FEASIBILITY ANALYSIS OF A CONNECTED VEHICLE WRONG-WAY DRIVER COUNTERMEASURE SYSTEM

A Thesis

By

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ABSTRACT

Despite existing countermeasures for addressing wrong-way driving, crashes relating to wrong-way driving continue to occur on Texas roads. These crashes tend to be more severe than typical crashes since they tend to be head-on collisions at high speeds. This study considers a countermeasure designed to use connected vehicle communications, on high-speed, controlled access, freeway-type facilities. This study quantifies the impacts of a connected vehicle wrong-way driving countermeasure (CV-WWD) system, translates them into a benefit-cost ratio that represents the economic value of the system, and performs the analysis on a generic case and case study to draw conclusions on potential deployment needs for the system.

To determine the probability that a vehicle received a warning about the wrong-way driver (WWD) early enough to be able to make an informed decision earlier than if they were not equipped, calculations were done to determine vehicle presence, connected vehicle capability probability, and successful warning message transmission. The increased time for response was translated into reduced crash probability for various market penetration rates (MPRs) of connected vehicles. Each analysis used the baseline scenario as the case where the MPR of zero, representing no connected vehicles, was used as a baseline for the economic analysis. Reduced crash probability for a single event was used to estimate the benefit over the life of the system. The benefit-cost ratio was this benefit divided by the cost of the system.

The findings of the study indicate that the WWD crash rate is the driving factor for economic feasibility. Each traffic density considered had similar MPRs for feasibility across each crash rate, with a rate of one WWD crash ever five years needing about 37 percent MPR and a rate of once a year only needing 17 percent MPR to break even. The case study on US-75 in downtown Dallas, TX, which has a crash rate of 1.8 WWD crashes per year, showed that a system installed there could be feasible with an MPR as low as seven percent. These results show that the system has potential to be economically feasible at low MPRs with a sufficiently high crash rate.

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This topic was largely guided by Dr. Alireza Talebpour and Dr. Kevin Balke. These two worked a great deal with me to refine the topic into something that I could analyze within the time frame available to me. Dr. Talebpour has been a large aid in helping me formulate my analysis and talk through my results. His guidance has surely improved the quality of this thesis beyond what I could do on my own. Dr. Balke has guided my early career and aided me with my technical writing skills. His insight into this topic and other projects we have worked on together has helped me achieve a higher level of analytical ability which has, and will continue to, improve my job performance.

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Mrs. Melisa Finley, the principal investigator of the TTI project developing the system analyzed in this study, deserves recognition for allowing me to work my thesis around her project. Throughout my research, she has provided insight into wrong-way driving behavior and provided data that was crucial to the analysis performed for this thesis.

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CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Professor Alireza Talebpour and Dr. Kevin Balke of the Civil Engineering Department and Professor Srinivas Shakkottai of the Department of Electrical Engineering.

The data for wrong way crash information was provided by Mrs. Melissa Finley, the principal investigator of the Texas A&M Transportation Institute project considering a connected vehicle wrong-way driving countermeasure system. All work for the thesis was completed by the student, with economic advisement from Professor Mark Burris of the Department of Civil Engineering.

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NOMENCLATURE

AIS	Abbreviated Injury System
BAC	Blood Alcohol Content
BSM	Basic Safety Message
CRIS	Crash Records Information System
CV	Connected Vehicle
CV-WWD	Connected Vehicle - Wrong Way Driving
DSRC	Dedicated Short Range Communications
FDOT	Florida Department of Transportation
I2V	Infrastructure to Vehicle
ITIS	International Traveler Information Standard
ITS	Intelligent Transportation Systems
MPR	Market Penetration Ratio
NCTCOG	North Central Texas Council of Governments
NTSB	National Transportation Safety Board
OBU	On Board Unit
OR	Odds Ratio
RITA	Research and Innovative Technology Administration
RSA	Roadside Alert
RSE	Roadside Equipment
SAE	Society of Automobile Engineers
TIGER	Transportation Investment Generating Economic Recovery
TTI	Texas A&M Transportation Institute
TxDOT	Texas Department of Transportation
USDOT	United States Department of Transportation
V2V	Vehicle to Vehicle
WWD	Wrong Way Driver/Driving

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CHAPTER I

INTRODUCTION

Wrong-way driving (WWD) events do not happen often but, the crashes involving a WWD are often severe. Numerous countermeasures have been attempted to prevent WWD maneuvers, but WWD events continue to occur. WWD violations are often the result of physical or emotional impairment of the driver (*1*). Impaired drivers are not as responsive to traffic control devices as alert drivers, so additional signage and in-road markings may not be the best method for preventing WWD events. Connected vehicles (CVs) can be used to warn the WWD and anyone upstream of the WWD about the situation in real time. CVs are a technology that allows messages to be sent to vehicles to display a message to the driver inside the vehicle. These messages can be sent over a limited distance and are customizable to many different situations. Additionally, it gives vehicles traveling the correct direction a warning about the violation so that they can take appropriate actions to maintain safe travel. Using CVs as a countermeasure provides the chance to warn every equipped vehicle potentially affected by the WWD about the WWD event faster and more effectively than existing countermeasures. Even though a CV-WWD system will be able to inform a WWD of their error and warn vehicles traveling the correct direction of the danger, the system will be significantly more expensive than other countermeasures.

Equipment, maintenance, and operational costs for the system would only be offset if the system were able to warn enough travelers about WWD events occurring on the facility to accumulate benefits equal to or greater than the cost of the system. To deploy a system effectively, there must be a way to determine if the system would make economic sense. This study aims to create guidelines that could be used to determine if a location would economically benefit from a CV-WWD system deployment. The guidelines account for the abilities of the system (including message propagation), potential reduction of crashes of varying severity, and the costs of deployment.

Problem Statement

Quantification of the performance and translation of performance into economic value is necessary for determining the feasibility of the CV-WWD system over other countermeasures. This research produces guidelines and criteria for the deployment of CV-WWD system on a facility based on the costs and conditions of the facility in question. Increased costs will be manifested in the costs to install and maintain the system over other countermeasures. The tradeoff is the increased ability for the CV-WWD system to inform travelers over traditional WWD detection and warning systems. The benefit of the CV-WWD system is reduced crashes and the information about the danger ahead. However, the effectiveness of the CV-WWD system is highly dependent on the number of equipped vehicles on the facility. This study aims to evaluate potential performance the CV-WWD system at various market penetrations which will be compared to traditional sensor based detection and warning system and a no warning or detection system. The comparison will consider the time for any warning to be issued, if there is one, and the potential for the countermeasure to save lives. This analysis will aid the Texas Department of Transportation (TxDOT) in determining when to deploy the CV-WWD system by using a cost-benefit analysis which compares the CV-WWD system with varying market penetration ratios (MPRs) to existing WWD countermeasures.

The system analyzed in this thesis is designed for a specific type of facility. The system boundaries are: high-speed, controlled access, freeway-type facilities. These boundaries include the main lanes of TxDOT freeways and toll facilities, and their entrance and exit ramps. Frontage roads, cross-street of the frontage road intersections, the cross-streets themselves, urban roadways operated by municipalities, or rural freeways without a physical barrier are *not considered* within the system boundaries.

Objectives

The main goal of this thesis is to provide a framework for determining if a CV-WWD countermeasure could make economic sense for a site compared to other WWD countermeasures. These subtasks support the completion of this objective:

- Determine analytical formulation to explain the communication capabilities of the CV-WWD in different combinations of traffic characteristics. Characteristics considered including traffic behavior (i.e. vehicle density on the facility during the WWD event and free-flow speed), market penetration of CV technology, and the length of time the WWD event lasts.
- Develop an economic analysis framework to compare different WWD countermeasures. This study seeks to find the market penetration/density/WWD rate configuration needed for the CV-WWD system to be economically reasonable in a general case.
- Employ a case study on a stretch of US-75 in Dallas, TX to act as an example of how to use the analysis to make a decision on installation.
- Summarize generic guidelines for an average Texas corridor and identify potential geometric factors in WWD movements.

Overall, this thesis is attempting to describe the performance of a WWD countermeasure system that uses CV communications to transmit warnings about a WWD via infrastructure and vehicle-to-vehicle message propagation to send a warning about a detected WWD so drivers have more time to respond and can avoid a crash. This advanced warning is anticipated to allow vehicles to make informed decisions early and greatly reduce the odds of a crash occurring. This is so that an agency looking to deploy the system can decide if it is economically feasible to install the system on a facility.

Thesis Organization

This thesis contains five chapters. Chapter I provides an introduction into needs associated with wrong-way driving and presents the objective is the study. Chapter II contains a literature review to better identify WWD characteristics, existing countermeasures, and connected vehicle technology. The study methodology, including the steps to represent connected vehicle communications, procedure for the economic analysis, and the procedure to develop guidelines for the CV-WWD system, is outlined in Chapter III. Chapter IV delivers the results for a generic facility that follows a crash distribution identical to the state of Texas and a case study over US-75 in Dallas, Texas. Finally, Chapter V summarized conclusions from the generic analysis and case study, study limitations, and topics to be addressed in future research.

CHAPTER II

LITERATURE REVIEW

Wrong Way Driver Characteristics

A study by the Texas A&M Transportation Institute (TTI) showed that WWD collisions account for only 0.2 percent of total crashes in Texas. However, when these crashes occur, they are often fatal, accounting for about 1.4 percent of fatal crashes on divided highways (*1*). The WWD crash represents a disproportionate number of fatal crashes. To put this into better perspective, one out of every 100 crashes in rural Texas highways are fatal, but 15 out of every 100 WWD crashes are fatal (*1*). The National Transportation Safety Board (NTSB) report found that the primary WWD maneuver is entering the freeway the wrong-way on an exit ramp (*2*). NTSB also found that WWD collisions are more likely to occur on the weekends at night, with 78 percent of fatal WWD collisions occurring between 6:00 pm and 6:00 am (*2*). The nighttime WWD crashes tend to occur in the early morning hours (*3*). This is consistent with the times that bars typically close on the weekends. Therefore, it is no surprise, that alcohol impairment is a major contributing factor in most WWD incidents (*2,3*). Some of the more interesting findings of previous studies showed that crashes usually occur in the lane closest to the median (*2,3*). It makes sense that most of the WWD crashes occur in the lane closest to the median because that is the lane that is the rightmost lane, or the slow lane, for the WWD. In attempts to drive safely, the WWD would likely choose the rightmost lane, so anyone traveling the correct direction in the leftmost lane, or the fast lane, would be set for a head on collision.

A recent study, done by Ponnaluri, on the odds of wrong-way crashes and resulting fatalities helps reinforce these statistics (*4*). This study took a data set from the Florida Department of Transportation (FDOT), separated the data into separate databases based on crashes, occupants, and vehicles, and created models to assess which variables were statistically significant when comparing WWD and non-WWD crashes and fatal versus non-fatal WWD crashes (*4*). Each significant variable had an odds ratio (OR), which presented how much more likely involvement in a WWD crash or fatal WWD crash was than the reference variable (*4*). The odds of a WWD crash increased by 5 to 15 times when the blood alcohol content (BAC) was twice or four times the legal limit and the odds of a fatal crash increased up to 20 times when compared to the legal BAC limit (*4*). The results also confirmed that a WWD event was more likely to occur on the weekend (OR of 1.57) and the early morning hours (OR of 4.17 for WWD crash and 2.44 for fatal crash when compared to the early afternoon) (*4*). Interestingly, limited access facilities, like tollways or freeways, were not as likely as non-limited access, like arterials (OR of 2.29 for arterials) (*4*). However, non-limited access facilities were under a quarter of the likelihood (OR of 0.24) of having a fatal WWD crash (*4*). This is makes sense since it would be easier to drift into the opposing direction's travel path in a non-limited facility, but the speeds are not as high. A WWD on a limited access facility would think that they are traveling on the freeway and would be traveling at high speeds, drastically increasing the odds of a collision being fatal.

This information suggests that WWD situations involve an impaired driver. A TTI study, done by Finley, aimed to determine where impaired drivers tend to look while they drive, in an attempt to identify where to place WWD countermeasures. The study found that alcohol-impaired drivers tend to look at the pavement in front of the vehicle and not look ahead of the vehicle as much as non-impaired drivers (*5*). This means that the most effective traffic WWD countermeasures may be the in-road devices. One of the recommendations of the study was to explore the use of CVs for WWD detection, warning and intervention (*5*). CVs would offer in vehicle messages that could be effective at alerting the driver traveling the wrong-way about their error and to warn equipped vehicles traveling the correct direction on the same facility about the WWD detected ahead.

Existing and Innovative Countermeasures

Another TTI study, done by Cooner et al., looked at the existing countermeasures around the United States to see what measures existed, at the time, to try to prevent WWD maneuvers. Cooner et al. found that a variety of signs and markings were used for WWD countermeasures including (*3*):

- DO NOT ENTER signs with and without flashing beacons
- WRONG WAY signs with and without flashing beacons
- ONE WAY signs
- Red-backed pavement markers
- Wrong-way pavement arrows
- Lowered mounting heights for signs
- Supplemental signs saying RAMP or FREEWAY
- Overhead mounting of WRONG WAY signs

Cooner et al. also reported some intelligent transportation systems (ITS) applications as countermeasures. These systems typically involve detection of the WWD using a series of vehicles detectors to determine the direction of travel on a location that the WWD could begin traveling the wrong direction (*3*). New Mexico and Washington use flashers and LED wrong-way signs respectively in conjunction with detectors to implement the WWD countermeasures when a WWD is detected (*3*). FDOT uses loop detectors a bridge in Florida to detect vehicles traveling in the wrong-way which triggers an alert to a nearby police substation and activates an overhead signal system on span wire which warns motorists traveling in the proper direction that a WWD may be approaching (*3*). This same system also uses the in-pavement warning lights that are activated by wrong-way vehicles consisting of lights that are placed laterally across the travel path (*3*). In light of the study done by Finley, these countermeasures may not be very effective because the impaired driver tends to look at the pavement in front of the vehicle more than the surroundings. Thus, there is still a need for a better countermeasure system.

In another study, done by Finley et. al., data on Texas Freeways from 2007 to 2011 was collected and analyzed WWD crashes (*6*). Their study found that 86 percent of wrong-way crashes in Texas occurred in urban areas (*6*). Finley et. al. also identified the top ten freeways with the highest number of wrong-way crashes. These are shown in Table 1. Finley et. al. obtained the data used to create Table 1 from the Crash Records Information System (CRIS) which contains information about crashes in Texas from 2010 to 2014. Wrong-way-related crashes were identified by employing the Contributing Factor ID variable.

Table 1. Top 10 Texas Freeways with Highest Number of Wrong-Way Crashes (2010–2014) (*6*)

Highway System	Highway Number	Non-fatal	Fatal	Total	Percent Total Crashes[a]	Percent Fatal Crashes[b]
I	35	130	19	149	13	14
I	20	93	18	111	9	13
I	10	88	16	104	9	11
I	45	86	8	94	8	6
I	30	53	15	68	6	11
I	410	32	3	35	3	2
I	35E	27	1	28	2	1
I	610	24	5	29	2	3
US	290	24	1	25	2	1
US	75	22	2	24	2	1
Total		579	88	667	56	63

I = Interstate; US = United States

[a] Percent computed out of all wrong-way crashes (n = 1187).

[b] Percent computed out of all fatal wrong-way crashes (n = 139).

Finley et. al. also summarized current WWD response protocols in the state of Texas. The study notes that most wrong-way vehicles are currently detected by motorists using their cell phones to call law enforcement agencies to report the event through 911 (*6*). Data from the San Antonio Police Department showed that the average duration of a WWD event, based on 911 calls, was about 4 minutes (*6*). However, WWD events are skewed towards shorter durations with 61 percent of events lasting less than or equal to 2 minutes (*6*).

Connected Vehicles

Connected Vehicles (CVs) are part of a plan set by the United States Department of Transportation (USDOT) to develop Intelligent Transportation Systems (ITS). The Research and Innovative Technology Administration (RITA) has focused the plan on connected vehicle research. CVs use radios to send messages containing traveler information to other CVs within range. The messages are sent anonymously and are received and decoded by any radio that receives the message. These radios use dedicated short-range communications (DSRC), which is a 75 MHz electromagnetic band around the 5.9 GHz spectrum, for location-based vehicle-to-vehicle (V2V) and infrastructure-to-vehicle (I2V) messaging (*7*). This message system is designed to have a range of 3,000 feet and can send messages in as little as 200 microseconds (*7*). One of the focuses RITA made in the effort was privacy. This objective is currently accomplished by using certification for each message to ensure anonymity can be maintained (*8*).

The Society of Automobile Engineers (SAE) wrote a standard for the DSRC messages called “SAE J2735 – Dedicated Short Range Communications (DSRC) Message Set Directory”. Two messages described in this standard are the basic safety message (BSM) and roadside alert (RSA). The BSM is sent ten times a second by the on-board unit (OBU), which is a message rate that many safety applications require (*9*). This message contains information about the sending vehicle's position, speed, acceleration, heading, and steering wheel angle (*10*). These messages are meant to exchange safety data with the vehicles around them. Alternatively, the RSA is meant to send alerts for nearby travel hazards. For this reason, the structure of the RSA includes information about the type of event and priority of the event (*10*). The RSA can also contain additional text codes to describe event, applicable headings, distance the message applies, and information about the position of the subject of the message (*10*). The International Traveler Information Standard (ITIS) codes make up the information communicated in an RSA. ITIS codes are part of another SAE dictionary: SAE J2540. An ITIS code already exists for wrong way scenarios, ITIS code 1793: "vehicle-traveling-wrong-way" (*11*). This code can be used to identify the message type as "Unusual Driving" (*11*). The system discussed in this thesis would likely employ these two message types. The BSM could be used for detection of a WWD and the RSA would be the warning message transmitted CVs to inform them about the WWD.

CHAPTER III

STUDY METHODOLOGY

The feasibility of the CV-WWD system hinges on the ability to broadcast a warning. This creates a need to describe the probability of receiving a message along the facility over space and time. To accomplish this, a DSRC communications model is used to describe the probability of vehicles receiving a message, either from infrastructure or another vehicle, at every section of the analysis zone throughout the duration of the WWD event. Any economic benefit is manifested as the ability for a CV to avoid a crash by receiving an alert ahead of time. The baseline was considered as the zero market penetration ratio (MPR) scenario. As the MPR increased the odds of a CV being present on the facility and the message propagation performance increase, reducing the odds of a crash and increasing the benefit of the CV-WWD system. The benefits for a single event are used to find the benefit over the life of the system and the feasibility of deploying the system at the location in question.

This chapter describes the tasks taken to describe message transmission, analyze the economic benefit-cost ratio, and develop guideline development for this research. The calculations performed for the message transmission behavior and economic analysis were performed in MATLAB (*12*). The code is provided in Appendix A.

Warning Transmission Analysis

Proper representation of CV communications is needed to identify the performance of the CV-WWD system. This number will be evaluated analytically by combining the probability of a vehicle being within a distance and the probability of a vehicle within that distance receiving a message. This will be accomplished using a Poisson distribution for the vehicle distances and a Nakagami distribution with m=3, where m is a variable representing moderate radio conditions when it is equal to 3, proposed by

Killat et. al. (*13*). The Nakagami distribution was chosen for its simplicity and the ability to match empirical data in low volume scenarios (*13*). Since WWD events tend to occur in early morning hours, low traffic volumes can be assumed. A figure of the Nakagami distribution with m=3 is shown in Figure 1. The formula for the Nakagami distribution is presented in Equation 1. Although Figure 1 only shows a distance to 1600 feet, the analysis zone is set to 2.5 miles, or the average length of a WWD event (*6*).

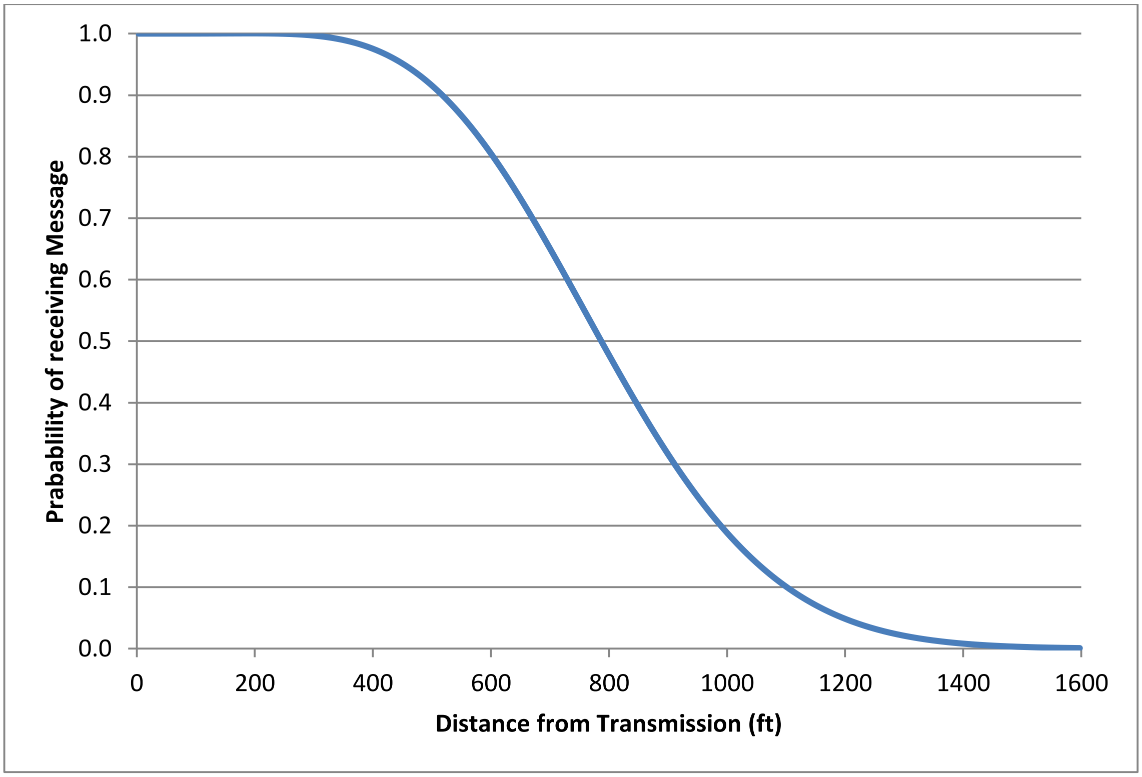

Figure 1. Continuous Nakagami Distribution with m=3 for DSRC Message Transmission Performance

$$\mathbf{Pr}(\boldsymbol{d},\mathbf{CR}) = \mathbf{e}^{-3(\frac{\boldsymbol{d}}{\mathbf{CR}})^{2}}\left(\mathbf{1}+\mathbf{3}\left(\frac{\boldsymbol{d}}{\mathbf{CR}}\right)^{\mathbf{2}}+\frac{\boldsymbol{g}}{\mathbf{2}}\left(\frac{\boldsymbol{d}}{\mathbf{CR}}\right)^{\mathbf{4}}\right) \qquad \textbf{Equation 1}$$

Where:

Pr is the probability of successful transmission at distance *d* and range CR

d is the distance between sender and receiver in meters

CR is the communication range in meters

g is the gravitational coefficient

Since the Poisson distribution was used to describe the probability of a vehicle being at a distance range on the facility, the Nakagami distribution needed to be discretized. The discretization divides the facility into segments that correspond to the distance a vehicle travels in a second. This was done for ease of calculations for the economic analysis and can be justified because the DSRC messages are being transmitted once a second. The probability of successful warning transmission for any CV in one of the segments is determined. For example, discretization resulting in 50 foot segments, representative of a vehicle traveling 50 feet per second, is presented in Figure 2.

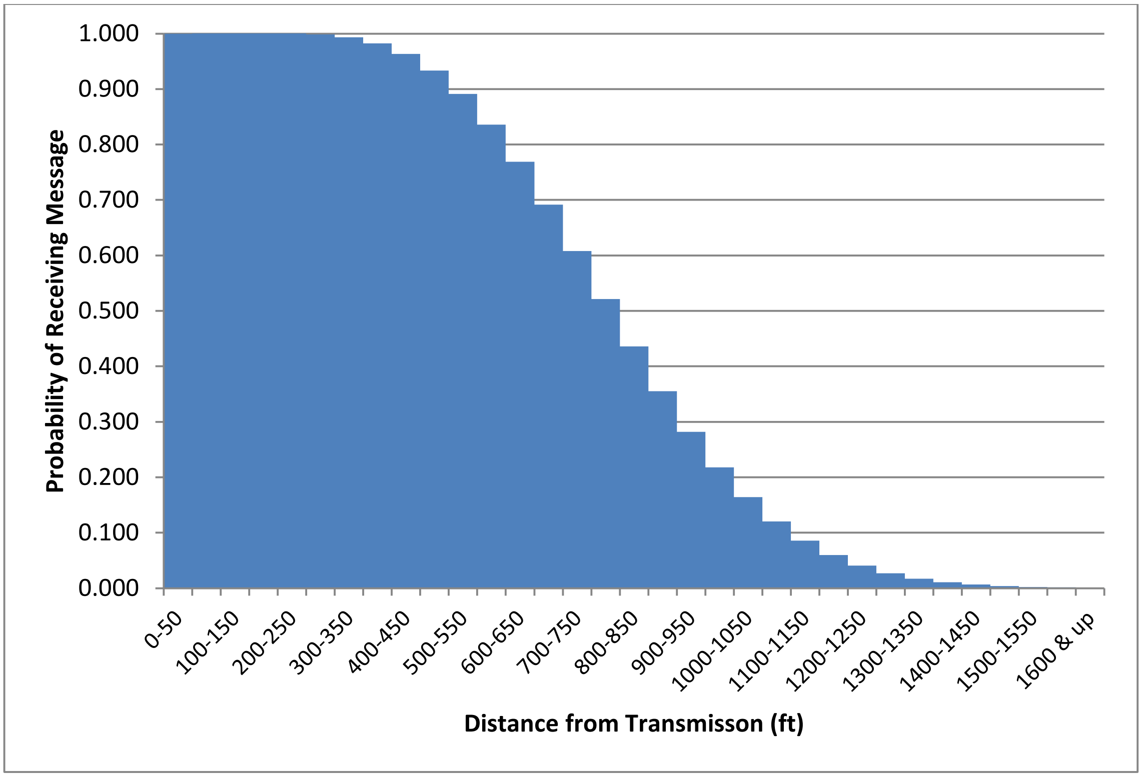

Figure 2. Discretized Nakagami Distribution with m=3 for DSRC Message Transmission Performance

Future images representing the discretized Nakagami Distribution with m=3 are done with line graphs since the distance across which the communication effectiveness is so large that the step size is negligible compared to the distance considered. The communications are still represented by the discretized model, but the figures are best represented with a line.

Single and multiple-hop communications are derived for the analysis. Single hop communications are considered from a roadside DSRC radio and multi-hops are assumed to be from vehicles on the facility that successfully received and transmitted the message one second after reception. Furthermore, the market penetration of CVs was included as a variable in the analytical derivation.

Single Hop Communication

Single hop communication is considered as the successful transmission of a RSA to a vehicle on the facility from the roadside infrastructure. The probability of a vehicle being present, according to the Poisson distribution, is multiplied by the probability of successful transmission to get the probability of a vehicle being present on the facility and receiving a message at any section of the freeway, shown in Equation 2.

$$\boldsymbol{P_{ftx,j} = P_{tx,j}P_{v,j}P_{MPR}}$$ **Equation 2**

Where:

$P_{ftx,j}$ is the total probability of a vehicle receiving a message from infrastructure at distance *j*

$P_{tx,j}$ is the probability of a vehicle receiving a message at distance *j*

$P_{v,i}$ is the probability of a vehicle being present at distance *j*

P_{MPR} is the market penetration ratio of connected vehicles

Since wrong-way events typically occur at the early morning hours and the market penetration rate is expected to be low initially, traffic volumes on the facility are assumed to be low. If vehicles are spaced far apart, the message propagation may fail. Therefore, this analysis considers market penetration required for effective message propagation at very low volumes.

When incorporating time into the analysis, it is known that the very first transmission of the RSA will be from the infrastructure. All V2V communications will rely on the propagation of the messages from vehicles that received the message from the infrastructure. The probability of receiving a message from the infrastructure at each time interval is does not change over time for each distance along the facility. Figure 3 shows the probability of receiving the message from the infrastructure component of message transmission across the analysis zone. This illustration, and other similar illustrations for combined I2V and V2V transmissions, should be read as the horizontal axis representing the location of the subject vehicle, the vertical axis representing the probability of receiving a message, and the curve representing the probability of receiving a message at the time during the event represented by the curve. The curve in each figure showed the probability across the entire 2.5 mile analysis zone considered for a WWD event. Notice, since V2V communication requires a vehicle to receive the warning before broadcasting, the first warning message sent, represented in Figure 3, has zero V2V communication contribution.

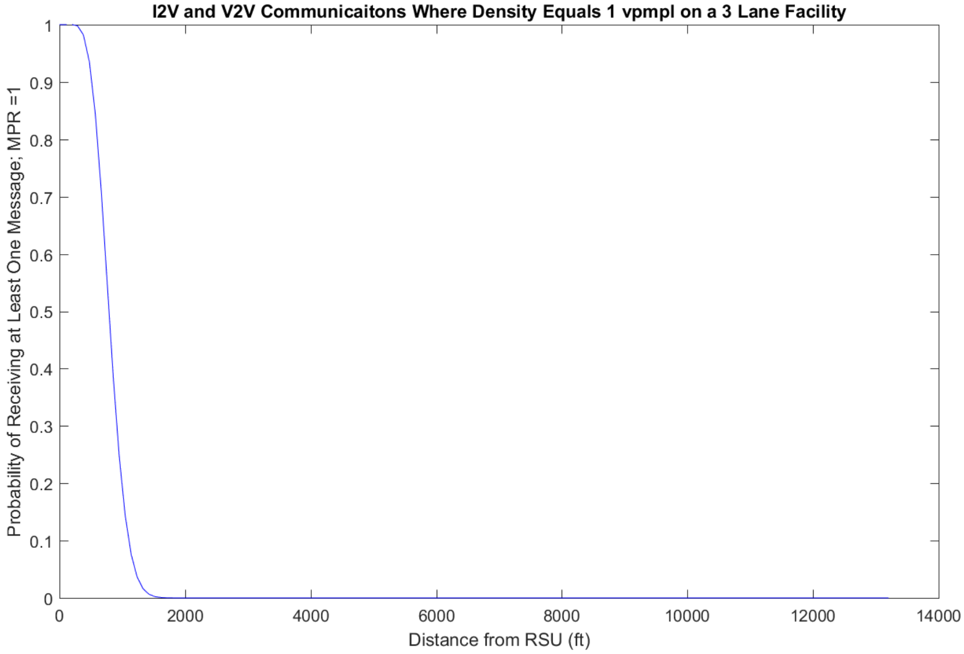

Figure 3. Probability of Successful Transmission of Initial Warning Message (I2V only)

Multiple Hop Communication

Multiple hop communication assumes that a vehicle that received the warning RSA will begin broadcasting the message with their own DSRC unit. The Nakagami Distribution with m=3 is used to determine the probability of the message being in a vehicle other than the broadcasting vehicle, both downstream and upstream of the broadcasting vehicle. In low density scenarios expected for WWD events, negligible interference is expected from multiple vehicles transmitting on the facility. Therefore, transmission failure from interference is not considered in this analysis.

Vehicles traveling on the other side of the facility from the WWD may not need the warning but can contribute to the propagation of the DSRC message to another traveler in potential conflict with the WWD. For this reason, vehicle on the other side of the facility are considered as contributors to the propagation. This is accomplished by multiplying the transmitting vehicles by two, assuming densities and odds of having the message on both sides of the facility are equal.

Any vehicle on the facility would only need to receive the message once to get the benefit of knowing about the WWD event. This means that there is no benefit in receiving the message from multiple broadcasters. There could be some benefit from receiving the message multiple times throughout the event, since the system could provide real time information on the WWD, but this is considered to be negligible because the majority of the benefit occurs with the first notification. From statistics, we know that the probability of receiving the message from at least one entity at time *t,* is equal to one minus the probability of not receiving the message from any transmitting vehicle at time *t*, reflected in Equation 3.

$$\boldsymbol{P_{vtx,jt} = 1 - \prod_i (1 - P_{vtx,ijt})}$$ **Equation 3**

Where:

$P_{vtx,jt}$ is the probability of a vehicle at distance *j* receiving a message from another vehicle at time *t*

$P_{vtx,ijt}$ is the probability of a transmitting vehicle, which received the message at time
t-1, at distance *i* successfully sending a message to another vehicle at time *t*

Note that Equation 3 does not yet adjust for the probability vehicle presence at *j* or the probability of a vehicle at *j* being a connected vehicle. This adjustment is done in similar fashion to Equation 2. The probability of V2V and I2V communications are calculated in this way so that the probability of receiving at least one message from any entity can be graphed for a given time step for a vehicle at any distance on the facility. Any messages transmitted after the first I2V message will have some aspect of V2V communication. To illustrate this, the second through fifth message transmitted after the initiation, shown in Figure 3, are presented in Figure 4, 5, 6, and 7.

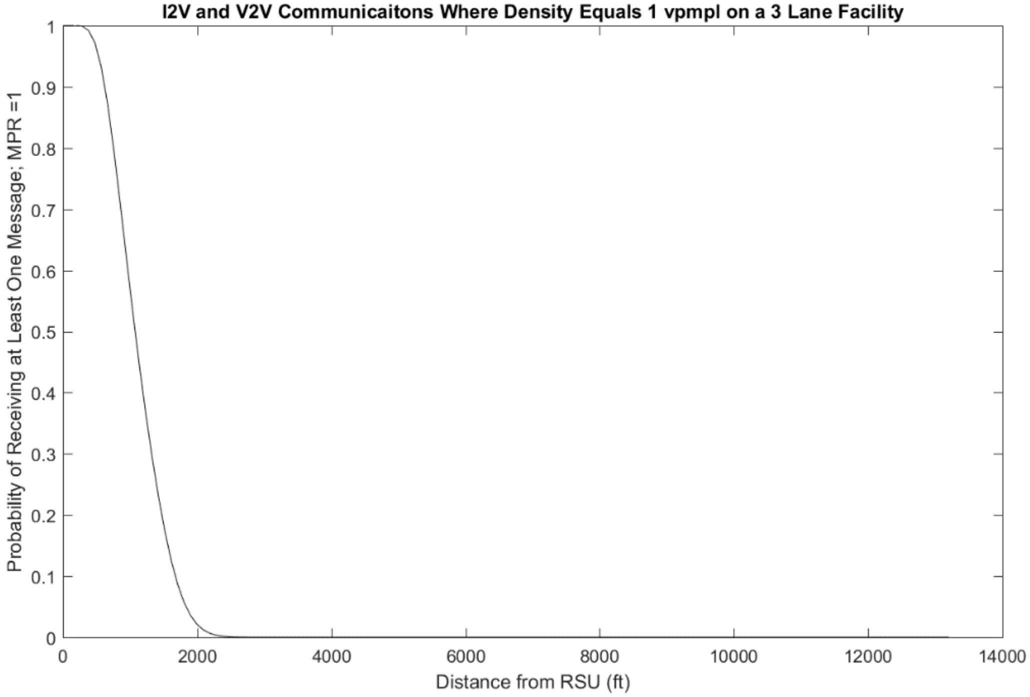

Figure 4. Probability of Successful Transmission for Second Warning Message

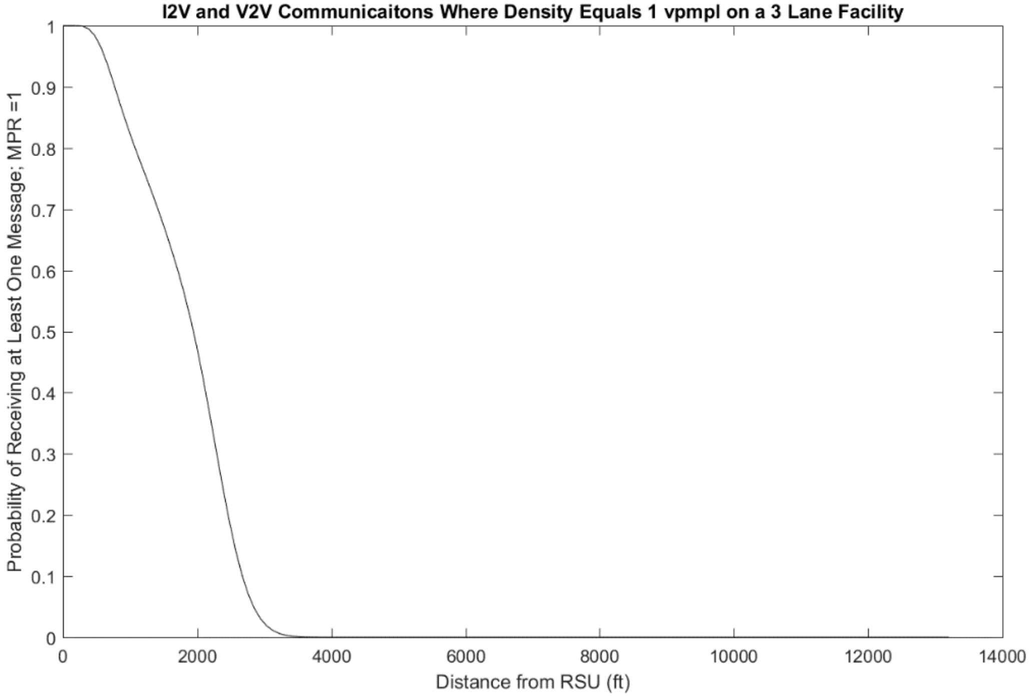

Figure 5. Probability of Successful Transmission for Third Warning Message

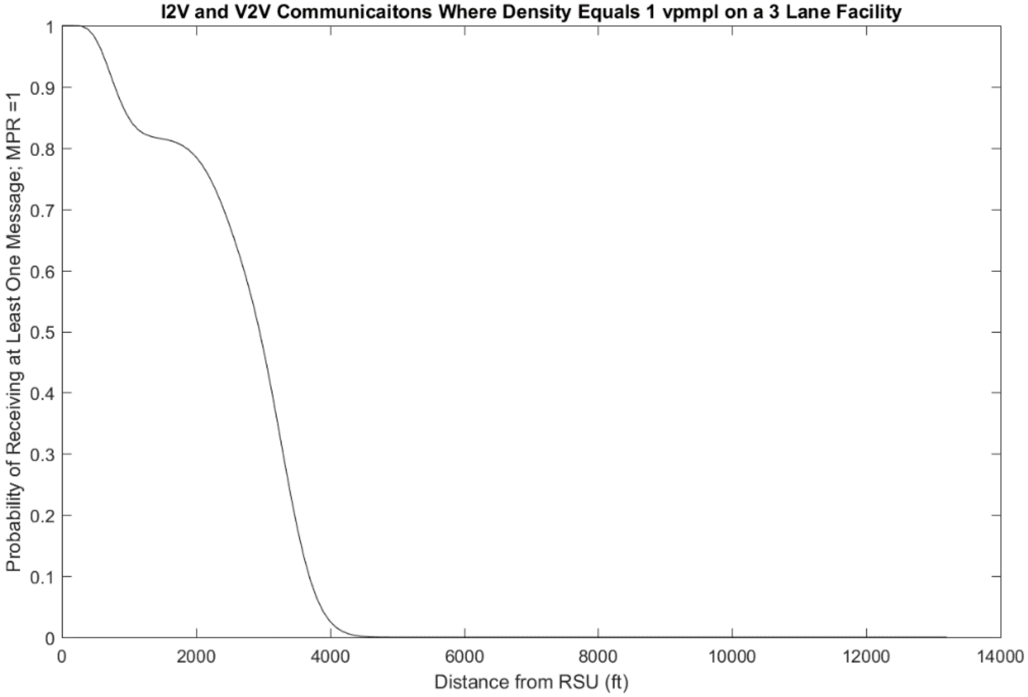

Figure 6. Probability of Successful Transmission for Fourth Warning Message

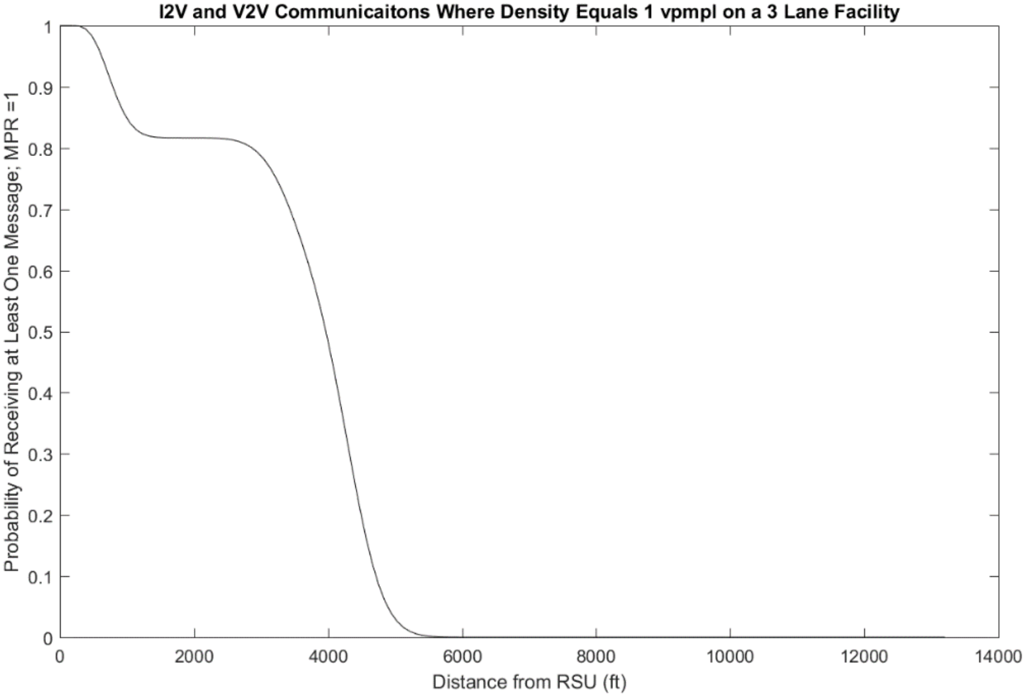

Figure 7. Probability of Successful Transmission for Fifth Warning Message

By the third warning message, represented by Figure 5, V2V communication begin to bend the probability of successful message transmission such that vehicles at increased distances have a larger likelihood of receiving the messages. At some distance the probability of message transmission is governed by V2V communication and the probability of message transmission levels, as shown at a distance of about 2000 feet in both Figure 6 and Figure 7. The probability that corresponds to the level line is the maximum probability of receiving a DSRC message via V2V communications, which occurs when all the CVs around the subject vehicle are transmitting the warning. This value depends on the MPR and the density.

Another factor that can be observed is the speed at which the V2V message propagation occurs. The curve appears to travel at a speed of about 1000 feet per second. This can be observed from Figure 6 and 7, where the latter curve has the 0.5 probability intersect shifted about 1000 feet farther than the former after only one second. This shows that propagation occurs at speeds much greater than the WWD. For this reason, CVs far upstream can be warned about the WWD long before they encounter the WWD, driving their probability of crashing to zero. At some point the message propagates such that the entire analysis zone of 2.5 miles has leveled out, depicted in Figure 8.

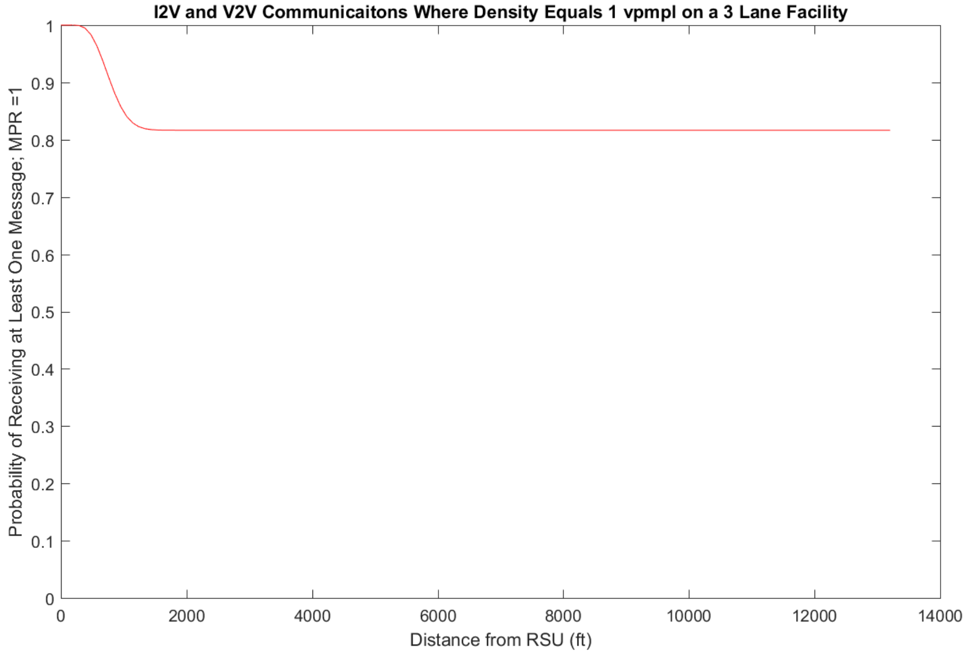

Figure 8. Probability of Successful Transmission of Warning Message After Entire Analysis Zone is Covered

Even though MPR and density dictate the maximum probability of receiving the message, the speed of propagation remains constant among each scenario. This is caused by the Nakagami Distribution used for the study which has a very high likelihood of receiving a message from transmitters at a short range.

Economic Analysis

The economic analysis follows the guidance provided in the U.S. Department of Transportation's Transportation Investment Generating Economic Recovery (TIGER) grant program Benefit-Cost Analysis Resource Guidance document (*14*). Methods to determine the cost of a crash, including converting crash severity values from the KABCO scale (a commonly used injury severity scale developed by the National Safety Council) to the Abbreviated Injury Scale (AIS) for determining the value of a crash. The values of the six AIS scales, in terms of the fraction of the value of a statistical live and the monetary value, are shown in Table 2.

Table 2. AIS Injury Scale Values (*14*)

AIS Level	Severity	Fraction of VSL	Unit Value ($2013)
1	Minor	0.003	$28,200
2	Moderate	0.047	$441,800
3	Serious	0.105	$987,000
4	Severe	0.266	$2,500,400
5	Critical	0.593	$5,574,200
6	Not survivable	1.000	$9,400,000

The table provided to convert the KABCO injury scale to the AIS injury scale by the TIGER grant program is presented in Table 3.

Table 3. KABCO/Unknown – AIS Data Conversion Matrix (*14*)

		O No injury	C Possible Injury	B Non-incapacitating	A Incapacitating	K Killed	U Injured Severity Unknown
AIS	0	0.92534	0.23437	0.08347	0.03437	0.00000	0.21538
	1	0.07257	0.68946	0.76843	0.55449	0.00000	0.62728
	2	0.00198	0.06391	0.10898	0.20908	0.00000	0.104
	3	0.00008	0.01071	0.03191	0.14437	0.00000	0.03858
	4	0.00000	0.00142	0.0062	0.03986	0.00000	0.00442
	5	0.00003	0.00013	0.00101	0.01783	0.00000	0.01034
	Fatality	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000
Sum(Prob)		1.00000	1.00000	1.00000	1.00000	1.00000	1.00000

The average cost of a crash at a site can be computed by converting the number of crashes in the KABCO system to the AIS scale, multiplying the value of each AID scale, and summing across all values. Note that in the AIS scale there is no value of a level zero crash.

To determine the impacts of the CV-WWD system, the probability of an equipped vehicle receiving the warning with enough time to be able to react and perform a maneuver to avoid a crash was determined for each vehicle in conflict. Vehicles that have passed the WWD are not considered in this study. If a vehicle has passed the WWD, meaning that there is no more potential conflict between them, there is no more need to consider their odds of crashing into the WWD. Therefore, the analysis only considers the segments that are upstream of the WWD. Since low densities are assumed, the analysis considers evasive maneuvers to be always possible given enough reaction time. That is, any vehicle can change lanes at any time to avoid a crash. Another assumption is that every vehicle on the facility is in immediate danger. Since vehicles traveling in the wrong-way tend to be erratic, the analysis assumes that it could crash into any other vehicle on the same side of the facility.

A critical tool in determining the probability of a crash is the crash probability function. In their paper, Kim and Jeong describe the crash probability rates for head-on collisions based on time performing a maneuver (*15*). The analysis considered different relative speeds of the vehicles and vehicle characteristics for 1000 simulations performed to find the crash probability for a closing speed and action time. The highest considered closing speed in the paper is 160 km/h, which is similar to 100 mph. With highway speeds in Texas being at least 65 miles per hour, a closing speed of 160 km/h is slow for this study. Nonetheless, it can behave as a conservative estimate since the actual probability of a crash at a higher closing speed would be higher. The perception-reaction time used in this study is from the NCHRP 400 report for an unexpected event: 1.25 seconds mean and 0.44 standard deviation (*16*). Beyond the perception time, an action time of 2.5 seconds with a standard deviation of 0.5 seconds was assumed for travelers. This means that the human reactions modeled in this study are assumed to be aware of the event if they have less than 3.75 seconds to respond with a standard deviation of 0.67 seconds. While determining the crash probability with the function, the action time is determined by subtracting the perception-reaction time is from the time before collision.

The process in determining the minimum crash probabilities for each vehicle on the facility is displayed in Figure 9. The minimum crash probability is the value of interest because it will be determined by the maximum reaction time, either by line of sign or receiving the DSRC warning, a subject vehicle has before it crashes.

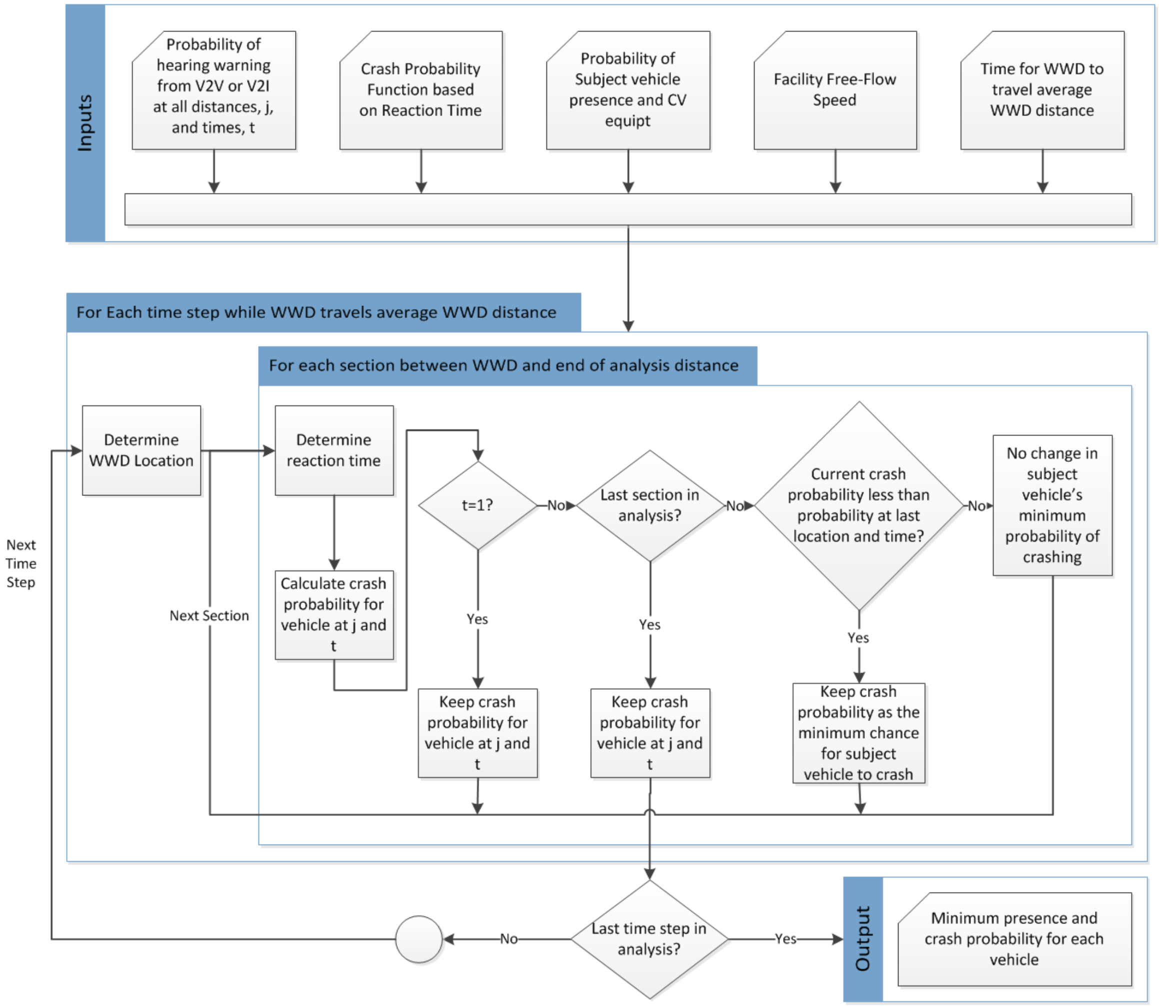

Figure 9. Crash Probability Determination

The minimum crash probability is averaged for each vehicle involved in the event. This gives a single value to act as a measure of performance for the system. If more vehicles in a scenario have a lower probability of a crash than another scenario the average crash probability will be lower, therefore indicating a benefit. The crash probability is multiplied by the probability of vehicle presence, according to the Poisson distribution, and then multiplied by the average cost of a crash.

The baseline case for the economic analysis is the case where the market penetration of CVs is zero. Meaning that there are no CVs present on the facility to receive a message. With zero market penetration, all vehicles are reacting based on physically seeing the WWD. Cases where the MPR is greater than zero have some gain over the baseline, since CVs that successfully receive the message will have more time to react to the WWD. This gain is the benefit for a single event. That benefit needs to be multiplied by the expected number of events per year and the number of years in the system life. This study considers the expected number of events to be equal to the average number of crashes in a year for a considered facility divided by the calculated crash probability from the baseline for the site characteristics. This determines the expected number of events to produce the measured annual crashes for the site. To find the expected number of events across the system life, the value would need to be multiplied by the life of the system.

Since the system is based on electronics, especially a technology that changes quickly, the life of the system of the system is considered to be five years. The components and corresponding costs, as determined by the TTI project team, is given in Table 4.

Table 4. Connected Vehicle Wrong-Way Driver System Costs

Item	Description	Quantity	Price
RSE	DSRC infrastructure-mounted device	1	$3,500
RSE-Complete	RSE stand-alone installation hardware (excluding RSE device)	1	$4,000
RADAR	Dual RADAR WWD detection device with camera and other equipment	1	$15,000
Processor		1	$3,000
Ethernet Switch		1	$1,000
Transceiver		1	$2,000
Construction	Installation of poles, etc.	1	$100,000
Other	Portable power unit	1	$15,000
		Total	$143,500

To account for costs associated with powering the system, labor (from operations and maintenance), and any additional unexpected costs, the analysis considers the cost of the installation to be $200,000. Costs associated with equipping CVs are not considered in this analysis because the travelers on the facility are expected to have covered that cost in the purchase of their personal vehicles. The benefit over the system life is divided by the cost to produce the benefit-cost ratio. This benefit-cost ratio is used to determine if the system a reasonable countermeasure under the conditions for the facility in question.

Develop Guidelines

The transmission and economic analysis will produce numeric results that can be used as guidelines for the CV-WWD system. These results will be presented as a benefit-cost ratio for the system for a certain market penetration and vehicular density. This task identifies the traffic characteristics and market penetration thresholds for the system to break even for a standard 3-lane facility.

Another function of this task is to identify features or geometries that could increase the likelihood that an improper maneuver is performed. This is done by taking note of different attractions and geometric features near an area identified as a high density WWD area.

A potential corridor in Texas was identified as a candidate for the CV-WWD system. This facility had the analysis applied to it as a case study. The results and the recommendation according to this study are provided to show how the analysis would be applied to a real facility.

CHAPTER IV

RESULTS AND CASE STUDY

Generic Results

Before diving into a case study, a generic case for overall Texas wrong-way crash data was created. The speed of the fictitious facility was assumed to be 65 miles per hour and the number of lanes equal to three. Densities, wrong-way crash rate, and MPR were varied to perform a sensitivity analysis on traffic characteristics. The overall crash severity distribution for Texas according to the Crash Records Information Systems (CRIS) data gathered from 2010 to 2014 is shown in Table 5.

Table 5. Wrong Way Crash Severity Distribution for Texas (n=1190)

Crash Severity	Percentage
Fatal	11.7%
Incapacitating Injury	9.6%
Non-Incapacitating	18.1%
Not Injured	39.5%
Possible Injury	19.2%
Unknown	1.9%
Grand Total	100.0%

The generic scenarios considered use a variety of densities and WWD crash rates. The densities considered for the generic cases are 1, 2, and 5 vehicles per mile per lane (vpmpl). These values represent sub-typical, typical, and high densities for an early morning time of day on a facility. Five WWD crash rates are considered: 0.2, 0.4, 0.6, 0.8, and 1.0 expected per year. This translates to 1 through 5 crashes throughout the life of the system. Each of these fifteen scenarios are calculated and the resulting benefit cost ratios for each MPR are presented in three different graphs: Figure 10, 11, and 12.

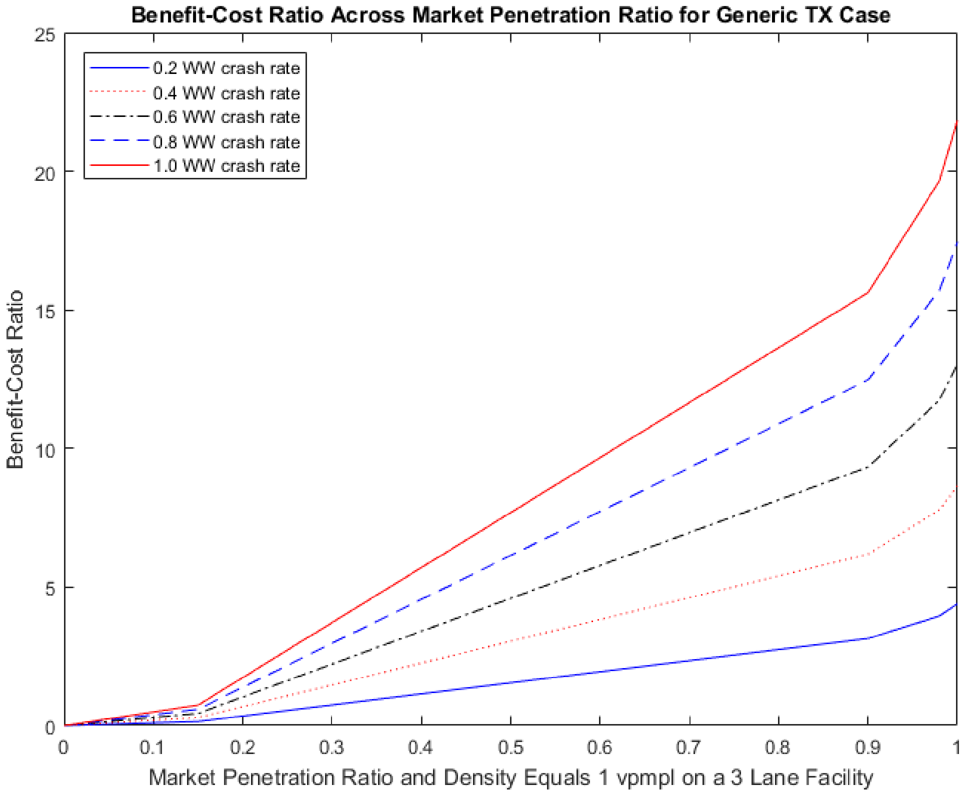

Figure 10. Benefit-Cost Ratio Across MPR for Generic TX Case with 1 vpmpl

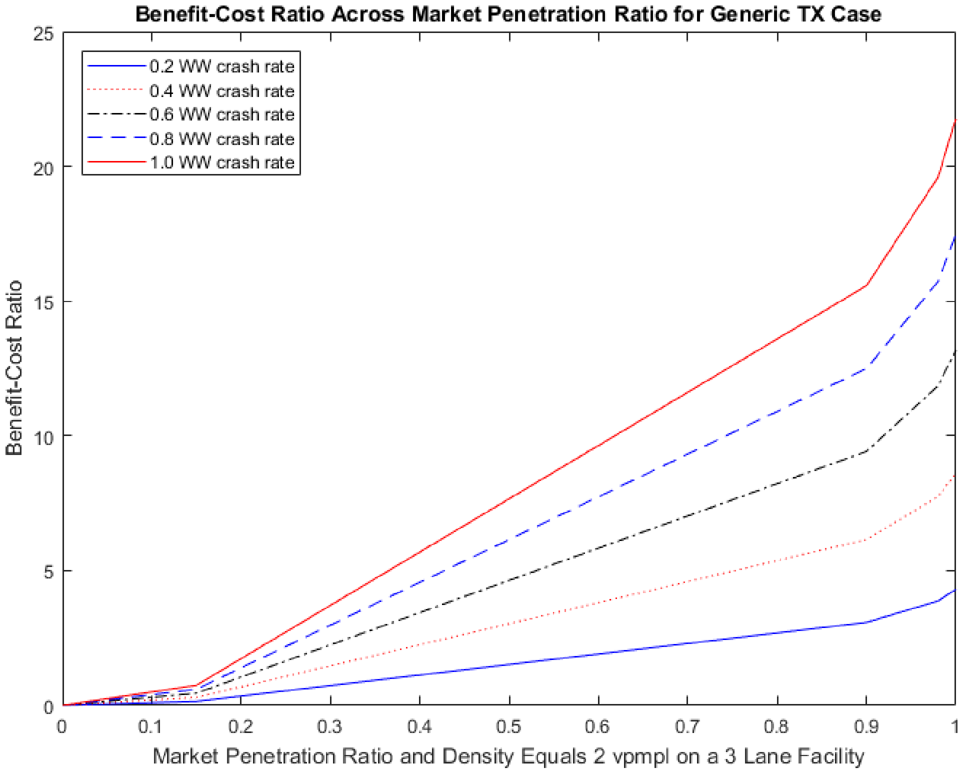

Figure 11. Benefit-Cost Ratio Across MPR for Generic TX Case with 2 vpmpl

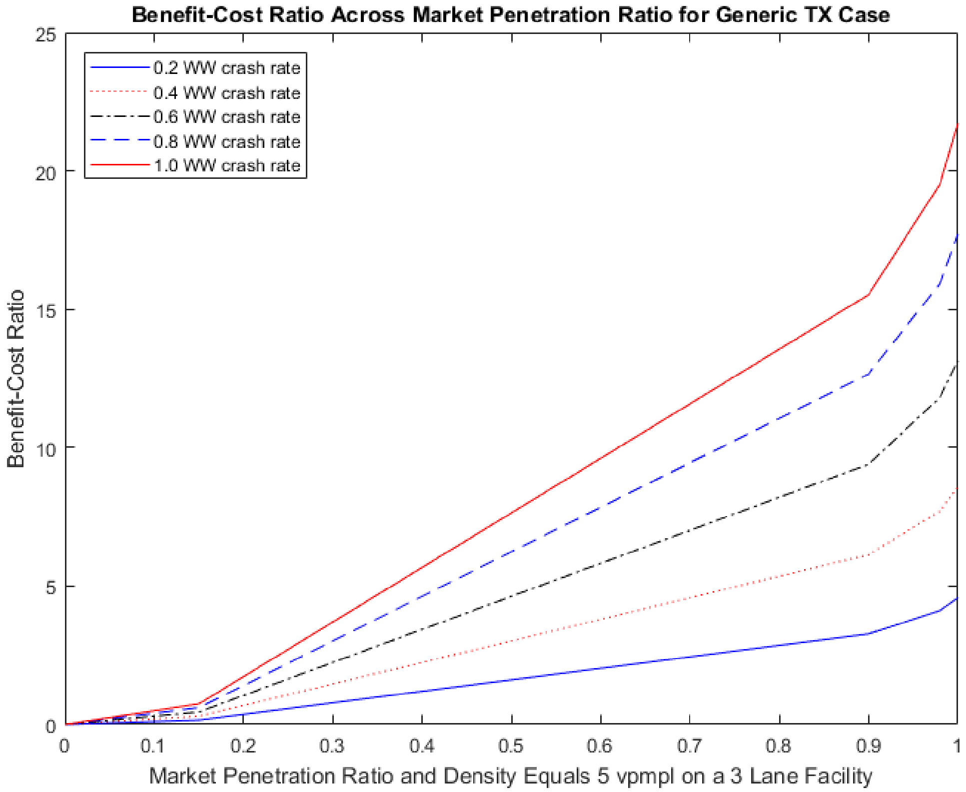

Figure 12. Benefit-Cost Ratio Across MPR for Generic TX Case with 5 vpmpl

It is clear from Figure 10 through Figure 12 that the change in density does not have a large effect on the benefit-cost ratio. As a matter of fact, the curves in each figure appear nearly identical. The results indicate that the effect is so small that it hardly changes the MPR required for a ratio greater than one. This is better displayed in Table 6, which contains the MPRs for the different generic cases at which the benefit-cost ratio first became greater than one.

Table 6. MPRs for Benefit-Cost Ratio Greater Than One for Generic Cases

	Density		
WWD Crash Rate	1 vpmpl	2 vpmpl	5 vpmpl
0.2 per year	37%	37%	36%
0.4 per year	24%	25%	25%
0.6 per year	20%	20%	20%
0.8 per year	18%	18%	18%
1.0 per year	17%	17%	17%

This shows that density is not a very large factor in the benefit-cost ratio determination. The reason for this is that at any density there is still a probability of vehicle presence, the probability is just higher for larger densities. The other factors driving the benefit-cost ratio overpower the role of density.

One factor driving the benefit-cost ratio is the market penetration rate. In each scenario, the increase of the MPR corresponds to the increase of the benefit-cost ratio. Although this result is intuitive, it is validating to observe such a result. Every scenario had a point that the system was economically appropriate as the MPR increased. In high MPRs every scenario had the benefits outweigh the costs several times over.

The driving force in the benefit-cost ratio is the wrong-way crash rate. The MPRs for the different crash rates in Table 6 were practically constant across each of the densities. The higher the WWD crash rate, the lower the MPR needed because the number of expected events increased. Therefore, the lower MPR is not showing that the system will perform better with an increased number of wrong-way crashes, but that it will be utilized more often.

Case Study

To exemplify how the procedure would be applied to an existing facility and further develop guidelines for the system deployment, a case study was performed. The following sections of this chapter describe the process of site selection, describe site characteristics, and present the results and conclusions of the analysis.

Site Selection

The case study location was determined using the data from the CRIS which contains information about crashes in Texas from 2010 to 2014. Wrong-way-related crashes were identified using the contributing factor variable. The data gathered focused on four metropolitan areas in Texas: Dallas, Fort Worth, Houston, and San Antonio. Traffic count data by time-of-day for freeway facilities in Dallas and Fort Worth is available through the North Central Texas Council of Governments (NCTCOG) (*17*). Therefore, Dallas and Fort Worth were primarily considered for site selection. Crash data for Dallas and Fort Worth were filtered to exclude entries with crash severity of “unknown” and “not injured” to focus potential locations on more severe crashes. An image of the crash locations for the filtered data from Dallas and Fort Worth is shown in Figure 13. This map was manually searched for locations that had a high WWD rate over a 5 mile stretch. The site is a 5 mile stretch instead of a 2.5 mile stretch because the CV-WWD system is bi-directional. If a WWD is detected, the warning can propagate along whichever direction the WWD is traveling with the same system installation.

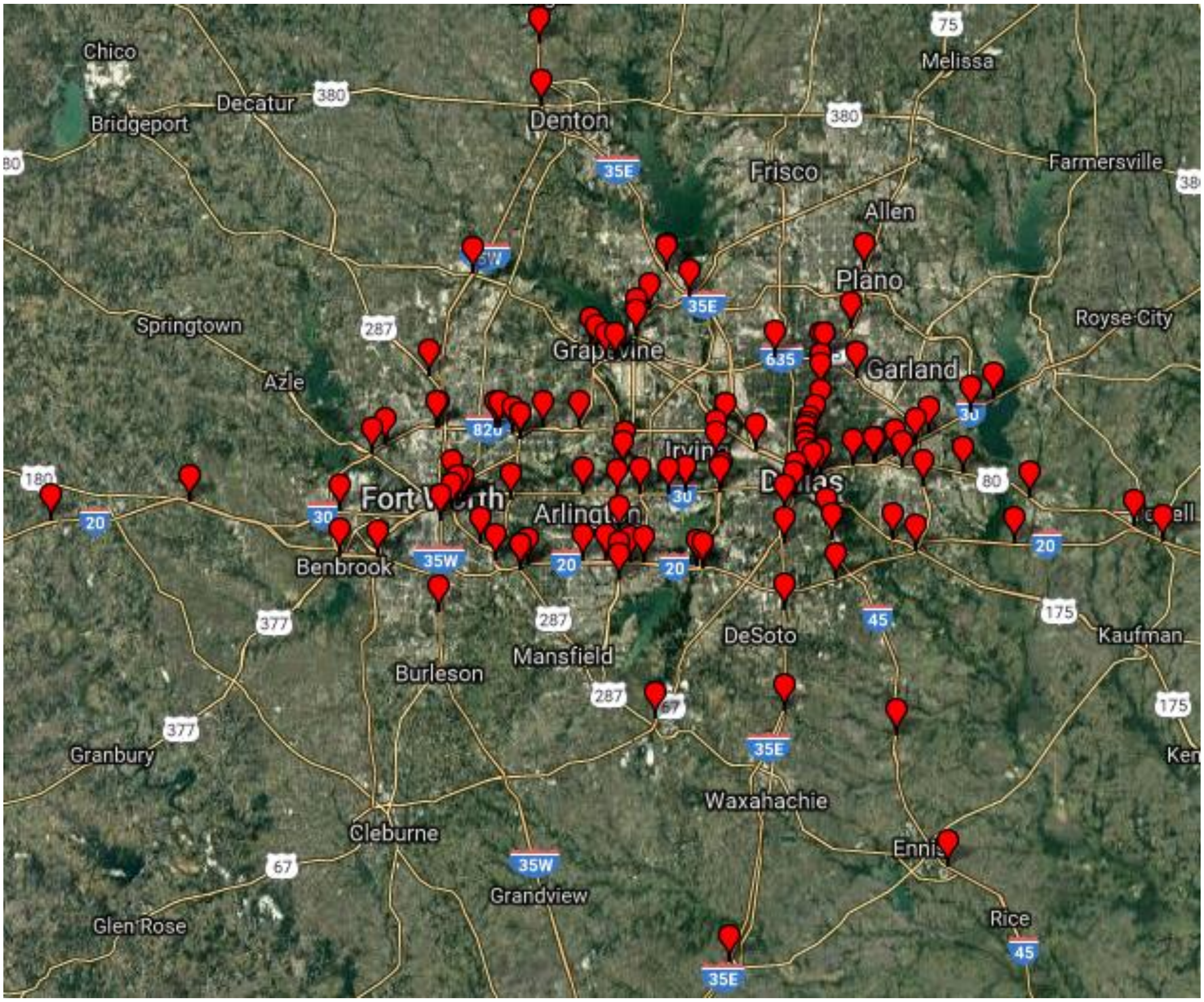

Figure 13. KAB Severity Wrong-Way Crash Locations in Dallas and Fort Worth

The search for a site was done in conjunction with identifying potential causes for a wrong-way movement. Many of the locations that appears to have a high amount of wrong-way crashes were either downtown, with one way streets, or in areas that drivers are likely to be unfamiliar, like near the airport. Downtown Dallas has particularly high densities. Upon further inspection, there were some areas where one-way streets, bars, and night clubs were all within close proximity. One such site, and the site selected for the case study, is US-75. The 5-mile study location begins where US-75 begins, splitting off from I-45, and extends north to mile marker 4. An image of the site, with all the crashes in the CRIS data from 2010 to 2014, their respective severities, and the potential installation location is provided in Figure 14.

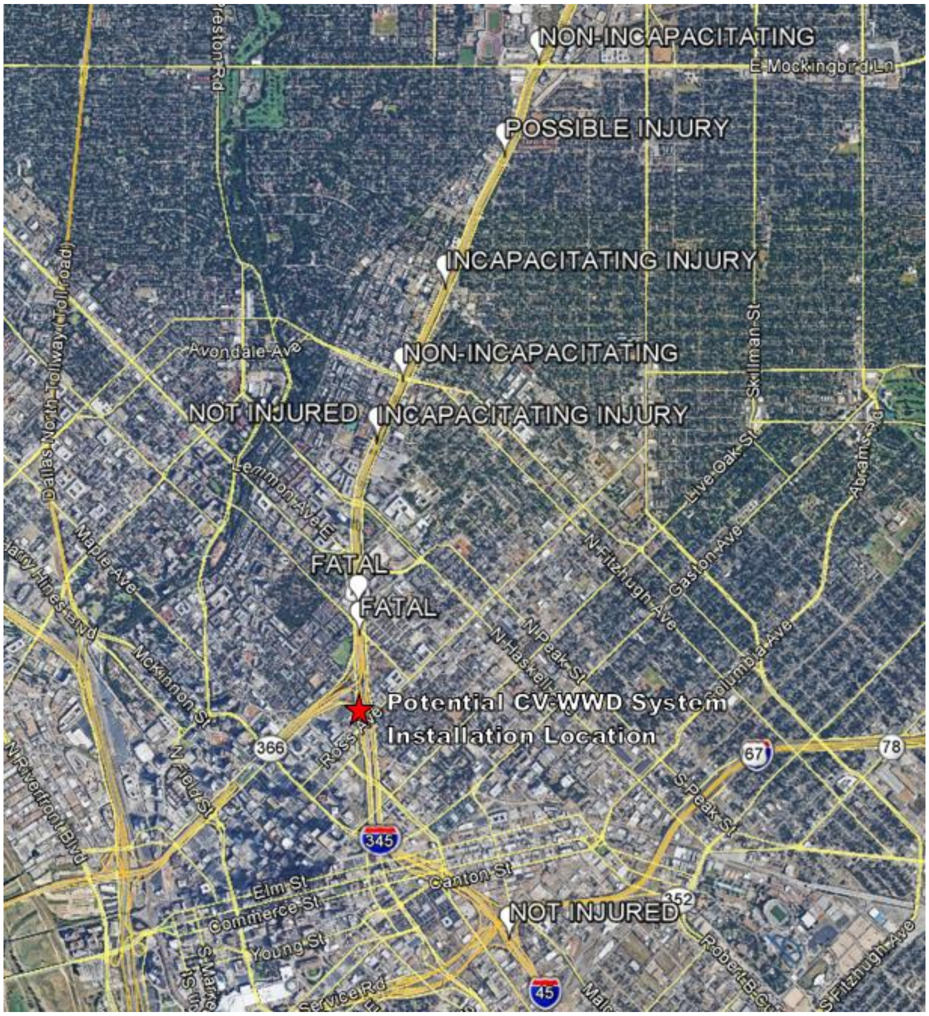

Figure 14. US-75 Site Wrong-Way Crash Locations and Severity from 2010-2014

The suggested location was selected by attempting to find an intersection at which a one-way street comes near an exit ramp near the midpoint of the crashes. There is no data on the entry locations for the WWD crashes on this facility, so the location could not be determined from WWD entry points. A zoomed in map of the potential location is provided in Figure 15. At this location, San Jacinto Street merges with Ross Avenue just before encountering the frontage road for US-75.

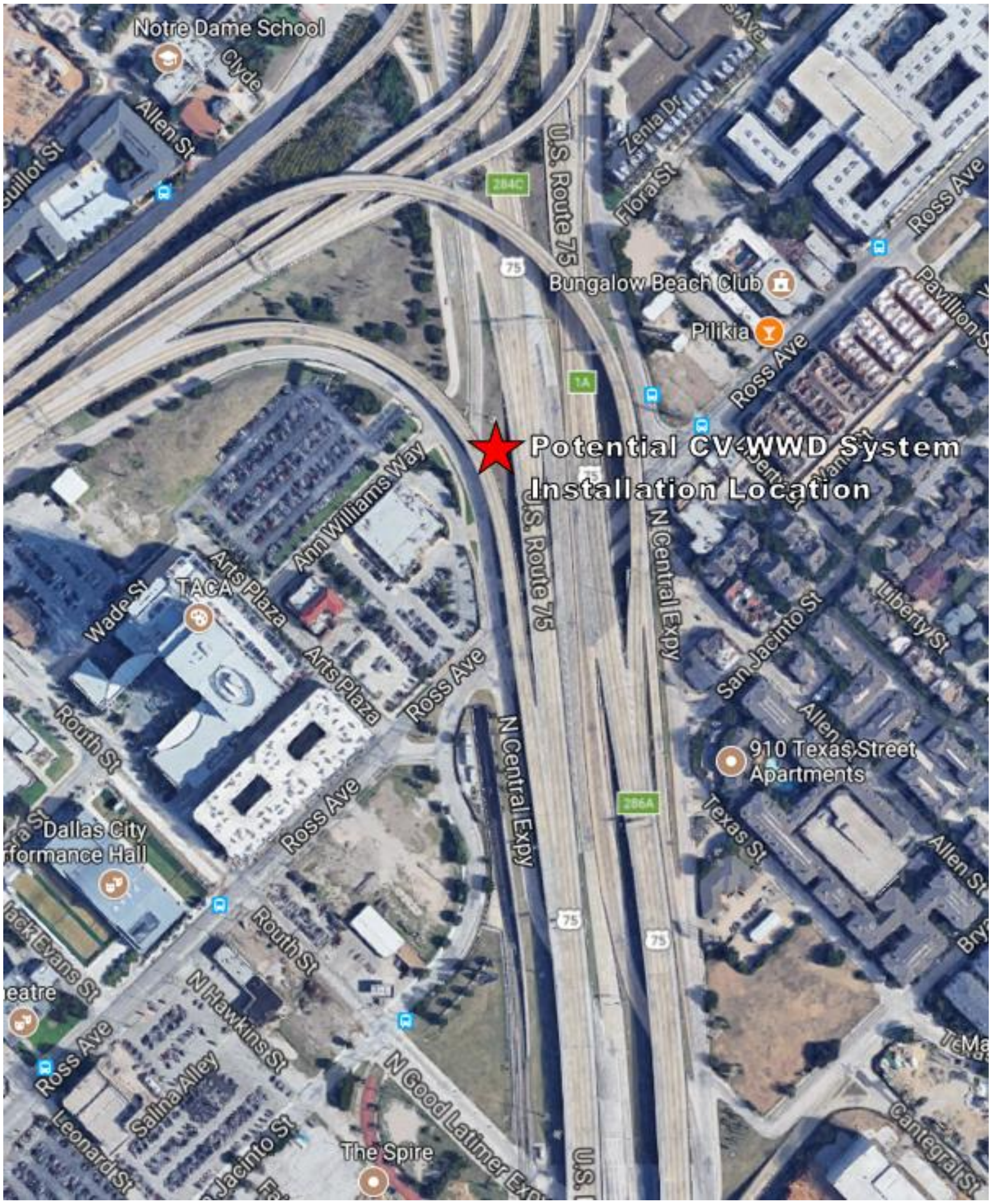

Figure 15. Recommended Location of CV-WWD System on US-75

Site Characteristics

The posted speed limit on this section of US-75 is 65 miles per hour. The facility has three lanes and the hourly volumes from midnight to 3:00 am from the NCTCOG website were averaged for traffic in both directions of the freeway to determine the density. This yielded an average flow of 440 vehicles per hour and a corresponding density of 2.3 vpmpl. Over the course of five years, there were nine crashes along the 5 miles, meaning that the wrong-way crash rate for the site is 1.8 crashes per year. The severity distribution of the crashes reported is given in Table 7.

Table 7. Wrong Way Crash Severity Distribution for US-75 Site in Dallas (n=9)

Crash Severity	Percentage
Fatal	22.2%
Incapacitating Injury	22.2%
Non-Incapacitating	22.2%
Not Injured	22.2%
Possible Injury	11.1%
Unknown	0.0%
Grand Total	100.0%

Feasibility Analysis

The analysis required the speed, density, and crash distribution for the calculations to be performed according to what is outlined in Chapter III: Study Methodology. The resulting benefit-cost ratio across market penetration for the graph is included in Figure 16.

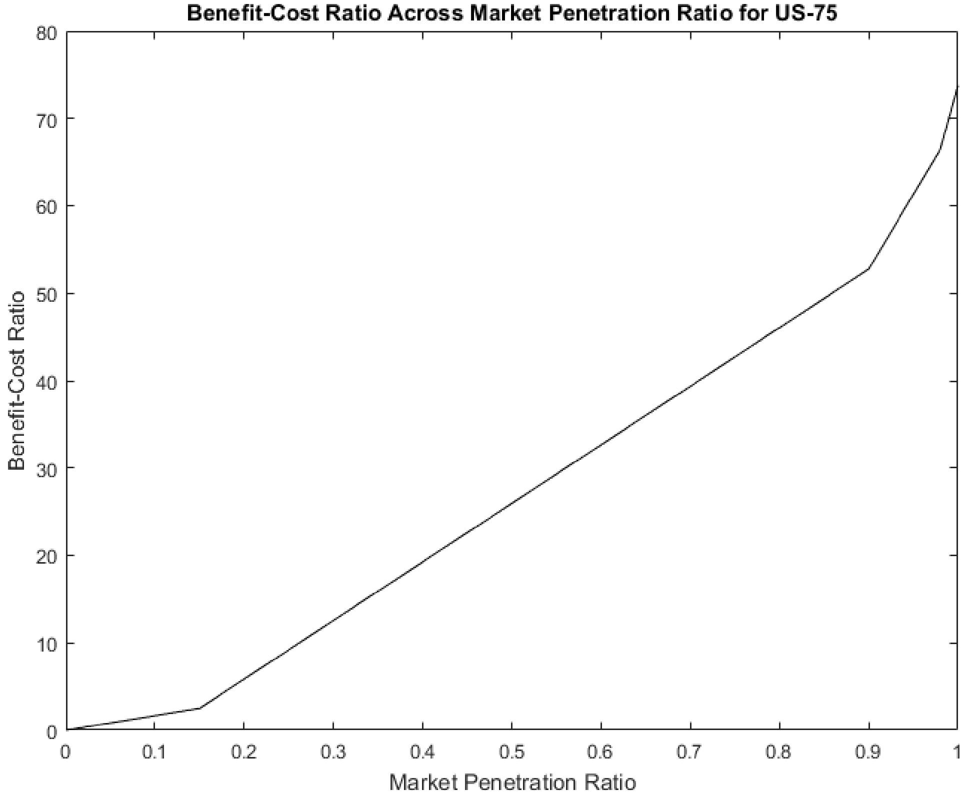

Figure 16. Benefit-Cost Ratio for CV-WWD System Across MPR for US-75

Notice the change of scale in the vertical axis of this figure compared to previous figures. The maximum benefit-cost ratio calculated is about 73. The MPR at which the benefit-cost ratio becomes greater than one is seven percent. This is lower than the generic cases mainly because the WWD rate is higher and the crash distribution is skewed more towards the more severe, and valuable, crash types.

Case Study Conclusions

The results of this analysis indicate that the CV-WWD countermeasure system would be a cost-effective countermeasure for the stretch of US-75 from splitting off from I-45 north to mile marker 4 as long at the MPR for CVs is seven percent or greater.

CHAPTER V

SUMMARY AND RECOMMENDATIONS

As part of the development of a connected vehicle wrong way driving countermeasure system, this study formulates and conducts a feasibility analysis for the system in a generic case and in a case study. This countermeasure is designed to detect a WWD and transmit a warning over dedicated short range communications to vehicles in potential conflict with the WWD. In addition to the infrastructure transmitting a warning, equipped vehicles will be able to relay the message to other vehicles on the facility. A communication model to represent CV transmission success was used to represent all DSRC communication in this study. These warnings ultimately allow a CV to be aware of a WWD situation earlier and have more time to react and reduce crash risk. Special care was made to represent economic benefit based on the minimum crash risk experienced by each vehicle on the facility. The crash probability was averaged for each case and translated to crash costs from a crash severity distribution. The difference of potential crash costs between a case of zero MPR, which represents a baseline case from an economic standpoint, and each MPR was determined to find the potential benefit for that MPR in a single event. The benefit from a single event was multiplied by the expected number of events over the system life to find the cumulative benefits for the system. This value was divided by the cost of the system to find the benefit-cost ratio, which represents economic feasibility for the system. The MPR at which the benefit-cost ratio became greater than one was identified for each case analyzed.

A case study over US-75 in Dallas, Texas was completed to exemplify the use of the analysis. The crash severity distribution, vehicle density, and wrong-way crash severity for the site was used in the analysis to find the benefit-cost ratio and MPR relationship.

Deployment Guidelines

This study found that the CV-WWD system would be economically feasible depending mostly on the WWD crash rate and MPR. If the WWD crash rates are high, like they are at US-75 between 2010 and 2014 with a rate of 1.8 crashes per year, the system could be economically feasible with the MPR as low as seven percent. As the crash rate lowers, the MPR to break even increases. Crash rates of one wrong-way crash a year would be feasible at about 17 percent MPR and crash rates of one every five years would need an MPR of about 37 percent to be feasible. High MPRs led to each scenario having benefits that far exceeded the costs of the system. The benefit-cost ratio becomes so large because the system is relatively cheap compared to the costs of the crashes it is designed to prevent.

Furthermore, site selection in Dallas and Fort Worth showed that WWD crashes appear to have high densities around downtown areas, with one-way streets, and areas with unfamiliar travelers, such as airports. The site did have bars and night clubs nearby in downtown Dallas. This was simply an observation and had no computations to verify its legitimacy.

Limitations

The limitations identified for this study are as follows:

- The entry location of a WWD on a limited access facility is not commonly known, and this case is no exception. The analysis assumes that the system is installed at the entry location of the WWD to provide the warning messages once the event begins. However, the system is only capable of providing warnings once the system detects the WWD. With better data on WWD entry locations, this system can be better deployed at high WWD entry locations.

- This analysis does not consider installing multiple roadside DSRC units to broadcast warnings along the facility. In an actual installation, there could be multiple roadside units to broadcast the message to warn more upstream traffic traveling in the correct direction about the WWD event.
- The assumption about being able to perform a maneuver to avoid the WWD at all times may not be valid at higher densities and market penetrations. There could be difficulty performing the recommended maneuver, like take the next exit, if all the vehicles are attempting to take the next exit as quick as possible. This potential problem could be evaluated with a microscopic analysis.
- There is no consideration of alternatives such as using a changeable message sign to display information to all drivers, connected or not, upstream of the WWD. A changeable message sign could increase the chances of a non-CV being aware of the WWD and responding in an informed fashion.
- The DSRC communications were calculated entirely with the Nakagami Distribution with m=3. The results of the analysis could be biased towards this communication model, especially if the CVs at a facility being considered follow a different model for communication.
- The crash probability function used in this study varied from conditions expected in this scenario. Identification of a crash probability function at higher speeds in a WWD scenario could aid the analysis in this study.

Future Research

To further analyze the potential performance of a CV-WWD system, future work could consider the following topics:

- The analysis done in this study is macroscopic. That is, the traffic stream is represented as a function and stochasticity of traffic is captured by probabilities. The analysis could benefit from a microscopic simulation that analyzes a facility with the same inputs, but simulates communications between other vehicles. This would add certainty in the potential performance of the system.

- Next steps for the research would be to consider the impacts of installing multiple roadside units. Multiple units will increase the capability of the DSRC communications component of the CV-WWD system and will change the behavior of message propagation.
- Similarly, other countermeasures, such as the use of changeable message signs (either instead of or in conjunction with the CV-WWD), need to be considered. These different configurations would impact the performance of the system and could increase costs if a changeable message sign needs to be installed. The impacts of these configuration on the feasibility need to be considered.
- One potential feature of the CV-WWD system is to warn the driver of the wrong-way vehicle about their error. Research on the potential impacts and structure of such a warning to a potentially impaired driver is needed. If implemented successfully, such a warning could provide further benefits by stopping the erroneous maneuver completely.
- Better representation of the crash probability of drivers encountering a WWD, both with and without CV capabilities, would improve the results of this study. This could be accomplished with driving simulation where subjects unknowingly encounter a WWD and measuring the behavior.

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APPENDIX A

MATLAB CODE FOR MESSAGE TRANSMISSION AND ECONOMIC ANALYSIS

```
% Author: David Florence
% Created for Master's Thesis on CV-WWD
%
% This script calculates the probability of vehicle presence and
message
% transmission for entered site characteristics and simulation time.
%
clear; clc; close all;

tic

%Site characteristics
v = 65;                             %free flow speed on the facility in
mph; WWD and right-way
                                    %      traffic are assumed to be
traveling at this speed
v = round(v*5280/3600);             %Convert free-flow speed from mph
to fps
dist=2.5*5280+2000;                 %Average distance of WWD event in
feet
time = round((dist-2000)/v);        %average duration of WWD event
lanes = 3;                          %number of lanes on the subject
facility
k = 5.0;                            %density on subject facility during
WWD event in vh/mi/ln
MPR = 0:0.01:1;                     %market penetration of connected
vehicles
f2m = 3.28084;                      %feet to meters conversion
SystemCost = 200000;                %Cost of installation and
maintenance of system

int=v;                              %space interval considered for
distribution
VSL=9300000;                        %Value of Statistical Life
life = 5;                           %Life of system
wwdcr = 0.2:0.2:1;                  %Average number of crashes on
facility
Bmpr = zeros(length(MPR),length(wwdcr));        %Benefits at all MPRs
CCmpr = zeros(length(MPR),length(wwdcr));       %Crash costs at all
MPRs
PCmpr = zeros(length(MPR),length(wwdcr));       %Overall probability of
crash at all MPRs
BCmpr = zeros(length(MPR),length(wwdcr));        %Benefits at all MPRs
AIS = [0 0.003 0.047 0.105 0.226 0.593 1];
```

```
KABCO2AIS = [0.92534    0.23437 0.08347 0.03437 0.00000 0.21538
    0.07257 0.68946 0.76843 0.55449 0.00000 0.62728
    0.00198 0.06391 0.10898 0.20908 0.00000 0.10400
    0.00008 0.01071 0.03191 0.14437 0.00000 0.03858
    0.00000 0.00142 0.00620 0.03986 0.00000 0.00442
    0.00003 0.00013 0.00101 0.01783 0.00000 0.01034
    0.00000 0.00000 0.00000 0.00000 1.00000 0.00000];


CrshDist = [0.395 0.192 0.181 0.096 0.117 0.019];

CrashCost = 0;

for i=1:6
   for j=1:7
       CrashCost = CrashCost + KABCO2AIS(j,i)*CrshDist(i)*AIS(j)*VSL;
   end
end


I2V_dist = 0:int:dist;
n = length(I2V_dist);
I2V_tx = zeros(n,1);
V2V_dist = zeros(n);
V2V_tx = zeros(n);
X2V_tx = zeros(n,n,time);
X2V_1tx = zeros(n,time);
X2V_vtx = zeros(n,n,time);
X2V_v1tx = zeros(n,time);

cut = n - round(2000/int);

rng default;
NonCV_rt = normrnd(1.25,0.44,cut+time-1,1)+normrnd(2.5,0.5,cut+time-
1,1);

wwdf=zeros(1,length(wwdcr));

%Vehicle step size for finding where vehicles were in the last time
step
for w=1:length(wwdcr)
    for m=1:length(MPR)
        NCrshProb = zeros(cut+time-1,1);  %Crash probability for each
vehicle throughout event
        NCrshjt = zeros(n,time);
        %Poisson distribution for density using the site density and
lanes.
        Poisson = @(c) ((((k/5280)*int*lanes)^c)*exp(-
1*(k/5280)*int*lanes))/factorial(c);
        P1CV = Poisson(1)*MPR(m);
        P1nCV = Poisson(1)*(1-MPR(m));
```

```
        %Nakagami Distribution with m=3 to describe probability of
successful
        %message transmission. Assume communication range is 250 meters
        NakaD = @(d) exp(-
3.*(((d/f2m)/250).^2)).*(1+3.*((d/f2m)/250).^2+(9.81/2).*((d/f2m)/250).
^4);




        %Calculate the probability of receiving the message from
roadside radio
        %along the facility
        for i=1:n
                I2V_tx(i) = NakaD(I2V_dist(i));
        end


        for i=0:n-1
           for j=0:n-1
              V2V_dist(i+1,j+1) = abs(int*i-int*j);
              V2V_tx(i+1,j+1) = NakaD(V2V_dist(i+1,j+1));
           end
        end


        for t=1:time
            for i=1:n
               for j=1:n
                  if t == 1
                      if i==j
                           X2V_tx(i,j,t) = I2V_tx(i);
                           X2V_vtx(i,j,t) = I2V_tx(i);
                      end
                  else
                      if i==j
                          X2V_tx(i,j,t) = I2V_tx(i);
                          X2V_vtx(i,j,t) = I2V_tx(i);
                      else
                           X2V_tx(i,j,t) = (1-prod(1-X2V_tx(:,i,t-
1)))*V2V_tx(i,j);
                           X2V_vtx(i,j,t) = 2*P1CV*X2V_tx(i,j,t);
                      end
                  end
               end
            end
        end
```

```
        for t=1:time
            for j=1:n
                X2V_1tx(j,t) = 1-prod(1-X2V_tx(:,j,t));
            end
        end



        for t=1:time
            for j=1:n
                X2V_v1tx(j,t) = (1-prod(1-X2V_vtx(:,j,t)));
            end
        end

        for t = 1:time
           jww = round((v*t)/int);

               for j=jww:cut
                   r = ((j-jww)*int)/(2*v);
                   Pvc = Pc(r);

        %            Determine based on reaction time if either CVs or
NonCVs are aware of WWD
                   if r<=NonCV_rt(j+t-1)
                       NonCVaware=1;
                       CVaware=1;
                   else
                       NonCVaware=0;
                       CVaware=0;

        %               Determine cumulative probability of CV
        %               awareness based on all transmissions across
        %               time
                       for jj = j:j+t-1
                           for tt = 1:t
                               if jj==j && tt==1
                                   CVaware=X2V_v1tx(jj,t-tt+1);
                               else
                                   if jj>cut || X2V_v1tx(jj,t-tt+1)==0
                                       break;
                                   end
                                   CVaware=1-((1-CVaware)*(1-
X2V_v1tx(jj,t-tt+1)));
                               end
                           end
                       end
                   end

        %            Probability of the subject vehicle(CV or not) NOT
crashing
                   NCrshjt(j,t)=P1CV*CVaware*Pvc+P1nCV*NonCVaware*Pvc;
```

```
        %            Keep probability of no crash if maximum for
subject vehicle
                       if t == 1
                            NCrshProb(j+t-1) = NCrshjt(j,t);
                       elseif j==cut
                            NCrshProb(j+t-1) = NCrshjt(j,t);
                       elseif NCrshjt(j,t)>NCrshjt(j+1,t-1)
                            NCrshProb(j+t-1) = NCrshjt(j,t);
                       end
               end
        end

        % Find probability of overall crash during event
        PCmpr(m,w) = Poisson(1)*mean(1-(NCrshProb(:)/Poisson(1)));

        % Find cost of potential crash for event
        CCmpr(m,w) = CrashCost*Poisson(1)*mean(1-
(NCrshProb(:)/Poisson(1)));

        % Compare any crash cost to baseline case(with 0 MPR) to find
benefit
        Bmpr(m,w) = CCmpr(1,w)- CCmpr(m,w);


    end

    % Calculate WWD frequency from crash frequency and calculated
baseline
    % crash probability
    wwdf(w) = round(wwdcr(w)/PCmpr(1,w));

    % Calculate benefit cost by multiplying single event benefit by
rate and
    % lifespan and dividing by system costs.
    BCmpr(:,w) = (Bmpr(:,w)*wwdf(w)*life)/SystemCost;
end

toc

figure(1)
p1 = plot(MPR(:),BCmpr(:,1),'b-');
title('Benefit-Cost Ratio Across Market Penetration Ratio for Generic
TX Case')
xlabel(['Market Penetration Ratio and Density Equals ' num2str(k) '
vpmpl on a ' num2str(lanes) ' Lane Facility'])
ylabel('Benefit-Cost Ratio')

hold on
p2 = plot(MPR(:),BCmpr(:,2),'r:');
p3 = plot(MPR(:),BCmpr(:,3),'k-.');
p4 = plot(MPR(:),BCmpr(:,4),'b--');
p5 = plot(MPR(:),BCmpr(:,5),'r-');
```

```
legend('0.2 WW crash rate','0.4 WW crash rate','0.6 WW crash rate','0.8
WW crash rate','1.0 WW crash rate','location','northwest')


%Some function to represent probability of crash based on reaction
%time
function Pcrsh =Pc(r)

r = round(r-1.25,1);
Pcr = [1 1 1 1 1 1 1 1 0.85 0.6 0.4 0.25 0.17 0.1 0.1 0.08 0.07 0.06
0.02 0.02 0.01];
           if r>2
               Pcrsh = 1;
           elseif r<=0
               Pcrsh = 0;
           else
               ii = 10*r+1;
               Pcrsh = 1-Pcr(ii);
           end
end
```