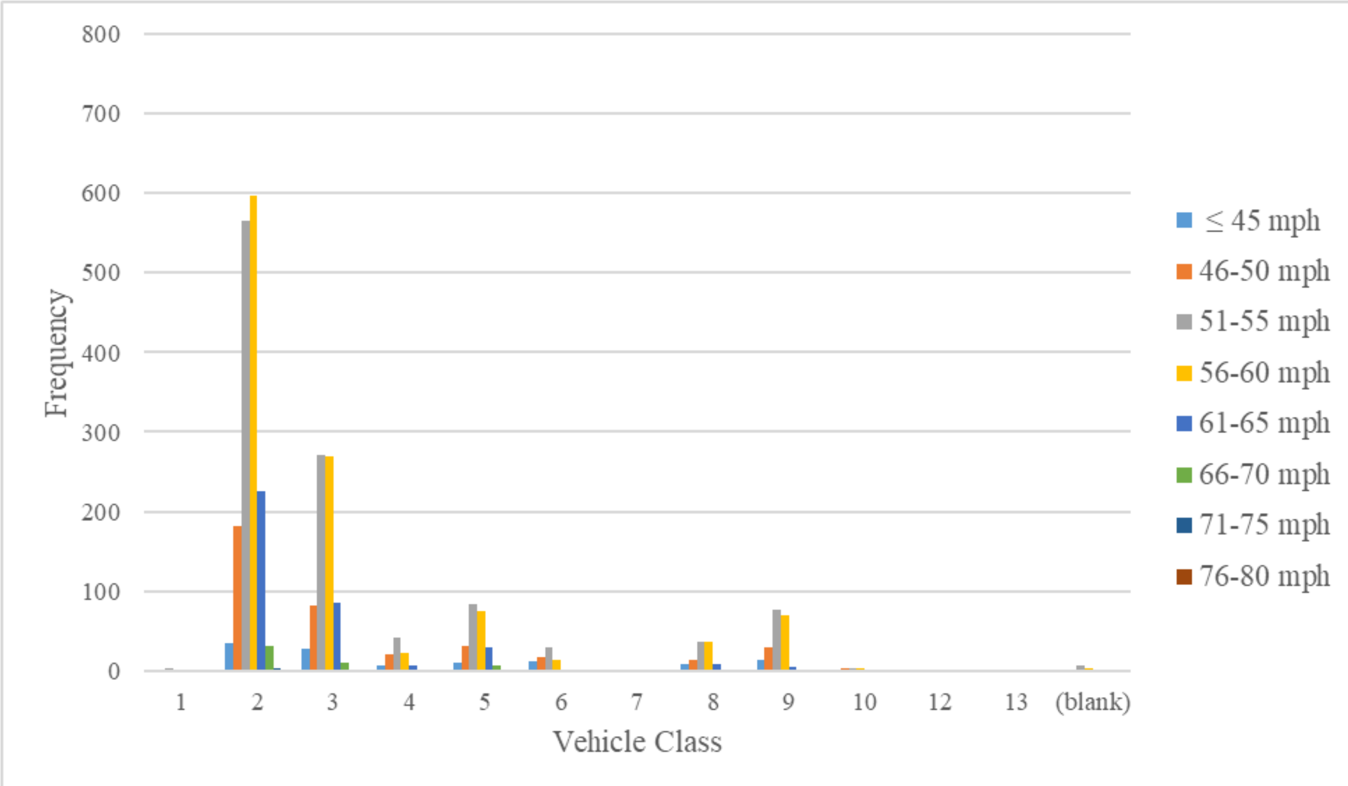


Figure A.38: Work Zone 3 Counter 4 -Before (Night)



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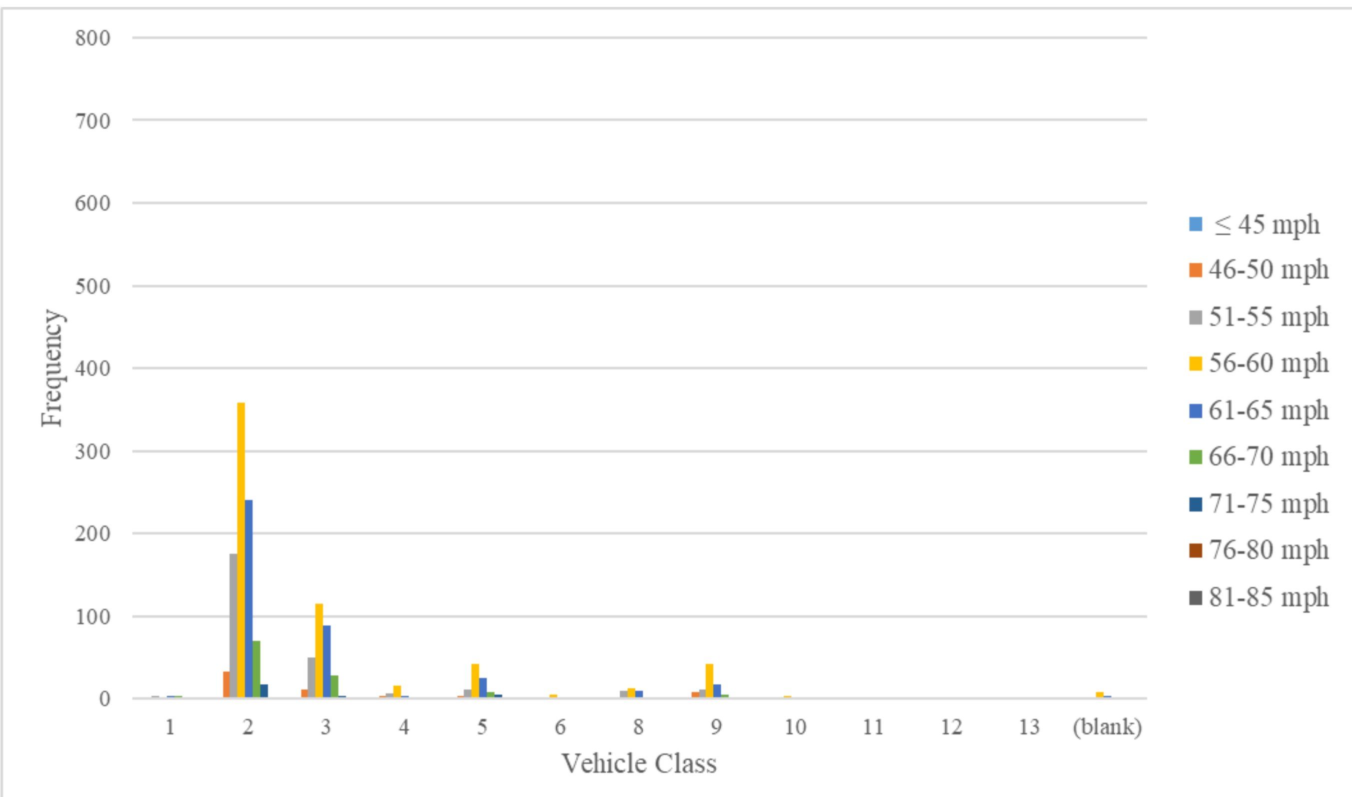

Figure A.40: Work Zone 3 Counter 4 -After (Night)

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