An evaluation of low-cost wrong-way driving countermeasures at partial cloverleaf interchanges on Kansas interstates

by

Jack Reid Cunningham IV

B.S., Kansas State University, 2016
M.S., Kansas State University, 2017

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Civil Engineering
Carl R. Ice College of Engineering

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Abstract

Wrong-way driving (WWD) incidents and crashes continue to be a serious concern for communities across the United States. Wrong-way drivers have been found to typically travel at high rates of speeds, during low light conditions, and on roadways with limited horizontal maneuverability resulting in reduced reaction times. These variables, along with ones that cannot be quantified are likely the reasons wrong-way crashes result in higher rates of fatalities and serious injuries as compared to other traffic crashes. Previous research on WWD includes statistical analyses of crash data, multiple countermeasure comparisons, investigation of driver characteristics, and proposed rewording of the MUTCD. While research has been conducted on countermeasure effectiveness, research has been varied on the type of interchanges evaluated. This study specifically evaluated low-cost countermeasures at partial cloverleaf interchanges in Kansas. Six ramps were selected in the Topeka, KS metropolitan area, including four study sites and two control sites. Three sets of WWD incident data were gathered over a 10 to 14 day period, one before and two after studies, using two sets of pneumatic road tubes on each ramp. Three cases were established to grade the severity of wrong-way incidents based on wrong-entry, self-correction, and error and the results converted to a rate of incidents per 100,000 entering vehicles (ev). The before study found that incident rates ranged from 3.7 to 92 incidents per 100,000 ev. The countermeasures that were selected for evaluations were red retroreflective delineators, oversized and lowered wrong-way signs, and flashing LED wrong-way sign. The first set of after data were collected immediately after installation of the countermeasures and showed improvements at all but one of the study sites with incident rates ranging from 3 to 103 incidents per 100,000 ev. The second set of after data were collected months after installation and showed more improvement at all of the study sites with incident rates ranging from 0 to 40 incidents per 100,000 ev. The study found that the red retroreflective delineators and the oversized and lowered signs were effective in reducing the number and type for WWD incidents; however, the results for the flashing LED sign were inconclusive. Finally, a study was conducted to evaluate the effectiveness of a WWD incident data collection. Multiple sets of pneumatic road tubes were installed at a partial cloverleaf interchange and it was found the proposed data collection methodology indicated the established WWD incident cases were accurate in their representations of the vehicular movements. The study recommended locations for placement of the two primary counters and the use of a third counter.

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Major Professor
Dr. Eric J. Fitzsimmons, P.E.

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Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
DNE	Do Not Enter
DOT	Department of Transportation
FARS	Fatality Analysis Reporting System
KDOT	Kansas Department of Transportation
MUTCD	Manual on Uniform Traffic Control Devices
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
TxDOT	Texas Department of Transportation
WWD	Wrong-Way Driving
WW	Wrong-Way

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Dedication

I would like to dedicate this dissertation to my family. My wife Karen has been my biggest supporter and has always been there for me. My sons Jack and Matt, who have assisted me during my studies, whether it is comic relief or being extras in my projects. And my exchange children; Pablo, Julianne, Cat, and Ste, you have all been there to offer support and listen when I have been frustrated. Thank you all for everything.

Chapter 1 - Introduction

Wrong-way driving (WWD) incidents and crashes continue to be a serious concern for communities around the world, especially in developed nations were high-speed roadway facilities are common. Subsequently, transportation officials, state highway agencies, and researchers in the United States are committed to finding ways to prevent these incidents. According to the National Transportation Safety Board (NTSB), WWD occurs when a vehicle accidentally or intentionally travels in a direction opposite of the legal direction (NTSB, 2012; Tamburri, 1965). WWD vehicles traveling at high speeds pose a serious safety risk to other drivers. On average, approximately 300 to 400 people are involved in a fatal crash each year due to a WWD incident in the United States (FHWA, 2020). The Fatality Analysis Reporting System (FARS) database reported that an average of 269 fatal crashes resulted in an average of 359 fatalities each year from 2004 to 2011 (Baratian-Ghorghi et al., 2014a). The 2011 FARS database also showed an average fatality rate of 1.24 per WWD crash compared to 1.09 fatalities for all other roadway crashes in the United States (NTSB, 2012). The NTSB analyzed the FARS database and found that one-half to three-quarters of WWD crashes in the United States were caused by an intoxicated driver, with 60% of those crashes resulting in a fatality. An overwhelming majority of these fatal crashes were found to occur at night (NTSB, 2012).

Although WWD crashes occur less frequently than other crashes, they are more likely to result in fatalities (Baratian-Ghorghi et al., 2014b; Cooner et al., 2004). Furthermore, WWD crashes frequently result in head-on crashes, which are often fatal (Baratian-Ghorghi et al., 2014b). Although WWD crashes in Kansas account for only approximately 0.05% of all vehicle crashes, they result in approximately 2% of all fatalities in Kansas (KDOT, 2017). WWD crashes were also found to have much higher rate of fatalities and serious injuries per fatal/serious injury crash than all other types of fatal/serious injury crashes (2.0 to 1.4) (KDOT, 2017). High vehicle speed was also a factor in over half of all WWD crashes that resulted in at least one fatality or serious injury. Additionally, research found that approximately 35% of WWD crashes in Kansas involved alcohol or drugs (KDOT, 2017). In addition to the loss of life, each fatal crash in the state of Kansas has an economic loss of approximately $4 million. Therefore, reducing the number of WWD incidents that can lead to a potential fatal and / or serious injury crashes would significantly benefit the state of Kansas.

Chapter 2 - Literature Review

This dissertation specifically focused on WWD incidents on high-speed, divided interstates with interchanges for several reasons. Coding in the KDOT Crash Report lists any crash that happens with a vehicle on the wrong side of the road as a wrong-way crash. For non-divided highways, this may include crashes that are not a typical wrong-way crash such as where a vehicle drifts over the centerline. These crashes are difficult to alleviate through countermeasures other than rumble strips, which may or may not help depending on why the vehicle drifted over. However, divided highways typically have the opposing directions of travel separated by a barrier or a wide median to prevent traffic from easily crossing over into the opposing lane of traffic, restricting traffic to one side of the roadway. With access to divided highways and interstates limited to interstate ramps, countermeasures for WWD can be targeted at specific points along the interstate.

When examining previous research concerning WWD, it was noted that this research fell into two categories, driver factors and countermeasures. Driver factors included many factors such as driver related, geometric, environmental, and locality factors that influence the performance of driving. Previous research on countermeasures were the most prevalent research found, covering every countermeasure currently available in a wide variety of conditions. Additionally, a focus to finding and summarizing previous research concerning research on WWD and partial cloverleaf interchanges, turning movements and data collection methods which was found to be a gap in knowledge with limited previous research. The following sections provide a summary of significant previous research relating to WWD which helped guide the methodology.

2.1 Wrong-Way Driving Factors

Factors involved in WWD incidents can take many forms of driver related (variables that affect the performance of driving), environmental (factors that affect the vehicle on the roadway), geometric (guidance of the driver), or locality factors (specific signs, businesses, or other objects that might be unique to the area). Several states have undertaken research on WWD and have come up with several factors that were found to be in common. However, it should be noted that many studies have found differing factors adding to the complexity of WWD incidents and crashes. These factors fall into several different categories included herein.

2.1.1 Driver Related Factors

Many studies have researched ways to develop and implement specific countermeasures and policies for WWD. Results have shown that driver-related factors such as driver age, sex, or level of impairment significantly contribute to WWD incidents. For example, an analysis of previous studies concluded that men are typically more likely to be involved in a WWD crash (Cooner et al., 2004; Saidi et al., 2014; Ponnaluri, 2015) due in part because, as determined by Bener (2013), men are more likely to drive at excessive speeds and consequently disregard traffic control (signs and traffic signal) indications. Similarly, a driver's level of impairment was found to be statistically significant in determining the likelihood of a WWD crash (Ponnaluri, 2015a), and previous studies showed that typically 60% of WWD crashes involve an impaired driver under the influence of alcohol and/or drugs (Cooner et al., 2004; Morena & Leix, 2012).

Previous studies have also concluded that elderly drivers (over the age of 65) are typically overrepresented compared to their proportion of the driving population (Cooner et al., 2004; Braam, 2006; Morena & Leix, 2012; Ponnaluri, 2015a; Langford & Koppel, 2006). Additionally, a study from Pour-Rouholamin et al. (2016) found that elderly drivers are nine times more likely to be involved in a WWD crash. Ponnaluri (2015a) determined that these results were most likely due to the age-related losses of physical, sensory, and cognitive abilities. A strong correlation was also observed between drivers older than 65 and WWD crashes occurring in the morning or afternoon with no impairment (Jalayer et al., 2017; Bergman et al., 2000; Hamilton, 2008; Rudisill et al., 2014), as well as a strong correlation between young drivers and WWD crashes occurring at night on the weekends (Jalayer et al., 2017; Ponnaluri, 2016; Rogers et al., 2015; Ruer et al., 2014; Simpson & Bruggeman, 2015; Zhou et al., 2015; Howard, 1980; Fisher & Garcia, 2016). These studies concluded that the young (under the age of 24) and elderly (over the age of 65) driving populations are most at risk for involvement in a WWD crash.

Fortunately, potential countermeasures were found to mitigate the negative effects of driver-related factors associated with WWD crashes. Educational countermeasures included safety and awareness programs for older drivers and drivers convicted of impairment violations. Development of a safety program geared towards elderly drivers was found spread awareness of alternative transportation modes for the elderly population and were found reduce the number of

WWD crashes involving elderly drivers (NHTSA, 2014; Jalayer et al., 2017). Similarly, DUI prevention efforts were recommended to be implemented to spread awareness to potential DUI drivers and stronger enforcement initiatives with the objective to mitigate WWD incidents related to driver impairment (Jalayer et al., 2017; Ponnaluri, 2015a). Ignition interlock devices were also found to be considered to reduce the occurrence of driver-impaired WWD crashes (Jalayer et al., 2017).

2.1.2 Environmental Factors

Environmental factors such as the time of day and the day of the week have been found to strongly affect the likelihood of a WWD crash. Previous studies have found that WWD crashes were more prevalent in the nighttime hours, from 11:00pm to 6:00am, and typically represent approximately 80% of the total number of crashes (Pour-Rouholamin et al., 2016; Morena & Leix, 2012; Clay, 2011). Additionally, Morena & Leix (2012) found that 71% of fatal and incapacitating crashes occurred in the nighttime hours. WWD crashes were found to be more prevalent in locations with no roadway lighting (Das et al., 2017), and these crashes were more likely to occur on the weekends (Howard, 1980; Fisher & Garcia, 2016; Ponnaluri, 2015a), suggesting a strong correlation with alcohol impairment may exist.

2.1.3 Geometric Factors

Researchers also found that certain geometric factors that also increased the likelihood of a WWD crash. These primarily included interchange ramps which were known to be more prevalent to WWD movements. Interchanges most susceptible to WWD incidents included partial cloverleaf (ParClo) interchanges, half-diamond interchanges, full-diamond interchanges, and diverging diamond interchanges (Garber & Fontaine, 1999; Monsere et al., 2017; Howard, 1980; Copelan, 1989; Zhou et al., 2014a; Moler, 2002, Baratian-Ghorghi et al., 2014b). Special attention should be given to WWD entry points specifically at interchange exit ramps and crossroad intersections. Left-side exit ramps have also been shown to be prime locations for WWD entry points with increased crash severity compared to other ramps (Monsere et al., 2017; Cooner et al., 2003; Cooner et al., 2004; Howard, 1980; Chen et al., 2011). Roadways that are not physically separated and have no traffic control devices also typically have a higher frequency of WWD crashes (Das et al., 2017).

Studies have shown that full cloverleaf interchanges have the lowest numbers of WWD entries and crash rates (Zhou et al., 2014a; Howard, 1980), while previous studies have shown that

ParClo interchanges have the highest occurrences of WWD crashes (Garber & Fontaine, 1999; Copelan, 1989; Howard, 1980; Morena & Leix, 2012; Morena & Ault, 2014; Baratian-Ghorghi et al., 2014b; Moler, 2002). According to these studies, parallel and closely spaced exit and entrance ramps make these interchanges prone to wrong-way (WW) maneuvers. However, raised channelization and narrow median openings for a crossroad were found to be effective, low-cost geometric modifications for ParClo (and other) interchange locations (Morena & Ault, 2014; AASHTO, 2011).

Potential geometric countermeasures include raised medians, channelized islands, adjusted turning radii, additional/improved signage and pavement markings, adaptive traffic signals, and additional lighting if lighting conditions are insufficient (Jalayer et al., 2017; Morena & Leix, 2012; Pour-Rouholamin, 2016; Zhou & Pour-Rouholamin, 2014). Closing the median opening at the crossroad between a two-way street and an exit ramp was also shown to be an effective countermeasure to eliminate WW left-turn movements (Ouyang, 2014). The use of roundabouts at the intersections of an exit ramp and a crossroad was also found to be an effective countermeasure because the roundabouts enhance directional movement (Pour-Rouholamin, 2016). For locations with no traffic control, the addition of Stop, Yield, or Do Not Enter signs was recommended (Das et al., 2017), and the addition of raised medians or median barriers between two abutting exit and entrance ramps (i.e., trumpet interchange) can help mitigate WW movement (Moler, 2002).

2.1.4 Locality Factors

Although the *Manual on Uniform Traffic Control Devices* (MUTCD) does not distinguish between rural and urban locations or high-speed and low-speed facilities for WWD crashes, previous studies have shown that locality directly impacts WWD incidents and crash risks. For example, WWD crashes have a higher likelihood on divided, rural roadways with no nighttime lighting and with full access control, highlighting the need for unique WWD guidelines according to location (Das et al., 2017; Ponnaluri, 2017).

2.2 Countermeasures for Wrong-Way Driving

The MUTCD, a handbook issued by the Federal Highway Administration (FHWA) pertaining to transportation design standards, includes policies for WWD and countermeasures that state departments of transportation (DOTs) and local communities may implement. However, these policies are a minimum, and some state DOTs have added additional policies and countermeasures due to safety concerns. Although more than 30 state DOTs have supplemented their state MUTCD, a survey from Baratian-Ghorghi & Zhou (2017) showed that some of the added WWD traffic control devices do not meet MUTCD guidance and standards.

Studies have shown that repairing deficient signs and enhancing the visibility of pavement markings are effective, low-cost countermeasures that help deter WWD (Cooner & Ranft, 2008; Jalayer et al., 2017; Zhou & Pour-Rouholamin, 2014; Khalilikhah & Heaslip, 2016; Pour-Rouholamin, 2016). Faded pavement markings and/or deficient signs can lead to driver confusion, which increases the risk of WWD incidents. The implementation of pilot projects determining the effectiveness of technology alternatives with advanced signage would be beneficial for areas that are more at risk to WWD movements (Das et al., 2017).

2.2.1 Lowering and Oversized Signs

Lowering the Do Not Enter and Wrong Way signs, that are mounted together on one post, have been found to be an effective and common countermeasure used to mitigate WWD movements (Baratian-Ghorghi & Zhou, 2017; Das et al., 2017; Staplin et al., 2001; Cooner et al., 2004; Kaminski Leduc, 2008). California has adapted to this practice and the Do Not Enter and Wrong Way signs are placed 2 ft above the pavement (Cooner et al., 2004). In California, this countermeasure decreased WWD incidents from 50 to 60 entries per month to 2 to 6 entries per month (Baratian-Ghorghi & Zhou, 2017). This countermeasure was shown to be particularly beneficial during nighttime hours because low-beam vehicle headlights shone directly onto the lowered signs (Staplin et al., 2001; Cooner et al., 2004). These lowered signs specifically benefitted impaired and elderly drivers because those drivers typically focus their attention on the pavement in front of their vehicles, so the lowered signs readily attracted their attention (Finley et al., 2014; Baisyet & Stevens, 2015; Kaminski Leduc, 2008). It should also be noted that a survey, conducted by Cooner & Ranft (2008) (including 29 state DOTs and 12 TxDOT Districts), found that there were not any crash tests to justify the safety of lowering signs. Additionally, oversized signs and additional signs are effective countermeasures that increase sign visibility and give drivers repetitive cues (Zhou et al., 2012; Baisyet & Stevens, 2015; Staplin et al., 2001; Jalayer et al., 2017; Zhou et al., 2014b).

2.2.2 Flashing LED Signs

Studies by Ponnaluri (2015) and Clay (2011) found that Wrong Way signs with LED lights that flash upon detection of WWD effectively attracted attention and alerted drivers. The installation of these signs in Texas reduced WWD incidents by 30% (Clay, 2011). These signs were particularly beneficial for WWD locations with a high frequency of nighttime crashes because the LED lights effectively alert drivers

2.2.3 Sign Supplements

Sign supplements such as fluorescent red sheeting and retroreflective sheeting effectively increase sign visibility, especially during dawn and dusk hours when drivers need additional guidance (Staplin et al., 2001; Pour-Rouholamin, 2016; NTTA, 2009). Figure 2.1 illustrates the use of a Red Retroreflective Beacon (RRFB) to supplement a Wrong Way warning sign. A RRFB is a set of red lights that are attached above and below a sign that flashes when a vehicle is detected going the wrong way. RRFBs were found to effectively attract drivers' attention due to the beacon's high intensity and flashing light (Ozkul & Lin, 2017; Ponnaluri, 2015), and they were a more effective countermeasure for deterring WWD than red flashing beacons (Ozkul & Lin, 2017). Public surveys have shown that drivers prefer RRFBs over other countermeasures such as LED Wrong Way signs, especially if the Wrong Way signs were placed on the left and right sides of a roadway with RRFBs on the top and bottom sections of the signs, similar to Figure 2.1(Sandt et al., 2015; Ozkul & Lin, 2017).

Figure 2.1: Red RRFBs on Wrong-Way sign

Source: Ozkul & Lin (2017)

2.2.4 Pavement Marking Arrows

The use of lane direction pavement marking arrows downstream from an exit ramp and on a two-way frontage road (Figure 2.2) was found to be an effective safety countermeasure that helps mitigate WWD incidents (Shrock et al., 2005; Zhou et al., 2014b). Installing reflectorized WW pavement arrows has also been found to be an effective countermeasure if they are placed upstream on the exit ramp and downstream near the crossroad (Cooner & Ranft, 2008; Das et al., 2017; Schrock et al., 2005; Monsere et al., 2017). Pavement arrows have been proven to be effective when placed on the left side exit ramps, locations known to be susceptible to WWD crashes (Cooner et al., 2003; Cooner et al., 2004). In a general, pavement marking arrows have been found to be an effective low-cost countermeasure because drivers can quickly and easily comprehend the markings.

Figure 2.2: Lane Direction Pavement Arrows on Two-Way Frontage Road

Source: Schrock et al. (2005)

2.2.5 Directional Rumble Strips

Directional rumble strips, which are variations of transverse rumble strips, are used to catch the attention of WW drivers. Zhou et al. (2018) compared different rumble strips to determine which strips were most effective. Figure 2.3 shows the directional rumble strip configurations that produced effective sound and vibration effects and increased visual alertness. These configurations produced an adequate sound increase for drivers traveling in the wrong direction compared to vehicles traveling in the correct direction.

Figure 2.3: Effective Directional Rumble Strips
Source: Zhou et al. (2018)

2.2.6 Pavement Marking Supplements

Arrow markings may also be supplemented by Red Reflective Pavement Markers (RRPMs) and Wrong Way signs located along the exit ramp, as shown in Figure 2.4 (Caltrans, 2014; Vaswani, 1977; Cooner et al., 2004; Zhou & Pour-Rouholamin, 2014). RRPMs are small raised markers placed on the pavement that appear red to a driver traveling in the wrong direction and white to drivers traveling in the correct direction. These markers are typically placed in such a way as to form an arrow pointing in the correct direction of movement. A study by Ponnaluri showed quick driver recognition of RRPMs because RRPMs on the pavement are within the driver's cone of vision (Ponnaluri, 2015).

RRPMs, shown in Figure 2.5, are used on undivided highways to indicate that a driver is traveling in the wrong direction. The state of Hawaii uses these markings to remind tourists that they are not driving in a country that drives on the left side of the road (Miles et al., 2008). Although these markings were found to be most effective at night, concerns have been raised about whether drivers understand the markings. A study by Miles et al. (2008) determined that pavement marking arrows increase drivers' understanding of the correct direction of travel more than RRPMs.

Figure 2.4: Wrong-Way Arrow with RPMs and Supplemental Wrong-Way Signs
Source: Zhou & Pour Rouholamin (2014)

MUTCD Section 3B.13 states that RRPMs should not be used to supplement edge lines because drivers traveling in the correct direction on undivided highways can see the red RRPMs from the opposite side of the roadway, which can lead to driver confusion. However, Section 3B.14 states that the side of the RRPM that is visible to WW drivers may be red (FHWA, 2009).

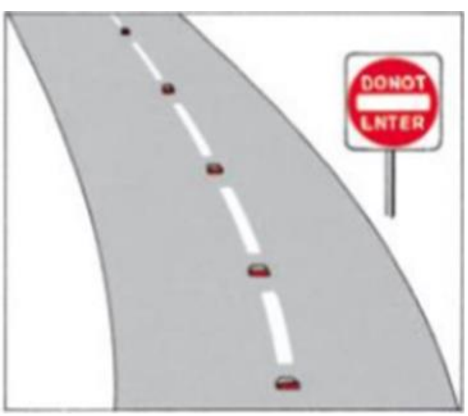

Figure 2.5: Red Retroreflective Pavement Markings
Source: Monsere et al. (2017)

2.2.7 Delineators

The installation of delineators along exit ramp barriers have been shown to effectively catch drivers' attention, especially at night, but yellow delineators should be installed on the left side for vehicles traveling in the correct direction and red delineators should be installed on the right side for vehicles traveling in the wrong direction (Zhou & Pour Rouholamin, 2014).

As described in this section, a significant breadth and depth of previous research has been conducted to understand WWD. This includes studies that have focused on quantifiable factors that relate to the driver, environment, countermeasures to reduce WWD incidents and crashes. Specific focus of the literature review targeted wrong-way incidents and roadway geometry which included interchange ramps, turning movement at intersections, and interchange types. However, it was found through the review of literature that limited studies have investigated WWD incidents at ParClo interchanges, a common type of interchange found in the Midwest. Additionally, it was found through the review of literature that various data collection methods have been employed to collect WWD incidents (and crashes) ranging from video, road tubes, or a combination of data collection methods.

Chapter 3 - Research Objectives

As described in Chapter 2, a wide breadth and depth of literature exists that has investigated many aspects to WWD. Most notably, understanding driver characteristics, crash causation, countermeasure effectiveness, and roadway geometric characteristics using various data collection techniques.

However, a gap in knowledge was identified when considering WWD incidents and roadway geometry. This dissertation focused on ParClo interchanges where on- and off-ramps are located in proximity to each other. Additionally, these interchanges are located in areas where a traditional diamond, full cloverleaf, or other interchange types may not be conducive.

The primary objective of this dissertation is the evaluation of the effectiveness of low-cost WWD countermeasures located at ParClo interchanges to reduce WWD incidents. Effectiveness was determined based on a before-after analysis and long-term after-analysis. A low-cost countermeasure was defined as an intervention device that could easily be acquired by a community, or state highway agency with minimal technology and communication capabilities.

The secondary objective of this dissertation was to explore how to collect wrong-way incident data at ParClo interchanges in the field using pneumatic road tubes. This objective was designed to determine proper location, and understand traffic operations at the interchange while data were being collected.

These objectives are detailed fully in the following chapters presenting information on how sites and low-cost countermeasures were selected, data were collected, results of the analysis to fulfill the stated objectives, conclusions, recommendations for future studies and data collection efforts. Moreover, Chapter 4 provides information on a survey of practice to determine what other state highway agencies are doing to address WWD incidents.

Chapter 4 - State Department of Transportation Survey

Because WWD is a national issue, with WW crashes occurring in every state, many states have conducted research or implemented guidelines for installing WW countermeasures. However, each state has unique priorities and budgets for various levels of treatments that all exhibit varied levels of effectiveness. To determine which countermeasures may be effective in the Midwest, a survey was conducted of the Midwest states as well as other states with prior major research. Colorado and Oklahoma were included in the survey because they neighbor Kansas.

The survey was conducted in two stages. The first stage involved searching each state's DOT website for WWD-specific policies, and the second stage involved searching for specific research, guidelines, or countermeasures specific to each state. Researched states included Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, Wisconsin, Colorado, Florida, Texas, and Oklahoma. Only four states, Illinois, North Dakota, Ohio, and Wisconsin, have WWD policies that extend beyond the MUTCD, and only Indiana, Minnesota, South Dakota, and Oklahoma have no additional countermeasure guidelines.

A table was constructed using the data gathered from each state and can be found in Appendix A. The first column lists the state and the DOT abbreviation, and the second column shows the reference document for the countermeasure guidelines with the year(s) of research in the third column. The fourth column describes the countermeasures, research, or guidelines that have been conducted or implemented by the state agency, and the fifth column states whether the state has additional polices for WWD, beyond the MUTCD, and describes those policies. State agency countermeasures or policies were found in either the 'referenced documents' or were discussed with an employee from the state's DOT agency.

Although the WWD policies of the four states with additional WWD polices had some similarities, they were also unique to each state. Two states specifically address possible interchanges and interchange arrangements, but their solutions are not the same. Those two states address signage, additions to signage based on type of interchange, and ramp geometry based on interchange type, but no two solutions are identical. The other two states put every available countermeasure on the ramp, one state addressed only divided highways with median crossings, which is not the type of interchange this report examined, and the fourth state focused exclusively on interchange area geometry and the types of connections used between the interstate and the connector roads but not the signage specifically.

Almost all Midwest states utilize some sort of WWD countermeasure, but the countermeasures vary, including flashing LED signs, additional or doubled Wrong Way signs, lowered signs, RRFDs, and setups that alert a traffic management center (TMC). Some of the countermeasures are specified for certain interchange types, such as diamond or parclos, and other countermeasures depend on WW incidents at a particular interchange. While most states detail which countermeasures to use, a few of the states only offer alternatives for local officials if they want to use them.

Overall, state DOTs, even those from states in similar regions, have no consensus on what to do with ramp geometry or signage beyond the MUTCD: either all countermeasures, only what is needed, or almost nothing is used. This variety could be due to a lack of research or lack of funds to make changes. However, areas of disagreement exist even in states in which extensive research has been conducted due to varying degrees of effectiveness of each countermeasure within the regions and within each state. Although one general solution does not work for every state, a general selection of countermeasures can be used as a starting point.

Chapter 5 - Methodology

It was determined that this project could either target as many different types of ramps as possible or thoroughly evaluate one particular type ramp. It was decided to complete a thorough evaluation of countermeasures at one interchange type rather than study all interchanges, which would result in limited data and unreliable conclusions. Since previous research had identified ParClo interchanges as particularly susceptible to WWD incidents, ParClo interchanges were chosen for evaluation in this study.

5.1 Partial Cloverleafs

Ever since Henry Ford introduced the first mass-produced cars, people have been looking to go farther and faster. As dirt paths became gravel and then paved roads, safe interchanges to enter and exit these roads became essential. Although the cloverleaf interchange was the first interchange to be patented in 1912, the first cloverleaf was not constructed until 1928 (Leisch et al., 2014). Highways were initially constructed in a straight-line fashion, so the cloverleaf interchange fit perfectly with that design. As interstate and interchange designs from the 1950s gave way to new and improved designs in the 1960s through the 1980s, the objective became one of reducing the footprint of the interstate and increasing traffic flow (Leisch et al., 2014).

Figure 5.1 shows the typical layout of a cloverleaf interchange, which resembles a four-leaf clover. Cloverleaf interchanges have a total of eight exit ramps: four loop ramps and four directional ramps. Each directional ramp is paired with a loop ramp with one handling exiting and the other entering traffic from one direction of the interstate and one side of the crossroad. The interchange also has two ramps in each quadrant. The loop ramps are located closest to the crossroad with a very short weaving area where entering and exiting traffic cross each other onto and off the interstate. The directional ramps allow for a long weaving lane for merging and exiting traffic.

Each directional ramp of a cloverleaf interchange is typically located either before or after the intersection of the crossroad and the interstate, and the ramps intersect the crossroad in such a way that they can only be entered by traffic traveling in the correct direction. The loop ramps are situated closer to the intersection of the crossroad and the interstate, with two ramps located on each side of the interstate one after the other so that the entering ramp enters the interstate and then the exiting ramp exits the interstate. Both loop ramps share the same acceleration and deceleration lanes, forcing entering and exiting traffic to weave amongst themselves with the through traffic.

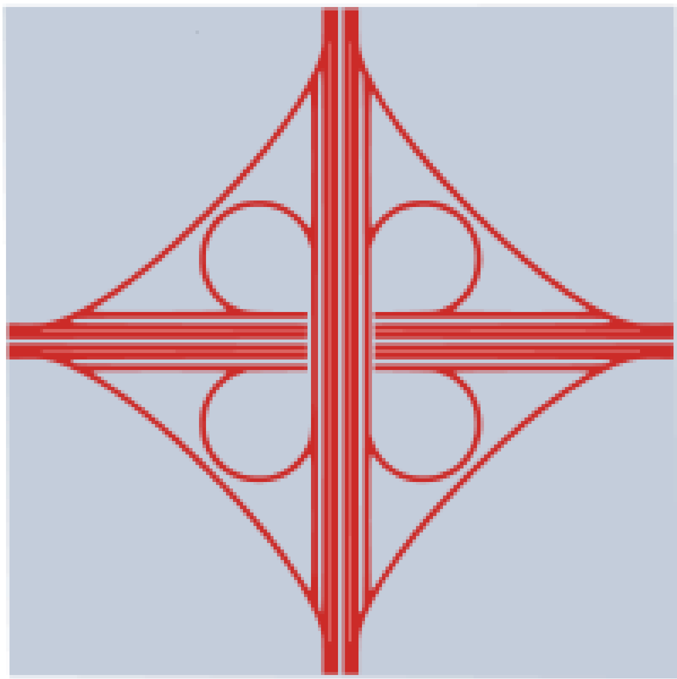

Figure 5.1: Cloverleaf Interchange

Source: *Original PNG: was Modification of de:Bild:AK-Kleeblatt.jpg *Original PNG: Original picture is an own work of user Wikoli Original .PNG info: 15:01, 11 February 2006 Newsflash (Talk)

Safety records regarding WWD incidents reveal cloverleaf interchanges to be one of the safest interchanges due to their eight-ramp design, with one ramp per direction entering or leaving the interstate. The ramp layout and design prevents incorrect ramp usage, but the massive space requirement for this design feature is a drawback. Therefore, the ParClo, as seen below in Figure 5.2, was created as a versatile interchange with a reduced footprint. Where a cloverleaf requires ramps in all four quadrants, a ParClo requires as few as two quadrants as long as they are on opposite sides of the interstate.

Parclo interchanges are identified by their interstate exit and entrance ramps and their location in relation to the crossroad with respect to the direction of travel. If the ramps begin before the crossroad, it is a ParClo A. If the ramps are located after the crossroad, it is a ParClo B. If the interchange has both ParClos, it is a ParClo AB. A ParClo is interchangeable and can be a ParClo A or B with a half diamond, collapsed diamond, or partial diamond depending on the space available for construction or, in most cases, the type of previous interchange.

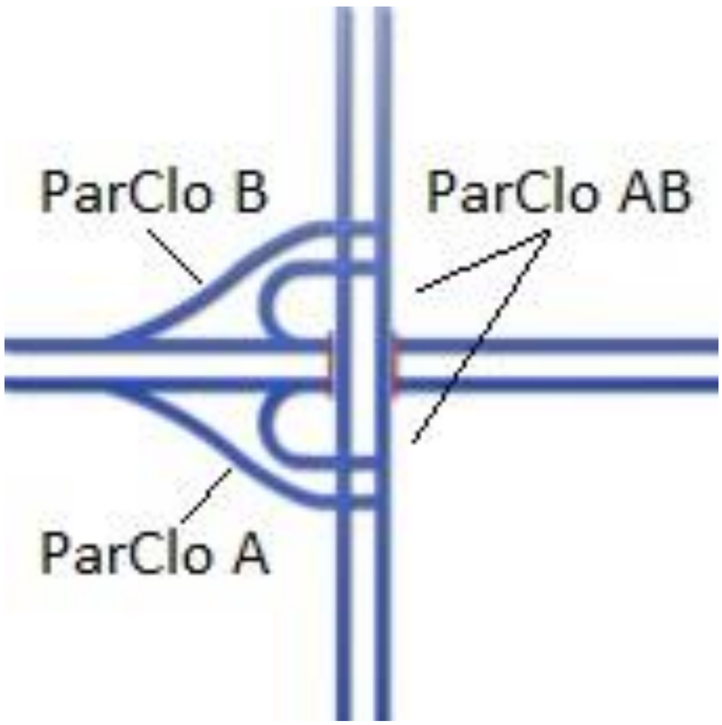

Figure 5.2: Partial Cloverleaf Interchange

ParClo interchange research has primarily focused on vehicle capacity; the only exception found is a paper on the history of interchange design (Leisch et al., 2014). When examining the capacity research, ParClos are one of the top 3 interchanges in capacity, depending on area. Although advances in ParClo design have been continuous, research on WWD on ramps with WW crash histories found that ParClos pose risks under certain circumstances (Howard, 1980; Campbell et al., 1988). The studies utilized a single set of pneumatic road tubes, one with cameras, to study ramps and evaluate countermeasures. One study found that WWD incidents increased immediately after the countermeasures were installed and then decreased after users became familiar with the new signs (Campbell et al., 1988), while the other study noted an immediate reduction in WWD incidents (Howard, 1980). However, other studies have found that ParClos are more susceptible to WW incidents (Garber & Fontaine, 1999; Copelan, 1989; Morena & Leix, 2012; Morena & Ault, 2014; Baratian-Ghorghi et al., 2014b; Moler, 2002).

5.2 Site Selection

It was decided to focus on ParClos after reviewing previous research and a discussion with the project manager at the Kansas Department of Transportation (KDOT). Similarly, several criteria were established for determining the sites for the study. The sites needed to be close enough to Manhattan, Kansas, to monitor regularly and be on a divided interstate in an area with a high volume of traffic. The sites also had to contain several proximate ramps, ramps on both sides of the interstate, and both ParClo A and B interchanges.

The study initially focused on I-70, which runs east to west through Kansas City and has traffic volumes that exceed 10,000 vehicles per day. The interstate is located approximately 8 miles south of Manhattan, Kansas. It was found that the highest traffic volumes occur on the section of I-70 that runs through the north side of Topeka, the capital and third largest city in Kansas, approximately 58 miles east of Manhattan. The team found six ParClo interchange ramps throughout the Topeka area, as shown in Figure 5.3. Sites 1–4 in the figure are test sites, and sites 5–6 are control sites. The control sites included one ParClo A and one ParClo B interchange on opposite sides of the interstate, and the treatment sites contained three interchanges on the westbound side and one interchange on the eastbound side. The four interchanges consist of one ParClo A, one ParClo B and one ParClo AB.

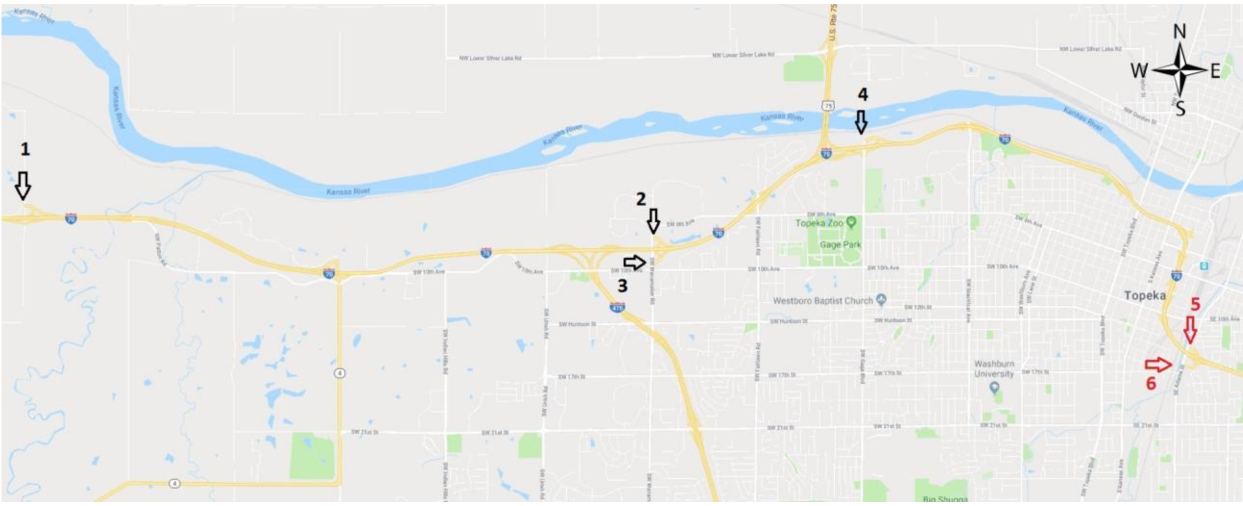

Figure 5.3: WWD Study Sites in Topeka, Kansas

The test ramps chosen on the westbound side of I-70 were exit 353, Auburn Rd; exit 356, Wanamaker Rd; exit 358, Gage Blvd, and the control ramp was exit 363, Adams St. The test site on the eastbound side was exit 356, Wanamaker Rd, and the control site was exit 363, Adams St.

5.3 Westbound Ramps

5.3.1 Auburn Rd

The Auburn Rd exit, shown below in Figure 5.4, is the last Topeka exit when heading west on I-70. This exit is a ParClo B that crosses underneath I-70 and covers three quadrants. The other side of the ramp is a diamond interchange. The exit and entrance ramps are divided by a low, curb-height median with 3-ft plastic delineators marking the centerline of the median. Prior to the study, there was a Do Not Enter sign on the left side of the entrance, a Keep Right sign on the median between the entrance and exit ramps, a Wrong Way sign located on the left side of the ramp approximately 300 ft from the crossroad, and another Wrong Way sign on the right side of the ramp 200 ft from the first sign.

To the north of the exit, Auburn Rd is a private drive with a material dump just prior to drive. The West Lawn Memorial Gardens cemetery is located in the northeast quadrant, and several businesses, including a sports bar, are visible from the interstate south of the exit. A frontage road, 10th St, runs parallel to the interstate and leads to Wanamaker Rd, a major thoroughfare in Topeka. Most traffic entering I-70 westbound at Auburn Rd makes a left-hand turn.

Figure 5.4: Aerial View of Exit 353, Auburn Rd.
Source: Google (2020)

5.3.2 Wanamaker Rd North Exit

The Wanamaker Rd North exit, shown below in Figure 5.5, is the westbound exit from I-70 to Wanamaker Rd. Wanamaker Rd North is a ParClo A interchange, and the crossroad crosses over I-70. The other side of the interchange is a ParClo B and another treatment site. The Wanamaker Rd interchange covers two quadrants. The exit ends with two lanes, one left-turn-only and one left and right turn. The exit contains a traffic signal where the exit ramp intersects the crossroad, and the exit and entrance ramps are divided by a continuous barrier until the entrance ramp bears right away from the exit ramp. Prior to the study, a Do Not Enter sign was located on the left side of the exit ramp, along with a Keep Right sign on the right, as well as a

Wrong Way sign on the left approximately 350 ft from the crossroad and a second Wrong Way sign on the right side approximately 160 ft past the first sign.

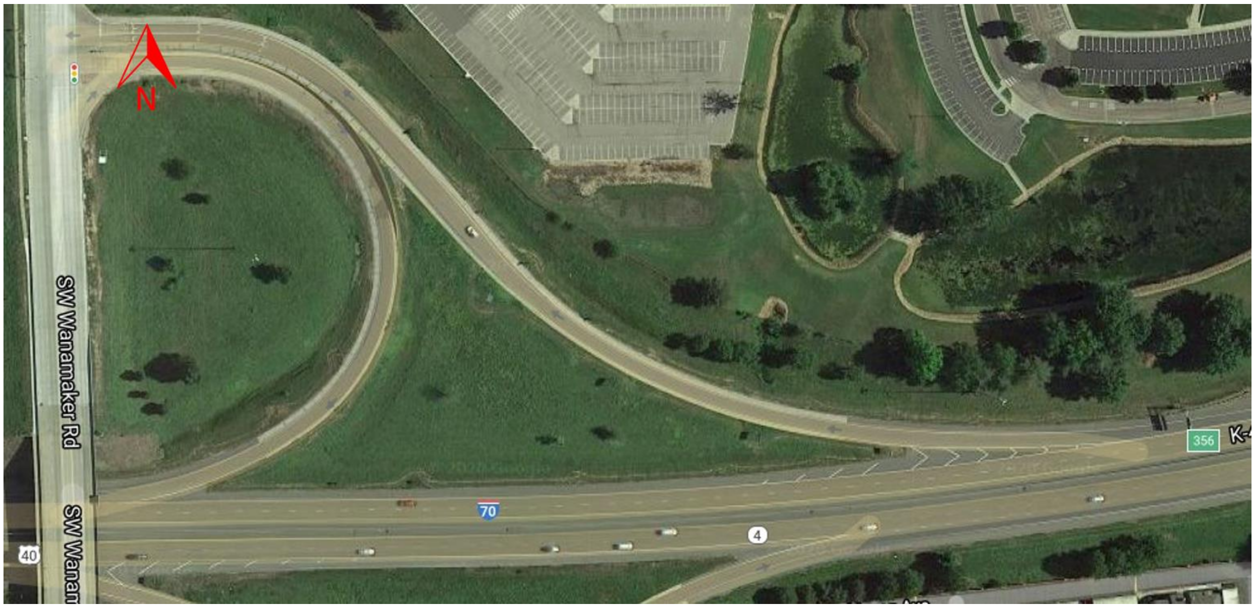

Figure 5.5: Aerial View of Exit 356, Wanamaker Rd North
Source: Google (2020)

Wanamaker Rd is surrounded by numerous restaurants, some of which serve alcohol, gas stations, hotels and strip malls. The main shopping district in Topeka, which includes an indoor shopping mall, is located directly south of I-70 along Wanamaker Rd and is a popular spot for travelers to stop for gas and food. Most traffic entering I-70 at this exit makes a right turn; the ramp has a traffic signal to control movement through the intersection.

5.3.3 Gage Blvd

The Gage Blvd exit, shown below in Figure 5.6, is the westbound exit from I-70. Gage Blvd is a ParClo A interchange that crosses underneath I-70. The exit to Gage Blvd on the eastbound side is also the exit to US-75 North and includes a weaving area for traffic to merge onto US-75 North and traffic exiting from US-75 South to merge with I-70 or exit to Gage Blvd. The treatment exit ramp is divided by a curb-height raised median that becomes a barrier dividing the exit and entrance ramp. Prior to the study, there was a Do Not Enter sign on the left side of the exit, a Keep Right sign on the median on the right side of the exit, a Wrong Way sign approximately 300 ft from the crossroad on the left side, and another Wrong Way sign approximately 350 ft from the first sign on the right side.

Figure 5.6: Aerial View of Exit 358, Gage Blvd
Source: Google (2020)

The Topeka Water Division, which handles water treatment and sewage treatment, is located north of the exit ramp, and the Metro Area Maintenance office is located directly to the west of the exit ramp. Large residential neighborhoods, various businesses and restaurants, and the local Veterans Affairs Hospital are located south of the ramp. Almost all traffic entering westbound I-70 from Gage Blvd makes a right turn.

5.3.4 Adams St North Exit

The Adams St North ramp, shown below in Figure 5.7, is located on the east side of Topeka on the westbound side of I-70. The exit is approximately three miles west of where I-470 ties into I-70 and the turnpike begins. The exit is a ParClo A interchange, and the crossroad crosses underneath I-70. The other side of the interchange is a ParClo B and was included in this study. Because this exit ramp was a control ramp, no changes were made to the sign configurations. The exit contains a Do Not Enter sign on the left, approximately 10 ft in front of the stop line on the right side, angled slightly to face traffic coming from the north. In addition, a Keep Right sign is located on the median on the right side of the exit ramp, a Wrong Way sign is on the left about 325 ft from the crossroad, and another Wrong Way sign is on the right side about 225 ft further up the exit ramp. The entrance and exit ramps are divided by a curb-height median for approximately 50 ft, which then rises to a barrier that divides the two ramps.

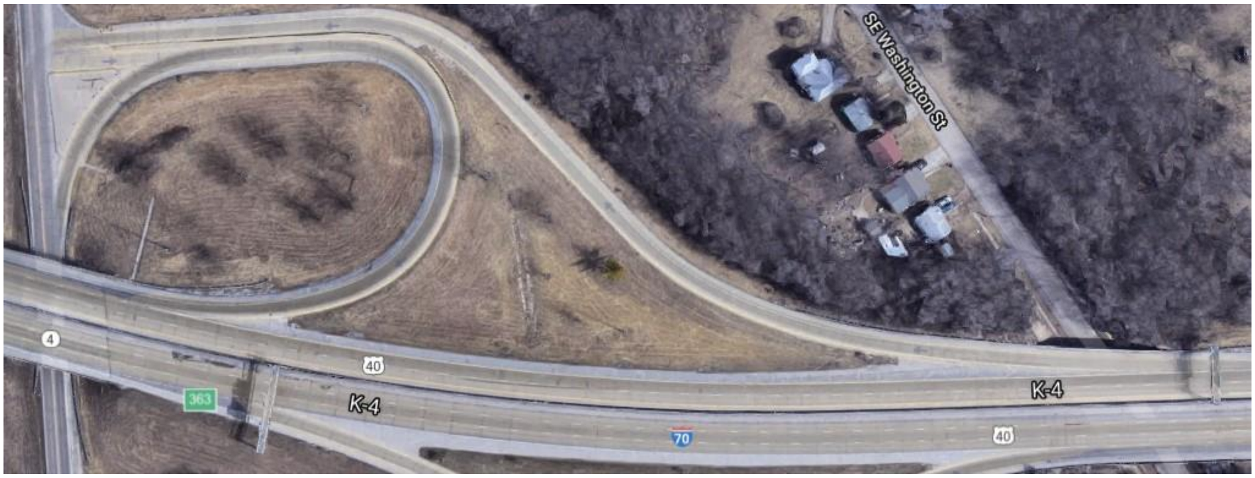

Figure 5.7: Aerial View of Exit 363, Adams St North
Source: Google (2020)

The Adams St North exit is surrounded by residential neighborhoods and small businesses. The westbound exit does not contain a traffic signal, but the eastbound exit is controlled by a traffic signal. A gas station convenience store is located south of the eastbound exit, but no other major shopping outlets are in the nearby area.

5.4 Eastbound Exits

5.4.1 Adams St South Exit

The Adams St South exit, as seen in Figure 5.8, located on the east side of Topeka, and is one of the last eastbound exits on I-70 within Topeka city limits. This exit is a ParClo B, and the crossroad passes underneath I-70. The exit ramp is the other control ramp in this study, so no changes were made to this ramp. The Adams St interchange covers two quadrants, both on the east side, and the exit and entrance ramps are separated by a flush median with double yellow lines. The curb-height median rises to a barrier to further divide the two ramps. The exit contains a Do Not Enter sign on the left side of the exit ramp, a Keep Right sign on the median on the right side of the exit ramp, a Wrong Way sign on the left side approximately 300 ft from the crossroad, and another Wrong Way sign on the right approximately 350 ft further up the exit ramp. Similar to the north exit, this exit is surrounded by residential neighborhoods and small businesses. The exit is controlled by a traffic signal with a gas station convenience store south of the exit. No other major shopping outlets are located in the nearby area.

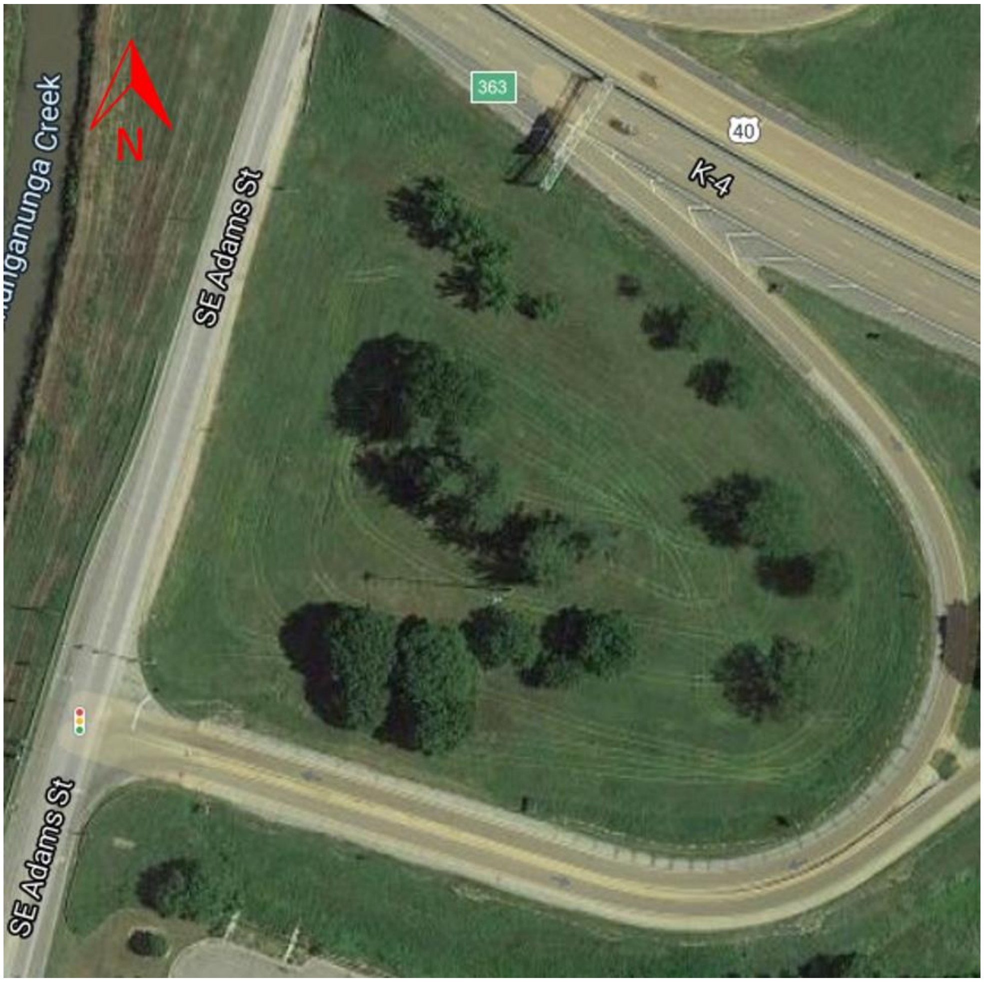

Figure 5.8: Aerial View of Exit 363, Adams St South
Source Google (2020)

5.4.2 Wanamaker Rd South

Wanamaker Rd South exit, as seen below in Figure 5.9, is the eastbound exit from I-70 to Wanamaker Rd. Wanamaker Rd South is a ParClo B interchange where the crossroad crosses over the interstate. The other side of the interchange is a ParClo A and another treatment site. The Wanamaker Rd interchange covers two quadrants. The Wanamaker Rd South exit ends as a one lane road that can either turn left or right. This is an unsignalized interchange controlled by a stop sign for the exiting lane. There is a continuous concrete barrier that begins as a slight raised median and rises to a full sized barrier and divides the exit and entrance ramps until the ramps bear away from each other. Prior to the study, there was a Do Not Enter located on the left side of the exit ramp at the entrance along with a Keep Right sign on the concrete divider. There is a Wrong Way sign on the left about 450 ft from the crossroad and another Wrong Way sign on the right another 100 ft further down the exit ramp.

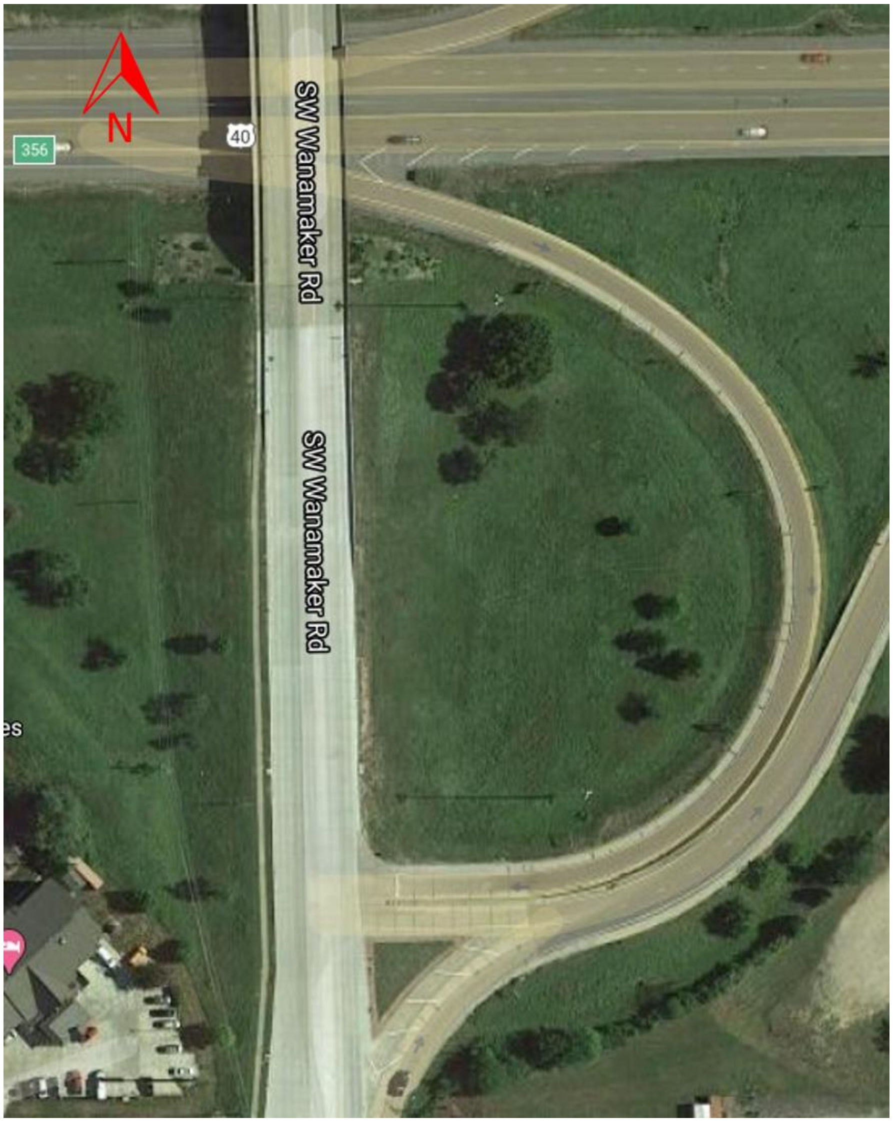

Figure 5.9: Aerial View of Exit 356, Wanamaker Rd South.
Source: Google (2020)

Wanamaker Rd is surrounded by numerous restaurants, some of which serve alcohol, gas stations, hotels and strip malls. The main shopping district in Topeka, which includes an indoor shopping mall, is located directly south of I-70 along Wanamaker Rd and is a popular spot for travelers to stop for gas and food. Most traffic entering I-70 at this exit makes a right turn; there is a signal just south of the ramps, but does not control traffic at the ramp.

5.5 Wrong-Way Driving Working Group

As a part of this dissertation, a WWD working group was convened to gather information about potential countermeasures. Working with KDOT, a Wrong-Way Driving Working Group was scheduled at the KDOT 2019 Transportation Safety Conference in Wichita, Kansas. The group was comprised of 27 participants, including KDOT personnel, private engineers, EMS workers, vendors, and researchers.

The workshop began with an overview of the background and state of research in WWD, including MUTCD guidance. The presentation then highlighted a previous statistical study of WWD crashes on Kansas interstates, followed by a description of the current study. Results of the before study were covered, as well as the chosen countermeasures. Each group was given a packet containing aerial color pictures of each ramp with counter placement; three street-level views from the exit, the midpoint, and to the I-70 entrance; color photos of the three chosen countermeasures; summaries of WWD incidents for both counters on each ramp and ramp volume data for counter 1; and MUTCD excerpts regarding WW signage. The packet that was handed out can be found in Appendix B.

The group was divided into nine groups of 2–4 people to discuss the countermeasures. The groups focused on the Auburn Rd ramp and the two Wanamaker Rd ramps. The groups then shared their selected countermeasures for each ramp, as summarized in Table 5.1. Due to time constraints, only three ramps were discussed, and some groups did not offer recommendations on the last ramp, Wanamaker Rd South.

Table 5.1: Summary of WWD Working Group Discussion

	Auburn Rd	Wanamaker Rd North	Wanamaker Rd South
Flashing LED Sign	5	0	1
RRFDs	6	4	1
Oversized & Lowered Wrong Way Sign	5	3	3

5.5.1 Auburn Rd

Most groups determined that flashing LED signs, oversized and lowered signs, and RRFDs would be the most effective countermeasures for the Auburn Rd ramp, although cost-effective options such as dashed pavement markings and pavement arrows for correct turning movements were also considered. Other options involved realigning the exit with the cemetery road, squaring up the exit to make it more prominent, and separating the entrance and exit ramps. The latter options are expensive, however, and require an impractical, invasive approach.

5.5.2 Wanamaker Rd North

Since most WWD incidents at this location occurred during the day, the most popular countermeasures were oversized and lowered signs and RRFDs. Adding dashed lines and pavement arrows to mark turning movements and adding red reflectors to the median barrier were also suggested. The most expensive ramp-improvement options included realigning the exit to reconfigure the lanes and raising the median.

5.5.3 Wanamaker Rd South

Although several groups did not have time to discuss the Wanamaker Rd South exit, the most popular suggested countermeasure was oversized and lowered signs. Additional suggestions included a video traffic-detection system and improved drivers' training to reduce WWD incidents at this location.

5.6 Data Collection Methodology

The use of video and pneumatic road tubes were the two methods considered for the collection of WWD incident data. Video recording is beneficial because a vehicle can be observed making an incorrect movement and then followed to see if the driver self-corrects or wrongly enters the interstate. When logging a WWD incident with video, the observer can note the date, time, and vehicle type from the video and determine total volume of the ramp by counting the vehicles. However, video recording requires someone to observe the video for the same amount of time it was set out, meaning a significant amount of time is often required for observation. Video systems may also have a restricted field of vision that results in an inability to observe vehicles at certain times, potentially resulting in missing information. Video recording also has limited storage capacity, which limits the time the system can be in place. Typical studies using video systems occur over a two- to three-day period.

In contrast, pneumatic road tubes can be emplaced and left for an extended period of time, and they have a large storage capacity that is unrestricted by video feedback. Pneumatic road tube counters have a multiple setup options, which can collect an abundance of valuable information, such as volume, speed, gap, vehicle class, date, time, and direction of each vehicle. Pneumatic road tubes are also less expensive than video systems, meaning multiple ramps can be monitored simultaneously. The primary disadvantage to pneumatic road tubes, however, is the inability to determine a vehicle's circumstances before and after the tube registers the WWD incident. Another disadvantage is that pneumatic road tubes require dry, sunny weather to emplace, and severe adverse weather can cause the mastic tape to come loose. Certain weather temperature limitations render the use of pneumatic road tubes impractical. After considering the advantages and disadvantages of both methods, pneumatic roads tubes were chosen for data collection.

Specific methodologies were determined to obtain the most accurate account of ramp incidents. Previous research only used one set of road tubes to track WWD incidents (Howard, 1980; Campbell et al., 1988). It was decided to use two sets of road tubes spaced out on the ramp to produce a more complete procedure.

Figure 5.10 shows the general layout for the pneumatic road tubes. The first counter was placed near the crossroad but far enough back so vehicles in the queue would not be standing on the tubes. The second set of road tubes was placed near the exit from the interstate. Road tubes were placed in the same spots for all studies, and data were collected before and after for data analysis. Since previous research reached different conclusions on when was the best time to conduct the after study (Howard, 1980; Campbell et al., 1988), it was determined to collect the after data immediately after installation and then again at least 90 days later.

Setting L6 on the JAMAR counter was used to collect the data, which is designed to collect traffic information in two directions, lane one and lane two. Data from the counters were extracted using JAMAR software and then exported to Excel to facilitate processing. The data could then be sorted by lane, with lane one as the correct direction and lane 2 as the WW movement. Initial examination of the data showed error rates between 1% and 3.6%, much less than the 20% error rate used as a threshold for the recollection of vehicle data. Data errors may have resulted from false positives, issues determining vehicle class, or because vehicles stopped on the road tube at intersections. Data flagged as an error were given a vehicle class of 14, which were then filtered out. Data were further filtered by lane and then sorted to determine WW movements. Once WW movements were identified for both counters for each ramp, the movements were compared to determine which case applied to each incident.

Figure 5.10: Road Tube Layout Used for Data Collection (Google 2020)

5.7 Wrong-Way Driving Incident Classification

Each ramp had two counters that were placed in the same locations for both the before and after studies. Each counter used two road tubes set 2 ft apart, as shown in Figure 5.11a, and the date and time of the counters were synced. The counters were set up to use layout L6 to capture data, which captures volume, speed, gap, vehicle class, and direction. Because this layout was designed to gather data on a two lane, two-way street and this study gathered data on ramps with one-way traffic, any movement in the other direction was considered a possible WW incident. The first counter was placed near the crossroad, approximately 50–100 ft back, depending on the ramp and determined by signalization of the intersection, number of exit ramp lanes at the intersection, and the traffic levels. The first counter was placed at a point before the exit ramp divided into more than one lane, and the second counter was placed on the ramp near the interstate. Figure 5.11b shows the counter placement at Auburn Rd, which was similar to the positioning at each ramp.

a) 

b) 

Figure 5.11: a) Tube Placement for Each Counter; b) Tube Placement for Each Ramp (Google, 2020)

Once the WW incident data were collected and processed into Excel spreadsheets, they were sorted by direction, and the hits that registered in the wrong direction were separated for analysis. Typical analysis of WWD data would count every hit as an entry to the interstate. It should be noted that according to the manual for the counters published by Jamar, counters placed out when vehicle speeds are likely going to be less than 10 mph should have tube lengths of 40 feet or less. The tubes used for this study were all 50 feet long. Utilizing two sets of road tubes on the ramp there were three different scenarios that could occur. Each of these scenarios were classified into one of three cases. Case 1 incidents were those hits that registered on counter 1 and then on counter 2 within a time frame that was appropriate for the distance between the road tubes. Each hit was examined to verify that it could be from the same vehicle, meaning the vehicle entered the ramp going the wrong way at counter 1 and continued until reaching the interstate, or the entrance to the exit ramp, at counter 2. Case 1 was assumed to indicate a WW entry onto the interstate, as shown in Figure 5.12. Although it was assumed these entries to be WW entries, the vehicle could have passed counter 2 and then performed a U-turn and proceeded the correct direction down the interstate.

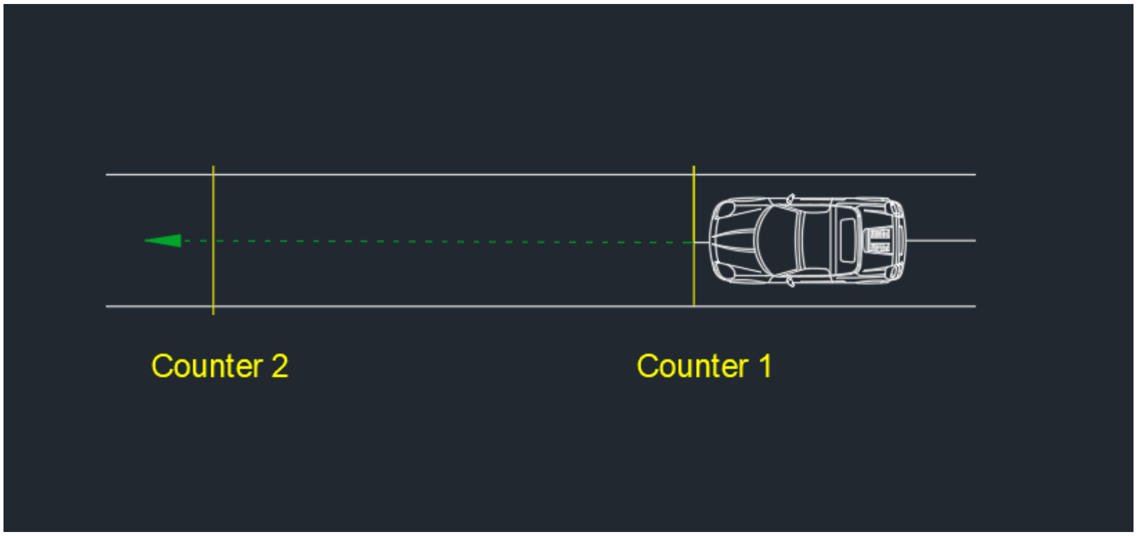

Figure 5.12: Case 1 Wrong-Way Incident

Case 2 incidents registered on counter 1 but no corresponding hit occurred on counter 2, indicating that the vehicle entered the exit ramp in the wrong direction but did not leave the exit ramp and enter the interstate. An example of this movement is pictured in Figure 5.13. In this case, the vehicle was assumed to self-correct the WW movement somewhere between counter 1 and counter 2. This self-correction could have taken the form of turning around on the ramp and going the correct direction or, if the ramp design allows, maneuvered from the exit ramp to the entrance ramp. Auburn Rd is a good example of a ramp design that allows for this maneuver and such WWD incidents may actually be intentional. In addition to vehicles self-correcting, hits registering as WWD movements may also be rollbacks due to traffic stopping near the counter or vehicles maneuvering into two lanes when the design is intended for one lane. For this reason, prior observation of the interchange intersection is helpful to determine the best location for counter 1 to ensure the queue does not affect the results. Although there is the potential for errors, since there were drivers who likely self-corrected, case 2 incidents were included in calculating the incident rates

Case 3 incidents registered hits on counter 2 without a corresponding hit on counter 1, shown in Figure 5.14. Examination of the ramp layouts showed that each ramp had barriers or concrete in the vicinity of counter 1, but open areas and grass around counter 2. Mowing and

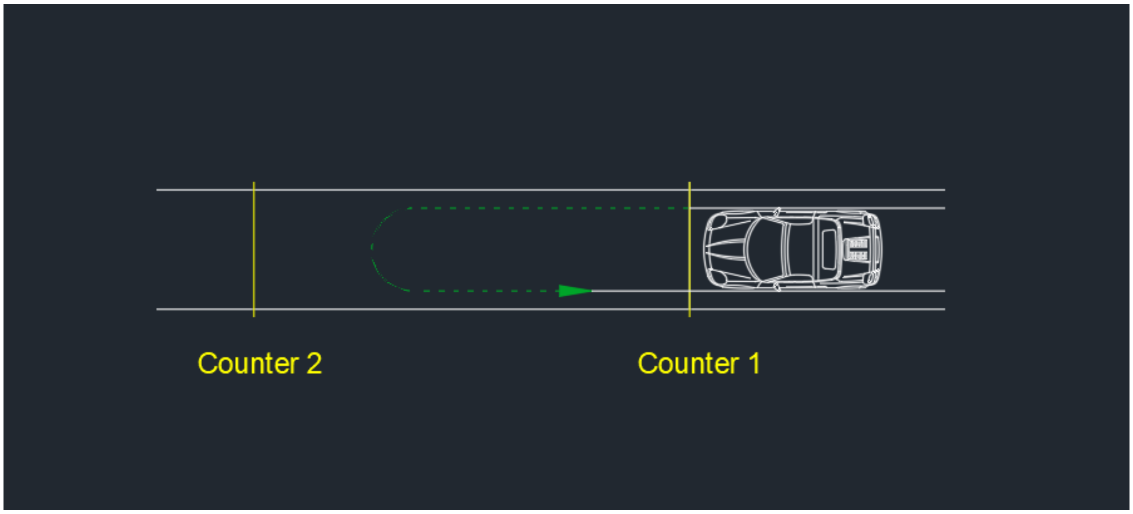

Figure 5.13: Case 2 Wrong-Way Incident

other maintenance takes place on the ramp with the mowers and other vehicles registering WWD hits on the counter. Additionally, there was no way to explain how a vehicle got to counter 2 without hitting counter 1 first. Examination of the before data showed almost all, 85% of all case 3 incidents, were class one vehicles with a wheelbase shorter than typical motorcycles. The wheelbase is more indicative of a mower or bicycle, neither of which are potential WWD vehicles. Additionally, almost all were during typical working hours. North Wanamaker Rd had 57 of 59, 97%, of the case 3 incidents on a single day over a two-hour period from just before 9am to 11am. Likewise, the other ramps showed indications of clustered case 3 incidents during normal working hours. There were five case 3 incidents that had speeds more than 70 mph, with a high of 119 mph. These incidents occurred during times where there was significant traffic entering the entrance ramp to the interstate, one during morning rush hour, three around noon and one early evening. Given the volume of traffic at that time, it seems unlikely that these hits are accurate and are more likely due to equipment errors. Since it seemed there was no indication that these hits represented vehicles entering the interstate, these incidents were considered errors and not used in calculating the incident rates. Many case 3 incidents seem to be due to maintenance on the ramps and some demonstrate likely misreads by the equipment. Due to these reasons, the case 3 incidents were not considered, but the second counter does provide confirmation of WWD incidents that actually enter the interstate.

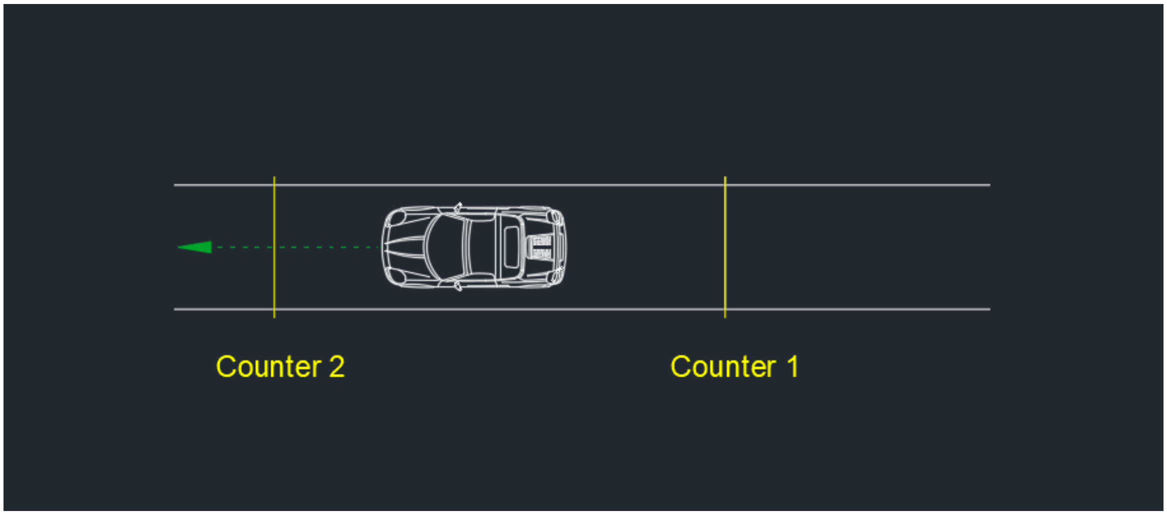

Figure 5.14: Case 3 Wrong-Way Incident

5.8 Selection of Low-Cost Countermeasure for Each Site

An initial examination of available countermeasures revealed a wide range of options, including pavement markings and signs to full-range countermeasures such as cameras, detection notification, and flashing LED signs. These countermeasures ranged in price from $200 to more than $60,000. An initial list of some of the low-cost countermeasures was developed, and each sign was studied to determine effectiveness, ease of installation, and maintenance requirements.

Results showed that countermeasure effectiveness varies depending on region. Countermeasures that worked well in the southern states, may not be as effective in the eastern or western states. In addition to researching the countermeasures, each ramp was investigated to determine what countermeasures were already in use as well as the surrounding area and businesses. The collected information was combined with the results from the before study to develop a working list of countermeasures that included Red Retroreflective Delineators (RRFDs) on posts with Do Not Enter and Wrong Way signs, Wrong Way signs with red flashing LEDs, and oversized and lowered Wrong Way signs, as shown in the figures below. These signs were chosen because, when examining the before data, three ramps were identified for countermeasure evaluation that had several daytime incidents. The RRFDs, shown in Figure 5.15a, are red delineators that are small reflective signs that are typically used on sign posts or median barriers and were chosen for their low light and nighttime effectiveness. Research conducted on nighttime driving has shown that RRFDs are effective at drawing the eye to the post and leading drivers to notice the signs (Finley et al., 2014). Research has also shown that drunk drivers shift their focus to the lower right area of the road where RRFDs can draw attention to the Wrong Way signs. This research also showed that flashing LED signs (Figure 5.15b) are effective at attracting driver's attention, both intoxicated and sober (Finley et al., 2014). The use of oversized, lowered signs (Figure 5.16) have also proven to effectively reduce WWD incidents, particularly in the daytime (Baratian-Ghorghi & Zhou, 2017; Cooner & Ranft, 2008; Das et al., 2017; Staplin et al., 2001; Cooner et al., 2004; Kaminski Leduc, 2008). The MUTCD allows signs along interstates and ramps to be lowered to 3 ft, the height used in this study, which places the sign at the driver's height, thereby increasing sign prominence.

a) 

b) 

Figure 5.15: Preliminary Countermeasures: a) RRFD; b) Flashing LED Wrong Way Sign

Figure 5.16: Preliminary Countermeasures: Oversized and Lowered Wrong Way Sign

After considering previous research, the WWD Working Group results, and discussions with the KDOT Project Manager, the following countermeasures were selected. RRFDs were selected as a countermeasure to be used on the Auburn Rd and Gage Blvd ramps. The RRFDs were installed on the Do Not Enter sign at the entrance of the ramp and on the first Wrong Way sign. Because WWD incidents at Auburn Rd occur primarily at night and incidents at Gage Blvd occur in the early morning and late afternoon, RRFDs were determined to be most effective during low light and dark conditions.

The second countermeasure used was oversized Wrong Way signs. These signs were installed lower than normal, at a height of 3 ft above the pavement, meaning the signs were at approximately the same height as a driver sitting in a car. The oversized signs were placed at Wanamaker Rd North, Wanamaker Rd South, and Gage Blvd. At the two Wanamaker Rd ramps, two existing Wrong Way signs were replaced by the oversized signs and lowered to 3 ft. One existing Wrong Way sign was replaced and lowered on Gage Blvd. Fortunately, the geometry of the Wanamaker Rd South ramp allowed the first lowered sign to be eye level to the driver on the left, while the second sign, when lowered, was directly in front of the vehicle as it entered the curve. The other two locations allowed for similar placement of the lowered signs, although they were not quite as prominent as the Wanamaker Rd South ramp. Because WWD incidents at both Wanamaker ramps primarily occur during daylight hours and most incidents at Gage Blvd occur early in the morning or late afternoon in lighted conditions, enlarging and lowering the Wrong Way sign was expected to increase sign visibility.

The third selected countermeasure was a Wrong Way sign surrounded with red flashing LEDs. Although this countermeasure was more expensive than the other selections, it was specifically chosen for the Auburn Rd site due to the minimal traffic on this ramp and the minimal lighting in the surrounding area. A private drive and a cemetery are located to the north of I-70 at this location, and the primary business to the south is a sports bar. In addition, the before data showed two case 1 incidents, both close to the bar closing times. Since research conducted in Texas has shown that flashing LED signs and RRFDs are very effective at night, especially with inebriated drivers (Finley et al., 2014), a targeted approach was chosen with a countermeasure that has proven to be effective with impaired drivers.

Each sign was evaluated for initial cost and ease of installation. The RRFDs for each pole consisted of 21 4 in. x 4 in. delineators placed flush together from the sign down to the ground. The cost per delineator was $5.95, totaling approximately $125 per pole, or $250 per interchange. However, during the installation process, the head of the maintenance crew for the area suggested using a roll of thin aluminum with red reflective material on one side to reduce cost and increase ease of installation. The oversized signs were approximately $85 per sign. The most expensive countermeasure evaluated was the flashing LED sign, which cost $1,500 per sign. The sign included a solar panel, a battery, and a control box that could be used to customize the time for the sign to flash. The RRFDs were installed on poles already in use, so only screws or other mounting materials were required. The oversized signs replaced existing signs, and the poles already had holes at the appropriate heights and intervals. The flashing LED sign also replaced an existing sign, using the same pole and existing holes and hardware.

Chapter 6 - Results

Before and after studies were designed to evaluate the effectiveness of the selected countermeasures. The before study was planned after ramp selection was finalized. The pneumatic roads tubes were placed on the ramps on October 28, 2018. The initial plan was to leave the road tubes in place for 14 days, but inclement weather forced the tubes to be removed after 10 days. Table 6.1 presents the results from the before study.

Table 6.1: Results from the Before Study

		Before Study (10 Days of Data)						
Study Site	Wrong-Way Countermeasure(s)	Wrong-Way Incidents	Case 1	Case 2	Case 3	ADT	Wrong-Way Incident Rate per 100,000 entering veh.	
							With Case 3's	Without Case 3
Auburn Rd	Retro-Reflective Strips and LED Sign	8	2	4	2	760	105.26	78.95
Wanamaker Rd North	Oversized and Lowered Sign	77	0	18	59	1,950	394.87	92.31
Wanamaker Rd South	Oversized and Lowered Sign	10	2	8	0	2,090	47.85	47.85
Gage Blvd.	Oversized and Lowered Sign and Retro-Reflective Strips	27	0	0	27	4,740	56.96	0.00
Adams St North	Control Site	3	0	2	1	2,175	13.79	9.20
Adams St South	Control Site	1	0	1	0	2,705	3.70	3.70

In Table 6.1, each study site is identified by the ramp and the proposed WWD countermeasure or as a control site. The results are presented as total WWD incidents and then broken down by case 1, case 2, and case 3 incidents. Results across the ramps and studies were compared, but differing ramp and daily volumes made comparisons difficult. Large volumes may result in more total incidents, but the high volume may not increase the rate of incidence. Therefore, the raw total number of WWD incidents was converted to an incident rate per 100,000 entering vehicles.

Previous studies on WWD incidents reported WWD incidents as a rate of incidents per 30 days (Parsonson, et al., 1978, Parsonson et al., 1979, Howard, 1980, Campbell, et al., 1988). While this gives a rate where ramps with a WWD problem can be easily identified, it does not take into account the ramp volume. Higher volume ramps may have a larger number of WWD incidents than a lower volume ramp, but may have a lower rate. Recently, WWD studies have begun to use incident rates based on ramp volumes.

When setting up the equation to determine the rate there were two ADTs that were available. There was the volume of vehicles exiting the interstate that were counted by the road tubes. While there was an actual count of the vehicles that were on the ramp, this is not the group of vehicles that have the opportunity to make an incorrect movement at the interchange. Discussions at the Transportation Research Board meeting in 2020 with Dr. Zhou, a leading WWD researcher from Auburn University, led to the realization that the number of vehicles taking the ramp to enter the interstate is the "pool" of vehicles that could potentially enter the ramp going the wrong way, and the vehicles that enter going the wrong way come from this pool. This number represents a better number to get a true incident rate based off the number of possible drivers who could make a wrong-way movement. KDOT provided ramp data from 2019 and the counts at each ramp were compared to the ADT for the entering ramp at the interchange showed that the ramps were split on whether the exiting or entering ramp had a higher volume of traffic. Additionally, some of these differences were as much as 4000 vpd. Given the disparity and the discussion at TRB, the ADT for the interstate entrance ramp was used in the ADT column for all of the studies. Using this volume, an incident rate per 100,000 entering vehicles was calculated using the following formula:

$$\frac{\#\, incidents * 100{,}000}{ADT\ *\ \#\, of\ Days} = Incident\ Rate$$

Equation 1: Equation to Determine Incident Rate

The incident rates for the ramps varied from 3.70 to 394.87. Examining the results by case revealed four total case 1 entries, two each at the Auburn Rd and Wanamaker Rd South ramps. Overall, although 152 hits occurred across all three cases, more than 75% of those hits were case 3 incidents, 98% of which came from the Wanamaker Rd North, Gage Blvd, and Adams St North ramps.

The first after study was conducted immediately after the countermeasures were installed on September 26, 2019. Initially the road tubes were going to stay out for the same length of time as the before study, but the time was extended to 14 days due to issues with the flashing LED sign. Technical support was able to fix the sign on October 4, 2019, seven days after the road tubes were emplaced. The tubes were left out another seven days to have the same amount of time with the sign working. Both control sites also had one set of road tubes that experienced issues during the first after study. At the Adams St South ramp, one road tube was damaged near counter 1, resulting in inaccurate data, and a tube became damaged at counter 2 at the Adams St North ramp, resulting in unreliable data. Data from the other two counters at the control sites also showed WW incidents in line with the before study, but all the data were excluded due to missing data from damaged tubes. Results from the first after study are presented in Table 6.2.

Table 6.2: Results from After Study #1

		After Study #1 (14 Days of Data)						
Study Site	**Wrong-Way Countermeasure(s)**	**Wrong-Way Incidents**	**Case 1**	**Case 2**	**Case 3**	**ADT**	**Wrong-Way Incident Rate per 100,000 entering veh.**	
							With Case 3's	**Without Case 3**
Auburn Rd**	**Retro-Reflective Strips and LED Sign**	12	0	11	1	760	112.78	103.38
Wanamaker Rd North	**Oversized and Lowered Sign**	26	0	20	6	1,950	95.24	73.26
Wanamaker Rd South	**Oversized and Lowered Sign**	9	0	4	5	2,090	30.76	13.67
Gage Blvd.	**Oversized and Lowered Sign and Retro-Reflective Strips**	2	0	2	0	4,740	3.01	3.01
Adams St North	**Control Site**	**Equipment Error**						
Adams St South	**Control Site**							

**Results for Auburn Rd are cumulative.

Results from the first after study showed that case 1 incidents decreased to zero, and three of the ramps showed marked improvement compared to the before study. One ramp, Auburn Rd., had a similar incident rate as the before study. One countermeasure used at Auburn Rd was the flashing LED Wrong Way sign. Although sign installation was successful and the sign was activated per vendor instructions to blink from 9:00 pm to 4:00 am each night, the sign did not blink as intended. Tech support discovered an issue with the sign operating through midnight into the next day, so a work around was developed where the sign successfully operated from 9:00 pm to 11:55 pm and then from 12:01 am to 4:00 am. However, the issue caused a seven-day span in which the sign did not work properly, and a seven-day span with data in which the sign did work properly. An incident rate was determined for each time period with their different sets of countermeasures, as shown in Table 6.3. The observed difference was an incident rate of 93.98 before the sign was operational compared to an incident rate of 112.78 after the sign was operational.

Table 6.3: Results from Auburn Rd; Before and After Flashing LED Sign

		Before the Flashing sign was working						
Study Site	**Wrong-Way Countermeasure(s)**	**Wrong-Way Incidents**	**Case 1**	**Case 2**	**Case 3**	**ADT**	**Wrong-Way Incident Rate per 100,000 entering veh.**	
							With Case 3's	**Without Case 3**
Auburn Rd	**Retro-Reflective Strips and LED Sign**	5	0	5	0	760	93.98	93.98

		After the Flashing sign was working						
Study Site	**Wrong-Way Countermeasure(s)**	**Wrong-Way Incidents**	**Case 1**	**Case 2**	**Case 3**	**ADT**	**Wrong-Way Incident Rate per 100,000 entering veh.**	
							With Case 3's	**Without Case 3**
Auburn Rd	**Retro-Reflective Strips and LED Sign**	7	0	6	1	760	131.58	112.78

Data for the long after study was scheduled to be gathered around mid-March 2020, approximately five months after the first after study, but unfortunately, the state of Kansas was placed under travel restrictions and lockdown due to the coronavirus pandemic, and traffic volumes dropped dramatically. Therefore, the second after study was delayed because reduced traffic volumes could skew the data, revealing the countermeasures to be more effective than they actually are or much worse. Once travel and lockdown restrictions were lifted and traffic volumes returned to normal, road tubes were set out for the long after study. The road tubes were emplaced June 7, 2020, and left in place for 14 days to match the first after study. Data showed that the overall traffic volumes for the ramps were within 10%–15% of the first after study, proving that traffic volumes had returned to near-normal levels and that the data could be trusted. Although one of the road tubes for counter 2 on Gage Blvd was damaged, the data did not show any errors, so the data was used. Table 6.4 presents results from the second after study.

Table 6.4: Results from After Study #2

		After Study #2 (14 Days of Data)						
Study Site	Wrong-Way Countermeasure(s)	Wrong-Way Incidents	Case 1	Case 2	Case 3	ADT	Wrong-Way Incident Rate per 100,000 entering veh.	
							With Case 3's	Without Case 3
Auburn Rd	Retro-Reflective Strips and LED Sign	4	0	3	1	760	37.59	28.20
Wanamaker Rd North	Oversized and Lowered Sign	24	0	11	13	1,950	87.91	40.29
Wanamaker Rd South	Oversized and Lowered Sign	4	0	4	0	2,090	13.67	13.67
Gage Blvd.	Oversized and Lowered Sign and Retro-Reflective Strips	12	0	9	3	4,740	18.08	13.56
Adams St North	Control Site	4	0	4	0	2,175	13.14	13.14
Adams St South	Control Site	0	0	0	0	2,705	0.00	0.00

Data from WWD incident rates for ramps from the second study showed zero case 1 incidents and a decrease in the number of case 2 incidents, including the two control ramps. Case 3 incidents showed a slight increase, but none of the case 3 incidents occurred on the control ramps. Overall, incident rates decreased from the first after study for three of the four treatment ramps. The fourth ramp, Gage Blvd, increased from an incident rate of zero to 13.14. Table 6.5 below summarizes all incident rates across all studies. The results summary shows both the incident rate with the case 3 incidents and without the case 3 incidents.

Table 6.5: Summary of All Incident Rates

		Before Study		After Study #1		After Study #2	
Study Site	**Wrong-Way Countermeasure(s)**	**Incident Rate w/ Case 3**	**Incident Rate w/out Case 3**	**Incident Rate w/ Case 3**	**Incident Rate w/out Case 3**	**Incident Rate w/ Case 3**	**Incident Rate w/out Case 3**
Auburn Rd	**Retro-Reflective Strips and LED Sign**	105.26	78.95	112.78	103.38	37.59	28.20
Wanamaker Rd North	**Oversized and Lowered Sign**	394.87	92.31	95.24	73.26	87.91	40.29
Wanamaker Rd South	**Oversized and Lowered Sign**	47.85	47.85	30.76	13.67	13.67	13.67
Gage Blvd.	**Oversized and Lowered Sign and Retro-Reflective Strips**	56.96	0.00	3.01	3.01	18.08	13.56
Adams St North	**Control Site**	13.79	9.20	Equipment Error			13.14
Adams St South	**Control Site**	3.70	3.70	Equipment Error			0.00

Typically, when evaluating WWD countermeasures using before and after studies a determination of success has been based on a reduction of WWD incidents. For this study, a statistical test was run to see if it indicated a significant reduction in WWD incidents. For this study a two proportion z-test was run. This test takes into account the varying volumes of traffic on each ramp as well as the differing number of days between the studies. The actual count of case 1 and case 2 incidents was used for each ramp. The results are shown below in Table 6.6

Table 6.6: Ramp z-values

		z-values	
Ramp	**Countermeasure**	**Before - After**	**Before - Long After**
Auburn Rd	**Retro-Reflective Strips and LED Sign**	-0.53320	1.52165
Wanamaker N	**Oversized and Lowered Sign**	-0.63093	0.69076
Wanamaker S	**Oversized and Lowered Sign**	2.25909	2.25909
Gage	**Oversized and Lowered Sign and Retro-Reflective Strips**	1.19524	0.56346

Table 6.6 has each ramp where a countermeasure was deployed and the countermeasures used in columns one and two. The z-values listed represent a comparison of the proportion of WWD incidents to the total number of vehicles that were entering the ramp. The last two columns show the z-values when comparing the before study to the after and then to the long after study. Two ramps showed a significant reduction in the proportion of WWD incidents across the studies. As shown in the table, Wanamaker Rd South has a z-value of 2.26 for both comparisons which indicates the reduction in WWD incidents is significant to the 98th percentile. Auburn Rd had a z-value of 1.52 for the before and long after comparison, indicating that the reduction in WWD incidents is significant to the 90th percentile. Wanamaker Rd north ramp did not show any significance in either of the studies. Gage Blvd had a z-value that was closer to being significant for the before and after study than the before and long after study comparison.

Chapter 7 - Proposed Enhanced Data Collection Method

7.1 Background

Effective placement of WWD countermeasures requires the evaluation of an interchange ramp. Since state highway agencies and communities have limited resources to collect data, emplacing countermeasures on a ramp that has had no WWD incidents may be unnecessary with limited resources. Additionally, proper evaluation of the ramps in a given area will allow for prioritization of resources to invest in technology, intervention strategies, or enhanced enforcement.

There are several different considerations to consider when evaluating a ramp. First is to determine the scope of your evaluation. Is a state highway agency or community considering installing permanent monitoring or temporary monitoring equipment? Are there several or one ramp area of concern or in a certain area of an urban community? When considering costs associated with preforming a safety analysis for WWD incidents, include the initial cost of the equipment, installation of the monitoring device, disposing of used equipment, and maintenance costs to ensure reliable data are collected. Contrasting equipment cost with equipment reliability is also based on the scope of a WWD incident investigation. The most economical, or basic setup option may be an appropriate use while data collection with enhanced technology capabilities may produce results that are impractical, hard to download, or rely on certain environmental and power conditions.

Knowing and understanding the scope of a WWD incident study is of primary importance in determining which intervention strategy to use. For example, permanent installations have different requirements (as compared to temporary) such as the installation of data collection equipment may be within in the roadway itself or mounted on poles above the roadway which may require additional coordination and maintenance costs. There are several research studies that evaluated various types of WWD incidents. A study performed by the FHWA provides a complete summary of various traffic detectors and associated vendor information (Mimbela, et al., 2007) such as Jamar and International Road Dynamics, Inc. for road tubes or Never Fail Loop Systems or Peek Traffic Corp. for in road loop detectors. This information provides Vendor name, address, phone number, email, and sales representative names. Additionally, they provide technical information pertaining to the specific collection method.

The Arizona Department of Transportation (AzDOT) published two studies evaluating multiple methods of data collection. The scope of the first study was to evaluate five different detection methods, microwave sensors, Doppler radar, video imaging, thermal sensors, and magnetic sensors (Simpson, 2013). Each of these detection systems were installed and evaluated under a test environment to determine their ability to detect WWD vehicles and false positives. Additionally, the devices were evaluated based on the ease of installation, notification ability when an incident was detected, overall maintenance requirements, and cost of the technology. This study led to a further study published by the AzDOT that included a more in-depth investigation into each of the systems under live traffic conditions (Simpson, et al., 2015). This study included evaluating the five different detection methods, six different notification systems, and nine different driver notification devices for both wrong-way and right-way drivers. Each device was scored using several different categories including reliability, cost, maintenance, and adaptability. It should be noted that all of these systems were designed to be permanent monitoring setups and not temporary data collection setups.

A study was conducted in Japan Xing (2016) which evaluated several methods of collecting data differing from the previously described AzDOT studies which included ultrasonic, microwave Doppler image processing, and photoelectric data collection methods which evaluated their effectiveness based on their detection ability. Each device was linked to a warning device for the wrong-way driver and were emplaced for an approximate period of two to two and a half years. Wrong-way occurrences and incorrect detections were evaluated on a number of occurrences per month. Although it was found that this evaluation indicated excellent detection rate using a multi-year study, the costs, ranging from $1.5 – $7.3 million per site, might be cost prohibitive to some communities.

While the previous studies evaluated various detection devices for WWD, the studies did not evaluate the effectiveness of temporary data collection devices. Additionally, the costs of the evaluated detectors might be prohibitive to some communities and state highway agencies, a listed benefit from the permanent detectors are when they are deployed at interchanges with a known numbers of WWD incidents. The most commonly used detection methods for traffic data collection (for both ordinary traffic studies and WWD driving studies) are pneumatic road tubes, with or without cameras. In studies conducted by Caltrans, and the Georgia and Virginia Departments of Transportation described the use of pneumatic road tubes as an efficient means to detect WWD vehicles (Parsonson, et al., 1978, Parsonson et al., 1979, Howard, 1980, Campbell, et al., 1988).

The methodology described in these reports included using two road tubes linked directly to a camera at a given roadway. Studies suggested using two road tubes spaced 3 inches apart. The counter was located at the stop bar and the camera further up the ramp to capture the vehicle just after hitting the road tubes. The device would detect a wrong-way entry and trigger the camera to take a photo to record and verify the wrong-way movement. The Georgia Department of Transportation (GDOT) noted several problems using this setup in their study. It was found that if there was a positive grade ramp, vehicle rollbacks were noted to cause quite a false positives. Furthermore, it was found that a disproportionate number vehicles detected with the device as compared to the camera, this also result in errors in the activation log. While the system worked well when deployed in California, GDOT noted that the camera did not perform as well in colder environments. The authors also found that when a slight loss in voltage was detected, this caused the camera to not work properly, and the batteries could not be recharged resulting in expense to replace them. The research studies noted led the Georgia Department of transportation to not recommend using these systems for long term studies (Parsonson, et al., 1979).

The Georgia Department of Transportation conducted two studies involving 45 ramps in the Atlanta metropolitan area and found that half diamond and ParClo interchanges were found to have the highest rates of WWD incidents. It was noted that by the researchers that work zones involving interstate interchanges resulted in drivers intentionally driving in the wrong direction on the ramp. However, drivers did corrected their direction of travel once on the interstate (Parsonson, et al., 1979). In order to minimize detection errors, pneumatic road tubes were moved upstream approximately 160 feet from the intersection stop line. Wrong way driving rates were determined based on number of incidents per month. It was noted that since there were days within the data collection timeframe where the detection system didn’t operate correctly, the pneumatic road tubes were deployed for more than 30 days to ensure a full month of data were collected and later analyzed (Parsonson, et al., 1979, Howard, 1980).

Another study in Georgia evaluated interstate ramp configurations of 10 ramps in the Atlanta metropolitan area. This study strived to achieve a total of 60 days' worth of acceptable data which were later used to develop a rate of wrong-way movements per 30 days. Campbell et al. (1988) recommended that the pneumatic road tubes and camera be located 400 feet from the intersection with the crossroad. This recommendation was implemented to avoid traffic queues from vehicles exiting the ramp and also to ensure vehicles captured by the road tubes were committed to the wrong-way movement. The authors found that this setup avoided some of the errors normally associated with this field data collection (Campbell, et al., 1988).

In a study conducted by the Virginia Department of Transportation (VDOT), researchers utilized the same data collection method, road tubes connected to a camera, at interchanges with a known WWD problem. This report offers a detailed look at the previous studies as well as the results from this one. One of the things identified was the over counting of wrong-way incidents. Any wrong-way trigger on the counters was counted as a WWD incident, even if the camera did not record a WWD vehicle. During this study, rollbacks were identified as a problem when the counter was located at the stop line of the interchange intersection. The study recommended an improved camera system and updated circuitry to improve performance. Another recommendation was to use just a set of road tubes initially to determine if an interchange has a problem with WWD incidents first, then bring in the camera system to verify (Howard, 1980).

There has been zero research conducted on or with the use of two sets of road tubes in conjunction with WWD research. The most common method used prior to this was a combination of road tubes linked to a camera has several limitations. Location of the road tubes resulted in errors, and no study agreed to the same location. The camera itself had problems with the battery and would require expensive upgrades to the camera system (Parsonson, et al., 1978, Howard, 1980). In order to overcome the problems with the camera and still collect the desired amount of data, the systems had to be emplaced for much longer periods of time. Furthermore, the system itself had problems with false positives where the camera and road tubes did not agree on whether or not there was a WWD incident.

7.2 Research Objectives

Based on the review of literature, a robust data collection methodology using pneumatic road tubes is needed. The proposed data collection methodology is designed to expand on the data collection methodology used in previous chapters to evaluate the effectiveness of WWD incidents at ParClo interchanges.

The primary objective of this WWD data collection methodology is to evaluate the effectiveness of using two sets of road tubes to collect WWD data. It was hypothesized that utilizing two pneumatic road tube counters will provide evidence of the WWD incident if a vehicle can be traced. The second objective of this study was to determine if other data collection points within the interchange can help determine where WWD incident originated. Furthermore, volume data was to be collected to verify KDOT's volumes to ensure accurate WWD incident rates. This will ensure data quality and reinforce the need to deploy more than one set of pneumatic road tubes at a given ParClo site.

7.3 Methodology

A proposed methodology was developed to evaluate a total of five sets of pneumatic road tubes at the Auburn Rd site after the completion of the low-cost countermeasure effectiveness study. This ParClo interchange was selected due to the proximity to Manhattan, KS and also because traffic conditions were already known. Other ParClo interchanges in the Topeka, KS metropolitan area as well as surrounding interstates were examined with respect to this study. However, these interchanges were removed from consideration based on the presence of other traffic infrastructure including a signalized intersection, unusual geometry, unsafe to collect data, or nearby features that may affect driver behavior. Once the ParClo interchange was chosen, a deployment plan was developed for safely installing the pneumatic road tubes as shown in Figure 7.1 to investigate all aspects of traffic movement into both the off- and on-ramps.

As shown in Figure 7.1, counters 1 and 2 were setup in the same location as they were in the low-cost countermeasure effectiveness study using the same layout, L6. Counter 3 was setup on the east side of Auburn Rd south of the interchange using the L11 layout for northbound through and left-turning traffic. The pneumatic road tube setup L11 layout detects traffic for two lanes going in the same direction – in this case, northbound. The left turning lane is the turning movement that enters the interstate in the correct direction of travel heading west as indicated by the purple arrows. Counter 4 was setup on the west side of Auburn Rd detecting vehicles traveling southbound either making a right or left turning movement, or a through movement.

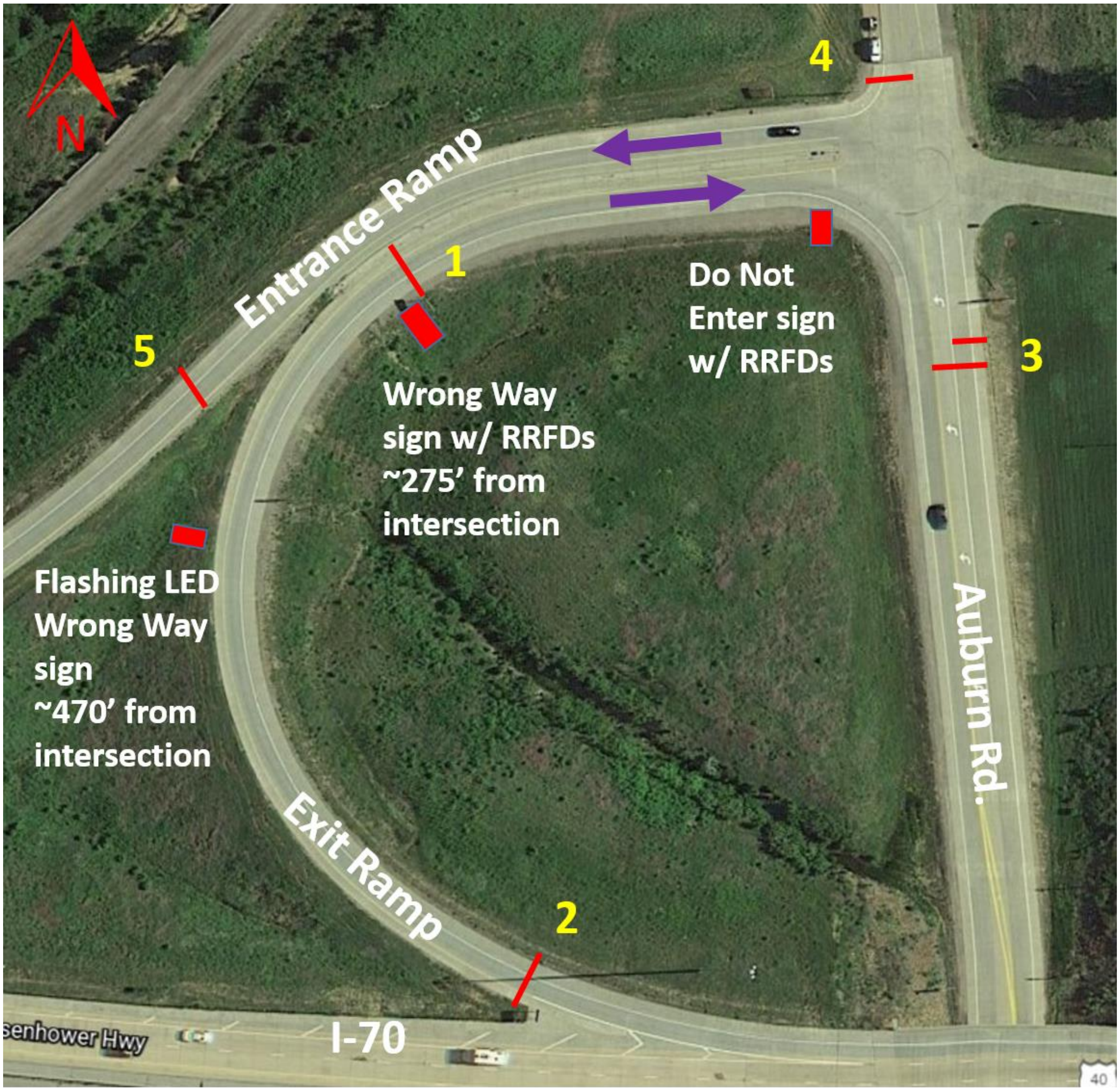

Figure 7.1: Map of Auburn Rd Interchange Showing Counter Locations

Furthermore, there is one lane for southbound traffic on Auburn Rd after exiting the on- and off-ramp area. It should be noted that there is an area behind counter 4 approximately 200 feet that is currently being used a commuter parking lot with minimal southbound traffic. To capture vehicles traveling in the correct direction onto the on-ramp, counter 5 was setup halfway up the on-ramp. In addition to where counters are placed,

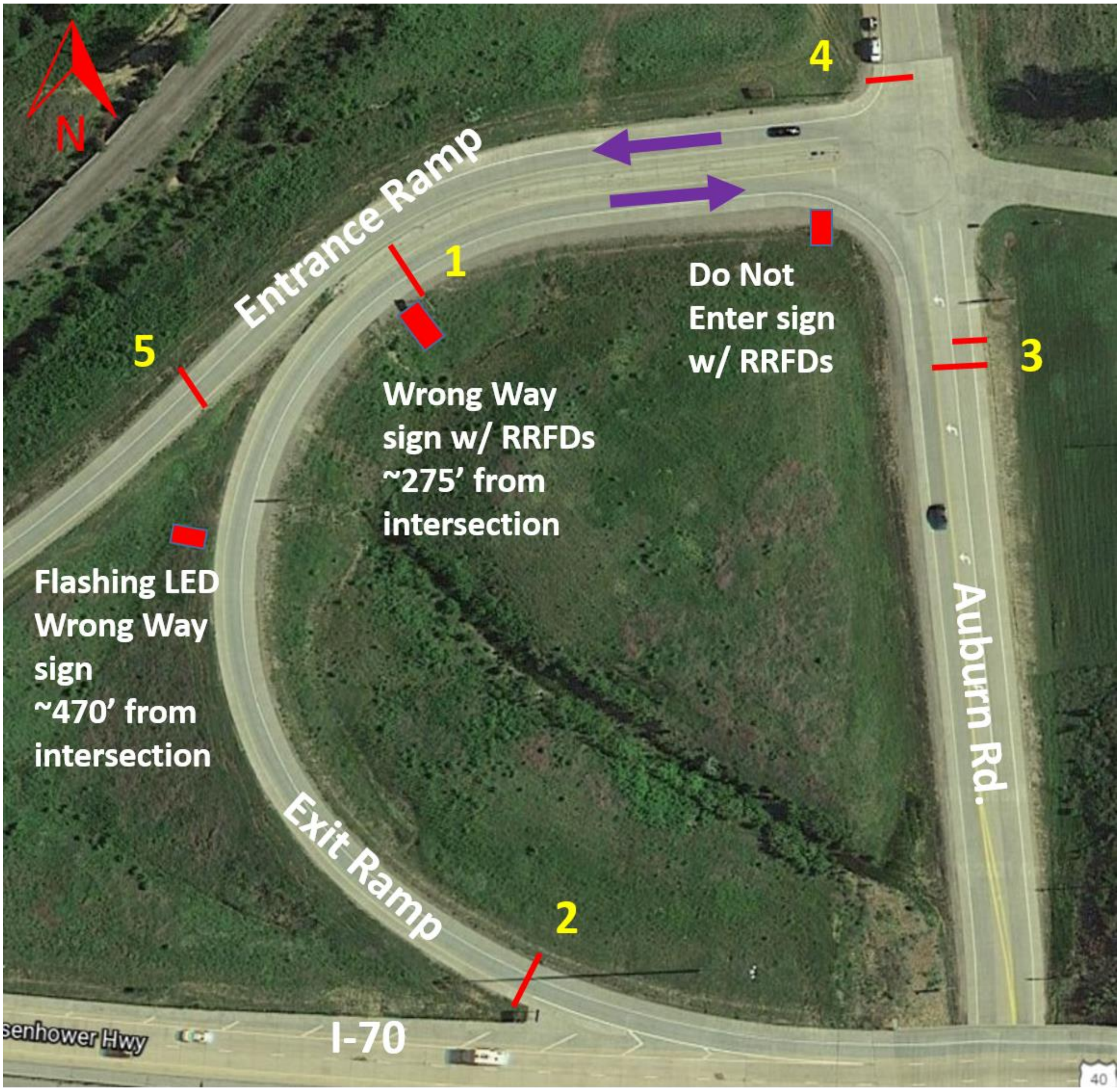

Figure 7.1 also provides where the wrong-way sign, enhanced LED wrong-way signs are located. As with previous data collection efforts, safety was taken into consideration and personal protection equipment (vest, lighting, etc.) were used while in the field.

7.3.1 Data Collection and Reduction Procedures

The pneumatic road tubes were installed on July 5, 2021 and retrieved on July 16, 2021 for a total of 10 days of data. The data extracted from the pneumatic road tube counters included time-stamped data which also provided such variables as direction of travel, vehicle speed, FHWA classification, vehicle wheelbase length, gap (time), and following (time).

Four out of the five pneumatic road tubes counters were able to collect a full set of data, however it was noted that counter 5 was unable to collect all of the variables due to a tube error, so only one tube was able to collect traffic volume.

The pneumatic road tubes were removed from the roadway after all equipment was inspected for damage. Each counter's data were processed using the propriety software TraxPro developed by Jamar technologies, which exported the data into Excel as a .xls file. One of the benefits found during the data reduction process using two tubes is the ease of detecting WWD incidents through sorting of the data by using the variable vehicle direction. For example, a data set may include thousands of "1" designations for the correct direction of travel, and "2" if the counter detected a vehicle traveling in the wrong direction, indicating the vehicle's front wheels hit the second road tubes then the first, instead of vice versa. Another advantage to using road tubes are the variables "vehicle class" and the "time stamp". Vehicle class refers to the FHWA vehicle classification system ranging from 1 -13 depending on the type of vehicle (e.g. 1 = motorcycle, 13 = multi-axle truck). If the pneumatic road tubes classified a vehicle as class 14 (outside of the FHWA classification), this was an error of some sort. Furthermore, the counter clocks were synchronized giving the ability to track a vehicle through multiple counters. For example, a vehicle could be tracked from counter 2 to counter 1 if traveling in the correct direction on the off-ramp. Errors in each of the counter datasets were identified and removed from the dataset if the vehicle could not be tracked, or the data for a particular vehicle appeared to be unrealistic given the conditions. For example, a class 14 (error) showed or a truck (class 13) traveling at over 100mph.

Furthermore, as described in Chapter 5, two pneumatic road tube counters were setup on the exit ramp (as shown in Figure 7.1) and the same three WWD cases were used as described previously.

7.3.2 Traffic Volume Verification

One important aspect to determining the magnitude of WWD incidents at a particular location is determining the rate at which they are occurring. This means understanding the average daily traffic (ADT) for each of the traffic movements. A total of 10 days of traffic data were used to establish ADT for each movement of travel and the results are shown in Figure 7.2.

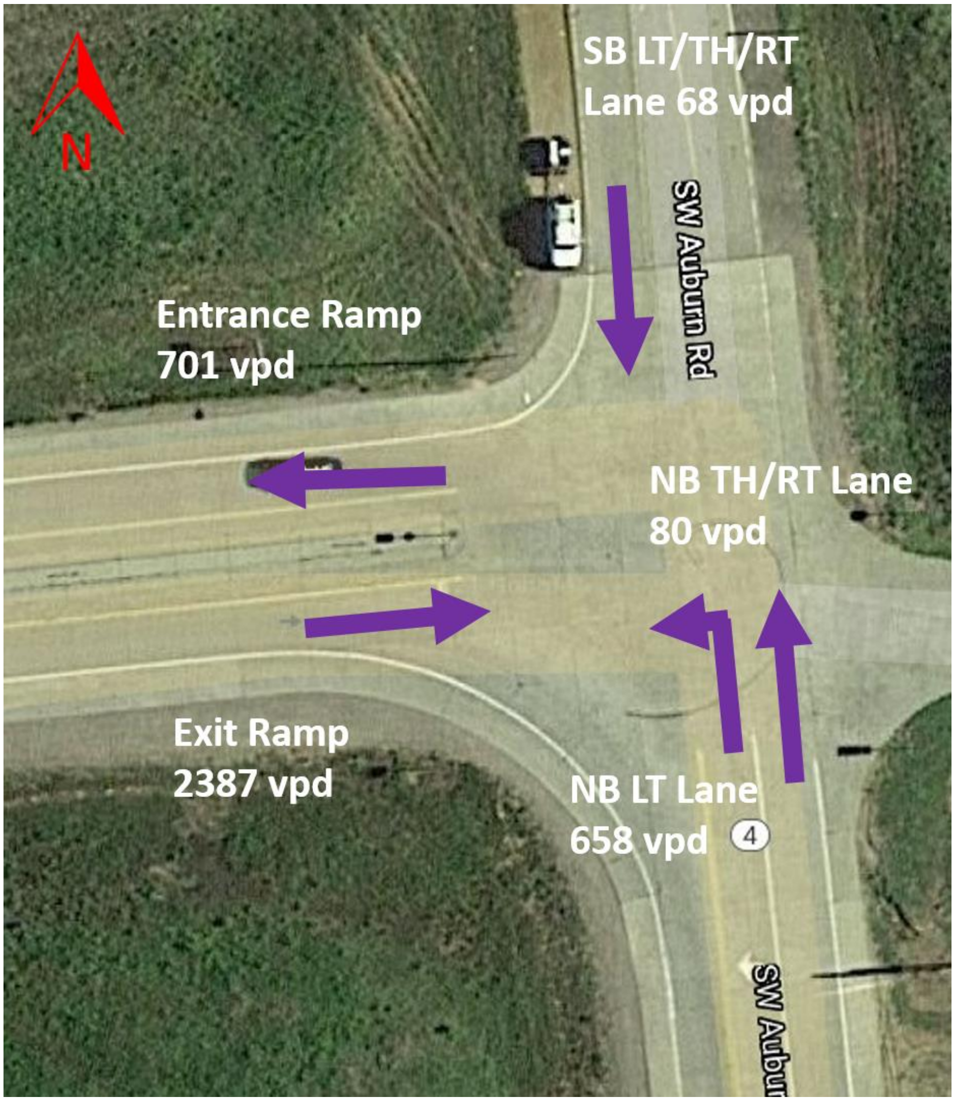

Figure 7.2: Auburn Rd. Collection Method Study ADTs

As shown in Figure 7.2, the entrance ramp had an ADT of 701 vehicles per day, this value was compared to KDOT's historical count of 760 vpd indicating a valid data collection effort by the pneumatic road tubes. Additionally, it should be noted that there is a significant difference between in vpd when comparing entrance to exit ramp, 701 vpd and 2,387 vpd respectively indicating a WWD incident will have a greater change at hitting a vehicle traveling the correct direction using the exit ramp. The collected volume data will establish a baseline to determine a WWD rate when compared to vehicles traveling in the correct direction on the correct ramp.

7.3.3 Wrong-Way Driving Incidents

During the 10 days of data collection, multiple WWD incidents were detected by the pneumatic road tubes. It should be noted that this additional study was performed months after the enhanced LED wrong-way sign was installed. When considering road tube counters 1 and 2, located on the exit ramp as shown in Figure 7.1**,** a total of six incidents were detected by one of the counters. This indicates that six vehicles had entered the exit ramp and drove in the incorrect direction. A single vehicle was detected by counter 2 only and classified as “14” indicating and error and this vehicle was removed from the dataset for consideration. The five confirmed WWD incidents were detected by counter 1 only as the data is shown in Table 7.1.

Table 7.1: Collection Method Study Wrong-Way Incidents

Veh. No.	Date	Time	Lane	Axles	Class	Length (In Inches)	Speed (In MPH)
1623	7/6/2021	6:50:54 AM	2	2	1	24	23
1907	7/6/2021	8:55:59 AM	2	2	1	22	24
9734	7/9/2021	6:43:42 AM	2	3	1	67	23
15740	7/12/2021	10:47:47 AM	2	3	1	66	22
14007	7/11/2021	11:18:29 AM	2	2	2	105	34
14008	7/11/2021	11:18:39 AM	1	2	2	115	27

Shown in Table 7.1 is an example of pneumatic road tube data. Each row is a vehicle assigned a number (a running count), the date, the time the vehicle traveled over the road tube, direction or travel (lane), axles, FHWA class (class), wheelbase length (inches), and vehicle speed (speed). The rows highlighted in yellow indicate a wrong-way incident detected by the pneumatic road tube counter 1 (closer to the intersection) while the rows in blue are assumed to be the same vehicle after making a correction after the first counter based on the timestamp. It should be noted that there is an area where a vehicle can make a correction and get to the correct ramp by traversing a median before the horizontal curve starts on the exit ramp.

Although the wrong-way incident data shown in Table 7-1 indicate events did happen where vehicles were traveling in the wrong direction, confirmation was needed based on another pneumatic road tube counter from the northbound pneumatic road tube counter, specifically the data from the left-turning movement as shown in Table 7-2.

Table 7.2: Counter 3 Movements Associated with Wrong-Way Movements

Veh. No.	Date	Time	Lane	Axles	Class	Length (In Inches)	Speed (In MPH)
733	7/6/2021	6:50:02 AM	2	2	1	72	14
1623	7/6/2021	6:50:54 AM	2	2	1	24	23
No corresponding hit							
1907	7/6/2021	8:55:59 AM	2	2	1	22	24
3603	7/9/2021	6:43:44 AM	1	2	1	60	23
9734	7/9/2021	6:43:42 AM	2	3	1	67	23
5494	7/11/2021	11:18:20 AM	2	2	1	52	10
14007	7/11/2021	11:18:29 AM	2	2	2	105	34
6302	7/12/2021	10:46:57 AM	2	2	1	56	11
15740	7/12/2021	10:47:47 AM	2	3	1	66	22

Shown in Table 7-2 is a combination of the pneumatic road tube data from counter 1 and counter 3. The rows highlighted in yellow are indicating a wrong-way incident as detected by counter 1 and the green rows indicate the corresponding vehicle detected by counter 3. It should be noted that clock drift has been identified by previous research studies, however the vehicle characteristics helped identify the same vehicle. Additionally, the data from counter 4 were examined and no matches to the wrong-way incidents identified on counter 1.

7.4 Summary of Findings

This study had two main objectives including detecting WWD incidents using two pneumatic road tube counters, and also collecting turning movement counts to determine which direction the WWD incident occurred. This study utilized ten days of data at a ParClo west of Topeka, KS under normal driving conditions. Vehicles per day were determined and a WWD incident rate of 100,000 ev was selected to express the rate of incident occurrence based on three different types of WWD occurrences as described in Chapter 5.

This study found five confirmed incidents of case 2, where the vehicles traveling in the wrong direction was detected by the first counter, but not the second counter (located closer to the interstate). Considering the vehicle per day collected during this study, this equates to a WWD incident rate of 70 incidents per 100,000 ev. Additionally, there were no wrong-way incidents for cases 1 and 3 which indicates that the driver was aware of the wrong-way movement and self-corrected. Finally, the pneumatic road tubes indicated that the WWD vehicle was detected as a motorcycle. The pneumatic road tubes at other locations within the ParClo interchange also provided volume and time data to support validating these incidents.

The northbound pneumatic road tube counter was able to assist with understand where these WWD incidents started from. The data indicated that all but one WWD incident originated from the northbound left turning lane. This provides additional support to enhance the entrance to the on-and -off ramps for drivers traveling northbound.

7.5 Recommendations and Limitations

As stated previously, the accuracy of understanding WWD events at ParClo interchanges is important to deploying countermeasures to reduce the number and potential severity if a crash were to occur. This study attempted to enhance the understanding of WWD incidents by enhancing the data collection effort using multiple pneumatic road tube counters. Based on this study the following recommendations are provided to practicing transportation safety engineers when a WWD study is warranted.

- Two setups of pneumatic road tubes are recommended to be installed on the interstate off ramp to detect WWD. One counter located near the intersection, and one located near the interstate / gore area.
- Two road tubes for each counter will provide an easy method to sort data and determine incidents when the counter is setup to evaluate both directions of travel.
- Multiple wrong-way diving cases can also assist with the determination of countermeasures, turnaround areas, or other enhancements to safely allow the driver to turnaround prior to entering the interstates in the wrong direction.
- Additional pneumatic road tubes at the intersection can provide turning movement information and WWD vehicles may be traced back to a certain movement. Additionally, pneumatic road tubes provide an easy method to collect traffic data, during all hours of the day with the exception of when the road is covered in snow, ice of debris.
- It should be noted that although road tubes are very effective in determining WWD incidents, they are susceptible to false-positives, damage if left on the roadway for more than two weeks, or significant damage caused by a mowing crew, objects hanging from a vehicle, or vandalism.

Although this study provided additional insights and support of the data collection efforts by the low-cost countermeasure effectiveness study, There were several limitations to this study. Only one interchange was studied using five counters to track. One of the limitations was the low volume of this interchange. An interchange with a low volume of local traffic there has increased likelihood of altered traffic patterns such as, cutting corners, disregarding lanes designations, and even deliberate wrong-way movements. Additionally, there was a preponderance of traffic coming from only one direction, northbound Auburn Rd. All of this can affect how drivers behave, which can then affect the data gathered. Another limitation was the treatments that were already deployed to this interchange. While there were several WW incidents, a road without treatments could have given better results.

Further studies should be conducted on higher volume roads with interchanges that have not received treatments for WWD, as well as interchanges controlled by signals. This will add further data to help establish procedures for prioritizing interchanges for treatments.

Chapter 8 - Conclusions

This dissertation had multiple objectives centered on the idea of understanding WWD at partial cloverleaf interchanges. Partial cloverleaf interchanges are common in the Midwest and are many times located in an area with constrained right-of-way, or an engineer's judgement at the time the interstate was constructed. WWD incidents continue to be a safety concern across the United States with many incidents resulting in high-profile serious crashes, oftentimes involving at least one fatality.

The dissertation was divided into two parts, the first part exploring the use of low-cost countermeasures at partial cloverleaf interchanges to reduce the number of WWD incidents. Interchanges were selected in the Topeka, KS metropolitan area based on input from KDOT. Proposed low-cost countermeasures were selected after a state-of-practice survey was completed and explained in both Chapter 4 and the Appendix. Additionally, an expert workshop was conducted to validate low-cost countermeasure selection.

WWD incident data were collected using pneumatic road tubes at treatment and control interchanges and countermeasure effectiveness was determined using a before-after short-term and long-term analysis. WWD rates were expressed in a rate of 10,000 ev and the results of each interchange are explained herein.

8.1 Countermeasures by Ramp

8.1.1 Auburn Rd

The Auburn Rd ramp demonstrated consistent results from the before study to the first after study, but a comparison of the data indicated that the time when the sign was not working, with an incident rate of 93.98, did slightly better than the time when the sign was working with an incident rate of 112.78. However, the case 1 entries at Auburn Rd were eliminated, which is a marked improvement from the before study even if the case 2 incidents increased, thereby indicating the countermeasures were effective. The increase in case 2 incidents could be attributed to the signs being noticed and then the drivers self-correcting. Results from the Auburn Rd exit showed marked improvement from after study 1 to after study 2, with the incident rate decreasing from 103.38 to 28.20 incidents per 100,000 ev. An examination of incident rates with the case 3 incidents included revealed a decline from 105.26 incidents in the before to 37.59 incidents per 100,000 ev in the second after study. Examination of the incident rates from all three studies shows the incident rate going from 78.95 up to 103.38 and then dropping to 28.20 incidents per 100,000 ev. Additionally, a statistical comparison of the proportion of WWD incidents between the before and long after study showed a reduction significant to the 90^{th} percentile. The results showed that the RRFDs and the oversized sign were effective, but results for the flashing LED sign were inconclusive. The sign itself is oversized, so that could have contributed to the RRFD effectiveness, but no evidence proved the effectiveness of the flashing LEDs.

8.1.2 Wanamaker Rd North

The Wanamaker Rd North exit showed a reduction from the before study to the first after study, dropping from 92.31 incidents to 73.26 incidents per 100,000 ev. The incident rate for the before study decreased from 394.87 to 95.24 incidents per 100,000 ev, even with the case 3 incidents. Data from the after studies showed that the incident rate of the ramp also improved, dropping to 73.26 incidents for the first after study and then 40.29 incidents for the second after study. However, examining the proportion of WWD incidents between the before and both after studies did not show a significant reduction. This steady improvement in the incident rate indicates that the combination of oversized and lowered Wrong Way signs effectively reduced WWD incidents.

8.1.3 Wanamaker Rd South

The Wanamaker Rd South exit showed a very large reduction in incident rate from the before study to the after study. This ramp also had two case 1 incidents during the before study and no case 1 incidents during the after studies, demonstrating a marked improvement for the ramp. The incident rate stayed the same during the long after study: the before study incident rate was 47.85 and then dropped to 13.67 during the first after study and maintained at 13.67 incident per 100,000 entering vehicles for the long after study. Statistically, the proportion of WWD incidents from the before to both after studies was significant to the 98^{th} percentile. In addition to eliminating case 1 incidents, the improvement in incident rates indicates that the combination of oversized and lowered Wrong Way signs were effective.

8.1.4 Gage Blvd

The Gage Blvd ramp had an incident rate of 0 in the before study and 3.01 for the first after study, with the incident rate rising slightly to 13.56 incident per 100,000 ev. Two WWD incidents occurred on this ramp during the first after study, but with the traffic volume on this ramp, the rate was very close to zero. The drop and then rise of the incident rates during the study rendered the results at Gage Blvd inconclusive and statistically, reduction of WWD incident proportions were not significant.. The oversized and lowered Wrong-Way sign and the RRFDs were used at the Gage Blvd ramp.

8.1.5 Control Sites

The control sites were expected to maintain the same incident rates across all three studies, but equipment error during the first after study left only the before and second after study for examination. The incident rate for both control sites were very close to each other from the before study to the second after study. The incident rate for the Adams St South ramp was 3.70 for the before and zero for the second after study, and the incident rate for the Adams St North exit for the before and second after study was 9.20 and 13.14 incidents per 100,000 ev. Since both control sites showed very similar incident rates during the before study and the second after study we can conclude that the changes at the treatment ramps were a result of the countermeasures.

8.2 Proposed Enhanced Data Collection Method

The second part of this dissertation involved the development of an enhanced data collection method. The objective of this effort was to determine if multiple sets of pneumatic road tubes could assist with determining the turning movement where a WWD incident started. As noted in Chapter 7, this was performed at the Auburn Rd partial cloverleaf interchange months after the first of the dissertation was completed. This study did produce some useful results including: 1) it verified the turning movement volume to support the WWD rates; and 2) it also supporting that almost all of the WWD started from the northbound left turning lane where vehicles could be traced between pneumatic road tube counters. Although this data collection methodology may not be suitable for all study sights, it did provide a way to investigate WWD incidents further.

8.3 Contributions to Highway Safety

WWD is a complicated highway safety concern from communities and state DOTs. The result of vehicle traveling in the wrong direction can lead to many times very serious crashes. The ability to understand the sequence of events leading up to a wrong-way incident or crash is complicated and still not understood fully, even though the interstate system has been around for over 50 years. This dissertation focused on a gap in a very wide breadth and depth of previous literature that has tried to explain WWD, test the effectiveness of countermeasures, and try a variety of intervention and geometric improvement strategies to prevent these crashes. Partial cloverleafs are a unique interchange found commonly in Midwest states. Their on- and off-ramps are located in close proximity which leads many drivers to turn onto the wrong ramp without proper lighting, pavement markings, or signage. This dissertation contributed to the body-of-knowledge by focusing efforts to reduce WWD incidents at partial cloverleafs through investigating countermeasure effectiveness as well as a more robust way to collect WWD incident data using pneumatic road tubes. Although quantifying the effectiveness of the deployed countermeasures may be hard to determine as explained in the next section, the reduction of just one WWD incident and possible crash had a significant economic benefit to the state of Kansas by at least one life potentially saved. Finally, it is of hope that this research study can provide some guidance for a community or state DOT to implement low-cost WWD countermeasures with the hope future studies can support the work that has been completed.

8.4 Limitations

Several limitations were identified while conducting this dissertation, some of these limitations could not be fully addressed due to the sponsor of this research having an input, while others were recognized and accounted for if possible. First, as the sponsor of this research project KDOT recognized the importance of this research project, however there were limitations on how the countermeasures were installed, which ones could be used, and past experience they had with maintaining countermeasures long-term. Additionally, some WWD countermeasures (e.g. raised pavement markings) could not be utilized due to Kansas environmental factors such as snow and ice. A significant limitation was evaluating the effectiveness of some of the countermeasures. As described previously, sites had one or more countermeasures and isolating which countermeasure was more effective could not be quantified. Additionally, using multiple types of countermeasures may have influenced driver behavior rather than focusing on just one type of countermeasure. Again, these decisions were influenced by the sponsor of the research project.

8.5 Future Research

Future research on WWD incidents in Kansas should look at several key items. This includes varying the type of ramps that are investigated, which includes those ramps that are known to be susceptible to WWD movements and those that are not known to be susceptible to WWD movements. The varying ramp types will provide an even greater data variation to help explain WWD incidents and why a driver chose to enter the ramp incorrectly. Further studies utilizing each individual countermeasure on a single ramp should be conducted to evaluate each countermeasure separately. By evaluating each countermeasure individually these ways, it could provide further quantifiable evidence to determine how each countermeasure assisted in reducing WWD incidents under control conditions. Each countermeasure should also be evaluated for their effectiveness on the various driver characteristics of known WWD crashes, such as age, or physical impairments. This data could provide data to assist local agencies with initial countermeasure selection. Furthermore, there is still a need to study data collection methods for WWD incidents, both at signalized and unsignalized interchange ramps as well at higher volume ramps. This will add further data to help evaluate countermeasures at interchanges.

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Appendix A - DOT Survey Table

State Agency	Referenced Document(s) / Source(s)	Latest Revision Date	WWD Countermeasures / Research / Guidelines	WWD Policy
Arizona (ADOT)	Countermeasures for WWD on Freeways / ADOT Traffic Engineering Guidelines and Processes	2016 / 2015	1. Improvements to static signs and pavement markings a. Larger signs: WRONG WAY 48''w x 36''h and DO NOT ENTER 48'' x 48'' b. WRONG WAY and DO NOT ENTER signs mounted on same post c. Low mounted signs: 3' minimum height d. Optional red reflective strips on posts e. Wrong-Way arrows with raised reflective markers surrounding the arrow at the exit ramps f. Left-turn pavement marking guides to assist drivers entering on entrance ramps g. If an overhead sign structure is present, overhead WRONG WAY signs and post mounted WRONG WAY signs are installed	1. Wrong Way signs should be used as a supplement to the Do Not Enter sign (R5-1) where experience indicates the need for such a sign on the basis of wrong way movements, or where an engineering evaluation indicates that it is desirable to install such signs because geometrics are conductive to wrong way entry. Locations where Wrong Way signs may be warranted include: a. Where an exit ramp intersects a two-way crossroad or frontage road b. Where a one-way, right-turning roadway joins a two-way, undivided roadway c. At a divided roadway intersection where traffic from the crossroad may tend to enter the wrong side of the divided road d. Where direct access from abutting property to an exit ramp is permitted e. Where a one-way roadway becomes two-way 2. Wrong Way signs shall not be installed in lieu of the standard regulatory and guide signs at freeway interchanges 3. Approval for use of Wrong Way signs is not required for use on freeway exit ramps or similarly designed traffic intersections

			2. Detection at entrance ramp with alerts to drivers and Transportation Management Center (TMC) a. High-definition radar b. Vehicle-activated flashing LED WRONG WAY signs	a. The use of Wrong Way signs at other locations shall be approved by the Regional Traffic Engineer before they are installed 4. At interchange exit ramp terminals where an exit ramp departing a freeway or highway intersects a crossroad in such a manner that wrong-way entry could inadvertently be made, DO NOT ENTER an WRONG WAY signs are installed to inform road users and discourage wrong-way travel 5. Diamond interchange or one-way exit ramp terminal: a. DO NOT ENTER / WRONG WAY assemblies should be installed adjacent to the left and right-hand sides of the exit ramp at or near the intersection of the crossroad. b. Additional WRONG WAY signs should be installed to the left and right-hand sides of the exit ramp upstream of the intersection. 6. Single-point diamond interchange (with no through frontage road) a. DO NOT ENTER / WRONG WAY assemblies should be installed to the left and right-hand sides of each exit ramp at or near the intersection of the crossroad. b. Additional WRONG WAY signs should be installed to the left and right-hand sides of the ramp upstream of the intersection. If overhead sign structure is present, overhead WRONG WAY signs should be installed. 7. Single-point diamond interchange (with through frontage road) a. DO NOT ENTER / WRONG WAY assemblies should be installed to the left and right-hand sides

				of each exit ramp at or near the intersection of the crossroad. b. Additional WRONG WAY signs should be installed to the left and right-hand sides of the ramp upstream of the intersection. If overhead sign structure is present, overhead WRONG WAY signs should be installed. 8. Partial Cloverleaf or Loop ramp interchange (without right turn island) a. DO NOT ENTER / WRONG WAY assemblies should be installed adjacent to the left and right-hand sides of the exit ramp. b. Additional WRONG WAY signs should be installed to the left and right-hand sides of the ramp upstream of the intersection. If an overhead sign structure is present, overhead WRONG WAY signs should be installed. 9. Partial Cloverleaf or Loop ramp interchange (with right turn island) a. DO NOT ENTER / WRONG WAY assemblies should be installed adjacent to the left and right-hand sides of the exit ramp and he right turn ramp b. Additional WRONG WAY signs should be installed to the left and right-hand sides of the ramp upstream of the intersection. If overhead sign structure is present, overhead WRONG WAY signs should be installed.
Arkansas (ArDOT)	Arkansas 2017 Strategic Highway Safety Plan / Arkansas Motor	2017/ 2017/ 2020	1. Emphasis area action plan: Older drivers	There are no additional policies beyond what is included in MUTCD

	Vehicle and Traffic Laws and State Highway Commission Regulations / Wrong-Way Crash Study		a. Install Wrong Way pavement markings to help warn older drivers b. Lower WRONG WAY sign heights to help alert older drivers and prevent wrong-way crashes 2. The ArDOT will analyze all reported wrong-way crashes on interstate highways and other freeways that are a part of the state highway system to determine whether the installation of additional traffic control devices is warranted and feasible in order to reduce the possibility of future wrong-way crashes 3. In 2018 the ArDOT implemented a low-cost countermeasure job based off the MUTCD including the optional and oversized signs	
Colorado (CoDOT)	I-25 "Wrong Way" Preventive Signage Updates / Work Zone Safety Guidelines	2019 / 2013	1. Crews are in charge of replacing “Wrong Way” signs, and updating highway markings for on-ramps and off-ramps 2. On ramp closure from cross street: a. Type 3 barricades are placed continuously across the on-ramp to prevent entrance	No policies (beyond the MUTCD) were found
Florida (FDOT)	A Data-Driven Approach to Implementing WWD Countermeasures	2018	1. FDOT has installed the required DO NOT ENTER and WRONG WAY signs and pavement markings per the Manual on Uniform Traffic Control Devices (MUTCD), as well as higher Signing and Pavement Marking Standards	No policies (beyond the MUTCD) were found

			a. Static signing and pavement marking (S&PM) standards b. Red rectangular rapid flashing beacons c. Red flush-mount internally illuminated raised pavement markers d. LED highlighted WRONG WAY signs, Sends alerts to RTMC/TMC e. Detection-triggered bank-out signs that flash WRONG WAY f. Delineators along off-ramps g. Wigwag flashing beacons	
Illinois (IDOT)	Emerging Safety Countermeasures for WWD / Wrong Way Driving Prevention Methods / Guidelines for Reducing Wrong-Way Crashes on Freeways / Bureau of Design and Environmental Manual	2014 / 2015 / 2014 / 2020	1. Enhanced DO NOT ENTER and WRONG WAY signing 2. Enhanced pavement marking and improved lane use arrows 3. Guidelines: a. Red retro reflective tape on mounting poles and signs can improve visibility b. Signs with LED lights are more visible, but more expensive c. Barrier delineator that would be visible when traveling the wrong way can help against WWD	1. Operation/ Safety considerations for wrong- way maneuvers: a. Provide channelized medians, islands, and adequate signing 2. Diamond interchange: a. Raised-curve channelization is used on the crossroad 3. Two-quadrant partial cloverleaf interchanges: a. To discourage wrong-way movements into an exit ramp, use a maximum left-turn control radius of 80' from the crossroad into the entrance ramp and a 100' left-turn control radius from the exit ramp onto the crossroad b. Type A: Both exit and entrance terminals are located in advance of the structure and two channelized "T" intersections are formed on the crossroad. However, all turning movements from the crossroad must undergo a "reverse" operation;

				i.e., drivers traveling to the right must turn left and those traveling to the left must turn right
			d. Acute angles between the interchanges and the access road can help guard against WWD	c. Type B: Because the "T" intersections allow normal operations for turning movements from the crossroad, the probability of wrong-way movements are greatly reduced. The exit terminals are located beyond the structure and, due to the lower design speed on the loop ramp, drivers tend to decelerate more on the mainline through lanes in advance of the exit
			e. Two-way frontage roads are more susceptible to WWD	d. Type C: No uniform pattern of operation is realized because traffic on the freeway exits in advance of the structure in one direction and beyond the structure in the other. Movements to the right or left from the crossroad are made by turning left for the opposite direction.
				4. Four-quadrant partial cloverleaf interchange:
				a. The left-turning path from the controlled ramp terminal of the four-quadrant partial cloverleaf Type A must intersect the crossroad downstream from the gore of the exit terminal. The minimum distance of 200' discourages wrong-way movements.
			f. Diamond interchanges have more incises of WWD than full cloverleaf interchanges	5. Interchange intersections:
			g. Detection of wrong-way drivers: Induction loop, magnetic sensors, video image processors, microwave radar	a. The preferred range for intersection angle is 35 to 45 degrees. Lower/shallower angles may increase the risk of WWD movements

			h. Use changeable message signs to alert drivers that a wrong-way driver is on the highway i. Pavement embedded warning lights can deter WWD 4. ParClo interchange: a. Install Keep Right sign if median width is greater than 8' b. Install DO NOT ENTER sign if median width is greater than 12' c. Interchange with island: Additional DO NOT ENTER and WRONG WAY signs can be placed on the island d. At exits, a painted island combined with a left-turn marking extension is recommended 5. Diamond interchange with continuous frontage roads: a. If there is an existing cross street or driveway near the exit gore area, a ONE WAY sign should be installed b. A pair of ONE WAY signs at the beginning of the entrance ramp is recommended if the intersection is unsignalized 6. Diamond interchange: a. No left turn sign near the entrance ramp can also be placed in the median 7. Half-diamond interchange:	b. Wrong-way movements may originate at the ramp/crossroad intersection onto an exit ramp. To minimize the probability of these movements, provide a raised-curb median on the crossroad and sign the ramp according to the ULMUTCD 6. One-way/Two-way rural and urban freeways: a. Off-ramps joining two-way frontage roads should not be used because of the potential for wrong-way entry

			a. Trailblazing signs should be provided to direct drivers to the closest entrance for ramp movements not provided at this interchange	
Iowa (IowaDOT)	Countermeasures for WWD on Freeways	2016	1. High definition radar detection at various mainline locations, with alerts to DOT personnel for Post-Processing 2. Video analytics software detection with alerts to DOT personnel 3. Improvements to static signing and pavement markings a. Targeted improvements: i. Red conspicuity tape ii. Larger signs iii. Two signs mounted on the same post iv. DO NOT ENTER signs installed on both sides v. Wrong-Way pavement marking arrows b. Spot treatments: i. Red conspicuity tape on all DO NOT ENTER and WRONG WAY signs ii. No Right Turn or No Left Turn signs at selected locations iii. Added "Re-check Cross Traffic Before Entering" signs at select locations	No policies (beyond the MUTCD) were found
Michigan (MDOT)	Countermeasures for WWD on Freeways / Guidelines for	2016 / 2014	1. Signing and pavement marking improvements a. Low-mounted WRONG WAY and DO NOT ENTER signs (4')	No policies (beyond the MUTCD) were found

	Reducing Wrong-Way Crashes on Freeways		b. Red reflective sheeting on WRONG WAY and DO NOT ENTER signs c. Stop bars at exit ramps d. Wrong-way pavement marking arrows on exit ramps e. Pavement marking extensions that guide drivers onto entrance ramps f. Paint island between exit and entrance ramps g. Red delineators along exit ramp (on guardrail or on posts) h. Land assignment arrows at top of exit ramp (selected locations; not mandatory) 2. All statewide ramps: a. Low mounted signs and red reflective sheeting on sign posts at all exit ramps, regardless of the interchange type b. Revised signing standard to require low height WRONG WAY and DO NOT ENTER signs (4') and red reflective sheeting on sign posts at exit ramps 3. Geometric modification: a. MDOT implemented a lane separator system that prevents drivers from making left turns onto the exit ramps 4. Partial cloverleaf (ParClo) interchanges:	

			a. Developed enhanced signing and marking treatments to be deployed at these interchanges across the state	
Missouri (MoDOT)	Countermeasures for WWD on Freeways	2016	1. Increased quantity of priority 1 signing a. Doubled up priority signing (ONE WAY, DO NOT ENTER, and WRONG WAY signs); now one sign on each side of ramps b. Deployed at exit ramps and divided highways including turn-arounds and at-grade crossings 2. Blinking LED WRONG WAY sign system with alert to TMC a. No alert to oncoming right-way traffic b. ONE WAY signs and DO NOT ENTER signs are placed at the intersection. Static and blinking WRONG WAY signs are placed along the ramp 3. Blinking LED WRONG WAY sign system without alert to TMC a. No alert to TMC or right-way traffic	No policies (beyond the MUTCD) were found
Nebraska (Nebraska DOT)	Email from a member of the Nebraska Department of Roads Technical Advisory Committee	2020	1. There are no additional countermeasures beyond what is included in MUTCD 2. Optional: a. Retroreflective red sheeting that can be used on sign posts for WRONG WAY an DO NOT ENTER signs	There are no additional policies beyond what is included in MUTCD

New Mexico (NMDOT)	Email from DOT State Traffic Engineer	2020	1. Cloverleaf interchanges: The state has not implemented wrong way detection on cloverleafs 2. Diamond interchanges: The state has started implementing the TAPCO system for four-ramps	No policies (beyond the MUTCD) were found
North Dakota (NDDOT)	NDDOT Policy Memorandum	2011	No countermeasures were found	1.This policy outlines how and where DO NOT ENTER and WRONG WAY signs should be installed at stop controlled divided highway intersections. This is not intended to take the place of engineering judgment. The signs shall conform with respect to size, color, legend, and placement to the latest standards in the MUTCD. a. DO NOT ENTER and WRONG WAY signs shall be installed at all intersections of State/US Highways and Divided Highways with median widths of 30' or greater. The signs will be installed on both sides of the road b. DO NOT ENTER signs may be installed at intersections of Local Roads and Divided Highways with median widths of 30' or greater, if the AADT on the Local Road exceeds 250. The signs will be installed on both sides of the road. c. WRONG WAY signs may be installed to supplement the DO NOT ENTER signs at intersections of Local Roads and Divided Highways with median widths greater of 30' or greater. The signs will be installed on both sides of the road.

				d. DO NOT ENTER signs may be installed at intersections of Local Roads and Divided Highways if there have been two or more crashes in three years related to a vehicle turning the wrong way onto a Divided Highway. The signs will be installed on both sides of the road. If the crash problem persists, WRONG WAY signs may be installed to supplement the DO NOT ENTER signs at the intersection.
Ohio (Ohio DOT)	Countermeasures for WWD on Freeways / Location & Design Manual - Volume 1 / Ohio DOT Roadway Design Standards	2016 / 2020 / 2020	1. Static signing and pavement marking improvements a. Two WRONG WAY signs on the same post, lower sign mounted at 3' b. Pavement marking extension lines to guide drivers onto entrance ramp c. Red reflective tape on sign posts: WRONG WAY and DO NOT ENTER signs d. Additional signs beyond MUTCD minimums (both sides of ramp) e. Yellow painted island between entrance and exit ramps f. Wrong-Way arrows on exit ramps (At some locations, this is not standard) g. At all ramps: Increased the number of DO NOT ENTER and WRONG WAY signs, now one signs on each side of ramp	1. Diverging diamond interchange (DDI): a. Large channelized islands b. The greater the crossover angle, the more the crossover will appear like a "normal" intersection of two different cross routes c. Provide left turn lanes on exit ramps with enough curvature to ensure drivers turn into the inside through lanes and not make a wrong way turn 2. Wrong-way arrow markings are placed on the ramps as follows: a. On ramps where lane-use arrows are not used, place the first wrong-way arrow 10 to 30 feet in advance of stop line. Place the second wrong-way arrow according to engineering judgment b. On ramps where lane-use arrows are used, place the wrong-way arrow in advance of the first lane-use arrow at a spacing equal to or greater than the spacing between the lane-use arrows c. On multi-lane ramps, a wrong-way arrow should be placed in each lane, side by side

			h. At side-by side partial cloverleaf ramps: Implemented the entire improved design configuration 2. Wrong-Way traffic control for partial cloverleaf interchanges (single-lane exit) 3. Wrong-Way traffic control for diamond interchanges (single-lane exit) 4. Flashing LEDs around Wrong-Way signs and alerts a. Alert to TMC and law enforcement b. Two sets of detection plus a camera for verification	2. Traffic control signs are placed as follows: a. Place the WRONG WAY sign in advance of the stop line. The height of the 2nd wrong-way sign should be 3' above the nearest edge of the pavement i. On ParClo interchanges, the WRONG WAY sign between the on and off ramps should be angled 45 degrees toward the off ramp ii. A second set of WRONG WAY signs may be placed on the ramp according to engineering judgement iii. On ParClo interchanges, the optional entrance ramp directional sign assembly should be angled 45 degrees toward the left turning traffic b. The red sign post reflectors shall be added to the STOP sign, DO NOT ENTER sign, and wrong-way sign assembly c. The DO NOT ENTER sign may be angled up to 45 degrees toward left and right turning traffic 3. Raised pavement markers are placed as follows: a. Raised pavement markers on the edge line- shall be two-way white/red on white edge line, two way yellow/red on yellow edge line, and eleven raised pavement markings shall be spaced 40' apart in advance of the stop line; the rest shall be installed per SCD TC-65.11. b. Raised pavement markings on the channelizing line/lane line- shall be two-way white/red, spaced 40' apart and eleven raised pavement markings shall be spaced 40' apart in

				advance of the stop line; the rest shall be installed per SCD TC-65.11.
Oklahoma (ODOT)	N/A	N/A	No countermeasures were found	No policies (beyond the MUTCD) were found
South Dakota (SDDOT)	Email from DOT State Traffic Engineer	2020	There are no additional countermeasures beyond what is included in MUTCD	There are no additional policies beyond what is included in MUTCD
Texas (HCTRA & TxDOT)	Countermeasures for WWD on Freeways	2016	1. Detection at ramps and mainline with alert to Incident Management Center (IMC) a. Initial installation included radar detection and in-pavement loop detectors along the mainline and at exit ramps 2. Alert to oncoming right-way traffic a. A message is displayed on dynamic message signs to warn oncoming right-way traffic 3. In-pavement LED lighting 4. LED-enhanced WRONG WAY signs 5. Enhanced signing at exit ramps, including LED-Enhanced WRONG WAY signs a. Additional static DO NOT ENTER and WRONG WAY signs beyond MUTCD minimums- one on each side of ramp	No policies (beyond the MUTCD) were found

			b. Red reflective tape on sign posts c. Two additional flashing LED WRONG WAY signs- one on each side of ramp d. If there is not enough room to implement all signs at a ramp, then install flashing WRONG WAY signs in lieu of 2 stanard WRONG WAY signs 6. Detection at exit ramps with alert to TMC 7. Mainlane detection with alerts (high definition radar detection devices are installed on overhead sign bridges) a. Mainlane radar detection triggers the following: i. Blank-out dynamic message sign displays WRONG WAY ii. Flashing LED signs downstream attemp to catch driver's attention iii. An alert is sent to the TransGuide TMC, to ebgin response efforts	
Wisconsin (WisDOT)	Countermeasures for WWD on Freeways	2016	1. Static signing and pavement marking improvements a. Additional signs- placed on both sides of ramp rather than one side as required b. WRONG WAY and DO NOT ENTER signs on same post, with lower WRONG WAY sign at 3' mounting height	1. Divided highway with wide median intersection with two-way cross street a. Allow the installation of DO NOT ENTER and WRONG WAY signs. Where the median width is 30 feet or greater, the signs shoul be installed on the median side. 2. Divided Highway with narrow median intersection with two-way cross street

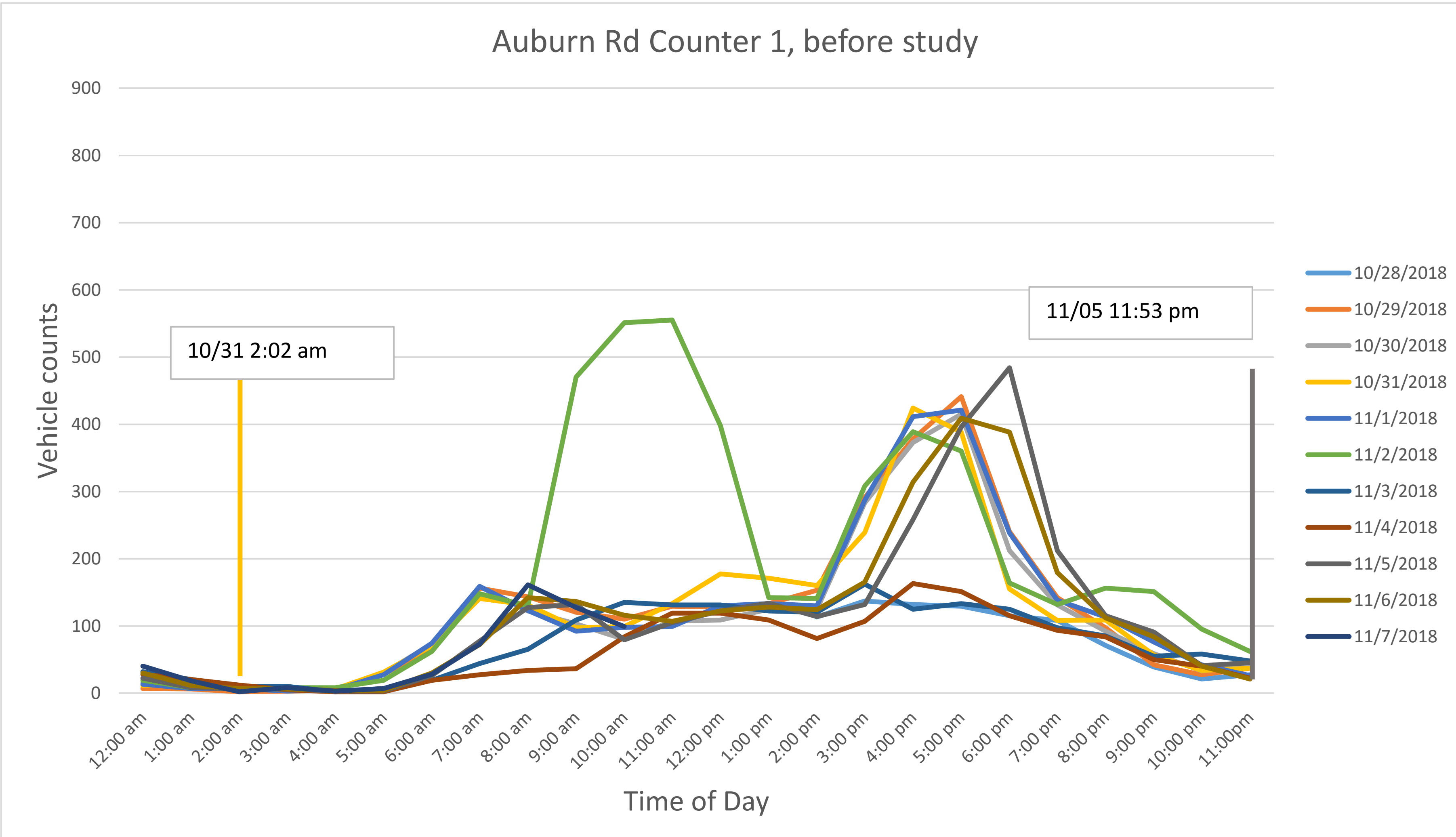
			c. Added NO LEFT TURN and NO RIGHT TURN signs d. Added freeway entrance signs at side by side ramps e. Red reflective tape in a few locations, especially side by side ramps f. Skip line pavement markings to guide drivers onto the entrance ramp 2. Detection with alert to TOC and Milwaukee County Sherrif's Office a. Radar detection devices b. Extensive CCTV camera system on freeways 3. LED-Enhanced WRONG WAY signs (blink continuously at night) a. The blinking LED WRONG WAY signs are typically placed halfway down the ramp with one sign on each side of the ramp. However, placement depends on each individual ramp configuration; need to positions signs so they can't be seen by right-way drivers on freeway	a. Allow for the single installation of DO NOT ENTER and WRONG WAY signs where he median wich is less than 30 feet, the signs should be installed on the outer side. 3. Divided highway with the wide median inersection with interchange ramps a. The typical signing plans according to MUTCD except that the Turn Prohibition signs are designated optional 4. Divided highway with narrow median intersection with interchance ramps a. The typical signing plans according to MUTCD except that the Turn Prohibition signs are designated optional 5. Two-way univided highway intersection with interchange ramps a. The typical signing plans according to MUTCD except that the Turn Prohibition signs are designated optional 6. Transition from two-way univided highway to divided highway a. The typical signing plan according to MUTCD except that the Turn Prohibition signs are designated optional 7. Divided highway with intersecting sideroad a. The typical signing plans according to MUTCD should be sufficient for most side roads of

				these types. Additional needs may be met by insalling additional signs b. Allow for the single installation of the DO NOT ENTER and WRONG WAY signs. Where the median width is less than 30 feet, the signs should be installed on the outer side. 8. Divided highway with narrow or wide median driverway a. The typical signing plans according to MUTCD should be sufficient for most driveways of these types. Additional needs may be met by installing additional signs b. Allow for the single installation of the DO NOT ENTER and WRONG WAY signs. Where the median width is less than 30 feet, the signs should be installed on the outer side. 9. Roundabouts a. The typical signing plans according to the MUTCD should be sufficient for the prevention of wrong way movements on roundabouts with single and multiple approach lanes and interchange off-ramps 10. Divided highway with signalized wide median intersection a. The typical signing plans according to the MUTCD should be sufficient for most intersections of this type. b. Allow for the single installation of the DO NOT ENTER and WRONG WAY signs. Where the median width is 30 feet or greater, the signs should be installed on the median side

				11. Divided highway with signalized narrow median intersection a. The typical signing plans according to the MUTCD should be sufficient for most intersections of this type. b. Allow for the single installation of the DO NOT ENTER and WRONG WAY singns. Where the median with is less than 30 feet, the signs should be installed on the outer side.

Appendix B - Safety Conference Materials

Group:	
______________________ Ramp	Recommendations for countermeasures
Which countermeasures? Where? Why?	

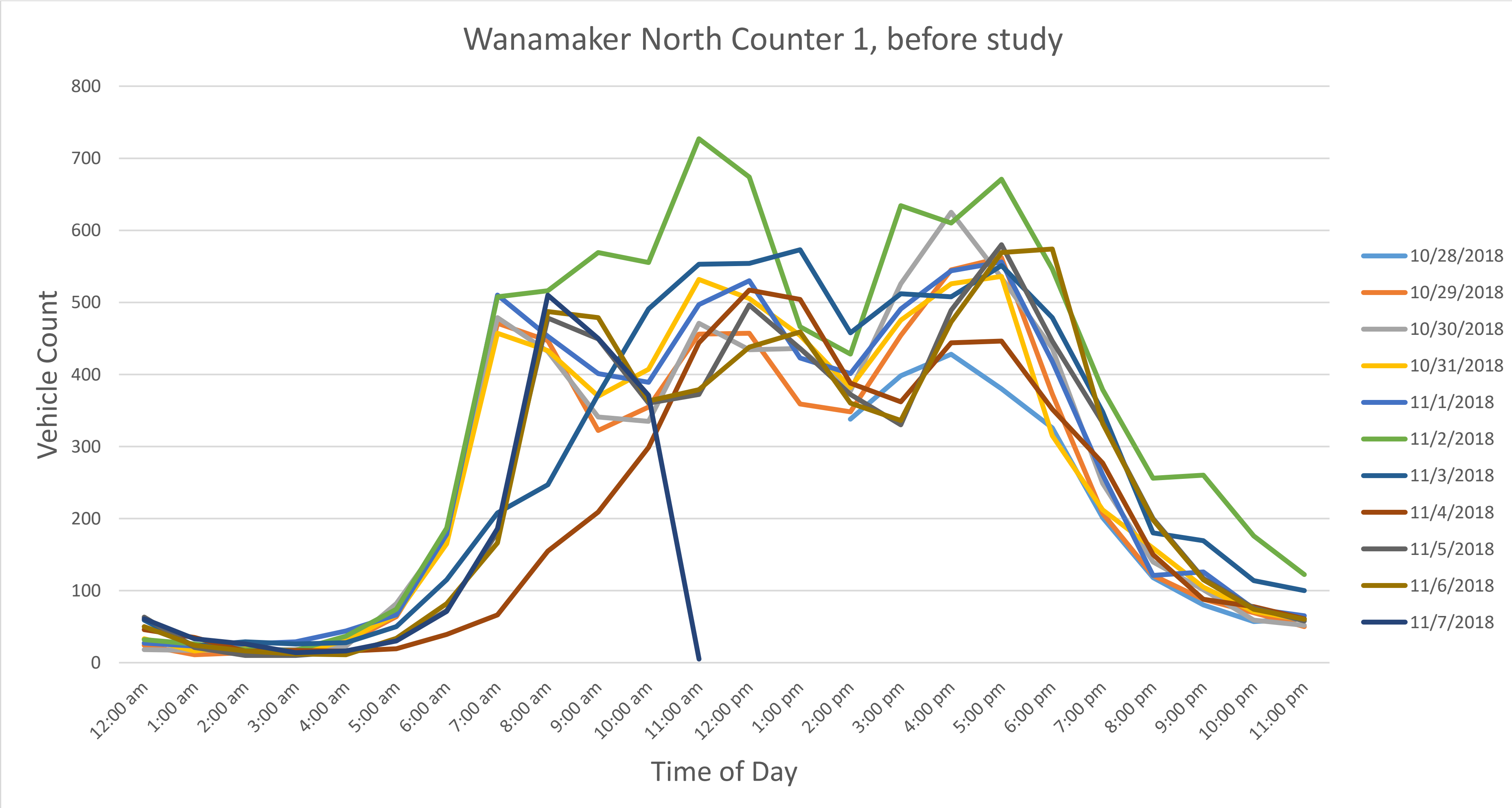


Auburn counter 1

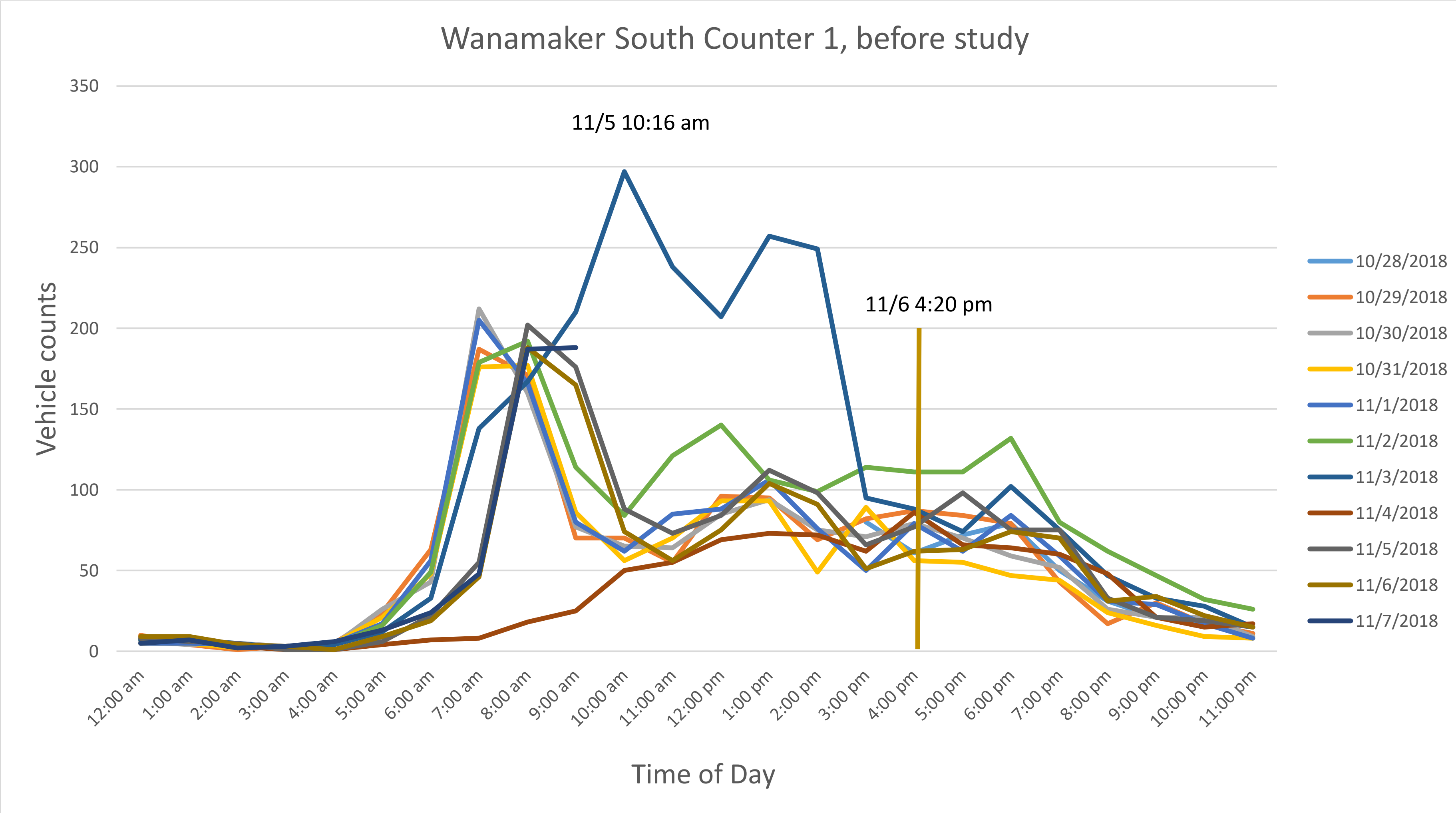
Date	Time	Class	Speed (In MPH)
10/28/2018	7:39:13 PM	2	32
10/29/2018	1:21:28 PM	1	17
10/31/2018	2:02:35 AM	2	34
11/2/2018	12:31:31 PM	1	21
11/5/2018	11:53:35 PM	2	35
11/6/2018	8:10:23 PM	2	26

Auburn counter 2

Date	Time	Class	Speed (In MPH)
10/31/2018	2:02:50 AM	2	34
11/5/2018	11:53:56 PM	2	31



N Wanamaker counter 1					N Wanamaker counter 2			
Date	Time	Class	Speed (In MPH)		Date	Time	Class	Speed (In MPH)
11/6/2018	12:36:58 PM	1	29		11/1/2018	7:29:45 PM	1	82
11/6/2018	8:26:31 AM	2	145		11/7/2018	9:48:39 AM	1	35
					11/7/2018	9:55:56 AM	1	21
					11/7/2018	9:57:41 AM	1	20
					11/7/2018	10:01:37 AM	1	119
					11/7/2018	10:05:46 AM	1	24
					11/7/2018	10:25:57 AM	1	24



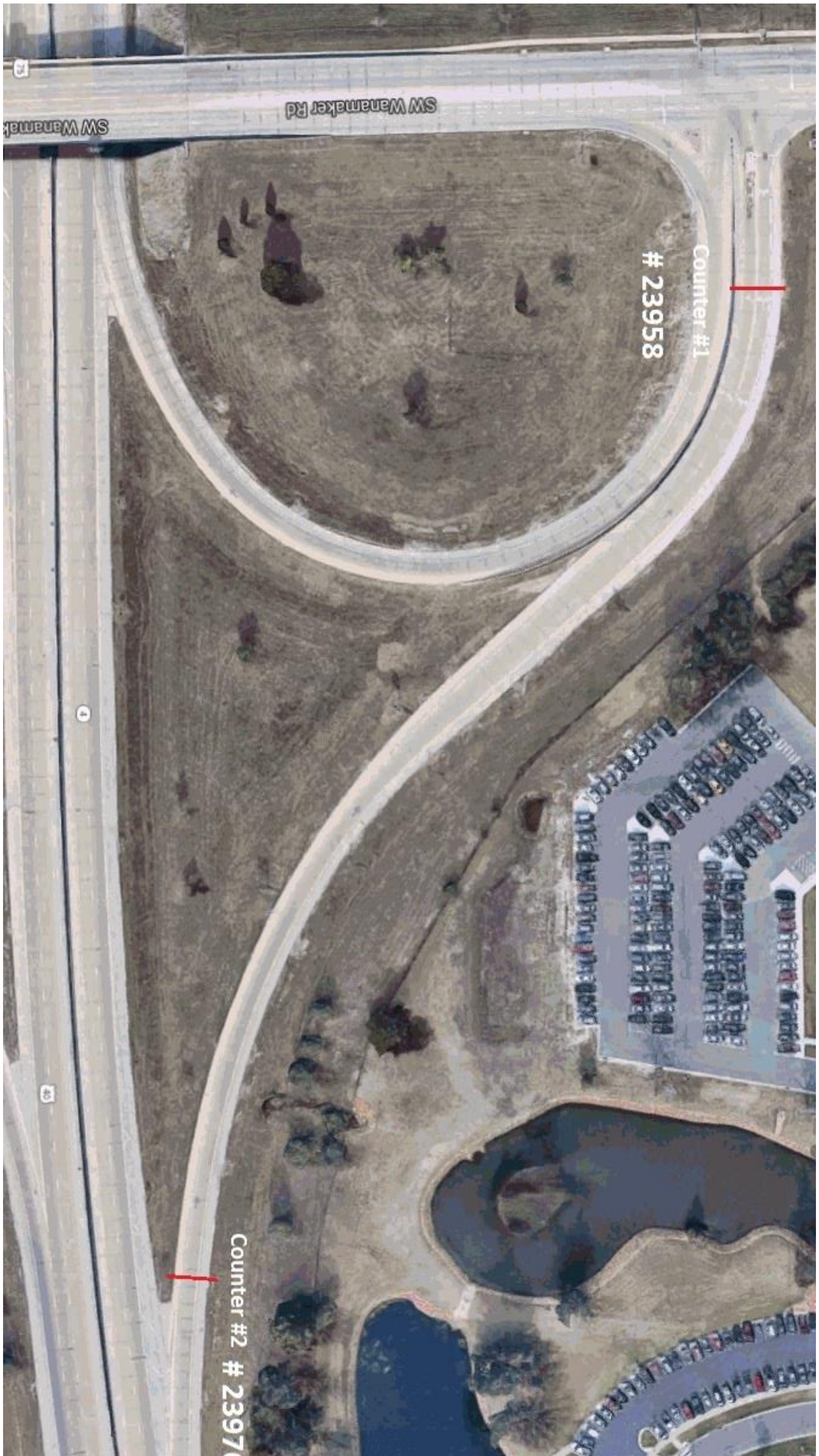
S Wanamaker Rd Counter 1					S Wanamaker Rd Counter 2			
Date	Time	Class	Speed (In MPH)		Date	Time	Class	Speed (In MPH)
11/5/2018	10:16:50 AM	2	29		11/5/2018	10:17:02 AM	2	35
11/6/2018	4:20:28 PM	3	26		11/6/2018	4:20:40 PM	3	32
11/5/2018	1:58:51 PM	5	24					

py places
Counter #1
32124
Counter #2
32125
SW Auburn Rd


WRONG
WAY
Auburn Rd ramp
view from midpoint
West Lawn


WAY
Auburn Rd ramp
View to I-70 entrance


Auburn Rd ramp
view from exit

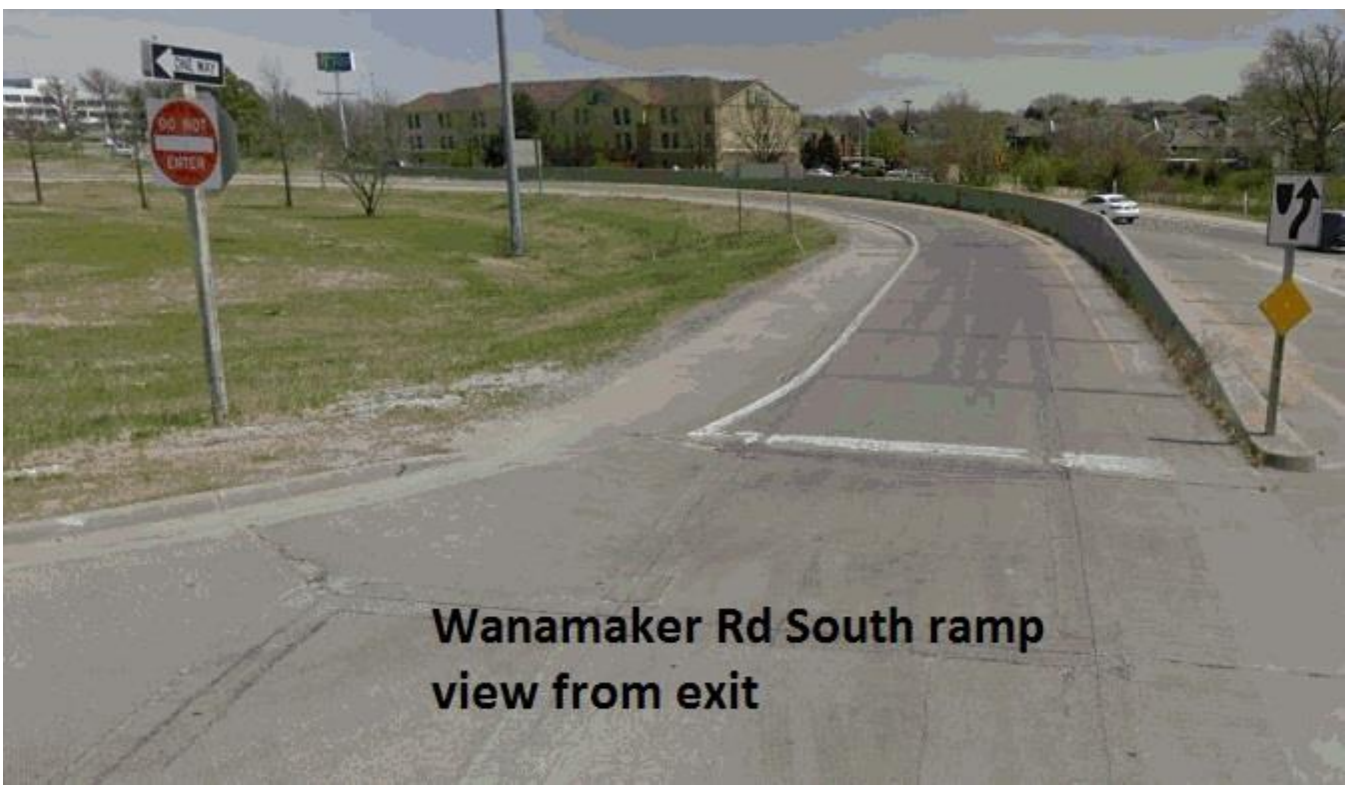

SW Wanamaker Rd
Counter #1
23958
Counter #2
23976


ONE WAY
DO NOT ENTER
Wanamaker Rd North ramp
view from exit

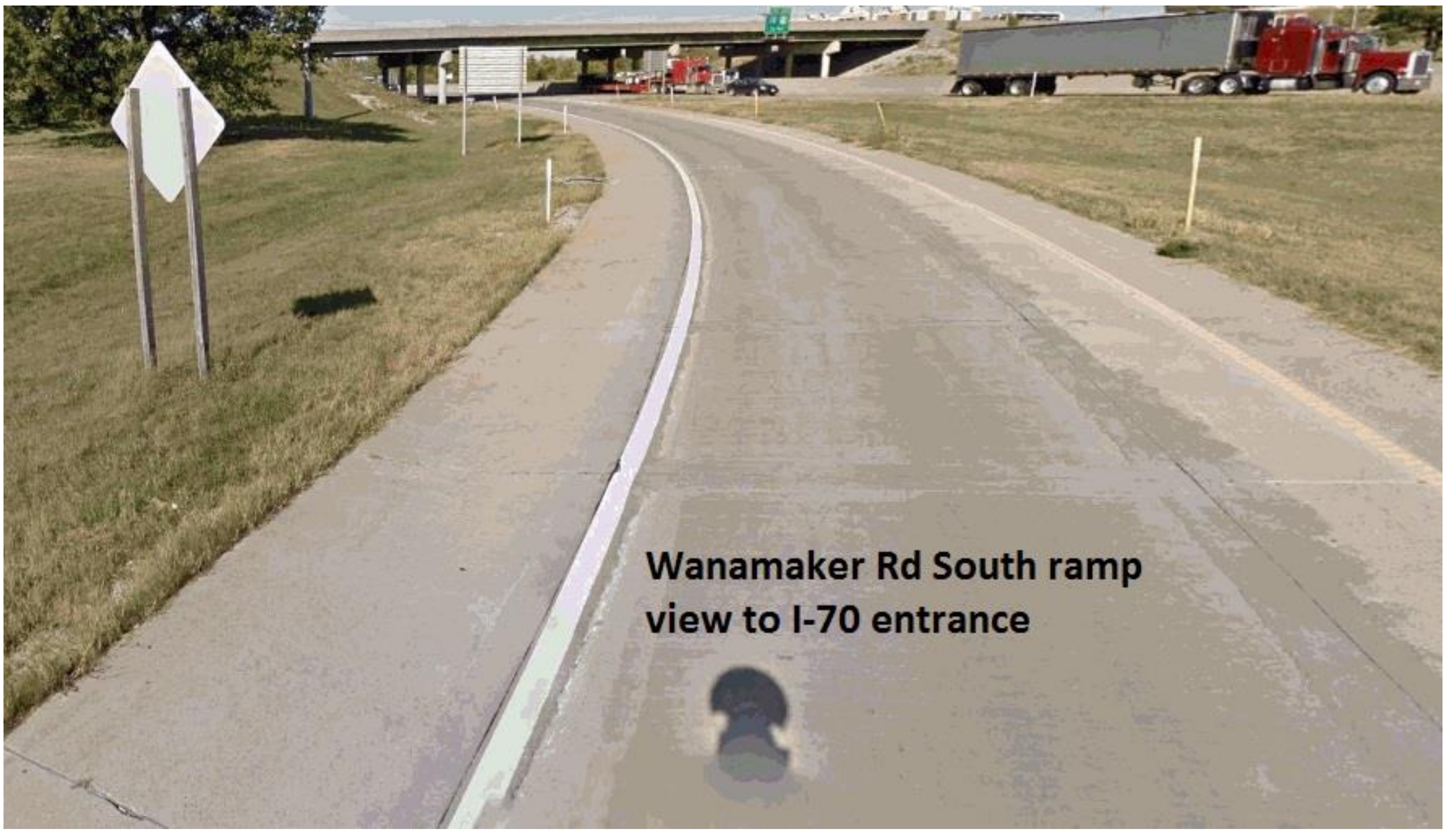

WRONG WAY
Wanamaker Rd North ramp
view from midpoint


Wanamaker Rd North ramp
View to I-70 entrance


maker Rd
Counter #2
23471
SW Wanamaker Rd
Holiday Inn Express
& Suites Topeka West...
SW Robinson Ave
SW Robinson Ave
31113
Counter #1


ONE WAY
DO NOT ENTER
Wanamaker Rd South ramp
view from exit

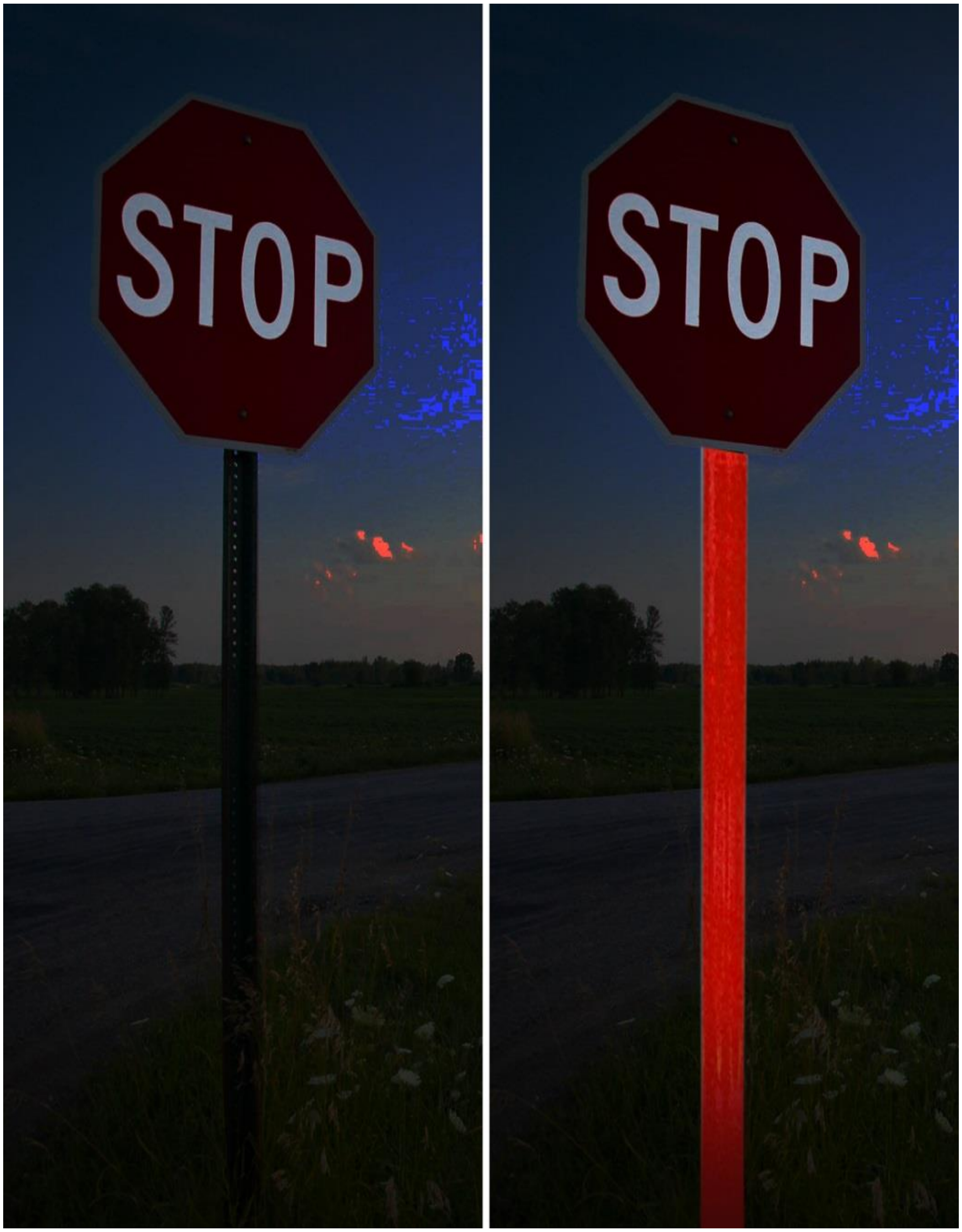

Wanamaker Rd South ramp
view from midpoint


Wanamaker Rd South ramp
view to I-70 entrance

Time actuated Flashing LED Wrong Way sign

Oversized Wrong Way sign (42 X 30)

Oversized and Lowered signs



Red Retroreflective Tape/Delineators

Appendix C - Additional Photos

C.1 Before Study

Figure C. 1: Adams South Counter 2

Figure C. 2: Adams South Counter 2

Figure C. 3: Adams South Counter 1

Figure C. 4: Adams South Counter 1

Figure C. 5: Adams North Counter 2

Figure C. 6: Adams North Counter 2

Figure C. 7: Adams North Counter 1

Figure C. 8: Adams North Counter 1

Figure C. 9: Gage Blvd Counter 2

Figure C. 10: Gage Blvd Counter 2

Figure C. 11: Wanamaker North Counter 2

Figure C. 12: Wanamaker North Counter 2

Figure C. 13: Wanamaker North Counter 1

Figure C. 14: Wanamaker North Counter 1

Figure C. 15: Wanamaker North Counter 1

Figure C. 16: Auburn Rd Counter 2

Figure C. 17: Auburn Rd Counter 2

Figure C. 18: Auburn Rd Counter 2

Figure C. 19: Auburn Rd Counter 1

Figure C. 20: Auburn Rd Counter 1

Figure C. 21: Wanamaker South Counter 2

Figure C. 22: Wanamaker South Counter 2

Figure C. 23: Wanamaker South Counter 2

Figure C. 24: Wanamaker South Counter 1

Figure C. 25: Wanamaker South Counter 1

C.2 First After Study

Figure C. 26: Adams Street South, Later Discovered Road Tube Damaged

Figure C. 27: Adams St North Counter 2, Broken Road Tube

C.3 Countermeasure Installation

Figure C. 28: Installation of Oversized and Lowered Wrong Way Sign at Gage Blvd Ramp

Figure C. 29: Installation of RRFDs on Gage Blvd

Figure C. 30: Installation of 2nd Oversized and Lowered Wrong Way Sign on Wanamaker Rd North

Figure C. 31: Installation of 1st Oversized and Lowered Wrong Way Signs on Wanamaker Rd North Ramp

Figure C. 32: Installation of 1st Oversized and Lowered Sign at Wanamaker Rd South ramp

Figure C. 33: Installation of 2nd Oversized and Lowered Wrong Way Sign on Wanamaker South Ramp

Figure C. 34: Installation of Flashing LED Wrong Way Sign at Auburn Rd Ramp

Figure C. 35: Installation of Flashing LED Wrong Way Sign at Auburn Rd Ramp

C.4 Data Collection Method

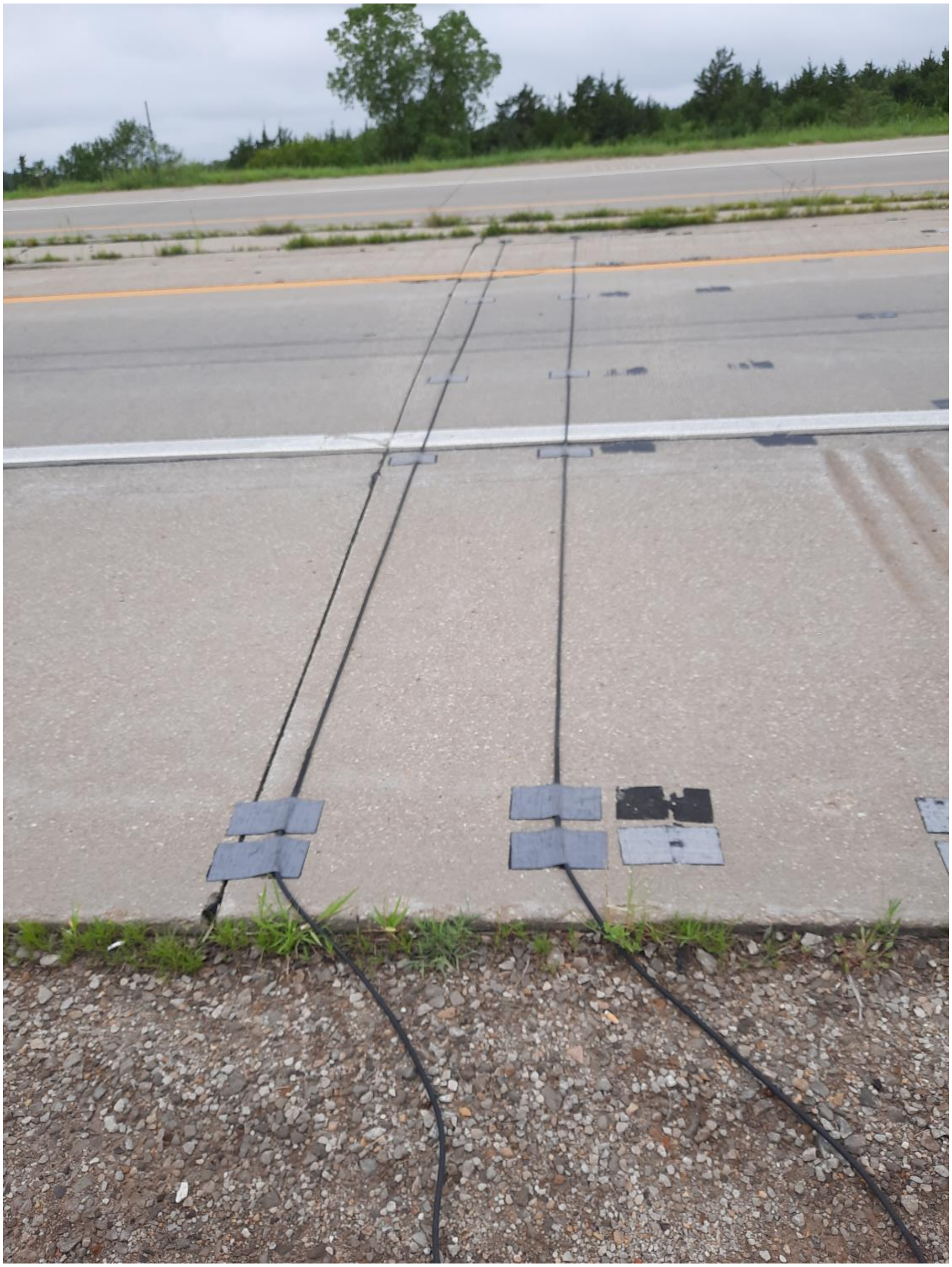


Figure C. 36: Counter 1 Location on Auburn Rd Ramp

Figure C. 37: Counter 2 Location on Auburn Rd Ramp

Figure C. 38: Counter 3 Location on Northbound Auburn Rd

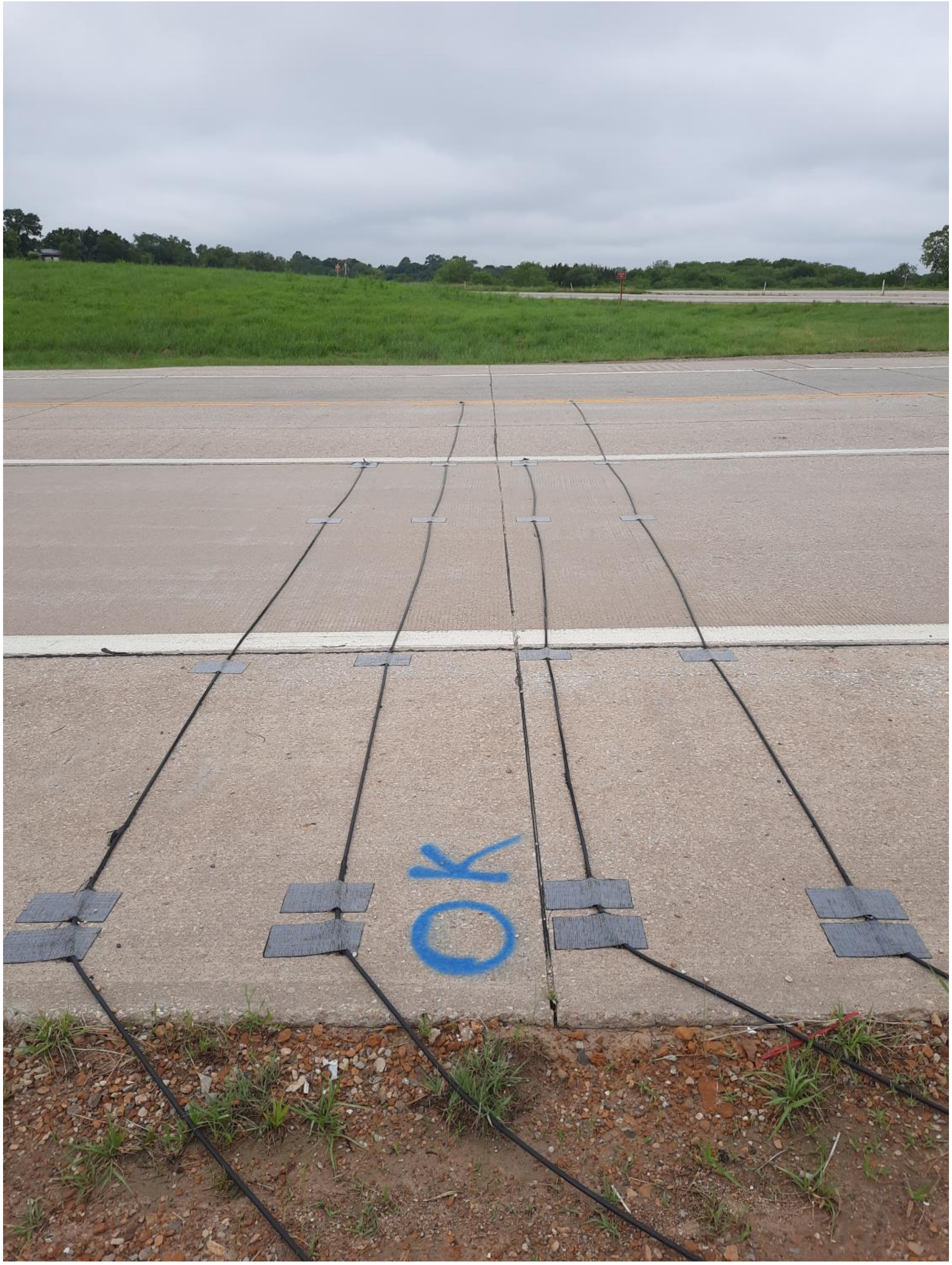


Figure C. 39: Counter 3 Layout on northbound Auburn Rd

Figure C. 40: Counter 4 Location on Southbound Auburn Rd

Figure C. 41: Counter 4 Location on Southbound Auburn Rd

Figure C. 42: Counter 5 Location on I-70 Entrance Ramp

Figure C. 43: Counter 5 Location on I-70 Entrance Ramp