EVALUATION OF A COLLISION AVOIDANCE AND MITIGATION SYSTEM (CAMS) ON WINTER MAINTENANCE TRUCKS

Research Administration
Reference Number: OR17-103

Prepared for
Michigan Department of Transportation
Division of Research
8885 Ricks Road
Lansing, MI 48917

Prepared by
Michigan State University
Department of Civil and Environmental Engineering
428 South Shaw Lane
East Lansing, MI 48824

Institute for Transportation
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010

FreezePoint Consulting
179 University Circle
Akron, OH

SEPTEMBER 21, 2018

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. MDOT Project Manager
OR 17-103	N/A	Steven J. Cook, P.E.

4. Title and Subtitle EVALUATION OF A COLLISION AVOIDANCE AND MITIGATION SYSTEM (CAMS) ON WINTER MAINTENANCE TRUCKS	**5. Report Date** September 21, 2018 **6. Performing Organization Code** N/A
7. Author(s) Ali Zockaie, Ramin Saedi, Timothy Gates, Peter Savolainen, Bill Schneider, Mehrnaz Ghamami, Rajat Verma, Fatemeh Fakhrmoosavi, Mohammad Kavianipour, MohammadHossein (Sam) Shojaei, Harprinderjot Singh, Jacob Warner, and Chao Zhou	**8. Performing Organization Report No.** N/A
9. Performing Organization Name and Address Michigan State University 428 S. Shaw Lane East Lansing, Michigan 48824	**10. Work Unit No. (TRAIS)** N/A **11. Contract or Grant No.** 2018-0060 **11 (a). Authorization No.**
12. Sponsoring Organization Name and Address Michigan Department of Transportation Research Administration 8885 Ricks Rd. P.O. Box 30049 Lansing, Michigan 48909	**13. Type of Report and Period Covered** Final Report 10/01/2017 to 09/30/2018 **14. Sponsoring Agency Code** N/A

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration. MDOT research reports are available at www.michigan.gov/mdotresearch.

16. Abstract

Snow removal and deicing activities are commonly performed by roadway agencies to enhance winter mobility and safety. Due to slower travel speeds during these operations, combined with low visibility and reduced pavement friction, the potential for rear-end collisions with winter maintenance trucks remains a persistent issue. A prototype collision avoidance and mitigation system (CAMS) was recently developed by a private vendor and was mounted on the rear of winter maintenance trucks (WMT) in southeast Michigan during the 2017-2018 winter season. The CAMS system includes a rear-facing radar, camera, and warning light bar, in addition to a cleaning/washing system, computer hardware, and an in-cabin display. Research was performed to evaluate the effectiveness of this prototype CAMS in consideration of potential broad implementation throughout the state of Michigan. Two MDOT CAMS-equipped winter maintenance trucks were utilized during plowing activities in early 2018 to evaluate both the operational performance of CAMS and the extent to which CAMS improves drivers' behavior when encroaching the rear of the truck. The study also investigated the potential of CAMS to reduce WMT-involved crashes along with the economic viability of widespread implementation of CAMS across Michigan. Although the CAMS showed potential for positive benefits on driver behavior, in terms of reaction time and encroachments to the rear of the WMT, several operational and performance issues were identified, both during field operation and from operator feedback, that require further investigation and remediation before the system can be recommended for widespread implementation. Specific issues included: 1.) persistent occlusion/blockage of the radar/camera housing unit by debris caused by inadequate performance of the cleaning system and 2.) inconsistent/imprecise activation of the CAMS warning light, which included false activations from vehicles in adjacent lanes and missed or delayed activations for vehicles encroaching within the warning zone behind the WMT. Several recommendations for improvement of the CAMS system were provided herein, and subsequent evaluation is necessary prior to broad implementation across Michigan.

17. Key Words	18. Distribution Statement
Collision avoidance and mitigation systems, winter maintenance operation, driver behavioral analysis, encroachment rate, response time, relative headway, safety improvement, warning light	No restrictions. This document is available to the public through the Michigan Department of Transportation

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified.	Unclassified.	92	N/A

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

EVALUATION OF A COLLISION AVOIDANCE AND MITIGATION SYSTEM (CAMS) ON WINTER MAINTENANCE TRUCKS

FINAL REPORT

September 21, 2018

Principal Investigator
Ali Zockaie, Ph.D.
Assistant Professor
Michigan State University

Authors
Ali Zockaie, Ramin Saedi, Timothy Gates, Peter Savolainen, Bill Schneider, Mehrnaz Ghamami, Rajat Verma, Fatemeh Fakhrmoosavi, Mohammad Kavianipour, MohammadHossein (Sam) Shojaei, Harprinderjot Singh, Jacob Warner, and Chao Zhou

Sponsored by
Michigan Department of Transportation

A report from
Michigan State University
Department of Civil and Environmental Engineering
428 South Shaw Lane
East Lansing, MI 48824

Institute for Transportation
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010

and

FreezePoint Consulting
179 University Circle
Akron, OH

CONTENTS

ACKNOWLEDGEMENTS VI

EXECUTIVE SUMMARY VII

CHAPTER 1 – INTRODUCTION 1

1.1 Background and Problem 2
1.2 Study Objectives 3
1.3 Research Tasks 4
1.4 Report Structure 4

CHAPTER 2 – CURRENT STATE OF THE PRACTICE 6

2.1 Literature Review 6
2.2 Survey of Michigan County Road Commissions 12
2.3 Nationwide DOT survey 15

CHAPTER 3 – COLLISION AVOIDANCE AND MITIGATION SYSTEM 19

3.1 Configuration of the CAMS 19
3.2 CAMS Logged Data 21

CHAPTER 4 – CONTROLLED FIELD TEST 22

4.1 Type of Following Vehicles 22
4.2 Warning Thresholds 22
4.3 Calculation of Relative Distance 23
4.4 Controlled CAMS Performance Tests 24
4.5 Summary of Major Observations during Controlled Testing 30

CHAPTER 5 – EVALUATION OF CAMS PERFORMANCE DURING WINTER MAINTENANCE OPERATIONS 32

5.1 Data Description 32
5.2 Washing System Performance 32
5.3 Warning System Performance 44
5.4 Summary of CAMS Performance Evaluation Findings 48

CHAPTER 6 – EVALUATION OF DRIVER BEHAVIOR IN RESPONSE TO CAMS WARNING ALERT 50

6.2 Results 55
6.3 Summary of Findings 61

CHAPTER 7 – WMT DRIVER FEEDBACK 63

7.1 Survey of Non-CAMS WMT Drivers 63
7.2 Survey of CAMS-equipped WMT drivers 64
7.3 Summary of Findings 66

CHAPTER 8 - EVALUATION OF WMT CRASH DATA AND ECONOMIC ANALYSIS 67

8.1 Data Query to Identify Potential WMT-Involved Crashes 67
8.2 Review of UD-10 Forms to Screen Non-WMT Crashes 69
8.3 Classification of WMT Crashes Based on Potential CAMS Influence 71
8.4 Economic Analysis for Statewide CAMS Installation 74

CHAPTER 9 – SUMMARY AND RECOMMENDATIONS 79

9.1 Summary of Findings 79
9.2 Study Limitations 81

9.3 Recommendations 82
REFERENCES 84
APPENDIX A – SURVEY OF WMT DRIVERS 86
A.1. The survey for drivers of WMTs equipped by CAMS: 86
A.2. The survey for drivers of regular WMTs: 89

LIST OF FIGURES

Figure 2-1 MDOT Automatic Vehicle Location (AVL) for Winter Maintenance Vehicles ... 7
Figure 2-2 Typical Warning Lights for Winter Maintenance Vehicles ... 9
Figure 2-3 Driver Assistive Systems on Winter Maintenance Vehicles ... 10
Figure 2-4 Surveyed Counties in Michigan ... 12
Figure 2-5 State DOTs Surveyed ... 15
Figure 3-1 Collision Avoidance and Mitigation System ... 20
Figure 4-1 Relative distance between the following car and WMT ... 23
Figure 4-2 Snapshot of the LIDAR data in Test 1 ... 25
Figure 4-3 Evaluating the relative distance using recorded video by CAMS ... 26
Figure 4-4 Evaluated relative distance for (a) first warning threshold (8 sec) and truck speed of 25 mph, (b) first warning threshold (8 sec) and truck speed of 35 mph, (c) second warning threshold (4 sec) and truck speed of 25 mph, and (d) second warning threshold (4 sec) and truck speed of 35 mph ... 27
Figure 4-5 Snapshot of the data collection in Test 2 ... 29
Figure 4-6 CAMS with muddy box in Test 3 ... 30
Figure 5-1 Trajectories of (a) Dataset 1 (MDOT 4004), (b) Dataset 2 (MDOT 4005), (c) Dataset 3 (MDOT 4004), and (d) Dataset 4 (MDOT 4005) – [Source: Google] ... 34
Figure 5-2 Four types of camera view quality during maintenance operations in (a) day and (b) night 35
Figure 5-3 (i) Duration of different categories of camera view quality and (ii) number of warnings recorded by CAMS for (a) MDOT-4004, (b) MDOT-4005, (c) MDOT-4004, (d) MDOT-4005, and (e) RCOC ... 37
Figure 5-4 Percentage of total time versus the percentage of total warnings for (a) MDOT-4004, (b) MDOT-4005, (c) MDOT-4004, (d) MDOT-4005, and (e) RCOC ... 38
Figure 5-5 Duration of camera views and the number of recorded warnings for (i) Friday (02/09/2018) and (ii) Saturday (02/10/2018) for (a) MDOT-4005, and (b) RCOC ... 40
Figure 5-6 Percentage of non-zero values in the logged data versus percentage of totally blocked duration for (a) MDOT-4004, (b) MDOT-4005, and (c) RCOC ... 42
Figure 5-7 Percentage of non-zero values in the logged data files for (a) MDOT-4004, (b) MDOT-4005, (c) MDOT-4004, (d) MDOT-4005, and (e) RCOC ... 43
Figure 5-8 Warning headway distribution for (i) Level 1 and (ii) Level 2 warnings for (a) MDOT-4004, (b) MDOT-4004, (c) MDOT-4005, and (d) MDOT-4005 ... 46
Figure 5-9 (a) Trajectories of two approaching vehicles to WMT, and (b) The snapshot of the CAMS recorded video at the time that the warning is triggered ... 47
Figure 5-10 Number of true positive and false negative warnings for the headways less than 7 seconds for (a) tangent segments, (b) curve segments, and (c) all segments ... 48
Figure 6-1 (a) Exposure zone for tangent segments and (b) different relative distance-based thresholds for encroachment rate analysis ... 52
Figure 6-2 Definition of encroaching vehicle on curved segments ... 53
Figure 6-3 Frequency distribution of encroaching vehicles on tangent segments for the two trucks MDOT 4004 and MDOT 4005 ... 57
Figure 6-4 Frequency distribution of encroaching vehicles on curve segments for the two trucks MDOT 4004 and MDOT 4005 ... 58
Figure 6-5 Frequency distribution of encroaching vehicles on all (tangent + curve) segments for the two trucks MDOT 4004 and MDOT 4005 ... 58
Figure 6-6 Encroachment decision tree for critical headway threshold of 4.5 sec ... 60
Figure 6-7 Regression tree for response time ... 61
Figure 7-1 Camera Wash Tank ... 66
Figure 8-1 Example of Crash Excluded After Review of UD-10 Form ... 70
Figure 8-2 Example crash likely to be influenced by CAMS ... 73
Figure 8-3 Example crash likely to be influenced by CAMS ... 73
Figure 8-4 Benefit/Cost Ratio for CAMS installation ... 78
Figure 8-5 Minimum required percent reduction in WMT crashes to ensure profitability of the CAMS for any given life cycle investment cost ... 78

LIST OF TABLES

Table 2-1 Evaluations of Winter Maintenance Technology and Safety 8
Table 2-2 Evaluations of Collision Avoidance Systems 11
Table 2-3 Responses to Survey of Michigan County Road Commissions 13
Table 2-4 Notable Comments from Surveys of Michigan Counties 14
Table 2-5 National DOTs Responses to Survey 17
Table 2-6 Notable Comments from Nationwide State DOT Surveys 18
Table 4-1 Specification of different runs in Test 1 24
Table 4-2 Specification of Test 2 28
Table 5-1 Datasets description 32
Table 6-1 Datasets for Driver Behavior Analysis 51
Table 6-2 Specifications of exposure zone for tangent segments 52
Table 6-3 Description of the warning data for each warning level 55
Table 6-4 Descriptive features used in the classification tree models 56
Table 6-5 Response time for different maneuvers for warning level 1 from all warning combinations 60
Table 8-1 Crashes Involving Construction/Maintenance Vehicles by Special Vehicle and Vehicle Use Criteria from UD-10 Crash Report Form 69
Table 8-2 Suspected WMT Crashes by Year 71
Table 8-3 Summary of Crashes by Contributing Circumstances 72
Table 8-4 Number of Crashes Likely to be Pertinent to CAMS 74
Table 8-5 Capital and Engineering Services Costs for CAMS 75
Table 8-6 Crash costs by KABCO severity level 76
Table 8-7 Determination of Weighted-Average Cost for Two-Vehicle Crashes 76

ACKNOWLEDGEMENTS

The research team would like to acknowledge the Michigan Department of Transportation (MDOT) for sponsoring this research and the Federal Highway Administration for State Planning and Research (SPR) funds used for this project. The authors also acknowledge the contributions of the members of the MDOT Research Advisory Panel (RAP) for guidance and direction on project tasks, with special recognition to project manager, Steven Cook, and research manager, Andre Clover. The authors also express gratitude to MDOT staff at Brighton garage, Matthew Pratt and Melissa Longworth who coordinated data collection activities and the Road Commission for Oakland County, Darryl Heid and his staff, for their willingness to provide a valued partnership and use of their WMTs to help ensure successful project deliverables and outcomes. In addition, to the numerous graduate students who assisted with the extensive data collection and compilation effort.

EXECUTIVE SUMMARY

Winter maintenance activities, particularly snow removal and deicing, help agencies improve roadway safety and mobility during winter weather conditions. However, due to slower travel speeds during these operations, combined with low visibility and reduced pavement friction, the potential for rear-end collisions between motorists and winter maintenance trucks (WMTs) remains a persistent issue. To counter such safety issues, a prototype collision avoidance and mitigation system (CAMS) was recently developed by a private vendor and was mounted on the rear of winter maintenance trucks (WMTs) in southeast Michigan during the 2017-2018 winter season. As this is a new and unproven system, research was needed to estimate its potential effectiveness as a tool to reduce rear-end collisions between WMTs and motorists in Michigan.

The CAMS system included a rear-facing radar, camera, and warning light bar containing three amber LED beacons. The CAMS radar system monitors the relative distance, speed, and acceleration, 10 times per second, for up to 32 vehicles following behind the vehicle to a maximum range of 600 feet**.** The CAMS system was programmed by the vendor to activate the warning light upon detection of a vehicle encroaching too close to the rear of the WMT in terms of the vehicle's time headway relative to the WMT. The system issued up to two levels of warning at two predetermined values of relative headway, which here refers to the amount of time it would take the front bumper of the following vehicle to hit the rear bumper of the truck if the relative speed between the truck and following vehicle remained the same. In this study, after initial testing in a controlled roadway environment, the headway values of warning levels 1 and 2 were established at 7 and 5 seconds, respectively.

A benefit/cost (B/C) analysis was performed to evaluate the economic performance of the CAMS. The installation and annual maintenance costs for 800 operating WMTs in Michigan are estimated based on the cost associated with equipping the four WMTs as part of this study assuming a 5-year life cycle for CAMS and 4% discount rate. It should be noted that the economy of scale for large-scale implementation was not considered here. Furthermore, the display and camera (used to evaluate the system performance in this study) costs were included in this estimation, which can be excluded for the large scale application to reduce the implementation cost. The system benefit is evaluated based on the likely reduction in the WMT-involved crashes over the 5-year life cycle due to implementation of the CAMS. A B/C ratio of 0.85 was calculated assuming the estimated maximum number of crashes that CAMS could prevent during the 5-year life cycle. This suggests that reducing the implementation cost is essential to economically justify incorporating the CAMS into the winter maintenance operations in Michigan. To that end, this study also provided a required crash reduction percentage for any given investment cost per WMT to ensure a B/C ratio of 1.

Although the CAMS showed potential for positive benefits on driver behavior, in terms of reaction times and encroachments to the rear of the WMT, several operational and performance issues were identified, both during field operation and from operator feedback, that require further investigation and remediation before the system can be recommended for widespread implementation. Specific issues included: (1) persistent occlusion/blockage of the radar/camera housing unit by debris caused by inadequate performance of the cleaning system and (2) inconsistent/imprecise activation of the CAMS warning light, which included false activations from vehicles in adjacent lanes and missed or delayed activations for vehicles encroaching within the warning zone behind the WMT. Several recommendations for improvement of the CAMS system were provided herein, and subsequent evaluation is necessary prior to broad implementation across Michigan.

CHAPTER 1 – INTRODUCTION

Winter maintenance of roadways remains a major challenge for transportation agencies in states with harsh winter climates, including Michigan. Low temperatures, poor visibility, and snow or ice on the roadway surface can all potentially degrade traffic safety and operations. Winter maintenance activities, particularly snow removal and deicing, help agencies improved roadway safety and mobility during poor winter weather conditions. Given limited winter maintenance resources, including vehicles, equipment, workers, and chemicals, it is crucial for state departments of transportation (DOTs) to perform these activities in as cost-effective manner as possible, while maintaining the highest level of safety for motorists and drivers of winter maintenance trucks (WMT).

One primary safety concern during snow plowing and deicing activities is the potential for rear end conflicts or collisions between motorists and winter maintenance trucks due to the reduced speeds used while performing these activities. Collisions involving WMTs can result in substantive property damage, vehicle repair, and medical costs. In addition, these types of crashes can put the WMTs temporarily out of operation, resulting in increased agency costs and reduced mobility and safety on the affected roadways. To counter these issues, state DOTs have attempted various means of enhancing safety and mobility during winter maintenance operations. One method is to provide education and outreach to motorists to improve driving on ice- or snow-covered roads, particularly around WMTs. For example, drivers are advised to accelerate and decelerate gradually, allowing extra time and distance to stop (Iowa DOT, 2017; MDOT, 2017). They are also advised not to follow WMTs too closely and to be mindful of the larger size of these vehicles, which results in potential blind spots, as well as slower travel speeds (IOWADOT, 2017). Despite these efforts to optimize safety during winter maintenance, and particularly snow removal procedures, the number of crashes that involve a WMT remains significant and represents an opportunity area for improvement.

To address these concerns, transportation authorities have begun assessing various collision avoidance technologies to warn drivers as they approach a WMT, with the objective of facilitating subsequent speed reductions and cautious driving behavior by motorists approaching such vehicles. One such system (developed by a private industry); referred to as the collision avoidance and mitigation system (CAMS), was installed on WMTs in Michigan for assessment under this study. This system includes a rear facing radar sensor that continuously monitors the speed and distance of vehicles following the WMT. This information is then utilized, along with the speed of the WMT, to calculate the headway between the WMT and following vehicles. If a vehicle is detected as encroaching too close to the rear of the WMT, the system triggers a special rear facing beacon to warn approaching drivers so as to prevent a possible collision. The CAMS system also includes an integrated rear facing video camera, which provides a view of approaching vehicles along with trajectory and warning alert information overlaid onto the video image. This video is transmitted to an LCD screen positioned in the cab of the WMT vehicle providing the driver with a view (which includes an overlay of approaching vehicle trajectories, along with the status of the CAMS warning light) of the rear of the vehicle. As this is a new and unproven system, research is needed to measure the potential effectiveness of this CAMS as a tool to reduce collisions between WMTs and passenger vehicles in Michigan.

1.1 Background and Problem

Historically, a significant portion of winter maintenance research has focused on operational aspects, such as determining optimal routing strategies for snowplows in consideration of historical and forecasted traffic and weather data (Moss, 1970; Bureau of Management Consulting, 1975; Tucker III, 1977; Atkins, Dierckman, & O'Bryant, 1990; Lemieux & Campagna, 1984; Chernak, Kustiner, & Phillips, 1990; Robinson, Ogawa, & Frickenstein, 1990; Hartman, Hogenson, & Miller, 1990; Perrier, Langevin, & Campbell, 2007). More recently, a greater emphasis of winter maintenance operations has been to ensure the safety of snow plow drivers and the traveling public during and after winter storm events. Although measures such as installing green warning lights on maintenance trucks or blade-mounted warning lights have helped further improve safety during winter maintenance activities, more advanced solutions, such as the CAMS system, present an opportunity for a more proactive means of increasing driver awareness and minimizing the potential for WMT-involved collisions. As such, since the CAMS technology has not been implemented or tested for winter maintenance operations in Michigan, its effect on roadway safety during winter maintenance activities remains uncertain.

An evaluation of the CAMS performance should consider various aspects. It will initially be necessary to assess the capability of CAMS to properly detect vehicles and issuing warning alerts based on the preset parameters during maintenance operations. As a part of this performance evaluation, it will also be necessary to assess the ability for the system to remain clean and clear of snow, ice, grime, salt, mud, and other debris that may impact CAMS performance during winter maintenance activities. After verifying the CAMS operational performance, it will be necessary to assess the impact of the warning alert on motorists' behavior. It is also of value to assess the opinions and desires of winter maintenance truck drivers, including regular operators of CAMS-equipped trucks.

1.2 Study Objectives

In addition to the above noted preliminary CAMS operational performance and warning alert assessments, MDOT sought to determine the effectiveness of broad statewide deployment of CAMS. To this end, the study sought to assess the extent to which CAMS improves drivers' behavior near WMTs and to determine if the potential exist for CAMS to help reduce WMT-involved crashes. In support of this broader goal, the following objectives are defined for this study:

1. Test the performance and effectiveness of the CAMS system using MDOT's CAMS-equipped winter maintenance trucks during plowing activities occurring during the winter season of early 2018.
2. Obtain feedback from winter maintenance personnel across Michigan and nationwide, including WMT drivers with and without experience using CAMS-equipped vehicles.
3. Identify potential benefits along with key issues and challenges of using CAMS on winter maintenance trucks.
4. Perform a cost/benefit analysis of CAMS used on winter maintenance trucks.
5. Develop recommendations for use of CAMS on winter maintenance trucks based on synthesis of the literature review, field evaluation, driver surveys, benefit/cost analysis, and other aspects.

1.3 Research Tasks

To accomplish the aforementioned objectives, the research team executed a detailed research plan to estimate the potential effectiveness of CAMS as a safety countermeasure to reduce conflicts and collisions between WMTs and passenger vehicles in Michigan. At a high-level, the research involves field data collection to discern the ability of CAMS, which was installed on two MDOT and two Oakland County Road Commission trucks, to accurately detect close-following vehicles, in addition to the action of close-following drivers upon receiving the CAMS warning alert. These field data are further supported by feedback from drivers of the CAMS-equipped trucks. These data are collectively used to estimate the potential safety effectiveness of the CAMS system, along with formulation of subsequent recommendations for future deployment of the system by MDOT and other road agencies throughout Michigan. The following tasks are performed during this research:

- Task 1: Literature Review
- Task 2: Review of Current Winter Maintenance Practices
- Task 3: Preliminary CAMS Demonstration
- Task 4: Controlled Performance Testing of CAMS
- Task 5: Collection of Field Data During Plowing Activities
- Task 6: Survey of CAMS Truck Drivers
- Task 7: Evaluation of Field Performance of CAMS
    - Vehicle Detection Accuracy
    - Driver Response to CAMS Alert
- Task 8: Assess Cost Effectiveness
- Task 9: Develop and Deliver Final Report

1.4 Report Structure

The remainder of this report is structured as follows. Chapter 2 provides a review of the current practices utilized by transportation agencies to prevent crashes that involve WMTs. Chapter 3 reviews the operational details of the proposed CAMS in this study. Chapter 4 provides details of a controlled field study to determine the operational capabilities of the CAMS. Chapter 5 provides an evaluation of actual field operations of the CAMS to evaluate the performance of the warning system, including whether the warning light was activated properly along with performance of the washing system for the sensor housing. Chapter 6 provides an assessment of the behavior of motorists in response to activation of the warning light, which was determined by comparing driver behavior with the warning beacon active vs. inactive (e.g., normal condition). Chapter 7 provides a summary of feedback obtained during surveys of CAMS truck drivers and non-CAMS truck drivers in Michigan. Chapter 8 presents an assessment of the crash and injury reduction potential, in addition to estimation of the cost effectiveness of the CAMS system. Finally, Chapter 9 includes a summary of findings, discussion of the study limitations, and the final recommendations for consideration by MDOT.

CHAPTER 2 – CURRENT STATE OF THE PRACTICE

A substantial proportion of vehicle crashes occur due to human errors (Harper, Hendrickson, & Samaras, 2016). Such issues are exacerbated during winter periods when weather and road conditions deteriorate, leading to reduced visibility and pavement friction. Recent research from Michigan State University found that the frequency, type, and severity of winter crashes are all impacted by snowfall levels (Michigan Vehicle Code Section 257.698), suggesting that further work is needed to mitigate crashes related to winter weather.

Although vehicle and highway automation are likely more complete solutions toward reducing crashes caused by human error (Vahidi & Eskandarian, 2003), a fully automated vehicle/highway system remains decades away. Until then, advancements in collision avoidance systems will seek to reduce the frequency and severity of crashes that occur due to human error (Harper, Hendrickson, & Samaras, 2016). This chapter presents a review of the current state of the practice for improvements to warning systems associated with winter maintenance operations and is divided into three sections:

- Literature Review,
- Survey of Michigan County Road Commissions, and
- Nationwide DOT Survey.

In particular, this review sought to determine the potential for collision avoidance systems to reduce crashes that occur during winter maintenance activities, particularly rear end crashes with WMTs. Combined, the three sources of information provided information regarding proven and emerging technologies and areas for further development. Additionally, the survey responses provided a synopsis of various safety concerns held by roadway agencies regarding winter maintenance activities.

2.1 Literature Review

The literature review targeted prior research regarding technological advancements for winter maintenance operations, particularly collision avoidance systems, along with research related to increasing safety during WMT operations. Historically, a significant portion of winter maintenance research has focused on operational aspects, such as determining optimal routing strategies for snowplows in consideration of historical and forecasted traffic and weather data. MDOT is one of several state DOTs to invest in advanced technologies to improve the effectiveness of its winter maintenance operations. One of the more common methods to improve efficiency is to equip WMTs with automatic vehicle location (AVL) systems, which when combined with road surface and weather data (e.g., RWIS or other sources), allow for real-time management of plowing and deicing operations. Figure 2.1 shows an example WMT and control center maintained for real-time management of plowing and deicing operations. Evaluations of the effectiveness of various technological advancements related to improving winter operations are summarized in Table 2.1 along with relevant safety related evaluations.

a) Truck equipped with GPS   b) Control center

Figure 2-1 MDOT Automatic Vehicle Location (AVL) for Winter Maintenance Vehicles

Table 2-1 Evaluations of Winter Maintenance Technology and Safety

Title	**Evaluation**	**Findings**	**Reference**
Prevalence of Operator Fatigue in Winter Maintenance Operations	An in-depth survey was conducted, 1043 operators, 453 managers, and 29 Clear Road members answered questions regarding fatigue.	75% of operators and managers feel that fatigue is a major safety issue. Need more research on countermeasures for fatigue.	(Camden, et al., 2018)
Evaluation of the GPS/AVL Systems for Snow and Ice Operations Resource Management	By the end of the study, 187 trucks were equipped with AVL systems for winter maintenance vehicles. Multiple pieces of equipment/ sensors were utilized to gathering salt, picture of the road, plow position, bed scales, and road temperature data.	Equipment, especially external equipment, must be calibrated frequently in order to be useful in inclement weather.	(Schneider, Maistros, Crow, Holik, & Gould, 2017)
The Intelligent Winter Road Maintenance Management in Slovak Conditions	The goal is to give dispatchers and driver spreader the best real-time weather data to optimize their work. AVL and mobile road weather data with thermal mapping is ideal for this concept.	AVL and RWIS systems are fundamental components for optimizing winter maintenance fleets. Linking the two systems is still needed in Slovakia.	(Kocianova, 2015)
Winter Road Maintenance and the Internet of Things (IoT)	Reviews and establishes winter maintenance corridor and corresponding IoT hub for meteorological data. Low-cost air temperature sensors were installed on lamp post within the test area.	This test presents some of the challenges for IoT in winter maintenance. The test air sensor is already outdated compared to new wireless technology. Cost of deployment and maintenance to calibrate are also significant factors. With more advances IoT could overcome any of the current limitations and help winter maintenance operations.	(Chapman, et al., 2014)
Quantifying Safety Benefit of Winter Road Maintenance: Accident Frequency	Using weather, road condition observations, traffic counts, and crashes, an investigation into vehicle crashes during winter events occurred. Three negative binomial models were used to analyze the data.	It is found that road surface conditions were a statistically significant in vehicle crashes.	(Usman, Fu, & Miranda-Moreno, 2010)

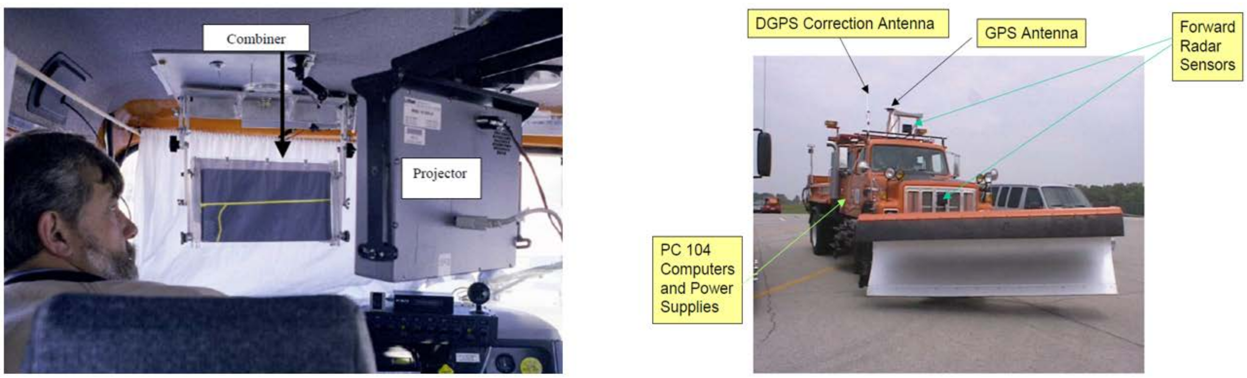
More recently, however, greater emphasis has been placed on ensuring the safety of snowplow drivers and the traveling public during plowing and deicing activities, particularly through the use of enhanced vehicular warning lights. One recent advancement in this area is the use of green warning lights, which increase visibility over traditional amber warning lights due to the sensitivity of the human eye to the green/yellow spectrum. Recently, the Michigan Vehicle Code was modified (Heqimi, Kay, & Gates, 2017) to allow for the use of green warning lights on winter maintenance vehicles, an example of which is shown in Figure 2.2b (Weingarten, 2016). The modest implementation cost of $100 per vehicle (Cranson & Donohue, 2016) has led to widespread implementation of green warning lights on maintenance vehicles throughout Michigan. It has also become increasingly common to include a warning light mounted on the top corner of the plow blade (Figure 2.2a).

a) MDOT vehicle with warning lights b) Green warning lights

Figure 2-2 Typical Warning Lights for Winter Maintenance Vehicles

However, from a safety perspective, the effectiveness of these enhanced warning light systems towards improving the behavior of motorists near WMTs, particularly under adverse winter weather conditions, remains unproven. Furthermore, while these types of passive warning devices provide a cost-effective means for improving conspicuity, more advanced solutions such collision avoidance systems, present an opportunity for a more proactive means of increasing driver awareness and minimizing the potential for WMT-involved collisions.

In-cabin assistive systems for WMT drivers are another method for improving safety during winter maintenance activities. Figure 2.3(a) depicts a typical example of how a projector and image combiner provide imagery of the roadway under low visibility conditions. These displays utilize data from antennas and sensors installed on the vehicle, as shown in Figure 2.3(b), which collect information about the environment, roadway, and weather conditions (Gorjestani, et al., 2003). The CAMS system evaluated as a part of this study provided both an active alert to motorists approaching too closely along with a driver assistive system to provide information to the WMT driver.



a) Driver assistive system inside the vehicle b) Driver assistive system outside the vehicle

Figure 2-3 Driver Assistive Systems on Winter Maintenance Vehicles

As MDOT has no experience with implementation of collision avoidance systems on winter maintenance vehicles, a review of literature pertaining to collision avoidance systems was performed. Ideally, it was desirable to ascertain the effectiveness of collision avoidance systems on winter maintenance vehicles. However, although numerous studies have investigated various aspects of collision avoidance systems, in none of these cases were the systems implemented on winter maintenance vehicles. Nevertheless, the literature review findings, which are summarized in Table 2.2, suggest that collision avoidance systems may be a cost-effective safety treatment when properly calibrated to consider the behavior of actual drivers.

Table 2-2 Evaluations of Collision Avoidance Systems

Title	**Evaluation**	**Findings**	**Reference**
A Collision Avoidance Scheme for Autonomous Vehicles Inspired by Human Social Norms	This paper reviews the idea of an artificial society of autonomous vehicles with different human personalities and social norms within their code. A standard modeling tool, NetLogo, is used to test the behavior of non-social norms to social norm-based artificial society.	For autonomous vehicles to be utilized by humans, humans must feel that it meets their standard for operating safely on the road. This paper provides optimal parameters suitable for avoiding road crashes in different road traffic situations.	(Riaz, et al., 2018)
Real Time Implementation of Socially Acceptable Collision Avoidance of a Low Speed Autonomous Shuttle Using the Elastic Band Method	In a high pedestrian density area, an autonomous shuttle's avoidance systems are evaluated. A Hardware-In-the-Loop connected vehicle was used to simulate this scenario. Using the data, a model was developed with the elastic band method.	This study presented the effectiveness of the elastic band method based on socially acceptable collision avoidance for low speed shuttles.	(Wang, Tota, Aksun-Guvenc, & Guvenc, 2018)
Cost and Benefit Estimates of Partially-Automated Vehicle Collision Avoidance Technologies	Reviews the benefits and cost for a large fleet implementation of blind spot monitoring, lane-departure warning, and forward collision warning systems in the US.	They found a $861 per vehicle net benefit assuming that an upper bound where all crashes were avoided, and a lower bound were observed insurance data are utilized.	(Harper, Hendrickson, & Samaras, 2016)
New Approach of Accident Benefit Analysis for Rear End Collision Avoidance and Mitigation Systems	Using German In-Depth Accident Study database, this research reviews the reactions of different drivers from warning, braking support, or autonomous braking with respect to motorist behavior. The accident avoidance and speed reduction were calculated for all driver types, warning system types, and applications.	The effectiveness of a collision avoidance system will depend on driver behavior and reaction time. Emergency Brake Assist function for a realistic driver is considered.	(Georgi, et al., 2009)
A Method of Evaluating Collision Avoidance Systems using Naturalistic Driving Data	Using real driver data, the research reviews algorithms without assumptions of reaction time and response inputs.	This method allows collision avoidance systems to be compared and provides data for development of these systems.	(McLaughlin, Hankey, & Dingus, 2008)
Evaluation of the Volvo Intelligent Vehicle Initiative Field Operational Test Version 1.3	Tested three systems on commercial vehicles: collision warning systems, adaptive cruise control, and advanced braking systems. Looked at safety benefits expected, survey for human perception, and cost benefit analysis	For the collision warning systems, one model and assumption resulted in a 52% elimination of conflicts with the vehicle. Adding the other two systems reduced another 9%.	(Battelle, 2007)
Research Advances in Intelligent Collision Avoidance and Adaptive Cruise Control	Reviews the current status of collision avoidance/warning systems as well as automation of vehicle longitudinal/lateral control tasks.	This paper reviews published papers to understand the impact of these systems within multiple factors such as driver comfort, increase safety, and increase highway capacity. In regards to warning systems, the appropriate warning and braking distances are the most important input for the success of these systems.	(Vahidi & Eskandarian, 2003)

2.2 Survey of Michigan County Road Commissions

The research team conducted phone interviews with Michigan county road commissions in the summer of 2018. The research team attempted to contact all 83 county road commissions in Michigan, although only 21 responded, as displayed in Figure 2.4. The intent of these surveys was to identify safety concerns associated with winter maintenance operations faced by county road commissions across Michigan. This survey was intended to serve as a companion to the MDOT truck driver survey presented later in this report. The questions were related to safety for WMT operators, particularly related to tailgating WMTs, and included the following:

1. Is your county on contract with Michigan DOT for winter maintenance?
2. Are or were you a WMT operator?
3. What are some of the major safety issues for WMT operators?
4. Do you think tailgating is a significant issue for WMT?
5. Do you have any suggestions to decrease tailgating of WMT?
6. Do you think a collision avoidance system on the rear of the WMT would improve safety?
7. Are there any other types of warning systems that would benefit WMT?

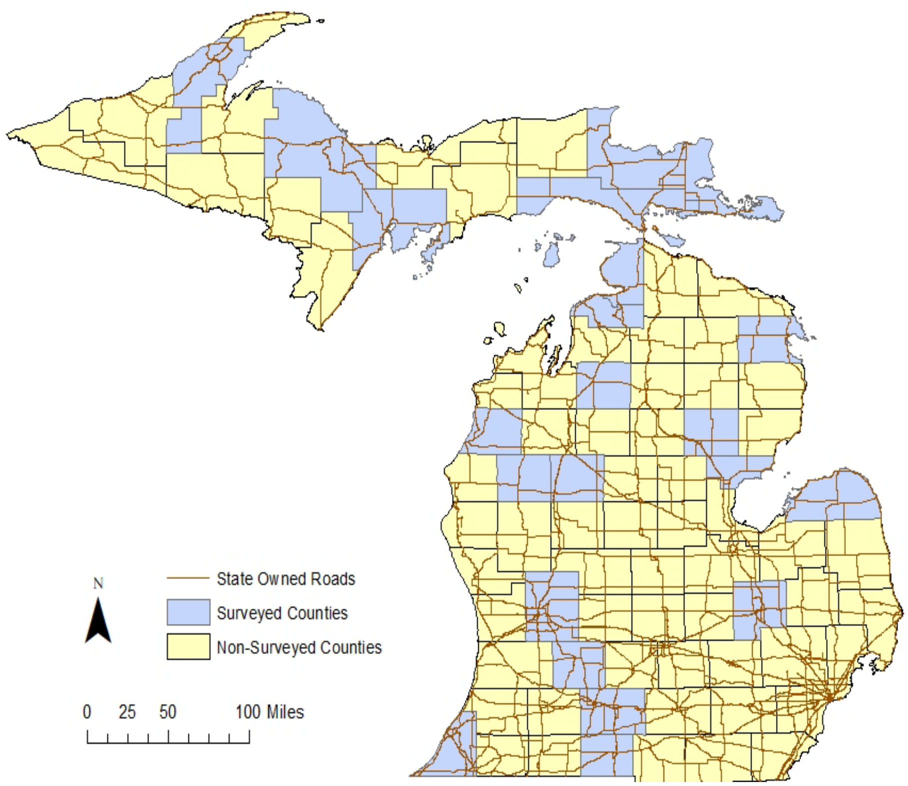


Figure 2-4 Surveyed Counties in Michigan

Table 2.3 presents the responses to the survey of county road commissions in Michigan.

Table 2-3 Responses to Survey of Michigan County Road Commissions

Questions and Responses [(1)]	**Response Tally**	**Response Percent**
Is your county on contract with Michigan DOT?		
Yes	15	71%
No	6	29%
Are or were you a WMT operator?		
Yes	13	62%
No	8	38%
Were you ever in a crash with another vehicle while operating a WMT?		
Yes	2	10%
No	11	52%
N/A	8	38%
What are some of the major safety issues for WMT operators? [(2)]		
Traveling Public	16	76%
Visibility	5	24%
Intersections	5	24%
Do you think tailgating is a significant issue for WMT?		
Significant Issue	16	76%
Not Significant	5	24%
Do you have any suggestions to decrease tailgating of WMT? [(2)]		
Education	12	57%
Lights	13	62%
No Suggestion	4	19%
Enforcement	2	10%
Do you think a collision avoidance system on the rear of the WMT would improve safety?		
Yes	4	19%
No	3	14%
Maybe	5	24%
Might Not Work Due to Weather Conditions	9	43%
Are there other types of warning systems that would benefit WMT? [(2)]		
None	7	33%
More Sign and Lights	8	38%
More Education	3	14%
Other	6	29%

(1) Surveys were conducted via phone interview in summer of 2018.
(2) Multiple responses received from select counties causing the total to exceed 100%.

As can be observed in Table 2.3, 76% of the respondents cited the traveling public as a major safety concern and the same number believe that tailgating is a significant issue. However, only 19% believe that a CAMS would work to improve safety, while 43% mentioned concerns about how well the system would operate during inclement weather conditions. Two-thirds of the respondents felt that some other types of warning systems would benefit WMTs, including more signs and lights (38%), more education (14%), or other systems (29%). The remaining one-third did not feel that any warning system would benefit WMT safety. Table 2.4 presents a summary of notable comments received during the in-state survey.

Table 2-4 Notable Comments from Surveys of Michigan Counties

Counties	**Comment**
Kent County	Would rather have the traveling public following behind them even if they are tailgating, then to be trying to pass where the road is not treated yet.
Alpena, Arenac, Barry, Charlevoix, and Marquette County	Noted intersection as a major safety concern for WMT operators.
Houghton County	Mentioned that the citizens in their county plow their driveways and move the snow across the street which becomes a major safety issue.
Lake County	Tries to decrease the amount of safety concerns by treating the roads as soon and quickly as possible.
Alpena, Arenac, Barry, Berrien, Branch, Calhoun, Charlevoix, Chippewa, Delta, Genesee, Huron, Kalkaska, Mackinac, Manistee, and Osceola County	All mentioned concerns with keeping equipment and back of the truck clear of snow and ice in order for the CAMS to work.
Osceola County	Tested rear deflector attachment (like a spoiler) to assist with keeping snow off the back of the truck.

Note: These findings are from phone interviews with county road commission maintenance personnel in the summer of 2018.

Most noteworthy, 15 of the 21 responding counties stated concerns with CAMS potentially not working properly due to snow and ice building up on the back of the truck during harsh winter conditions. Intersections were cited as a safety concern for five out of the 21 counties.

2.3 Nationwide DOT survey

Though much may be learned from the survey of Michigan counties, a nationwide survey of state DOTs allowed the research team to obtain a better understanding of the winter maintenance related safety concerns and warning systems implemented in other states. The research team attempted to survey all states that endure snow and ice events, and received responses from 14 state DOTs, which are indicated in Figure 2.5.

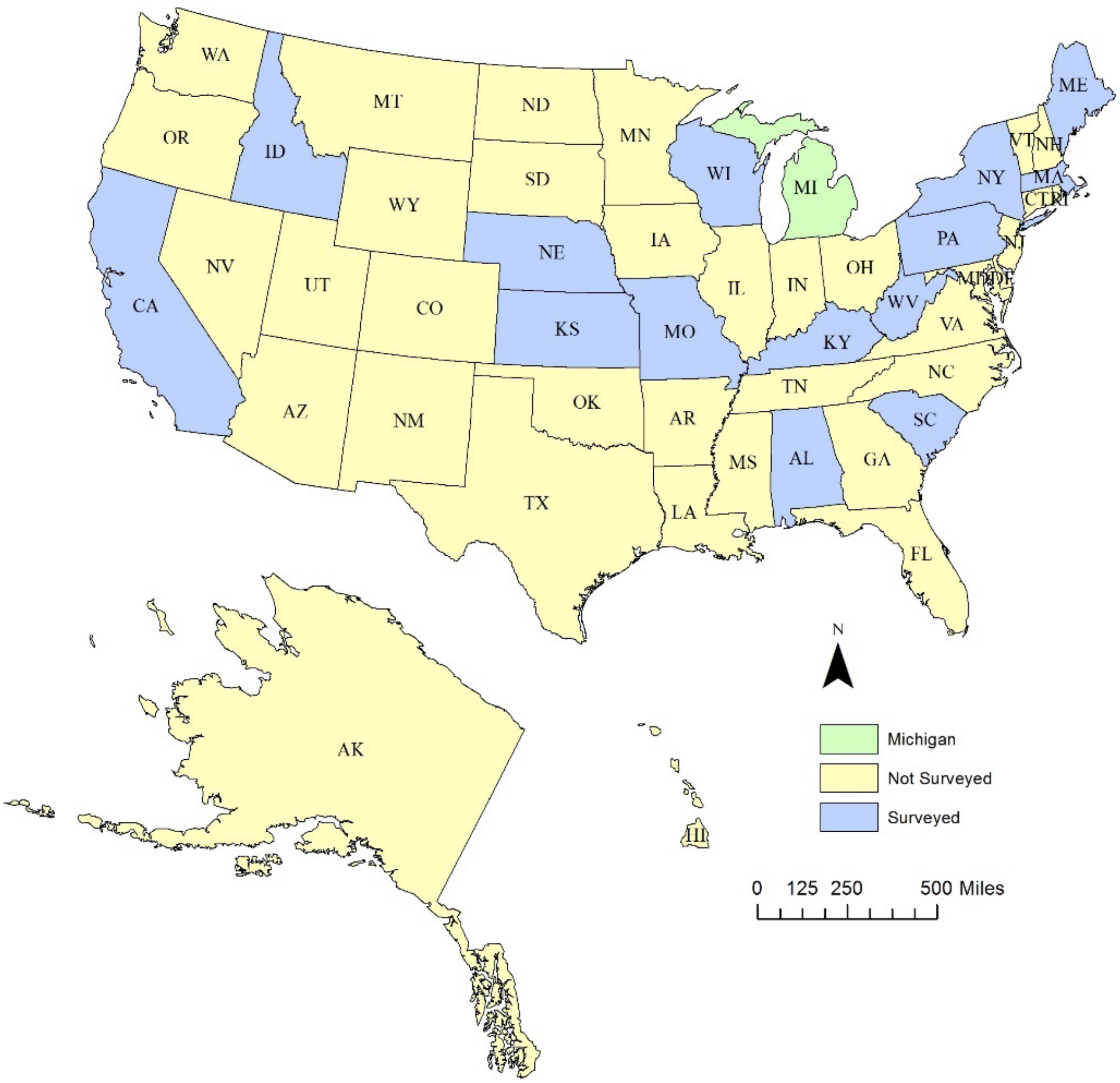


Figure 2-5 State DOTs Surveyed

As seen in Figure 2.5, the surveys conducted include states from the west coast to the east coast, affording a vast range of weather and terrain conditions. The national survey responses are presented in Table 2.5.

As shown in Table 2.5, 80% of the state DOTs feel that the traveling public is a significant safety issue for their WMT operators, while 67% of the DOTs think that tailgating is a major safety concern. Approximately 47% of respondents believe that a collision avoidance system might improve safety, which was markedly higher than the 19% found in the county surveys. More warning lighting and signing was mentioned by 53% of states as a potential benefit to WMT safety, which was also greater than in the county survey. In addition to the breakdown of responses from the DOTs presented in Table 2.5, Table 2.6 contains some additional noteworthy comments from the national surveys.

Table 2-5 National DOTs Responses to Survey

Questions and Responses [1]	**Response Tally**	**Response Percent**
Are or were you a WMT operator?		
Yes	4	27%
No	11	73%
Were you ever in a crash with another vehicle while operating a WMT?		
Yes	1	7%
No	3	20%
N/A	11	73%
What are some of the major safety issues for WMT operators? [2]		
Traveling Public	12	80%
Visibility	4	27%
Non-seasoned Staff	2	13%
Road Conditions	4	27%
Fatigue	4	27%
Do you think tailgating is a significant issue for WMT?		
Significant Issue	10	67%
Not Significant	5	33%
Do you have any suggestions to decrease tailgating of WMT? [2]		
Education	8	53%
Lights	4	27%
No Suggestion	2	13%
Follow-Vehicles	2	13%
Do you think a collision avoidance system on the rear of the WMT would improve safety?		
Yes	7	47%
No	2	13%
Maybe	5	33%
Not Sure	1	7%
Are there other types of warning systems that would benefit WMT? [2]		
None	3	20%
More Sign and Lights	8	53%
More Education	1	7%
Other	4	27%

(1) Surveys were conducted via phone interview in Summer of 2018.
(2) Multiple responses received from select states causing the total to exceed 100%.

Table 2-6 Notable Comments from Nationwide State DOT Surveys

State DOTs	Finding from Survey
California and Missouri	Both these states had a safety concern due to their "green" workforce. They are losing many seasoned drivers.
Idaho, Minnesota, New York, and West Virginia	All mentioned fatigue as a safety concern for their winter maintenance operators.
California, Idaho, Minnesota, Missouri, and New York	Don’t feel that tailgating WMT is a major safety concern.
Alabama and South Carolina	Mentioned follow-vehicles or shadow vehicles as a method to keep WMT safe from tailgating.
Massachusetts and New York	Don't think that a collision avoidance system would work well in their state.
Pennsylvania, South Carolina, Minnesota, West Virginia, and Wisconsin.	Mentioned message boards and app-based messages as a method to keep operators safe by warning the public of treatment activities.

Note: These findings are from phone interviews with state DOTs in the summer of 2018.

Officials from California and Missouri spoke about their safety concerns with the personnel reduction and turn-over in their states, which is causing an undertrained winter maintenance workforce. Respondents in five states believe safety may be improved through message boards and app-based messages warning the traveling public of the presence of a WMT. Not surprisingly, none of the states surveyed have tested a collision avoidance system. This provides further impetus to evaluate collision avoidance technology to determine the potential safety impacts for widespread implementation on winter maintenance fleets in Michigan.

CHAPTER 3 – COLLISION AVOIDANCE AND MITIGATION SYSTEM

This section provides details of the collision avoidance and mitigation system (CAMS) evaluated in this research study. As this is a new and unproven system, research was needed to measure the effectiveness of the CAMS as a tool to reduce rear-end collisions between WMTs and following vehicles and to subsequently estimate how such systems may improve safety during WMT operations across Michigan. The following sections provide details of the configuration and operation of the CAMS evaluated in this research.

3.1 Configuration of the CAMS

The CAMS evaluated in this study included a radar system, a warning light, and a camera installed on the rear side of WMTs. The radar system monitors the relative distance, speed, and acceleration of vehicles following behind the WMT to a maximum range of 600 feet. The radar system monitors up to 31 vehicles and logs the following information 10 times per second: relative distance (longitudinal and lateral), relative speed (longitudinal and lateral), and relative acceleration (longitudinal). This information is fed to an on-board computer, where the information is processed to determine the need for a warning alert. Upon detection of a following vehicle exceeding a pre-specified time headway threshold, an LED warning light-bar mounted on the rear side of WMT is activated. This warning light is intended to alert the drivers that have encroached too closely to the WMT with hopes that the encroaching driver backs off or changes lanes.

The system is also equipped with a rear-view camera that provides WMT drivers with a view of the rear of the truck and at the same time records the video in a hard drive for evaluation of the system performance. This video is overlaid with vehicle trajectory information from the radar unit. It should be noted that the camera is only used for monitoring, and does not have any vehicle detection capability. Figure 3.1 depicts the CAMS system mounted on an MDOT truck, along with the view afforded to the operator.

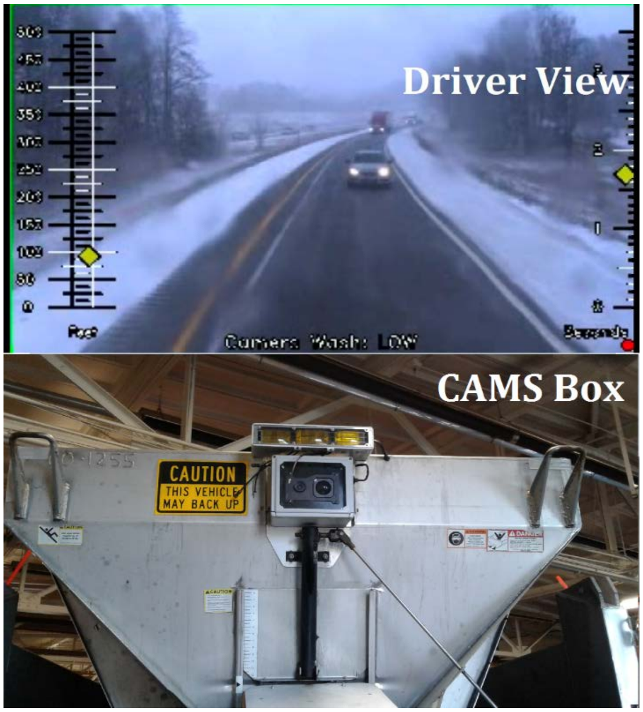


Figure 3-1 Collision Avoidance and Mitigation System

The warning light system is activated according to the following procedure. The ratio of the relative distance to relative speed between the detected vehicle and the WMT provides the relative headway, which is the basis for the warning light activation. When the following vehicle, traveling in the same lane as of WMT, encroaches towards the truck and crosses a pre-specified warning headway threshold, the warning light gets activated. The lighting system can be configured for different patterns in different headway thresholds to alarm the encroaching vehicles. For this study, two different warning alert patterns were established, termed Level 1 and Level 2, and were set to relative headways of 7 and 5 seconds, respectively, after initial controlled testing of the system. Chapter 4 discusses the process of choosing the proper thresholds in more detail. Note that in the current implementation of the CAMS, the warning light is only triggered if the relative headway drops below the threshold. Thus, a vehicle following the WMT with the same speed (i.e., with zero relative speed) would not trigger the warning light, regardless of the following distance, as the distance would remain constant based on the zero relative speed. This is a known drawback to the system as evaluated here, although the system can be reprogrammed to also include a distance-based threshold.

As the radar system performance might be hindered when it is occluded by layers of debris, the system must be kept clear of ice, mud, snow, and salt buildup. To counter this, the radar and camera were encased within a clear plastic housing that included a cleaning system. The cleaning system consists of a defrosting grid on the camera and radar box, and nozzles that spray water and air at certain frequencies to keep the CAMS box clean while the WMT is moving faster than a certain threshold (e.g. 10 miles per hour).

3.2 CAMS Logged Data

The CAMS evaluated in this study logs six different data files during the maintenance operations: four text-format files (Hardware.txt, Camera.txt, CAN_Driver.txt, and Display.txt) and two csv-format files (detected objects information and truck speed information). The content and application of each file are discussed in detail here. Text files are generated whenever the system is switched on. *Hardware*, *Camera*, and *CAN_Driver* files include the general information of the system, such as CPU settings, camera specifications, and the system start-up times. *Display* file provides the information of the triggered warnings during the operations, recording the level (1 or 2) and the exact time (with millisecond precision) of the issued warnings continuously, even when the truck is stopped.

The two csv-format files collect the information of detected objects and truck speed. They are periodically written at time intervals of 5 minutes. This means that each csv logged data file includes the information of at most 5 minutes operation until the truck is stopped and/or the operation is terminated. The first csv file contains the information of relative distance (longitudinal and lateral), relative speed (longitudinal and lateral), and relative acceleration (longitudinal) of up to 31 objects located or traveling behind the truck. It logs the information at every one-tenth of a second. The second csv file provides the truck absolute speed at every one-tenth of a second (in average).

The logged data files generated based on the radar system detections and recorded videos by camera are stored in an external hard drive to be used for the system evaluation. Once the hard drive is full, the oldest data would be overwritten. Thus, frequent data back ups from the system were required for evaluation purposes.

CHAPTER 4 – CONTROLLED FIELD TEST

This chapter focuses on the controlled test of the CAMS system performance, which was conducted on January 3, 2018 using MDOT truck number 4005. The controlled test investigated several variables, including type of following vehicle, winter maintenance truck travel speed, following vehicle travel speed, and alert time thresholds, to examine the impacts on the system performance. Furthermore, to determine the effect of dirt and grime build up, the system was also tested with mud smeared on the camera/radar encasement. In this chapter, the initial experiments that aimed to adjust the warning system thresholds are discussed initially. These experiments were performed using three different vehicles operated by members of the project team. Once the thresholds were adjusted, additional experiments on primary parameters were performed using only the passenger car. The detailed descriptions of these tests are explained in this chapter.

4.1 Type of Following Vehicles

Prior to implementing the controlled test runs, multiple preliminary experiments took place using three different vehicles (SUV, Large SUV, and Passenger car) as the following vehicle. The runs performed with the large SUV and the passenger car activated the warning light as prescribed. However, during the runs that included the standard SUV, which had an active radar-based forward collision avoidance system, the warning system did not work. Based on some unnecessary warning messages issued by the collision avoidance system of the SUV, it was possible that the radar-based forward collision avoidance system of the SUV interfered with the CAMS radar. However, further testing is needed to fully investigate any conflict between the (backward) CAMS system and other vehicles' (forward) collision avoidance systems. Based on the initial testing with the three different vehicles, it was determined that subsequent controlled testing of the systems performance would be performed using only the passenger car.

4.2 Warning Thresholds

One of the primary parameters was to establish appropriate warning thresholds. The first scenario was conducted considering three rear encroachment warning thresholds of 5, 3, and 2 seconds, which were established by the CAMS manufacturer. All test runs at this setting demonstrated that only the first threshold (e.g., 5 seconds) was useful, as the lower thresholds were triggered too close to the WMT. Due to the short gap between the truck and following vehicle, as soon as the warning system was activated (at 5 seconds), the following vehicle driver decelerated due to the uncomfortable short following distance. Therefore, it was not possible to activate the second or third thresholds or even distinguish different patterns of the warning system as the second and third warning thresholds were too close to the vehicle to be tested even in a controlled environment. Furthermore, even the initial 5 seconds threshold did not provide a large enough following distance, considering the aggressive braking needed by the test driver, who was expecting the warning system to be activated. Therefore, the thresholds are modified for further testing as follows: 8 second gap for the first threshold that activates a solid warning light, and 4 second gap for the second threshold that activates a flashing warning light.

4.3 Calculation of Relative Distance

During each test run, it was important for the following vehicle to maintain a prescribed distance and speed relative to the WMT. A LIDAR gun connected to a laptop was used in the following vehicle to monitor the relative speed and distance between the two vehicles. The relative speed between the WMT and the following vehicle could be easily monitored between the speedometer and LIDAR. Based on the prescribed speeds for each test run, it was necessary to calculate the relative distance between the following car and WMT (Figure 4.1) in advance using Equation 4.1.

$$x_{relative} = t \times (V_c - V_T) \times 1.47 \tag{4.1}$$

where, $x_{relative}$ is the estimated distance in feet, t is the threshold gap in seconds and V_c and V_T respectively are car and truck speed in mph. The following driver maintained these prescribed relative distances by monitoring the LIDAR data during the tests.

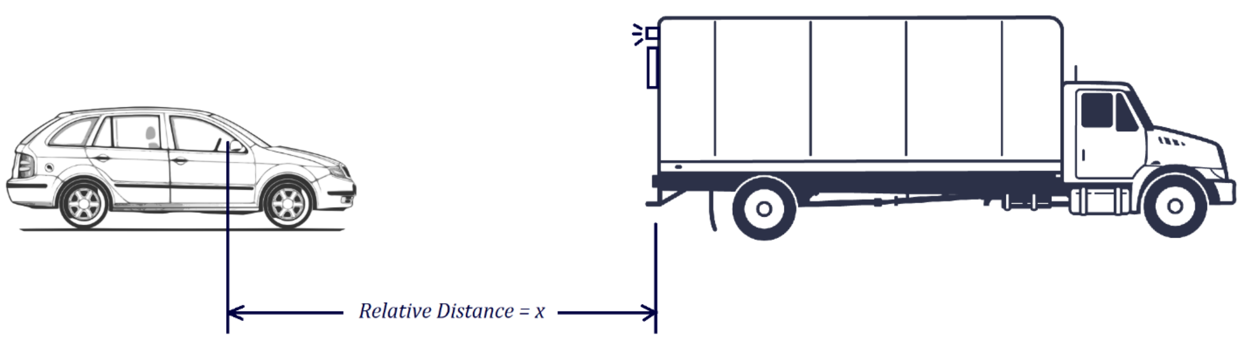


Figure 4-1 Relative distance between the following car and WMT

4.4 Controlled CAMS Performance Tests

Three main tests were performed after setting up the new thresholds and selecting the passenger car as the test vehicle to follow the truck. The objectives, procedures and numerical findings are provided hereafter.

4.4.1 Test 1 - Accuracy of Warning Light Activation

Objective

Investigate the accuracy of warning light activation at the pre-assigned headway thresholds.

Procedure

- The truck and the following car move with predefined constant speed at eight different runs (for different speed combinations). Table 4.1 illustrates the specification of the runs in Test 1.

Table 4-1 Specification of different runs in Test 1

Run	**Truck Speed**	**Car Speed**	**Run**	**Truck Speed**	**Car Speed**
1st	25	30	5th	35	40
2nd	25	35	6th	35	45
3rd	25	40	7th	35	50
4th	25	45	8th	35	55

- In each run, as the following car approaches to the truck, the relative distance is recorded via a LIDAR gun at the time that the warning system is activated.
- Note that test runs for each warning threshold were performed in separate attempts. The relative distance is easily recognizable in the logged data as the time at which the following vehicle speed decreases.
- The recorded relative distance via the LIDAR gun should be matched with the calculated distances (Equation 4.1).
- Also, a camera records the video of the data log on the computer screen and the situation in which the flash goes off (Figure 4.2)

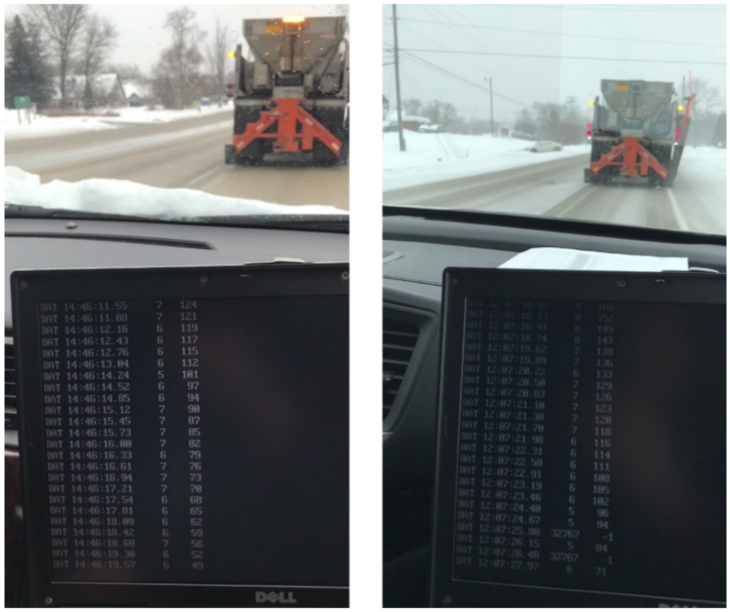


Figure 4-2 Snapshot of the LIDAR data in Test 1

Results

The relative distance between the following car and WMT for both specified warning thresholds are evaluated by four different methods. Expected values of the relative distance are calculated using the Equation 4.1. The second source incorporates the use of LIDAR gun for the relative distance estimation. The relative distance has also been estimated using the CAMS radar logged data file. This file includes the information of relative distance, speed and acceleration of the following vehicles up to 31 objects. It provides the information at every one-tenth of a second. Using the timestamp, the relative distance is extracted for target object (following vehicle). Receded video by the CAMS camera is another source for evaluating the relative distance (Figure 4.3). Relative distance is simply read from the left axis in the figure. Figure 4.4 illustrates the results of different types of relative distance estimation for the eight runs described in Table 4.1. Figures 4.4(a) and (b) show the results for the first level warning threshold and Figures 4.4(c) and (d) depict the results for the second level warning threshold.

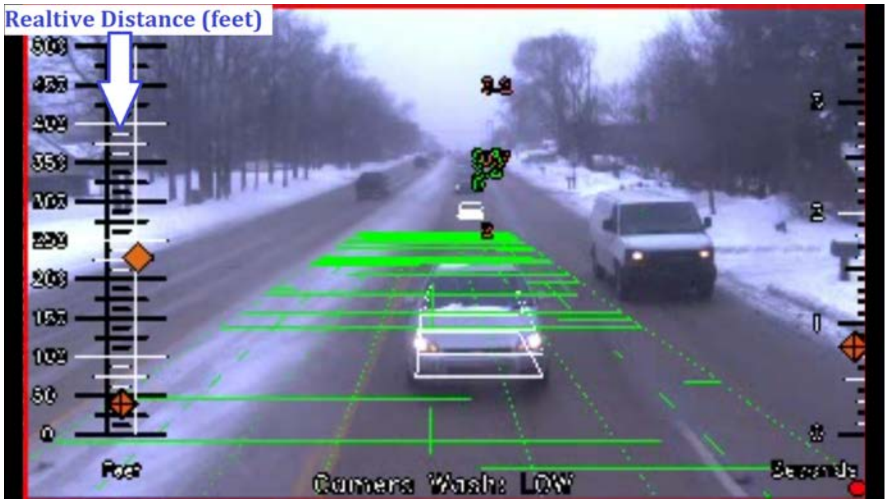


Figure 4-3 Evaluating the relative distance using recorded video by CAMS

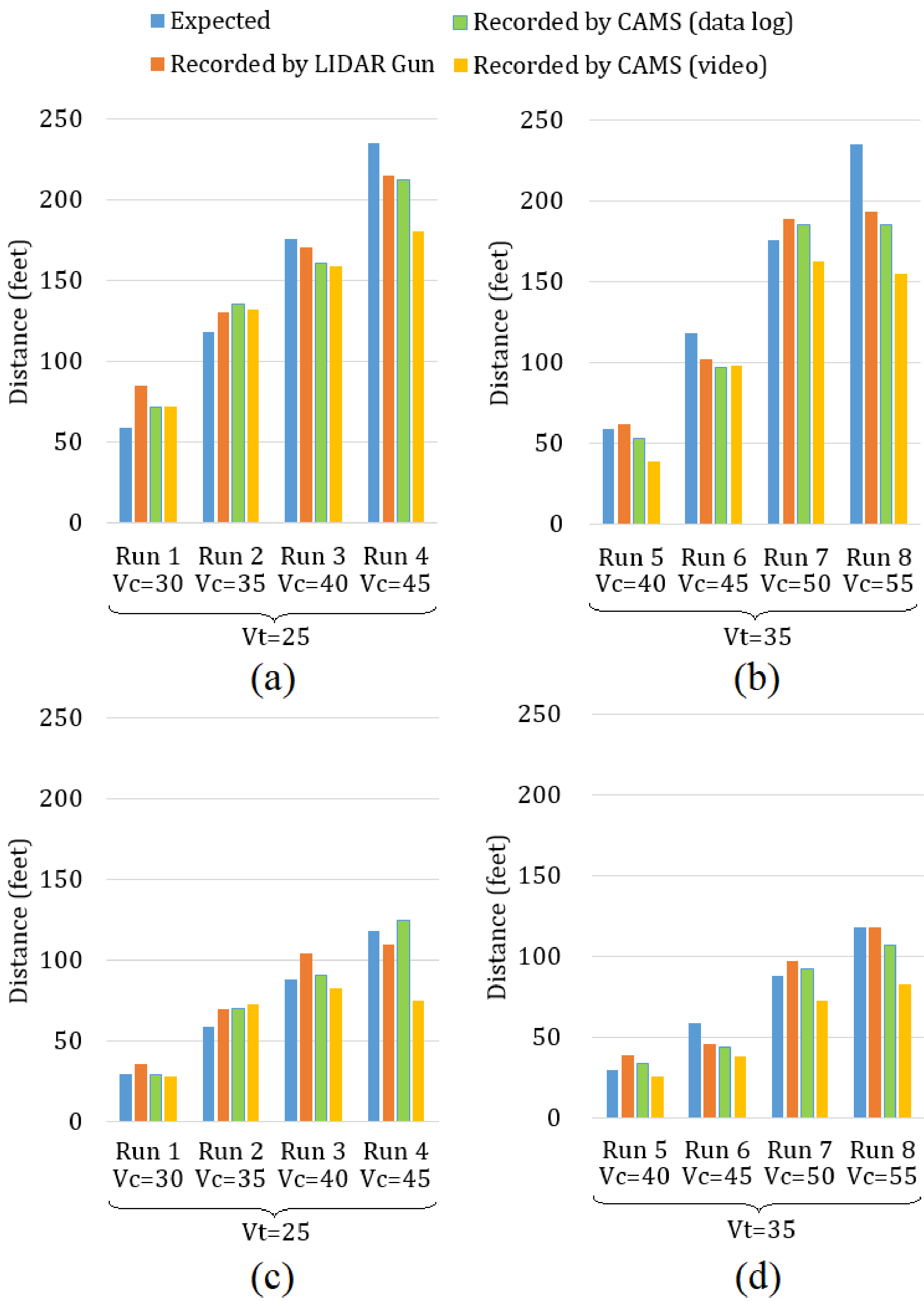


Figure 4-4 Evaluated relative distance for (a) first warning threshold (8 sec) and truck speed of 25 mph, (b) first warning threshold (8 sec) and truck speed of 35 mph, (c) second warning threshold (4 sec) and truck speed of 25 mph, and (d) second warning threshold (4 sec) and truck speed of 35 mph

The results indicate that for the second level of warning (4 seconds), the different methods all provided similar relative distances regardless of the speed, with the exception of the video. However, for the first warning level, by increasing the relative speed, the relative distance provided by the CAMS (both video and logged data) was lower compared to the expected relative distance. This may be due to the decreased ability for the radar to accurately detect objects at longer distances, such is the case for an 8 second relative threshold at high speeds.

4.4.2 Test 2 - Warning Light Deactivation Time

Objective

Measure the duration to deactivation of the warning light after the following car had receded.

Procedure

- This test aims to check the assumption that the warning system would be deactivated 1 second after the following car reduces its speed.
- To this end, as soon as the light is activated the following car brakes. A camera records the activation and deactivation of the warning system (Figure 4.5).
- This test is accomplished for both warning thresholds and a certain speed of truck and following vehicle (Table 4.2).

Table 4-2 Specification of Test 2

Run	Truck Speed	Car Speed
1st	25	30

Figure 4-5 Snapshot of the data collection in Test 2

Results

It is observed that for both warning levels the light is turned off up to about 3 seconds after the following car receded.

4.4.3 Test 3 - Impacts of Occlusion by Mud/Grime

Objective

Assess CAMS performance while the sensor and camera are being covered by grime (Figure 4.6).

Procedure

- The following car moves up to the truck by 5 mph relative speed (for instance $V_c = 30\ mph$ and $V_T = 25\ mph$).
- As soon as the light goes off the following car brakes.
- The recorded relative distance via the LIDAR gun should be matched with the calculated distances.
- The box housing the radar unit is covered with increasing amount of mud/grime and the test was repeated.

Results

The warning light was not activated when the housing for the radar unit was completely covered with mud/grime, such as that shown in Figure 4-6.

Figure 4-6 CAMS with muddy box in Test 3

4.5 Summary of Major Observations during Controlled Testing

- Relative speeds more than 20 mph were not tested due to the high risk of collision.
- Relative speeds less than 5 mph were considered as a non-significant condition.
- The first threshold (8 seconds) seems to be proper for the following vehicle driver who was expecting the warning light, although it might not be long enough for distracted drivers who are not aware of the speed difference between the WMT and their vehicle. However, increasing this threshold will likely increase the following distance to the point where radar performance is decreased, which may lead to inaccurate triggering of the warning light.
- The second threshold (4 seconds) seems to be too short, even for a prepared driver who was expecting it, leading to an aggressive brake and reaction from the following vehicle driver. For a distracted driver this number needs to be increased; otherwise, the driver may not have time to react and respond safely.
- Using two thresholds with solid (initial) and flashing (second) patterns seems to be more effective relative to the previous case with three thresholds.

- The estimated distance (according to the following section) and its comparison with the measured distance using the LIDAR gun (in the following 3 main tests), suggest that there is a lag (1 to 2 seconds) in the system activation and the 8 and 4 seconds thresholds are not actual headways for the system.
- In one of the initial experiments, the following vehicle was also equipped with a radar-based frontal collision avoidance system that measures the distance between the vehicle and any leading vehicle, which may have caused interference with the CAMS radar during testing. A more detail testing and analysis may be necessary to determine if radar-based frontal collision avoidance systems or other vehicle radar systems interfere with the CAMS radar.
- The warning light was not activated when the box was completely covered with mud/grime, which also occluded the camera view. A clear view must be provided for the radar to operate correctly, while the camera view must also be maintained to monitor the system's performance.
- The feedback from the WMT driver at the controlled test specifies that the camera view is blocked as soon as the plowing operations gets started. Based on this feedback, the washing system software was updated to automatically activate the washing system (whenever the truck speed is above 10 mph) to prevent accumulation of mud/grime. Automating the washing system requires the liquid container to be refilled frequently. This will require the driver to monitor the liquid container, which may create practical challenges while performing plowing and deicing activities.
- Also, based on this feedback, another nozzle was added to the washing system to spray both the radar system and camera lens to keep the CAMS box clean during the maintenance operations.

CHAPTER 5 – EVALUATION OF CAMS PERFORMANCE DURING WINTER MAINTENANCE OPERATIONS

This chapter provides details of the CAMS performance analysis using operational data collected during actual maintenance activities between January and March 2018. The first section reviews the collected data and trajectories of WMTs. In the second section, the performance of the washing system is analyzed. The third section discusses the warning system performance in terms of statistics on true positive, false positive, and false negative cases. The last section summarizes the collective findings from these evaluations.

5.1 Data Description

Five separate data collection periods are explored to analyze the performance of the CAMS system. These data sets represent data collected by two MDOT trucks and one RCOC truck that were equipped with CAMS. Table 5.1 illustrates the operation dates for different data sets. The data collected by CAMS included the videos recorded by the rear facing camera during the maintenance operations, in addition to the radar data log, and the log of triggered warning alerts. The radar data log includes up to 31 detected objects behind the truck for every tenth of a second. For each object, relative lateral and longitudinal distance, speed, and acceleration are recorded. For MDOT trucks, in addition to the CAMS data, the AVL system provides the exact location and speed of the trucks. The routes of the MDOT trucks mainly included US-23 from Six Mile Rd to Hyne Rd, and I-96 from N Burkhart Rd to Huron River Pkwy. Figure 5.1 depicts the trajectories for the MDOT trucks while performing winter maintenance activities during the operation dates. This trajectory information was used to identify data collected on ramps and when the WMT was turning.

Table 5-1 Datasets description

Dataset	Truck	Operation Dates
1	MDOT 4004	01/29/2018 - 02/07/2018
2	MDOT 4005	02/09/2018 - 02/11/2018
3	MDOT 4004	02/23/2018 - 03/08/2018
4	MDOT 4005	02/23/2018 - 03/08/2018
5	RCOC	02/09/2018 - 02/12/2018

5.2 Washing System Performance

The main objective of the CAMS system is to reduce the crashes during winter maintenance activities. Therefore, its performance should not be impaired by the buildup of snow, ice, and dirt/grime over the sensors during maintenance operations. The CAMS works based on a radar system that is capable of detecting objects even when it is somewhat occluded by snow or other precipitation. However, if it is covered by multiple layers of ice, snow, grime, salt, etc., then its performance might be impaired. Similarly, blockage of the camera view eliminates the ability for the driver to verify that the system is operational. It is typical for the backside of WMTs to quickly become covered with snow/ice/mud/grime during the winter maintenance operations. To combat this, a well-designed washing system is imperative to keep the radar and camera box clean and must be considered in CAMS design. Thus, to evaluate the performance of CAMS, it was essential to also investigate the washing system performance during WMTs operation and explore the impacts of its failure on the radar system performance.

Around 200 hours of recorded videos by CAMS were obtained by the MSU research team to evaluate the performance of the washing system. A review of these videos found that blockage of the CAMS box, which is identifiable by covered camera view, might disrupt the radar system performance. To evaluate the performance of the washing system, four levels of camera view clarity are specified, based on the blockage intensity, which are illustrated in Figure 5.2 for both day and night time operations and described as follows:

- In the “Clear” category, the following vehicles (or their headlights in the nighttime videos) are clearly visible and all the information of truck’s rear side is accessible.
- In the “Slightly Blocked” case, the objects (or headlights) are slightly faded but are still detectable.
- For the “Moderately Blocked” category, a small portion of the following vehicles (or headlights) is visible and it does not convey a complete information of truck rear side.
- In “Totally Blocked” case, the camera view is completely blocked and nothing is visible. Note that identifying the totally blocked cases during night operations is challenging, especially when there is no following vehicle to use the headlight as an indicator.

In this study, two types of analysis are performed to evaluate the CAMS washing system efficiency: (i) analysis of washing system performance based on the number of triggered warnings at different visibility conditions, and (ii) analysis of washing system performance based on the logged data size, which depends on the number of objects detected by the radar system.

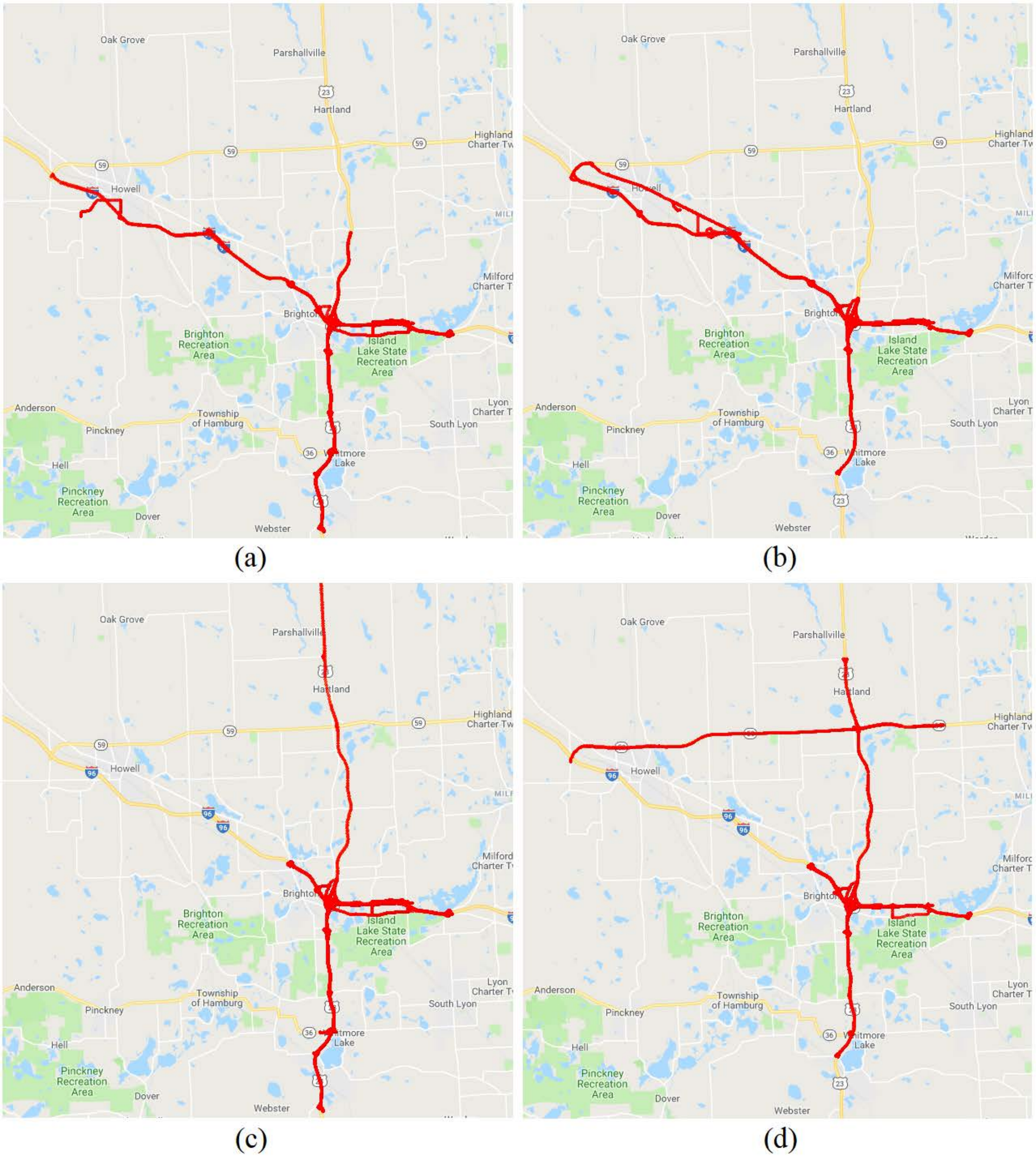


Figure 5-1 Trajectories of (a) Dataset 1 (MDOT 4004), (b) Dataset 2 (MDOT 4005), (c) Dataset 3 (MDOT 4004), and (d) Dataset 4 (MDOT 4005) – [Source: Google]

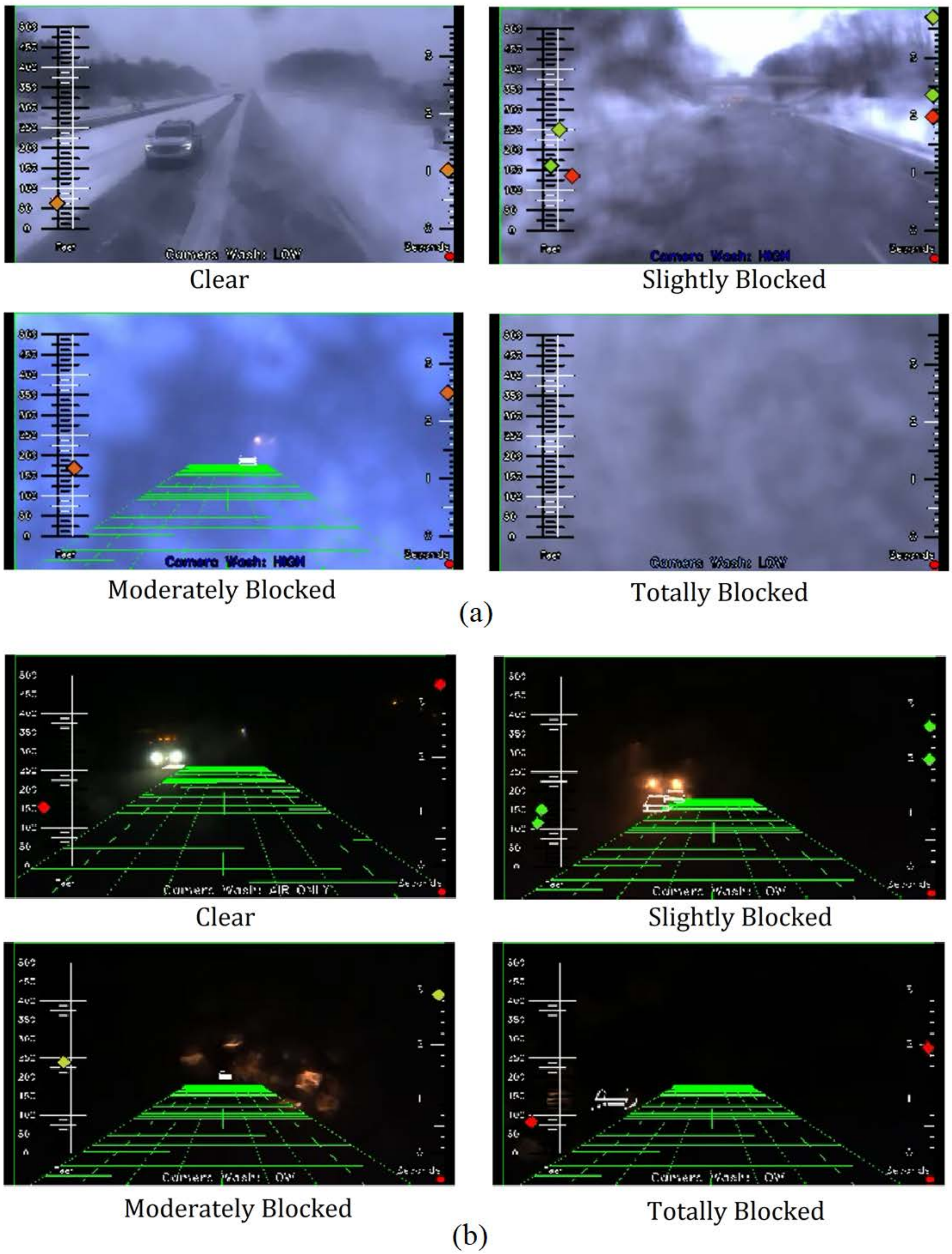


Figure 5-2 Four types of camera view quality during maintenance operations in (a) day and (b) night

5.2.1 Analysis of Washing System Performance based on Number of Triggered Warnings

Figure 5.3 shows the duration of each category of camera view qualities besides the number of warnings recorded by the CAMS. Results are separately presented for day and night operations due to challenges associated with identifying the "Totally Blocked" cases during periods of darkness. In this figure, the left side graphs (i) illustrate the total duration of recorded videos and duration of each camera visibility category for different data sets. The right side graphs (ii) show the total number of level 1 and level 2 warnings and their four different subsets: number of recorded warnings triggered by vehicles traveling in the same lane of WMT, number of recorded warnings triggered by vehicles traveling in the adjacent lane of WMT, number of recorded warnings while the truck is stopped, and number of recorded warnings in the case that camera is totally blocked and the situation of truck's rear side is not clear due to loss of visibility. For each graph, the data collection period is depicted on top.

Figures 5.3(a) through 5.3(d) show the results for MDOT trucks. Comparing the various blockage levels in Figures 5.3(a) and 5.3(b) shows that the total duration of recorded videos are the same but graph (b) includes a longer duration of totally blocked camera and as a result it has a smaller number of recorded warnings compared to graph (a). This suggests that an increase in the duration of totally blocked videos may contribute to a decrease in the number of warning alarms, perhaps due to occlusion of the radar in addition to the camera view. Figure 5.3(e) confirms this observation showing the same pattern. Figure 5.3(c) and (d) do not follow the same pattern, since the snow event is not significant for these two data sets.

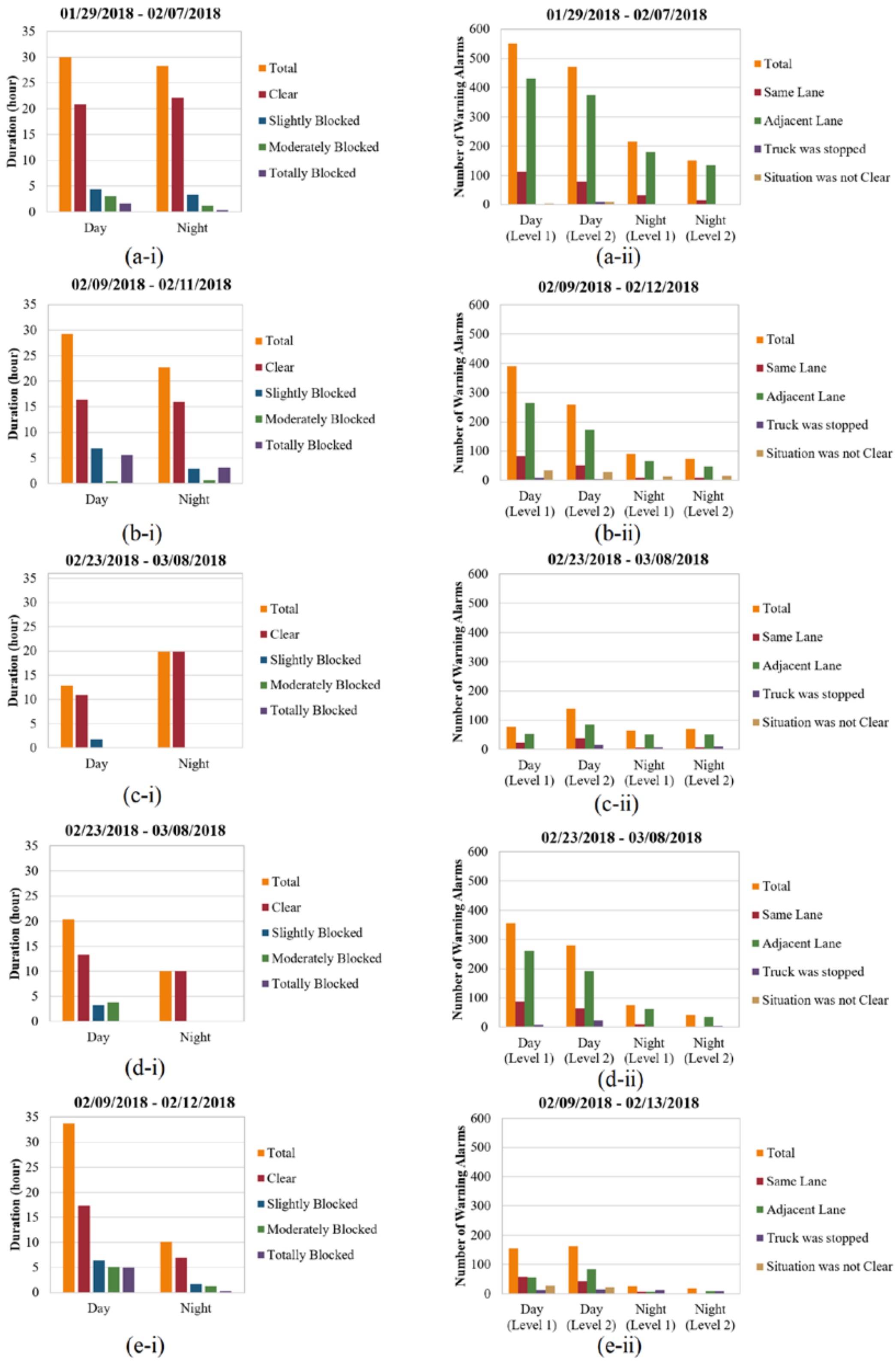


Figure 5-3 (i) Duration of different categories of camera view quality and (ii) number of warnings recorded by CAMS for (a) MDOT-4004, (b) MDOT-4005, (c) MDOT-4004, (d) MDOT-4005, and (e) RCOC

To better understand the relationship between the duration of camera blockage and number of recorded warnings, percent duration of each camera blockage level relative to the total time (of recorded videos) versus the percent of triggered warnings during each camera blockage level relative to the total recorded warnings are provided in Figure 5.4. To exclude possible errors due to classifying the night time situations, the durations of each camera view category are presented only for operations during day times in this figure.

Figure 5-4 Percentage of total time versus the percentage of total warnings for (a) MDOT-4004, (b) MDOT-4005, (c) MDOT-4004, (d) MDOT-4005, and (e) RCOC

The ratio of the percentage of recorded warnings during totally blocked time to performance of washing system during totally blocked time is 0.65, 0.24, and 0.15 respectively in Figure 5.4 (a), (b), and (e). This ratio is not available in Figure 5.4 (c), and (d), as the length of totally blocked time is zero for these data sets. The results show that only a small portion of warnings has been recorded during totally blocked time (this is not the case with other visibility categories), which suggests that the radar performance might also be negatively affected by the blockage.

Following the same method, the earlier analysis is repeated just for two specific days, instead of the entire duration of each data set. This analysis considers the same operational hours during the day time for the proposed two cases to avoid any biases in the operational comparison due to this factor. Figure 5.5(a) and 5.5(b) illustrate duration of camera views and the number of recorded warnings for two selected days. In both subfigures of (a) and (b), the total duration of recorded videos for the two selected days are the same. Therefore, it is assumed that both cases have similar traffic volumes. In both Figures 5.5(a) and 5.5(b) the left-side graphs (i) show a longer duration of totally blocked camera compared to the right-side graphs (ii). This is exactly vice versa for number of recorded warnings. This shows that a longer duration of total blockage of the camera view results in lower number of triggered warnings. Thus, it can be concluded that the CAMS housing is occluded for a significant duration of the maintenance operations. In the next section, the performance of the washing system is explored using a different strategy focusing on the data logged by the radar system, rather than through assessment of the warning alert activation log.

5.2.2 Analysis of Washing System Performance by Radar Logged Data File

The results presented in the previous section demonstrate that the CAMS box is blocked for a significant portion of maintenance operations during the adverse weather conditions. Furthermore, lower rates of triggered warnings during the periods that the CAMS box is blocked suggests that the CAMS box blockage might also hinder the radar system performance, in addition to obstruction of the camera view. To further assess the impacts of the CAMS box blockage on the radar system performance, the radar system logged data files are explored.

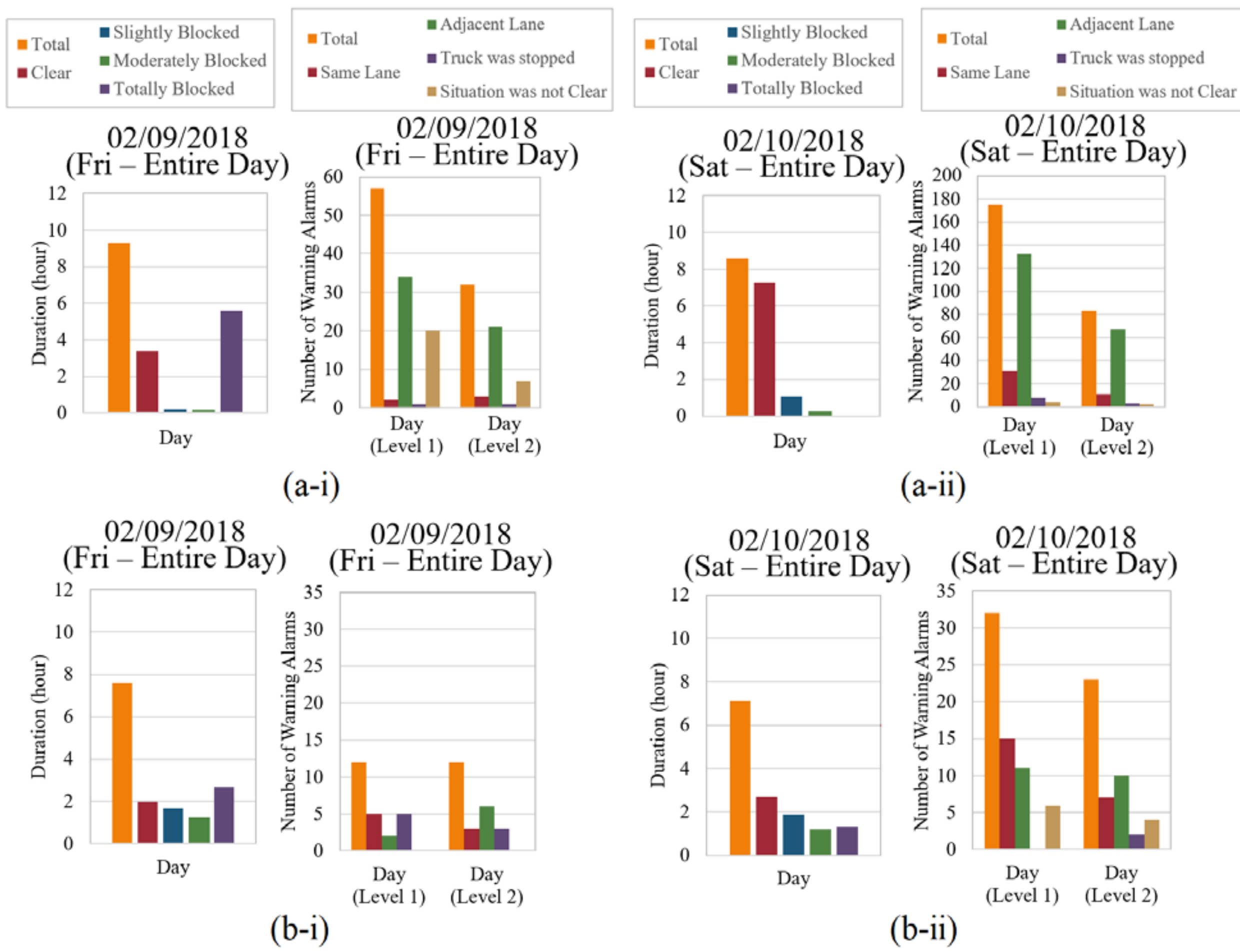


Figure 5-5 Duration of camera views and the number of recorded warnings for (i) Friday (02/09/2018) and (ii) Saturday (02/10/2018) for (a) MDOT-4005, and (b) RCOC

These files include the relative distance, speed, and acceleration of up to 31 objects detected by the radar system every one-tenth of a second. Each logged data file provides the information of detected objects for each 5 minutes of the maintenance operation, unless the operation is interrupted due to the truck stoppage. So, in most cases 3,000 (=5(min)×60(sec)×10(10^{th} of sec)) rows of data are included in each logged data file. Each file also contains some general information (6.3% of each data file has non-zero values), even if there is no object detected behind the truck. The percentage of non-zero values in each logged data file indicates how much information is collected by the system. Therefore, analyzing this value over different data logged files that are recorded with various CAMS box visibilities can help to understand if the radar system is impaired by the CAMS box blockage.

Figure 5.6 shows the percentage of the non-zero values in the logged data files versus the percentage of totally blocked duration. These graphs are presented for the data sets with heavy snow events that result into long periods of camera blockage. Each bar represents one logged data file for up to 5-minutes maintenance operation. The red line in the lower graphs represents the lowest possible percentage for the number of non-zero values in each data file (6.3%). Distribution of the percentage of non-zero values shows that when the camera box is all clear this percentage is high, and when it is totally blocked, it is dropped to 6.3%, which means that no object is detected at all. Note that a positive speed is recorded during these periods, demonstrating the ongoing maintenance operation. Thus, it is concluded that no object is detected by the radar system, although vehicles continue to follow the WMT. These graphs clearly illustrate that when the CAMS box is totally blocked, the radar system performance is impaired.

Following the same concept, Figure 5.7 illustrates the percentage of non-zero values for the entire data collection periods for all data sets. Each bar represents one logged data file for up to 5-minutes maintenance operation. The dark line represents the lowest possible percentage (6.3%). Duration of logged data with non-zero values are significant for part (a), (b), and (e). However, the same pattern is not observed in part (c) and (d). This is due to the fact that in the data sets associated with part (c) and (d), the snow events are mild relative to snow events associated with the data sets in part (a), (b), and (e).

Overall, results show that the washing system performance could affect the efficiency of the CAMS significantly. Thus, considering the fact that such systems are needed during adverse weather conditions, a well-designed and efficient washing system is strongly recommended.

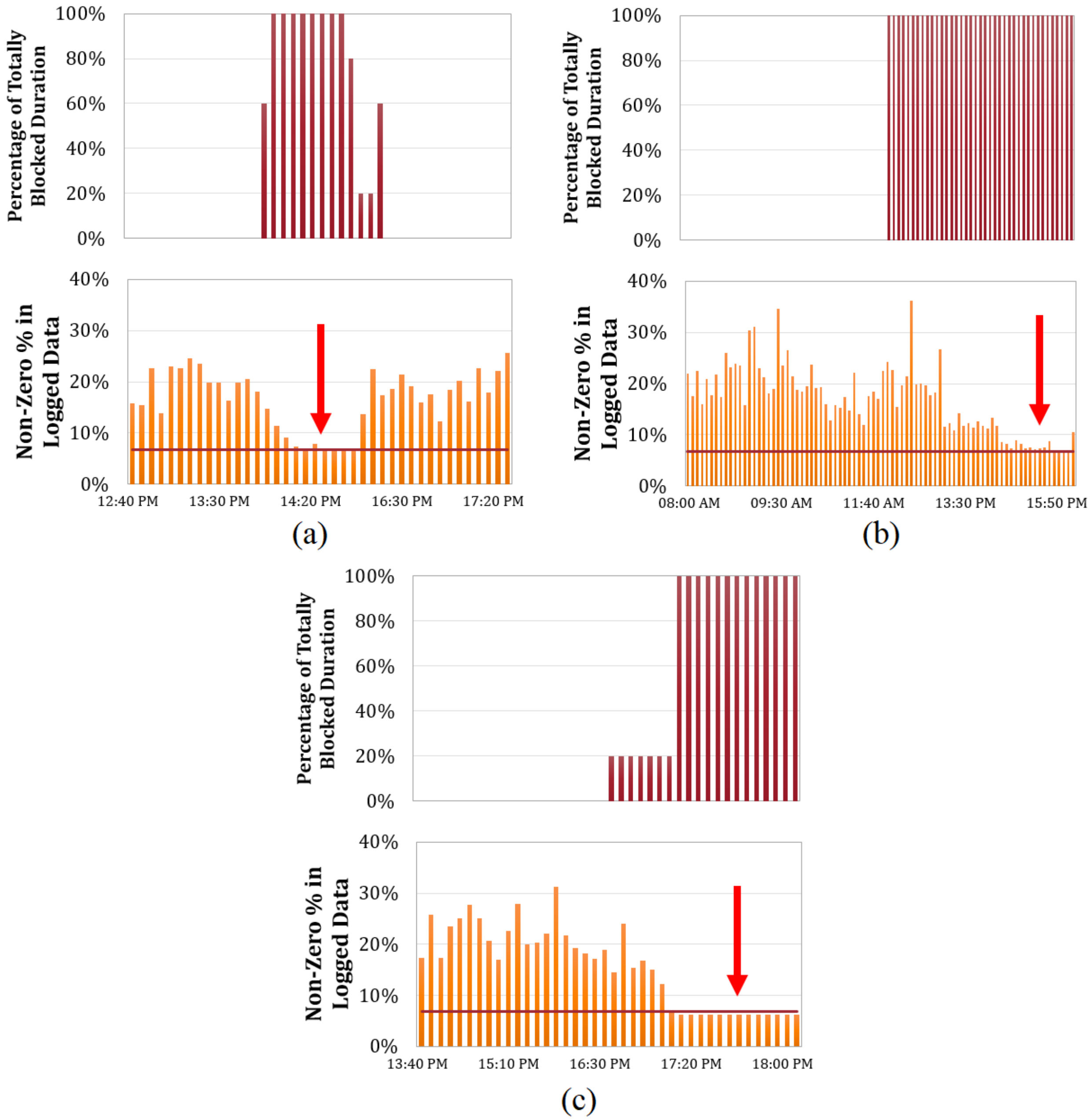


Figure 5-6 Percentage of non-zero values in the logged data versus percentage of totally blocked duration for (a) MDOT-4004, (b) MDOT-4005, and (c) RCOC

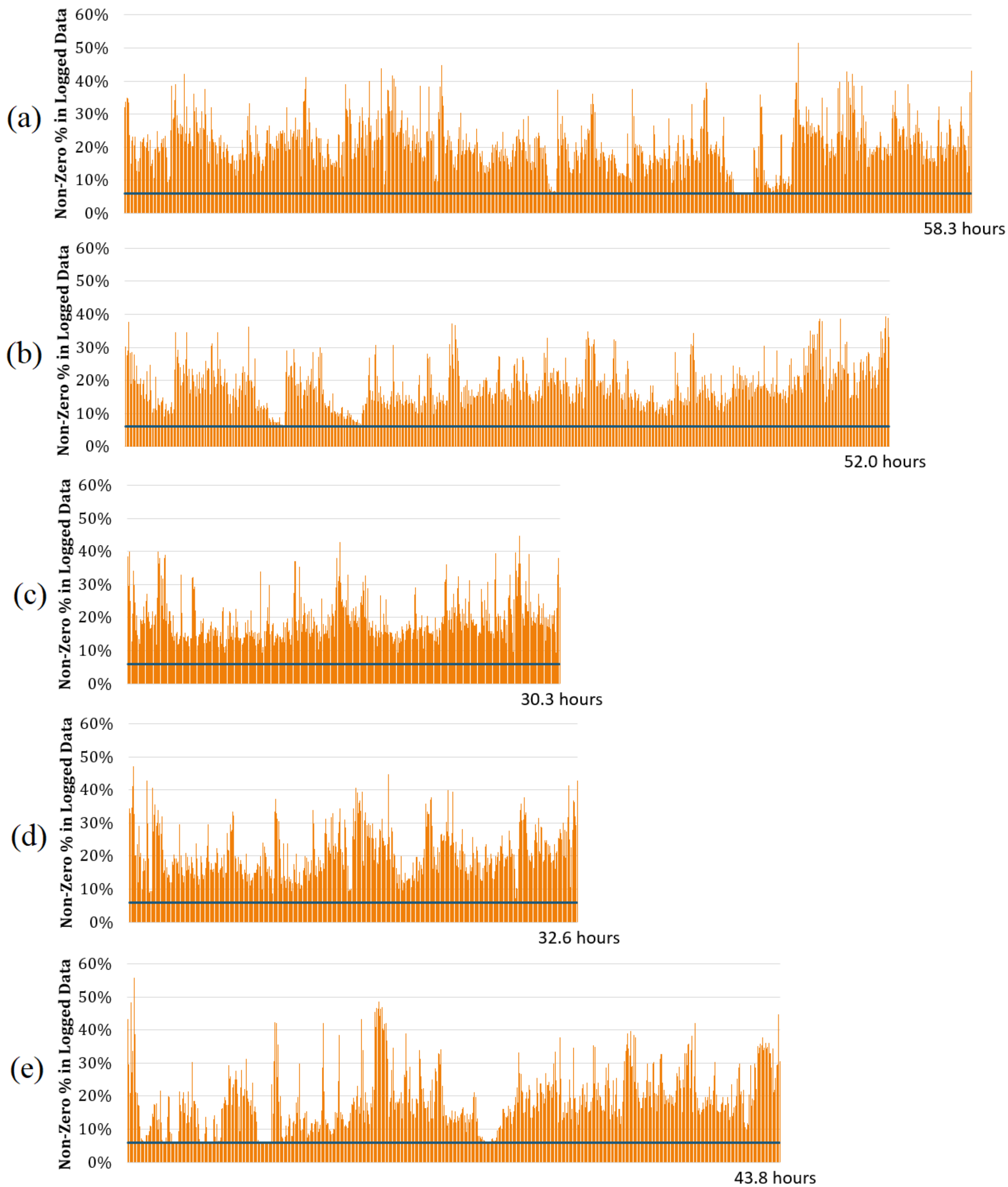


Figure 5-7 Percentage of non-zero values in the logged data files for (a) MDOT-4004, (b) MDOT-4005, (c) MDOT-4004, (d) MDOT-4005, and (e) RCOC

5.3 Warning System Performance

This section focuses on the CAMS performance by analyzing the triggered warnings. It is important to have a precise and well-deigned alarm system to inform distracted drivers encroaching towards WMTs. To this end, in this section, the distribution of the headway between the WMT and following vehicles in analyzed for cases where the alarm is triggered. Furthermore, the statistics on false positive and false negative triggered warnings are also analyzed here.

5.3.1 Warning Headway Distribution Analysis

As discussed previously, two levels of warnings are specified for the system. Level 1 is set up for 7 seconds relative headway and level 2 is set up for 5 seconds. It is expected to observe the actual relative headway of 7 and 5 seconds, consistent with the programmed thresholds, at the time that the warning is triggered. However, the collected data sets show that there is a distribution in the observed relative headway. To this end, headway distributions of level 1 and level 2 warnings that are triggered due to the vehicles traveling in the same lane of WMT (true positive warnings), are extracted and depicted in Figure 5.8. This distribution is separated for tangent and curve segments as well as for day and night time operation. In this figure, each bar represents for an issued warning. Results show that the warning alarm was not activated exactly on the pre-specified time thresholds, and experienced up to 2 seconds delay prior to activation - a significant deviation from the 7 and 5 seconds thresholds.

5.3.2 Analysis of False Positive Warning Alerts

It is observed that in many cases, vehicles passing by the WMT in its adjacent lane trigger the warning (see Figure 5.3(ii) for the distribution and values of different data sets). This is a false positive case as the warning should only being issued for following vehicles in the same lane with the WMT. This section aims to explore the reason behind this observation. In Figure 5.9 one of these false positive cases is studied in detail. Figure 5.9(a) illustrates trajectories of two vehicles following WMT at a certain time that a false positive warning is triggered. Figure 5.9(b) demonstrates a snapshot of the recorded video, which is captured exactly at the time that the warning is triggered (8:18:26 AM). Both vehicles are closing the gap towards WMT (because the absolute value of the relative headway is decreasing for both of them). The left side vehicle is traveling in the adjacent lane (because the lateral offset is more than a lane width) and the right side one is encroaching to the truck rear zone in the same lane of WMT (because the lateral offset is close to zero).

At the time that the warning light goes off, the headway of the adjacent lane vehicle is 6.9 seconds, which is less than level 1 pre-specified threshold (7 seconds). However, the following vehicle in the same lane has a large headway (331 seconds), since the relative speed between this vehicle and WMT is almost zero (0.1 km/h). The lateral offset for the adjacent lane vehicle at the time that the warning is triggered is recorded as 4.3 meters, which is more than a lane width. It means that the radar can precisely locate the vehicles and their relative coordinates consistent with the recorded video. However, the warning system is activated for the vehicles in the adjacent lane with even large lateral offset. This is an important observation as it shows that for many false positive cases due to adjacent lane following vehicles, there is no issue related to the radar system performance. This suggests that revising the detection and alert algorithm in the warning system to better exclude adjacent lane vehicles should resolve this issue.

5.3.3 Analysis of False Negative Warning Alerts

In this section, false negative cases are discussed, in which the following vehicle encroaches towards WMT and crosses the warning threshold, but it does not trigger the warning system. To this end, the trajectory of all following vehicles in the same lane as the WMT are explored and once the following vehicle crosses the CAMS thresholds, it is checked with the triggered warnings. Figure 5.10 illustrates the number of true positive and false negative warnings for the headways less than 7 seconds. Figure 5.10(a) and 5.10(b) show these numbers for the tangent and curve segments and Figure 5.10(c) depicts the overall values. There are significantly more false negative cases on curve segments relative to tangent segments due to issues associated with locating the following vehicle on curves using the lateral distance. Another major observation is that there are less false negative cases for observed relative headways less than 4 seconds on the tangent sections. This suggests that delays in the alarm activation (observed as up to 2 seconds, as discussed in the previous section) as the main factor resulting in the large number of false negative cases. All in all, the results show that there are a significant number of false negative warnings, which means that although the vehicles cross the warning threshold in the same lane of WMT, the warning system has not been activated. This suggests required system modifications to prevent these cases.

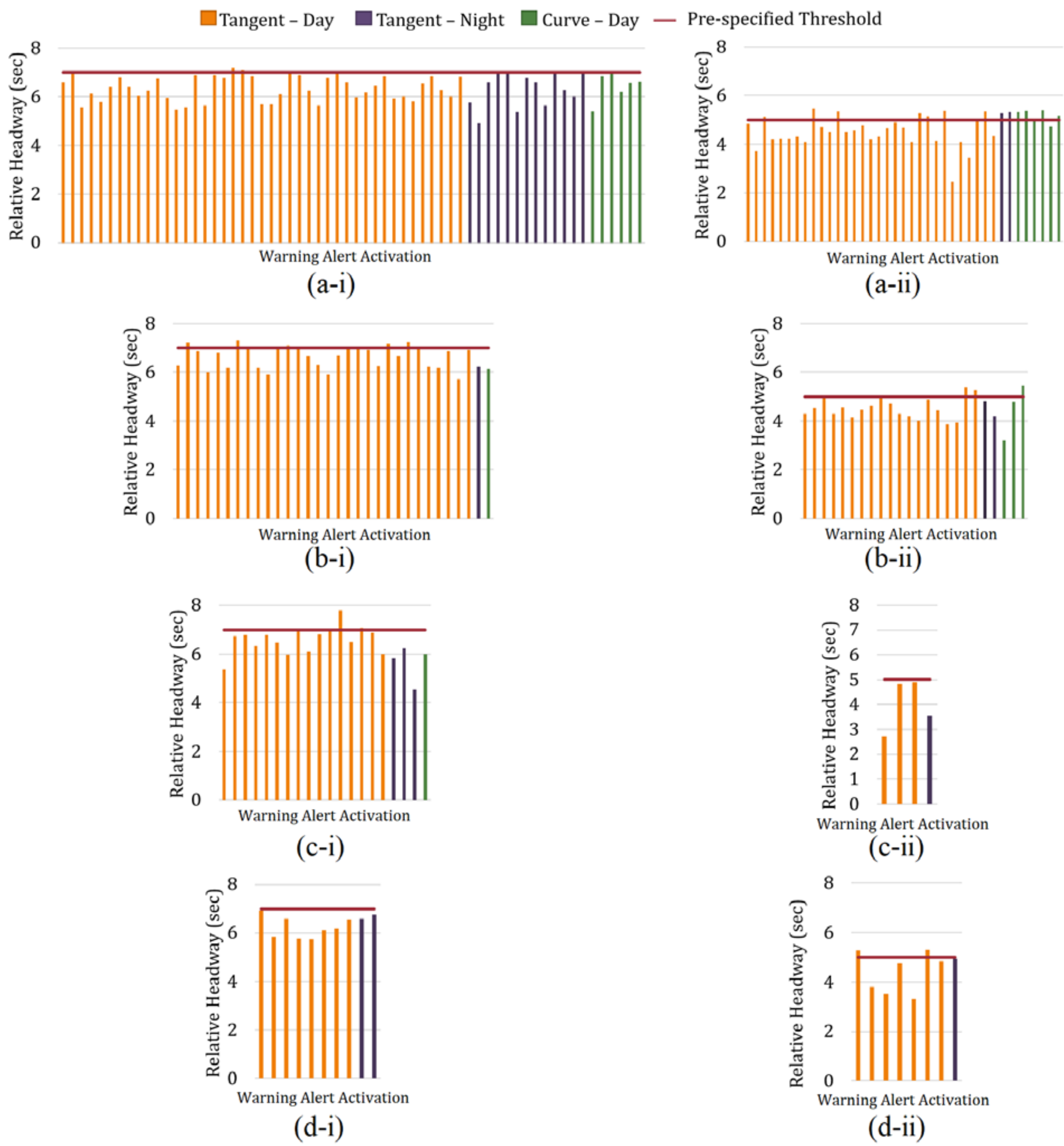


Figure 5-8 Warning headway distribution for (i) Level 1 and (ii) Level 2 warnings for (a) MDOT-4004, (b) MDOT-4004, (c) MDOT-4005, and (d) MDOT-4005

dx: space-gap (meter) vx: relative speed (km/h)
tx: headway (second) dy: lateral offset (meter)

Time	Adjacent Lane Car				Following Vehicle			
	Obj12.dx	Obj12.vx	Obj12.tx	Obj12.dy	Obj14.dx	Obj14.vx	Obj14.tx	Obj14.dy
8:18:25 AM	76.6	-9.7	-7.9	-4.4	41.4	0.3	165.5	0.0
8:18:25 AM	75.3	-9.8	-7.7	-4.5	41.3	0.2	220.3	-0.1
8:18:25 AM	74.8	-9.8	-7.7	-4.5	41.2	0.2	219.7	-0.1
8:18:25 AM	73.5	-9.7	-7.6	-4.3	41.3	0.2	220.0	-0.2
8:18:25 AM	72.4	-9.8	-7.4	-4.2	41.3	0.2	220.3	-0.3
8:18:25 AM	71.8	-9.8	-7.3	-4.4	41.4	0.2	220.7	-0.2
8:18:26 AM	70.5	-9.8	-7.2	-4.6	41.4	0.1	331.5	0.0
8:18:26 AM	69.2	-9.8	-7.1	-4.6	41.4	0.1	662.0	0.1
8:18:26 AM	69.1	-9.8	-7.0	-4.4	41.4	0.1	662.0	0.2
8:18:26 AM	67.8	-9.8	-6.9	-4.3	41.4	0.1	331.0	0.1
8:18:26 AM	67.0	-9.8	-6.8	-4.3	41.4	0.1	331.5	0.2
8:18:26 AM	66.3	-9.8	-6.8	-4.3	41.5	0.1	332.0	0.2
8:18:26 AM	64.4	-9.8	-6.6	-4.2	41.5	0.1	664.0	0.3
8:18:26 AM	63.8	-9.8	-6.5	-4.2	41.3	0.1	661.0	0.3
8:18:26 AM	63.1	-9.8	-6.4	-4.3	41.3	0.1	661.0	0.0

Recorded Warning Time (Display.txt) | Level 1 Warning is Activated | Adjacent Lane Vehicle Lateral Offset | Following Vehicle Lateral Offset

(a)

(b)

Figure 5-9 (a) Trajectories of two approaching vehicles to WMT, and (b) The snapshot of the CAMS recorded video at the time that the warning is triggered

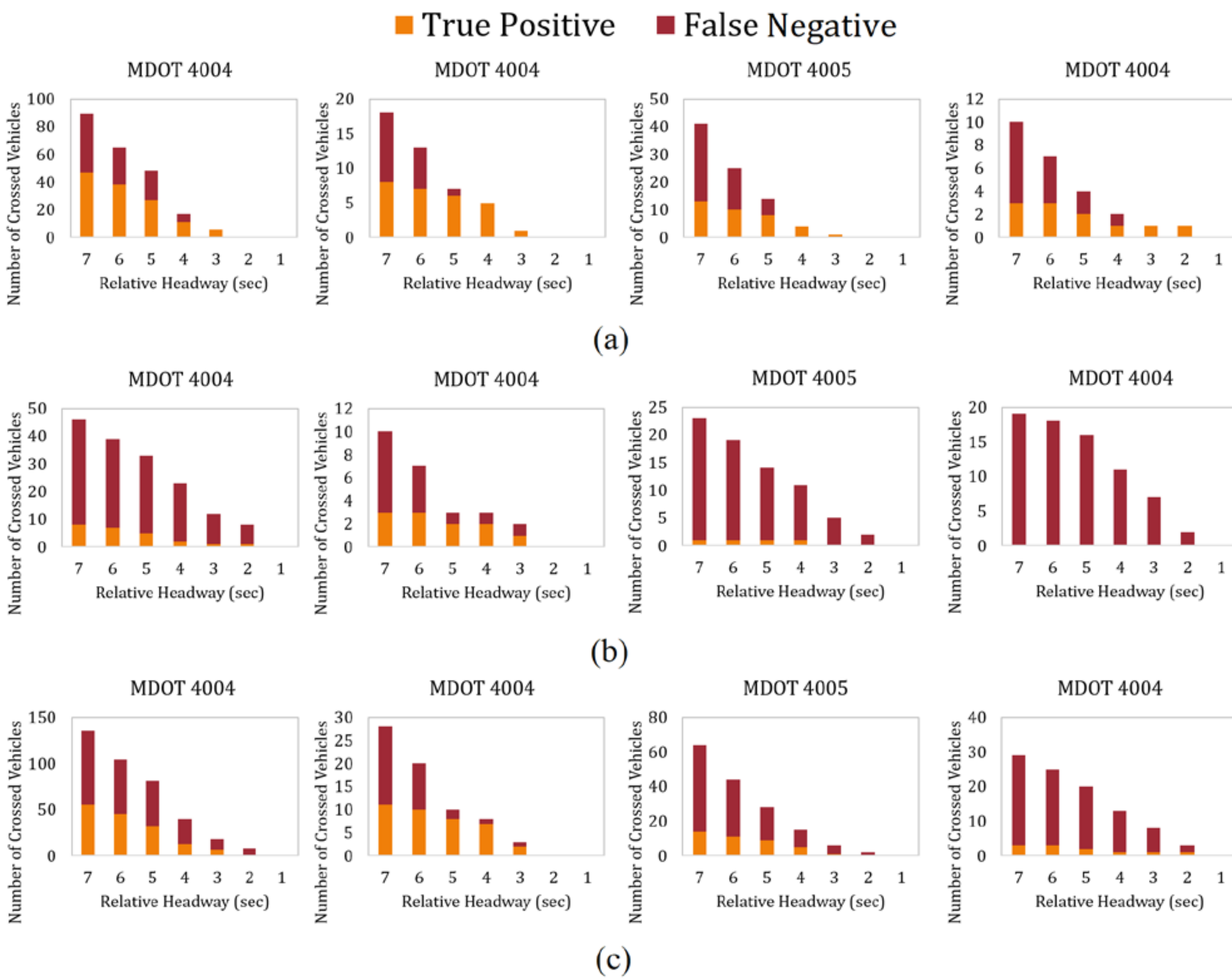


Figure 5-10 Number of true positive and false negative warnings for the headways less than 7 seconds for (a) tangent segments, (b) curve segments, and (c) all segments

5.4 Summary of CAMS Performance Evaluation Findings

The findings of this chapter can be summarized as follows:

1. Blockage/occlusion of the camera enclosure by debris (snow/ice/salt/mud/grime/etc.) also degrades performance of the radar detection system. Results show that when the camera view is fully blocked or occluded by debris, the recorded warning activations are significantly decreased. Furthermore, during periods when the camera view is fully blocked, there exists time intervals during which no object is detected in the logged data files.
2. The warning alarm is often not activated at the pre-specified relative headway thresholds (7-sec and 5-sec for level 1 and 2), with up to 2 seconds of delay observed.

3. There are a significant number of recorded warnings due to adjacent lane vehicles when there is no vehicle encroaching in the same lane of the truck (false positive warnings).
4. In many cases, the following vehicle was observed to have crossed the warning threshold but did not trigger the warning system at all (false negative warnings). This may likely be due to the aforementioned delay in the warning alarm activation and/or issues associated with the lateral distance recognition.

CHAPTER 6 – EVALUATION OF DRIVER BEHAVIOR IN RESPONSE TO CAMS WARNING ALERT

In addition to assessment of the CAMS system performance, evaluation of driver response to the CAMS warning alert system was also performed. In addition to collecting data with the CAMS warning light operational, it was also necessary to establish a baseline for the behavior of drivers when encroaching WMTs without the CAMS warning light to determine the incremental benefits associated with the CAMS warning light. To control for external biases, this evaluation was performed using the same CAMS-implemented trucks with and without the CAMS warning alert light in operation. Specifically, the CAMS-equipped trucks operated on the same routes with the radar, video, and data collection devices active, but with the associated warning light either enabled or disabled. This type of study design was deemed superior to a typical case-control design (i.e., comparing CAMS trucks versus other trucks without the CAMS), because it better isolated the effects associated with the warning alert by controlling for the effects of the truck, operator, data collection system, and route.

The behavior of the drivers following the CAMS system-enabled trucks was quantified based on two different measures, encroachment rate and response time, with the difference between the warning light on and off conditions representing the measure of effectiveness provided by the CAMS warning light. As stated previously, the CAMS radar system, camera, computer, and data storage system remained operational during all data collection periods, regardless of whether the warning light was disabled (hereafter called “OFF” periods versus “ON” periods when the warning light was enabled) or not.

The two CAMS equipped trucks operated by MDOT were used for this portion of the study and the Oakland County trucks were not utilized. The same data collection periods were utilized as described previously for the CAMS performance testing. The general info, including the truck number, operation period, and the status of the warning light, are presented in Table 6.1 for the four distinct data sets used in this section.

Table 6-1 Datasets for Driver Behavior Analysis

Dataset	Truck	Warning Light	Operation Dates
1	MDOT 4004	ON	01/29/2018 - 02/07/2018
2	MDOT 4005	ON	02/09/2018 - 02/11/2018
3	MDOT 4004	OFF	02/23/2018 - 03/08/2018
4	MDOT 4005	OFF	02/23/2018 - 03/08/2018

6.1.1 Encroachment Rate Analysis

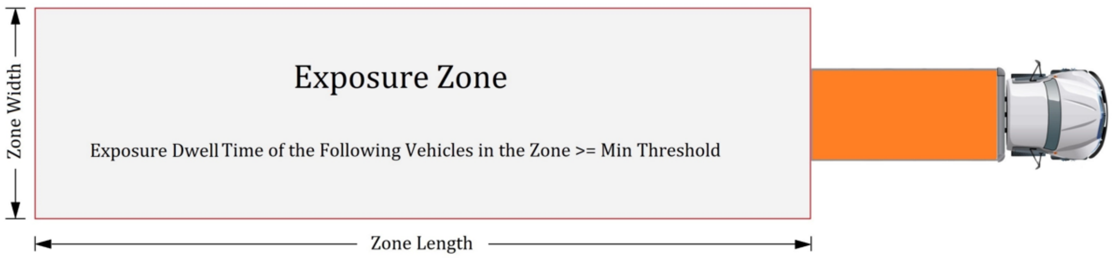
In this section, the impacts of the CAMS on the behavior of drivers following the WMT are assessed by analyzing the encroachment rates. Here, the encroachment is defined as the action of a driver entering into and staying in an exposure zone behind the WMT for a duration greater than a pre-determined dwell time. This is based on the general understanding that a driver should keep a safe relative distance, or a safe relative headway, behind the truck at all times. The closer the following vehicle encroaches towards the truck, the higher is the risk of hitting the WMT. Thus, data for vehicles approaching the rear of the WMTs were assessed for both the ON and OFF cases to assess the impacts of the warning light. Note that only vehicles that have triggered a warning are included here. Also, different analyses are provided for curve and tangent segments due to different following trajectories in these two types of road segments.

Tangent Segments

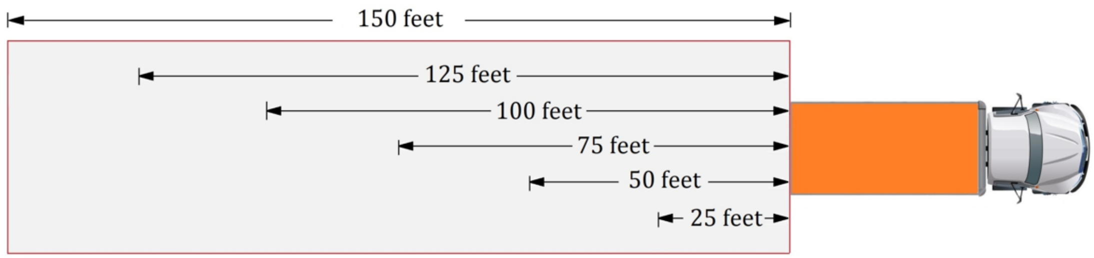
The exposure zone on tangent (straight) segments is defined as an imaginary rectangle extending longitudinally from the rear bumper of the truck up to the zone length (see Figure 6.1(a)). This length is set differently for the time-based and distance-based encroachment analyses. The exposure zone width is set in a way to only detect following vehicles traveling in the same lane of the WMT. The minimum dwell time is considered to filter out vehicles that moved out of the zone more rapidly than could be reasonably expected if occurring in response to the warning light. The specifications of the exposure zone and time/distance thresholds are given in Table 6.2. A computer program coded in MATLAB is used to extract and analyze the trajectories of vehicles moving on tangent segments detected in the defined exposure zone behind the WMT.

Table 6-2 Specifications of exposure zone for tangent segments

Property	Value
Maximum zone length	150 feet (45.72 m)
Zone width	10 feet (3.05 m)
Minimum exposure dwell time	3 sec
Distance-based length thresholds	[125, 100, 75, 50, 25] feet
Time-based length thresholds	[1, 2, 3, 4, 5, 6, 7] sec



(a)



(b)

Figure 6-1 (a) Exposure zone for tangent segments and (b) different relative distance-based thresholds for encroachment rate analysis

Curve Segments

The concept of a rectangular exposure zone cannot be applied to identify the vehicles of interest on curve segments, since the geometry of the road locates majority of a rectangular exposure zone out of the curve segment. Therefore, curve segments are analyzed differently. Triggered warnings, when the WMT travels on curve segments, are inspected manually and the subject vehicle for each case is chosen as the following vehicle just behind the truck. Note that the trajectories of the vehicles on curve segments are filtered out based on the AVL data that provides the location of MDOT WMTs at any moment of the maintenance operation.

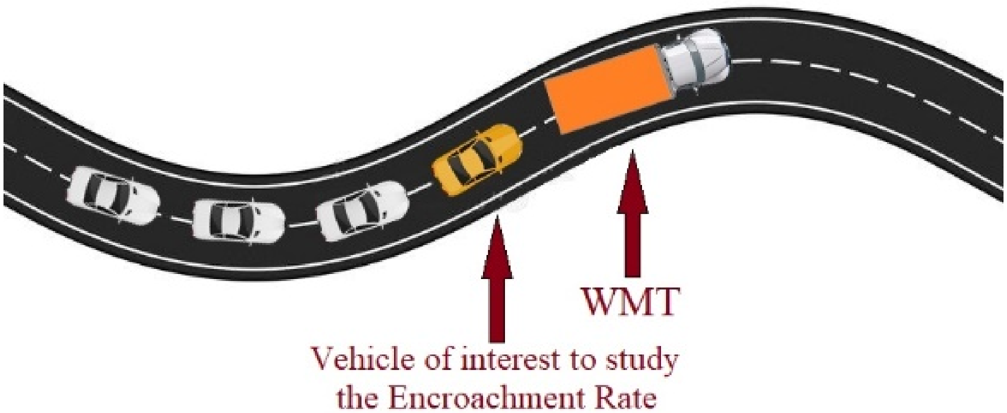


Figure 6-2 Definition of encroaching vehicle on curved segments

6.1.2 Response Time Analysis

In this section, the response time concept is utilized to assess the impacts of the CAMS warning light on the behavior of drivers approaching the rear of the WMT. The response time is defined as the time gap between the time that the warning is triggered (or supposed to be triggered in the OFF case), and the time that the minimum relative headway between the following vehicle and WMT is observed. Here, the warning activation time is used as a reference point to compare the behavior of the drivers in ON and OFF cases. The minimum relative headway is considered as the time that the driver's response to its speed differential with the WMT is completed and the following vehicle has the minimum relative distance to the WMT. Note that this response is expected to be completed earlier in the ON case versus OFF case as an extra warning light is activated to address the driver's attention to the speed differential. After the time that the minimum relative headway is observed, the relative distance between the following vehicle and WMT would increase, decreasing the risk of accident occurrence. Similar to the encroachment analysis, a computer program is used to estimate the response time by exploring the trajectory of each following vehicle that triggers the warning in the tangent segments. For the curve segments the trajectory of the following vehicles are explored manually to identify the following vehicle in the same lane properly, considering the road geometry.

6.1.3 Modeling Driver Behavior

For the encroachment rate and response time analyses, in addition to exploring statistics over different following vehicles triggering the alarm for both ON and OFF cases, certain models can be developed based on different variables (including the status of the warning light; ON versus OFF). The predictive modeling is used to generalize driver behavior in different conditions. Considering the low number of observations, especially for the OFF case, classification tree-based modeling is selected in this study. For each of these performance measures, the likelihood of encroachment, and response time, a "Classification-Regression Tree" is calibrated. Both models are based on the same set of features that describe the "state" or condition of the following vehicles and their environment.

The classification trees are used for predictive modeling as a commonly used technique in machine learning. A classification tree is a tree-like structure of decision-making splits (known as branches) that helps to predict a target outcome when a certain input is given in the form of a set of descriptive features, collectively known as the "state" of the query. The resultant trees are usually visually comprehensible and work very cohesively with categorical input variables. When the target feature is a continuous variable in such modeling, the resultant tree is known as a "regression tree". Also, this technique is one of the few that can operate adequately on small datasets, though large datasets are preferable for better modeling standards. Many programmatic algorithms are developed for finding the best classification trees out of a given data set, such as the popular 'ID3' algorithm. The fundamental idea behind this modeling approach is to split the input data set into subsets based on different levels of a given descriptive feature to create the most heterogeneous subset with respect to the target feature. Therefore, a subset with more information is more likely to describe the behavior of the data with respect to the target feature and is thus desirable.

The trajectory of the following vehicles triggering the warning are extracted for the tangent and curve segments similar to the encroachment rate and response time analyses. Then, their characteristics as recorded by the CAMS data log files are extracted for different timestamps as discussed in the first column of Table 6.3. Furthermore, other descriptive features, listed in the same table, are collected using the recorded videos by the CAMS camera at the time that the warning system is triggered (or supposed to be triggered for the OFF case). For the response time analysis, only records corresponding to response times greater than or equal to 0.25 seconds are considered. Response times shorter than this threshold were deemed impractically short to be associated with response to the warning light.

The descriptive features obtained from the prepared data are tabulated in Table 6.4. All of these features are categorical. The same features are used in both tree-based models. The classification and regression tree models are modeled in ‘R’ using the package “rpart”, which by default uses ‘ID3’ algorithm for building the tree.

6.2 Results

In this section, the results for the encroachment rate and response time analyses are presented for both ON and OFF cases. For each analysis, first general statistics (average values) are presented for different data sets. Then, for each analysis a classification-regression tree model is calibrated based on the collected data and the results are presented to compare the drivers’ behavior for ON and OFF cases.

Table 6-3 Description of the warning data for each warning level

<table>
<tr><th>Variable Set</th><th>Description</th></tr>
<tr><td>Truck data set</td><td>Identifies the different trucks as well as the status of their CAMS light system (as ON or OFF)</td></tr>
<tr><td>Timestamp at warning level 1</td><td rowspan="4">Trajectory of the following vehicle at each of these instants:
o epoch time (timestamp)
o truck speed
o relative distance
o relative speed
o relative headway (calculated as relative distance/relative speed)
o relative acceleration
o relative lateral offset
o absolute speed (of the following car, calculated as relative speed + truck speed)
o absolute acceleration (calculated as relative acceleration + truck speed / 0.1 s)</td></tr>
<tr><td>Timestamp at warning level 2</td></tr>
<tr><td>Timestamp at maximum deceleration</td></tr>
<tr><td>Timestamp at minimum headway</td></tr>
<tr><td>Environment</td><td>This feature set describes driving behavior characteristics such as space availability and desired maneuver:
o segment type (tangent/curve)
o number of lanes of the segment
o occupancy of the adjacent lane
o maneuver of the subject vehicle (back off/lane change)</td></tr>
</table>

Table 6-4 Descriptive features used in the classification tree models

Descriptive Feature	Description	Levels
Light	Indicates the presence or absence of the CAMS light signal.	1. ON 2. OFF
Warning	The activated warning level based on the headway threshold	1. Level 1 only 2. Level 2 only 3. Both level 1 and 2
Geometry	The physical environment of the site/segment.	1. Straight/tangent segment 2. Left/Right Turn 3. On/Off-Ramp 4. Merge/Diverge
Maneuver	Driving behavior characteristics such as space availability in the adjacent lane and the desired maneuver in response to encroaching WMT.	1. Single lane, follower backing off 2. Multi-lane, adjacent lane occupied, follower backing off 3. Multi-lane, adjacent lane occupied, follower changing lane 4. Multi-lane, adjacent lane vacant, follower backing off 5. Multi-lane, adjacent lane vacant, follower changing lane

6.2.1 Encroachment Rate Analysis

The encroachment rates of following vehicles are analyzed for both distance- and time-based gaps using collected data by the CAMS installed on two MDOT trucks – MDOT 4004 and MDOT 4005. The cumulative frequency distribution of the encroachment rate is plotted for both ON and OFF cases and various segment types. These plots show that how many of those vehicles that trigger the warning cross various distance-/time-based thresholds. Note that the relative frequency instead of the absolute frequency is used to compare the ON and OFF cases, since the numbers of vehicles triggering the warning in these two cases are not comparable.

The results indicate that, in general, a larger proportion of drivers cross smaller thresholds of distance- and time-based gaps for the OFF case relative to the ON case. This can be verified by the general trend of the plots for light 'OFF' appearing higher than that of light 'ON' on the vertical axis of cumulative frequency of encroachment (see Figures 6.3, 6.4, and 6.5). This indicates that the CAMS warning light system might be effective in pushing drivers to safer gaps. However, more data required, specifically on curve segments and for OFF cases to support this conclusion. The results for curve segments should be considered with caution because of the absence of observations of vehicles following truck 2 (MDOT 4005) for the OFF case. Overall, these results suggest that once the warning alarm is provided to the following vehicles, relatively less vehicles cross the lower and risky thresholds towards the WMT leading to a safer maintenance operation. However, it is crucial to have more observed data supporting this conclusion.

Decision Tree

The target feature for the classification tree model of encroachment rate is posed as a question – "given a situation of the driver following the truck, would he/she encroach into a certain threshold of the relative headway?" This certain threshold, which is a model parameter, is the critical relative headway to ensure safe maintenance operation for WMTs. The tree for the critical headway threshold of 4.5 seconds shows a concise distinction between the ON and OFF cases for a certain combination of maneuvers, warning levels, and segment types (see Figure 6.6).

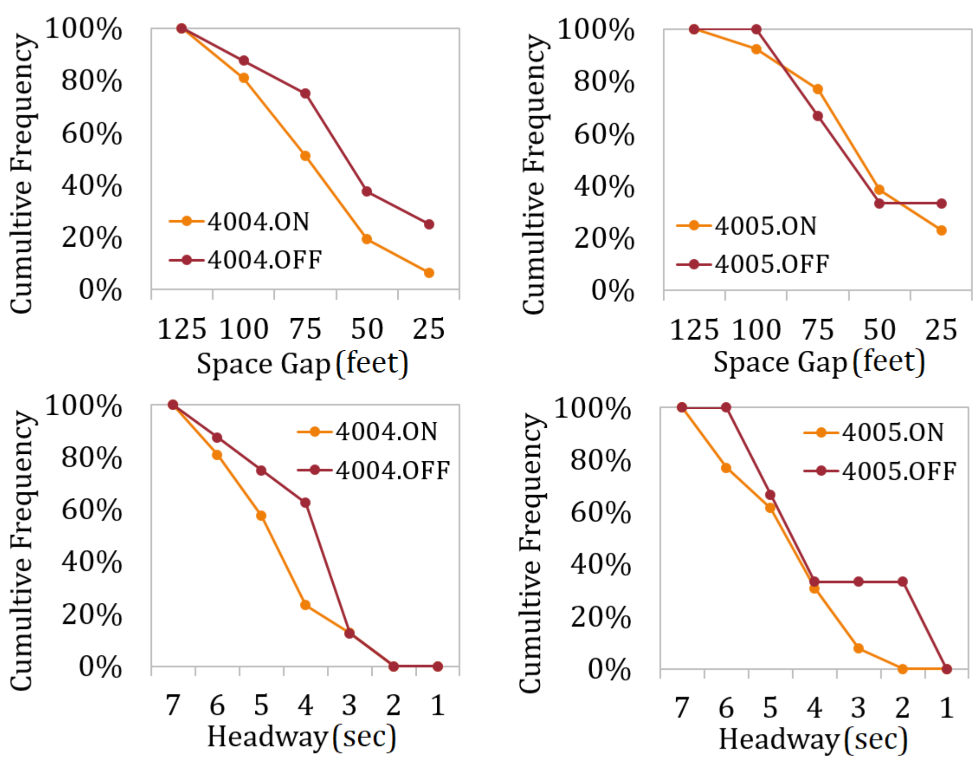


Figure 6-3 Frequency distribution of encroaching vehicles on tangent segments for the two trucks MDOT 4004 and MDOT 4005

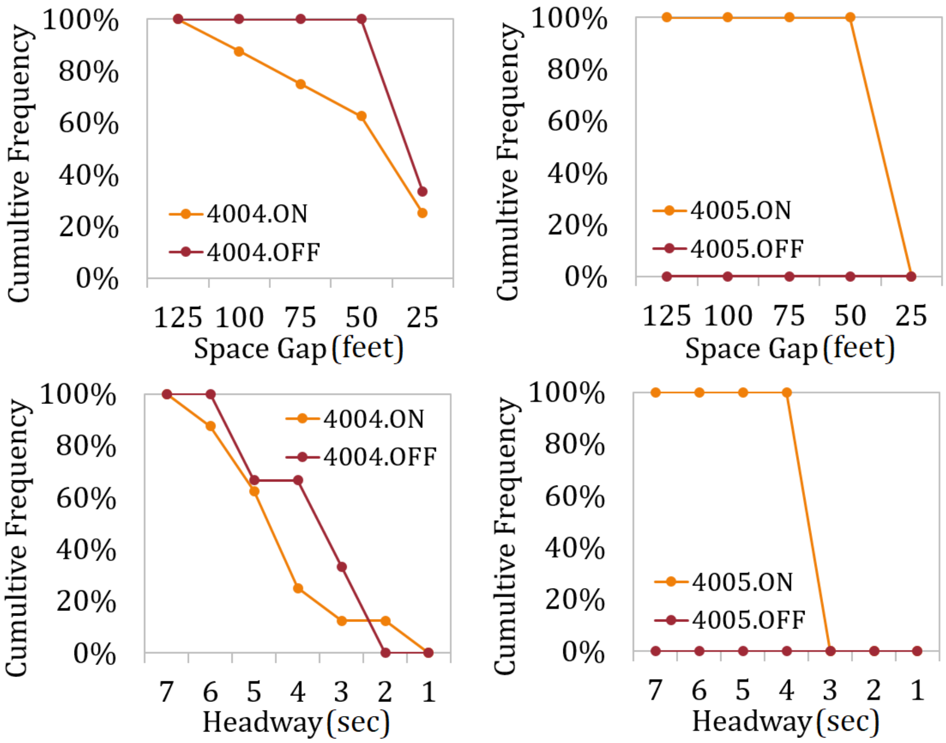


Figure 6-4 Frequency distribution of encroaching vehicles on curve segments for the two trucks MDOT 4004 and MDOT 4005

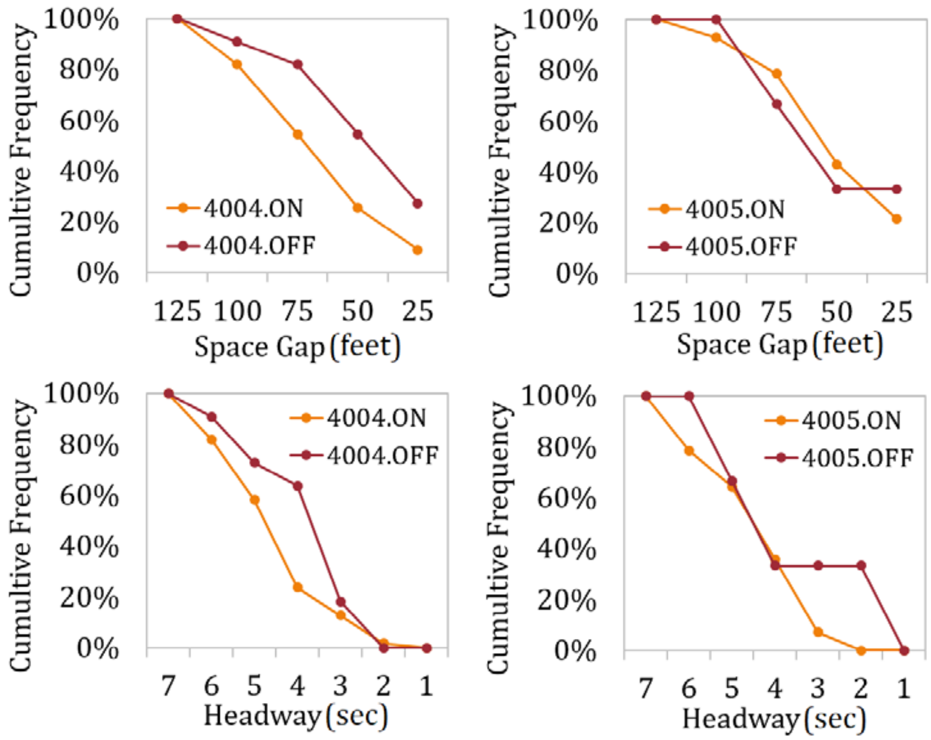


Figure 6-5 Frequency distribution of encroaching vehicles on all (tangent + curve) segments for the two trucks MDOT 4004 and MDOT 4005

The green color represents the “true” answer to the question of crossing the critical relative headway, implying an unsafe situation, while the red color represents “false” answer to the question of interest, implying a safer maintenance operation. The numbers beneath the classification results represent the confidence of classification, given in the form of a ratio with the number of cases in the classified category as the numerator and the total number of observations in that set as the denominator.

Figure 6.6 shows the impact of the CAMS warning light on the behavior of following vehicle drivers. The branches under the split of “Warning Level 1 Only” and “Maneuver = 1,3,5” show that drivers are not likely to cross a headway of 4.5 seconds, when the warning light is ON, unlike the OFF case. However, this conclusion is not statistically significant, due to the low number of observations for the mentioned branch. Note that the number of observations for other descriptive features is too low to make a distinction between different warning light statuses.

6.2.2 Response Time Analysis

Similar to the encroachment rate analysis, the trajectory of the following vehicles that trigger the warning on WMTs are studied to estimate the response time for both ON and OFF cases. The exposure zone/exposed vehicle is defined similar to the encroachment rate analysis.

Table 6.5 presents the average response time over different following vehicles that trigger the warning. The average response time is presented for multiple categories based on the warning light status (ON versus the OFF case), performed maneuver by the following vehicle in response to the speed differential with the WMT (backing off versus lane changing), and the segment type that WMT travels on (“Tangent” versus “All”, where the former includes both tangent and curve segments). Considering the backing off maneuver, there are a few number of observations for the OFF case (just 2). Thus, all maneuvers were utilized to compare the drivers’ behavior in ON and OFF cases. For the segment type, only results of the tangent segment were utilized, since there is only one observation for the OFF case on curve segments. The average value of response time is decreased by 0.55 seconds, which is about 20% improvement, once the warning light is used to alert the following vehicle drivers. Twenty percent change in the response time seems to be a really promising improvement in the response time of the following vehicles that may have significant safety benefits by preventing rear-end accidents with WMTs. However, it should be noted that there are just only 7 observations for the OFF case, which may question the statistically significance of the conclusion. One can see that adding just one OFF observation for the curve segments can underestimate this improvement. Thus, a more comprehensive study is needed to observe more data, specifically for the OFF case at different conditions.

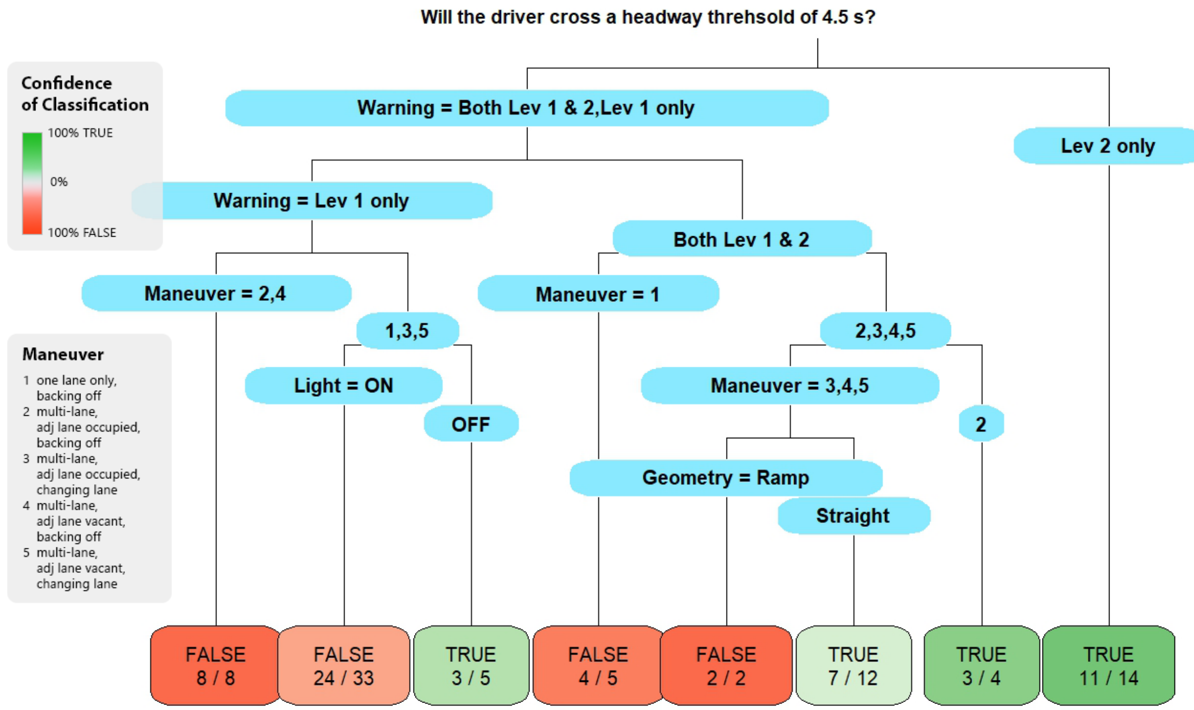


Figure 6-6 Encroachment decision tree for critical headway threshold of 4.5 sec

Table 6-5 Response time for different maneuvers for warning level 1 from all warning combinations

Maneuver	**Light**	**Tangent Segment** Average Value (s)	**Tangent Segment** No. of Observations	**All Segments** Average Value (s)	**All Segments** No. of Observations
Both maneuvers	ON	2.16	36	2.17	42
	OFF	2.71	7	2.46	8
Lane change only	ON	2.42	25	2.39	26
	OFF	2.94	5	2.57	6
Back off only	ON	1.56	11	1.82	16
	OFF	2.13	2	2.13	2

Decision Tree

Similar to the encroachment analysis a classification-regression tree-based model is presented for the response time in Figure 6.7. In this figure, based on the descriptive features and the associated response time to each of these features, two branches distinguish between the ON and OFF cases. The first branch is associated with "Level 1 only and both Level 1 and Level 2" warnings for Maneuver of "1,3,4". In this branch, 0.68 seconds reduction, which is about 27% improvement, is observed in the response time, once the warning light is used to alert following vehicles. The second branch associated with "Only Level 1" warning and maneuver "2,5" shows 0.76 seconds reduction, and 25% improvement in the response time, once the warning light is used to alert the drivers. Although these reductions are a significant improvement in terms of safety, it should be noted that the number of observations is limited, specifically for the OFF case. This suggests that there might be some potential for the CAMS to improve safety, but this needs to be confirmed by a more enriched data set including enough number of observations for both ON and OFF cases.

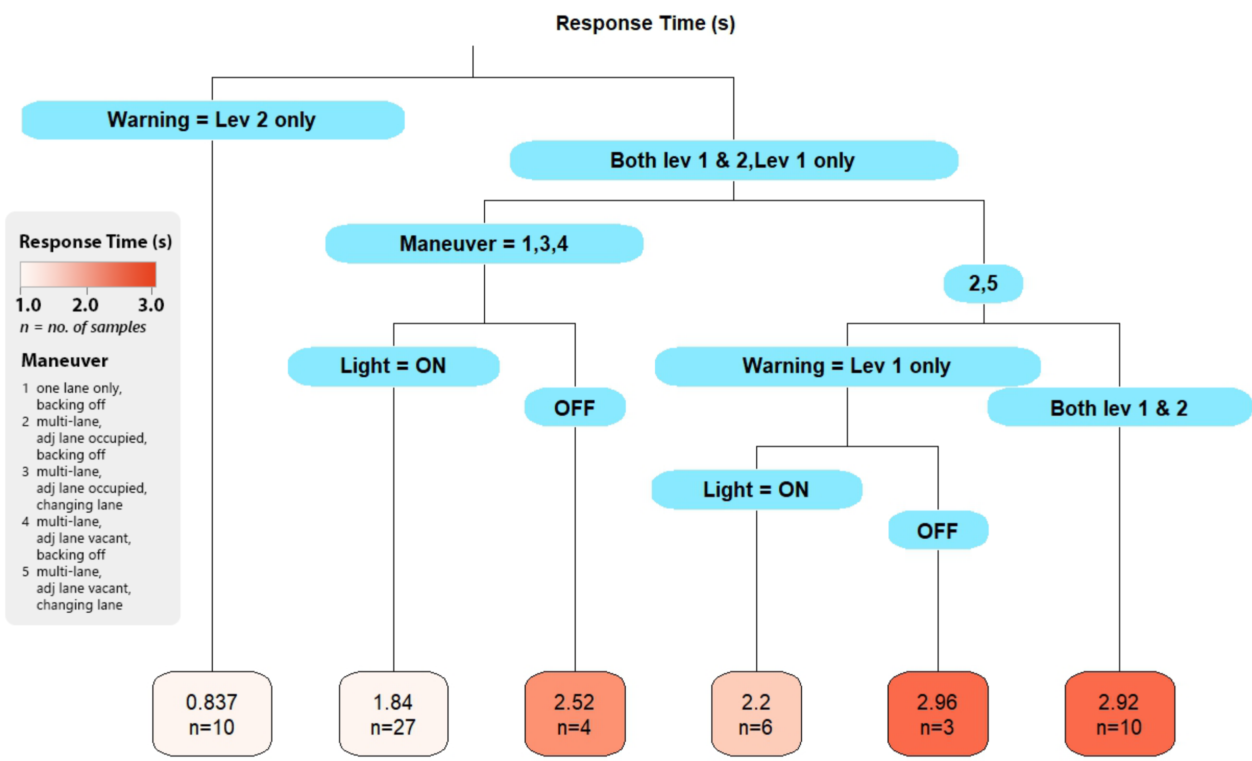


Figure 6-7 Regression tree for response time

6.3 Summary of Findings

The findings of this chapter can be summarized as follows:

1. The CAMS warning light is potentially effective based on observations of drivers' behavior during proper (i.e., true positive) activations of the warning light.
2. Encroachment rate, defined as the proportion of vehicles triggering the CAMS warning light vehicles that cross a pre-determined relative headway, was found to be reduced in the ON case versus the OFF cases during most of the data collection periods. However, it is necessary to collect more data for the OFF case and on curved segments prior to drawing conclusions.
3. A predictive model was generated to estimate the relevance of environmental and situational factors in determining drivers' likelihood of crossing a critical relative headway. It was observed that the CAMS light is an influential factor in changing this likelihood, though not very significant due to a small sample size.
4. The response time, defined as the time gap between when the warning is triggered (but only activated during the ON data collection periods) and when the minimum relative headway is observed was the other driver behavioral measure used in this study. An approximately 20% lower response time was observed during the ON data collection period. This suggests that the warning light may cause drivers to react and subsequently respond more quickly, thereby reducing the risk of a rear-end collision with the WMT. However, the low number of observations for the OFF condition reduces the significance of this finding and suggests that additional data are necessary, particularly in the OFF condition, before definitive conclusions can be formulated.
5. The regression tree based model for the response time also shows a positive effect of the CAMS warning light. However, more data are necessary to support the statistically significance of this conclusion.

CHAPTER 7 – WMT DRIVER FEEDBACK

This chapter analyzes the CAMS performance from WMT drivers' point of view. To this end, in-person interviews were conducted for two groups of drivers. First, the viewpoints regarding drivers assistive devices and safety improvement issues were collected from non-CAMS equipped WMT drivers. Then, the CAMS-equipped WMT drivers were interviewed for opinions on various aspects of the CAMS. The prepared questionnaires for each interview can be found in Appendix A. In the first section, the general driver responses are discussed, while in the second section, the feedback of the WMT drivers is provided. Finally, the summary of findings is listed at the end of this chapter.

7.1 Survey of Non-CAMS WMT Drivers

Four MDOT truck drivers (with no experience with the CAMS) were interviewed to get their opinion about the safety improvement issues related to WMT.

7.1.1 Interview Questions

WMT drivers provided feedback on the following items:

- Safety issues during winter maintenance activities (different types of conflicts because of WMT presence)
- Effectiveness of a collision avoidance system installed on the rear of a WMT on safety improvement (specially decreasing the number of rear-end collisions)
- Tailgating and its impacts on safety
- Other types of warning systems that can improve the performance of winter maintenance activities (e.g. green warning lights, back up alarms, lane departure warning, forward and collision warnings, blind spot warning, adaptive cruise control, and infrastructure assisted hazard warning)

7.1.2 Primary Responses

- The speed difference between WMTs and other vehicles on the road was listed as the major safety concern. In addition to the speed differential, passing by WMTs using the shoulder lane, and sharp maneuvers were discussed as other safety concerns.

- Prioritizing traffic signals for WMTs to avoid stop and go delays, new legislations to prevent cutting in front of WMTs, passing by WMTs from shoulder, and tailgating, and enforcing these regulations by significant fines were suggested to mitigate the conflicts between WMTs and other road users.
- Longer and wider median turnarounds and on/off ramp shoulders were suggested to facilitate smooth maneuvers and prevent crashes.
- During the heavy snow events, when the pavement is covered with snow and mud in front of WMTs, detecting the traffic signs and lane markings was stated as one of the major issues. In this regard, a lane departure warning system was proposed as one of the helpful safety improvement for WMTs.
- The prototype CAMS used in this study was discussed with the drivers, who confirmed some potential safety advantages for such systems. However, incorporating a different color for the warning light (other than regular lighting alarms on WMTs), and testing such systems in practice were proposed as the required initial steps in developing such systems.
- It was suggested to incorporate new technologies to develop a warning system to prevent side collisions and remove blind spots.

7.2 Survey of CAMS-equipped WMT drivers

Two WMT drivers, whom their truck were equipped with the proposed CAMS in this study during the maintenance operation of winter 2018, were interviewed with different sets of questions relative to the previous section. The main objective in this section is to get the drivers' feedback on the performance of the CAMS based on their actual experience (instead of relying on their expectations similar to the previous section). Note that the effectiveness of the CAMS on assisting truck drivers should be studied separately from the impacts of this system on the behavior of the following vehicle drivers. The former is considered in this chapter, while the latter is discussed in the previous chapter. Similar to the previous section, a discussion on the main content of the questionnaire is followed by the drivers' feedback.

7.2.1 Interview Questions

WMT drivers equipped with the CAMS provided their feedback on the following items:

- CAMS impacts on the safety improvement (visibility of WMT by other vehicles during winter maintenance activities, and impacts on the possibility of crashes and number of sharp braking or other evasive maneuvers)
- The possibility of causing distraction for truck drivers by CAMS
- The performance of the washing system
- CAMS performance during different operational or environmental conditions (plowing vs deicing, day vs night time operation, light vs heavy snow events)
- Effectiveness of the CAMS to in performing U-turn and stopping maneuvers
- The CAMS maintenance requirements

7.2.2 Primary Responses

- Both drivers believe that the CAMS does not provide any advantage relative to the current lighting alarms that WMTs are equipped with. Also, they do not anticipate any potential reduction in the possibility of crashes or critical maneuvers by installing the proposed CAMS on WMTs.
- Incorporating a sound/vocal alarm might improve the efficiency of the CAMS. However, such an alarm might be distracting to other road users in the general proximity.
- Both drivers stated that the CAMS in-cab screen was distracting and also due to the mirrored camera view, it could not be used as an extra view to cover the blind spots.
- Washing system performance was reported as too poor to keep the camera clean in the heavy snow events. The main reason behind this is a small tank for the reservoir. Also, the tank is located behind the plow and it is not easily accessible (Figure 7.1).
- Warning light gets muddy all the time, so the washing system should be modified to clean the light as well as the radar and camera box.
- The warning light angle has not been set up properly to inform the distracted drivers.

Figure 7-1 Camera Wash Tank

7.3 Summary of Findings

Tailgating and the speed differential between WMTs and other road users was stated as one of the major issues regarding the winter maintenance operations, which is consistent with the surveys of Michigan counties and nationwide state DOTs discussed previously. Drivers consider potential safety benefits that can be achieved via a well design warning system addressing this tailgating issue. However, the driver feedback shows that the CAMS system in its current format cannot be used. First of all, any changes in the behavior of the following vehicle drivers in response to the CAMS warning alert are considered by the truck drivers to be too small in magnitude to have relevance for safety benefits (See Chapter 6, the response time analysis). The surveyed drivers also recommended additional changes to the system, including using a warning light color that is distinct from the other warning lights on the WMTs, improving the washing system performance, and improving the in-vehicle display to improve blind-spot monitoring.

CHAPTER 8 - EVALUATION OF WMT CRASH DATA AND ECONOMIC ANALYSIS

Crashes involving winter maintenance trucks (WMTs) pose unique threats to traffic safety. WMTs typically travel significantly slower than the prevailing speed of traffic and these large vehicles have various blind spots. In addition, WMTs are generally deployed at times when visibility and roadway conditions make it more difficult for other drivers to identify them or to stop in time to avoid a crash. Installing Collision Avoidance and Mitigation Systems (CAMS) on WMTs presents a means to mitigate the visibility issues that could arise during snowy weather by making the WMTs more conspicuous to approaching motorists.

In order to assess the potential effectiveness of large-scale implementation of CAMS on WMTs, it is first necessary to understand the nature of traffic crashes that involve these vehicles and, particularly, the frequency with which they occur. To this end, a comprehensive analysis was conducted of police-reported crash data for WMT-involved collisions in the state of Michigan. This analysis had three primary objectives:

1. Estimate the annual frequency of crashes involving WMTs throughout Michigan;
2. Determine the proportion of WMT-involved crashes that could be mitigated by CAMS installation; and
3. Assess the cost-effectiveness of the CAMS through an economic analysis considering the sensitivity of results to various crash- and system-related factors.

8.1 Data Query to Identify Potential WMT-Involved Crashes

In order to identify crashes involving WMTs, UD-10 crash report forms were obtained through the Michigan Traffic Crash Facts (MTCF) website maintained by the Michigan Office of Highway Safety Planning (OHSP, 2018). The MTCF website provides real-time online access to a complete historical database of police-reported crashes that have occurred throughout the state of Michigan dating back to 2004. The site's Data Query Tool allows for targeted queries of crash records based on various criteria, including vehicle type and purpose.

The first objective of this investigation was to identify all crashes involving a WMT. Unfortunately, there is not a specific field on the UD-10 form that identifies WMTs explicitly. However, there are two fields that can be used to conduct an effective initial screening process to identify a subset of crash reports for more extensive manual review in order to make the determination as to whether the crash was WMT-involved or not. These fields include:

Special Vehicle – This field is used to identify unique vehicle configurations and includes nine discrete categories:

a. Not special vehicle
b. Police vehicle
c. Fire vehicle
d. Bus (commercial, private, school)
e. Ambulance
f. Farm equipment (non-registered)
g. Construction/maintenance equipment
h. Tow truck/wrecker
i. Uncoded & errors

Vehicle Use – This field categorizes the primary purpose of a vehicle at the time a crash event occurred and is classified into twelve categories:

j. Private
k. Commercial (business)
l. In pursuit/on emergency
m. Farm use
n. School/education
o. Club/church ("Y" tag)
p. Military vehicle
q. Other government nonemergency vehicle use
r. Utility (gas, cable, etc.)
s. Road construction/maintenance
t. Other
u. Uncoded & errors

Preliminary review of crash reports suggested that the special vehicle category for construction/maintenance equipment was the most effective screening criteria for WMT-involved crashes, followed by the vehicle use category for road construction/maintenance. Over a six-year analysis period from 2012 through 2017, a total of 6,084 crashes were coded to have involved construction or maintenance equipment while 2,419 crashes involved at least one vehicle where the primary use was road construction or maintenance. Table 8.1 provides a summary of the number of crashes where either or both of these criteria were met during the analysis period. Using the special vehicle field yielded more consistent values from year to year, with an average of 1,014.0 crashes per year (standard deviation = 183.1) while the vehicle use field yielded an average of 403.2 crashes per year (standard deviation = 213.9).

Table 8-1 Crashes Involving Construction/Maintenance Vehicles by Special Vehicle and Vehicle Use Criteria from UD-10 Crash Report Form

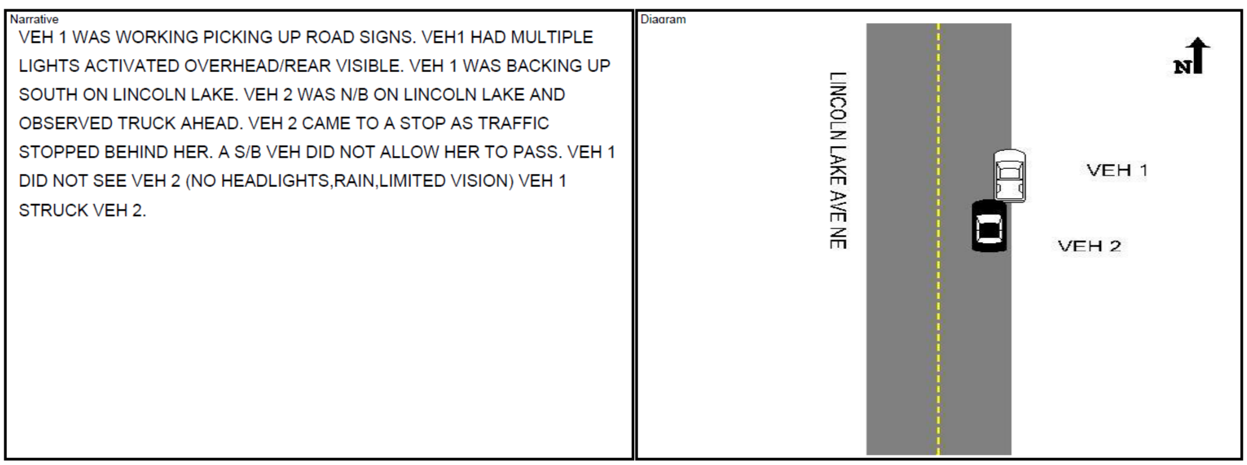
Year	Special Vehicle ONLY	Vehicle Use ONLY	BOTH Criteria
2012	713	351	219
2013	919	525	333
2014	1,248	699	453
2015	1,035	487	321
2016	1,122	267	183
2017	1,047	90	58
Total	6,084	2,419	1,567

The majority of crashes in the sample included either the special vehicle or the vehicle use criteria of interest being met, but not both. Furthermore, in addition to identifying crashes involving WMTs, these criteria also led to the identification of crashes involving construction equipment, as well as other types of maintenance vehicles (e.g., pickup trucks). Consequently, following the initial screening procedure, a detailed manual review was required of individual UD-10 crash report forms. This review included a review of the narrative and diagram sections of the report form, which generally provide significantly more detailed information than what is available from the standard categorical entries.

8.2 Review of UD-10 Forms to Screen Non-WMT Crashes

A preliminary review of the narrative and diagram sections of 100 randomly sampled forms from each query (special vehicle and vehicle use) showed that each performed similarly in terms of its ability to identify potential crashes of interest (i.e., those involving WMTs). Consequently, all crashes where either criterion was met were ultimately included in the set that was selected for full review. As an additional step to screen out non-WMT crashes, only crashes occurring during the winter season were included, which was defined from November through April of each year for the purpose of this analysis. Using these criteria, the six-year period included a total of 4,670 potential crashes of interest.

From this population of UD-10 forms, a manual review of the crash narratives and diagrams was performed. When the narrative indicated one of the vehicles was a snowplow or a vehicle performing winter maintenance, that crash record was included as a target crash for the purposes of this study. When the narrative indicated a vehicle was another type of construction or maintenance vehicle, or when the type of vehicle was not specified, the crash record was excluded from further investigation. An example of a narrative form for a crash that was excluded from the study is shown in Figure 8.1. This narrative shows that the construction/maintenance vehicle (VEH 1) was performing maintenance that did not involve snow removal.


Narrative

VEH 1 WAS WORKING PICKING UP ROAD SIGNS. VEH1 HAD MULTIPLE LIGHTS ACTIVATED OVERHEAD/REAR VISIBLE. VEH 1 WAS BACKING UP SOUTH ON LINCOLN LAKE. VEH 2 WAS N/B ON LINCOLN LAKE AND OBSERVED TRUCK AHEAD. VEH 2 CAME TO A STOP AS TRAFFIC STOPPED BEHIND HER. A S/B VEH DID NOT ALLOW HER TO PASS. VEH 1 DID NOT SEE VEH 2 (NO HEADLIGHTS,RAIN,LIMITED VISION) VEH 1 STRUCK VEH 2.

Figure 8-1 Example of Crash Excluded After Review of UD-10 Form

After this manual review was completed, 1,354 of 4,670 (29.0 percent) crash records were left to be considered for further review. A summary of the number of suspected WMT crashes by year is provided in Table 8.2.

Table 8-2 Suspected WMT Crashes by Year

Year	Crashes in Full Dataset	Suspected WMT Crashes
2017	596	153
2016	694	164
2015	845	201
2014	1131	471
2013	826	263
2012	578	102
Total	4,670	1,354

8.3 Classification of WMT Crashes Based on Potential CAMS Influence

Once the 1,354 crashes that were suspected to involve WMTs were identified, further efforts were involved in classifying each of these crashes based on two criteria: (1) the precipitating events and causal circumstances contributing to the event; and (2) the likelihood the crash could have been prevented if the crash-involved WMT had been equipped with the CAMS. These determinations were made during the course of the manual review using information available from the standard fields, narratives, and diagrams from the UD-10 crash report forms.

Table 8.3 provides a summary of the contributing circumstances that led to each crash occurring. A total of seven general categories were identified over the course of the manual review. These categories represent the most frequent scenarios from among the WMT crashes and include the following:

1. Blind spot – These crashes refer to cases where a WMT struck another vehicle that the WMT driver was unable to see.
2. Inattention/misjudgment (WMT driver) – This category distinguishes crashes where the WMT driver was unaware of their surroundings (e.g. the WMT struck a parked car or pulled out in front of a car at an intersection).
3. Inattention/misjudgment (other driver) – These are crashes wherein the driver of the other vehicle was inattentive or misjudged the actions of the WMT driver (e.g. they drove distracted, struck the side of a wide-turning WMT, misjudged the speed of a WMT).

4. Poor visibility – This category describes crashes that occurred due to limited visibility for the driver of the other vehicle due to the wintry conditions (e.g., snow, ice).
5. Loss of control – These crashes involved a driver losing control of their vehicle on slippery roads within the vicinity of a WMT, culminating in a collision.
6. Operating near intersection – These crashes include instances where a WMT was operating near an intersection, including instances where the vehicle was backing up to continue work on clearing an intersection. In these cases, the driver of the other vehicle involved generally did not realize the intent of the WMT driver, resulting in the crash.
7. Unknown/other – This category accounts for other situations, such as snow or other debris from snowplows causing damage to other vehicles, crashes between two plows, or crash reports that failed to elaborate on the context of the crash.

Table 8-3 Summary of Crashes by Contributing Circumstances

Contributing Circumstances	Number of Crashes	Percentage
Inattention/misjudgment (WMT driver)	520	38.4%
Loss of control	314	23.2%
Inattention/misjudgment (other driver)	309	22.8%
Poor visibility	50	3.7%
Blind spot	35	2.6%
Operating near intersection	30	2.2%
Unknown/other	96	7.1%
Total	1,354	100.0%

For each WMT-involved crash, a determination was also made as to whether the crash could have potentially been prevented if the CAMS was in operation. Figure 8.2 provides a sample narrative from a crash that was determined to be a scenario where the presence of the CAMS was likely to have a potential influence in preventing the crash from occurring or mitigating the severity of the crash if it did occur. This crash involves a vehicle striking a WMT that was slowing down while plowing snow. For this crash it was theorized that CAMS may have improved the other driver's visual acuity and ability to identify their proximity to the WMT, thereby reducing the likelihood of collision.

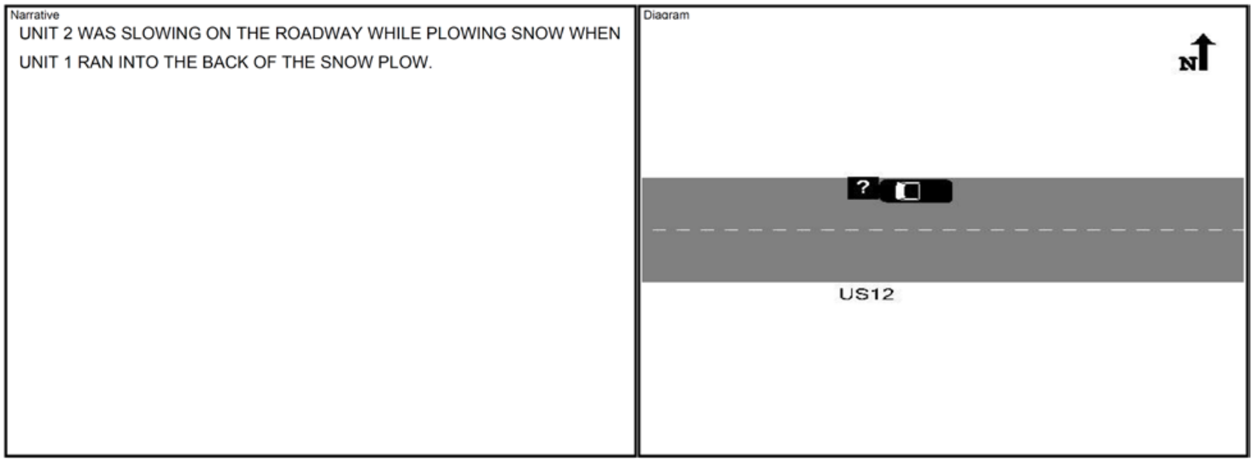


Figure 8-2 Example crash likely to be influenced by CAMS

Figure 8.3 shows an example narrative from another crash that was likely to have been influenced by the presence of the CAMS. In this particular case, the other vehicle experienced a loss of control. While the driver of the other vehicle had identified the WMT and attempted to slow down, they were unable to given the surface and/or visibility conditions. However, if the CAMS were active, the driver may have identified the WMT sooner and been able to decelerate more gradually to avoid the collision event.

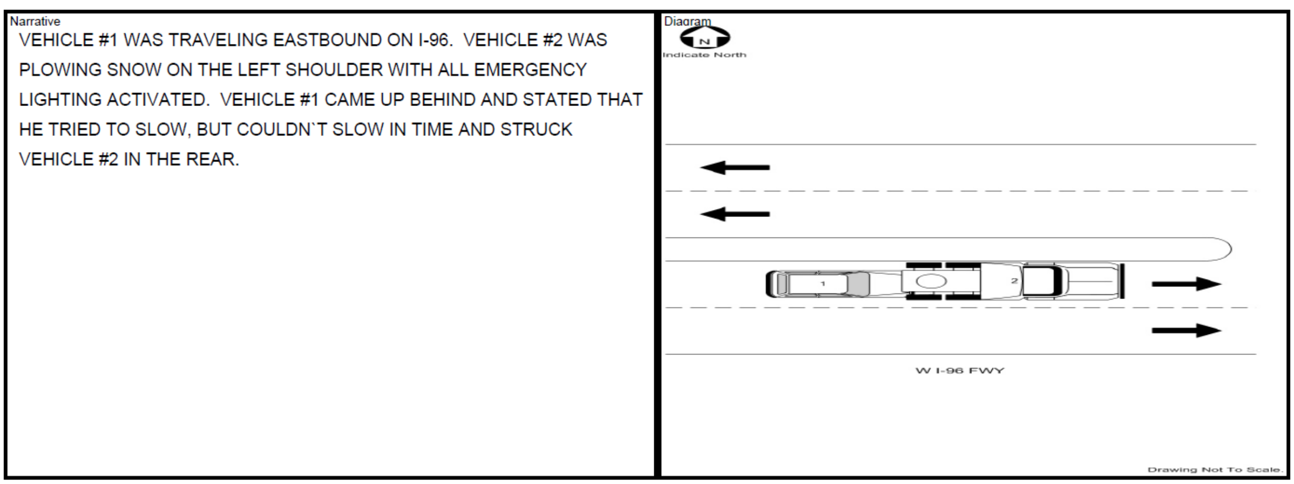


Figure 8-3 Example crash likely to be influenced by CAMS

There were numerous cases where a crash was not likely to have been influenced by the presence of the CAMS, with the most frequent instances being crashes in which the WMT driver was primarily found to be at fault for the crash. Ultimately, among the circumstances described previously and listed in Table 8.3, those that were most likely to be pertinent to the functionality of the CAMS are those crashes: (1) where the driver lost control of their vehicle; (2) due to inattention or misjudgment by the driver of the other vehicle; (3) occurring under poor visibility; or (4) involving a WMT that was backing up or operating near an intersection. Crashes involving (1) inattention or misjudgment by the WMT driver or (2) those in which the vehicle was operating in the WMT's blind spot were categorized as unlikely to be influenced by CAMS. However, a reasonable argument can be made that drivers may behave differently when CAMS is active and the system may have some degree of effectiveness in these settings, as well. Ultimately, the results of this manual review (Table 8.4) suggest that of the 1,354 relevant crashes, 703 (were likely candidates to have been influenced by the CAMS if it had been installed. This suggests that, on average, a total of 225.7 WMT crashes occur per year, of which 117.2 WMT crashes are likely to be pertinent to CAMS operation.

Table 8-4 Number of Crashes Likely to be Pertinent to CAMS

Likelihood Crash Was Pertinent to CAMS	Number of Crashes	Percent
Likely	703	51.9%
Unlikely	555	41.0%
Unknown	96	7.1%
Total	1,354	100.0%

It should be noted that these categories are very broad and there were many crashes that could have been classified into more than one category. For example, an inattentive driver could have seen a slow-moving WMT in front of them, but reacted too late, resulting in a hard braking maneuver and loss of control before striking the plow. Only one circumstance field was identified for each crash. However, most of these conflicts tended to occur among those circumstances that were likely to be pertinent to CAMS.

8.4 Economic Analysis for Statewide CAMS Installation

The preceding section outlined estimates of the number of WMT-related crashes that have occurred throughout the state of Michigan on an annual basis. Installation of the CAMS on WMTs is expected to have the potential to reduce the frequency of such crashes, resulting in crash cost savings due to lower numbers of traffic crashes, injuries, and fatalities. This section presents a sensitivity analysis to provide a preliminary estimate as to the economic viability of statewide installation of CAMS on WMTs.

To estimate the cost-effectiveness of CAMS installation, a benefit/cost (B/C) analysis was conducted to compare the crash cost savings to installation and maintenance costs associated with statewide CAMS deployment. Table 8.5 provides unit costs for capital costs, including acquisition, procurement, and installation of the CAMS hardware. These costs were estimated at $9,000 per WMT. In addition, engineering services were estimated at $8,250 for the first year of operation. These costs would include integration, installation, updates, and any required maintenance, again on a per-WMT basis. Given current market trends and rapid advances in technology, a five-year service life was assumed. It was also assumed that, following year one, approximately 10 percent of the first-year engineering services costs would be required on an annual basis. Assuming a 4 percent discount rate, this results in annual costs of approximately $4,520 per WMT. It must be noted that these costs were based on prototype CAMS implementation on a total of four trucks. Broad statewide implementation will likely lower these costs dramatically. Furthermore, additional cost reductions will occur if it is determined that the WMT drivers do not benefit from an in-cabin display, in which case both the display and camera could be eliminated.

Table 8-5 Capital and Engineering Services Costs for CAMS

Cost Category	Cost (per vehicle)	Time Period
Capital Costs	$9,000	Year 1
Initial Engineering Services	$8,250	Year 1
Annual Engineering Services	$825	Years 2-5

In order to estimate the benefits, or crash cost savings, associated with the reduction in crashes due to CAMS installation, comprehensive crash cost data were obtained from the *Highway Safety Manual* (AASHTO, 2010) and are summarized in Table 8.6 according to the KABCO (see Table 8.6 to for the abbreviations) injury severity scale. These costs include wage and productivity losses, medical expenses, administrative expenses, motor vehicle damage, and employers' uninsured costs, as well as a measure of the value of lost quality of life.

Table 8-6 Crash costs by KABCO severity level

Injury Severity Level	Comprehensive Crash Cost
Fatality (K)	$4,008,900
Disabling Injury (A)	$216,000
Evident Injury (B)	$79,000
Possible Injury (C)	$44,900
Property Damage Only (O)	$7,400

The WMT-involved crash estimates provided previously were in terms of total crashes per year. Consequently, the 225.7 WMT crashes per year were converted to an annual cost using the weighted average costs associated with two-vehicle crashes in the state of Michigan during this same six-year time period. Table 8.7 shows that the weighted average crash cost, based upon the proportion of all two-vehicle crashes resulting in each of the five injury severity levels, is approximately $26,206.83 per crash.

Table 8-7 Determination of Weighted-Average Cost for Two-Vehicle Crashes

Injury Severity	Proportion	Crash Cost ($)	Weighted Average Cost
K	0.2%	$4,008,900	
A	1.2%	$216,000	
B	4.1%	$79,000	
C	13.5%	$44,900	
PDO	81.0%	$7,400	
Total	100.0%		$26,206.83

Using these crash cost savings estimates, in combination with the capital costs and engineering services costs detailed previously, a sensitivity analysis was conducted to examine the potential cost effectiveness of statewide installation of the CAMS system. There are currently approximately 800 WMTs operated and maintained in the state of Michigan, with 330 of these under the jurisdiction of MDOT. Service costs per unit of $825 are assumed to occur annually from year 2 to 5. Assuming a 4% discount rate, the annual $825 service costs during years 2 to 5 are equivalent to a total lump sum cost of $2,880 at year 1. Thus, the equivalent total cost per WMT at year 1 is

$2,880 + $9,000 + $8,250 = $20,130. This total cost in year 1 can be annualized over the 5-year period using a 4% discount rate to $4,522 per WMT per year. Using this value, the total annualized implementation cost for 800 WMTs in Michigan is (800*4522) = $3.617 million per year over the 5-year period.

The annual crash cost savings would depend principally upon the percent reduction in WMT crashes associated with CAMS installation. Given that only preliminary data are available based upon one partial season of operation with four CAMS-equipped WMTs, it was not possible to perform a direct comparison of the safety effects associated with CAMS installations on WMTs. Thus, a sensitivity analysis was conducted assuming various reductions in annual WMT-involved crashes. Assuming an average cost of $26,207 per crash as detailed in Table 8.7, the total annualized costs of WMT crashes amounts to approximately $5.9 million. Consequently, if all such crashes could be eliminated by the CAMS, this would result in a benefit-cost (B/C) ratio of 1.64. However, CAMS will not prevent all WMT-involved crashes. To that end, assuming that only those 117.2 annual crashes identified as likely influenced by CAMS (51.9% of all WMT-involved crashes) are prevented, the B/C ratio would be 0.85, which is lower than 1. Figure 8.4 provides details of how the B/C ratio changes based upon various WMT-involved crash reduction proportions. These data suggest that, in order for CAMS to be cost-effective (i.e., B/C>1), the total number of WMT-involved crashes would need to be reduced by approximately 61 percent. Initial behavioral testing found about 20 percent reduction in driver reaction time in response to a properly triggered CAMS warning light. Although it is difficult to quantify the impacts of this reaction time improvement on rear-end collisions with WMTs, it may suggest that crash reductions will fall below the 61 percent necessary for a favorable B/C.

It is also important to note that eliminating certain costly, yet non-critical, components such as the camera and in-cabin display, would reduce the cost of the CAMS system and increase the B/C. Furthermore, the CAMS system costs will also likely decrease in the event of larger scale deployment. To help account for these considerations, Figure 8-5 presents a minimum required percent reduction in WMT crashes to ensure profitability (B/C>1) of the CAMS for any given life cycle investment cost. For example, as shown in Figure 8-5, if the total investment cost of the CAMS over a 5-year life cycle is reduced to $10,000 per WMT installation due to the economy of scale or camera and display elimination, then CAMS must prevent at least 30% of WMT-involved crashes for the benefits to outweigh the costs. As noted previously, the maximum percentage of WMT-involved crashes that may be prevented by CAMS has been estimated at approximately 52%.

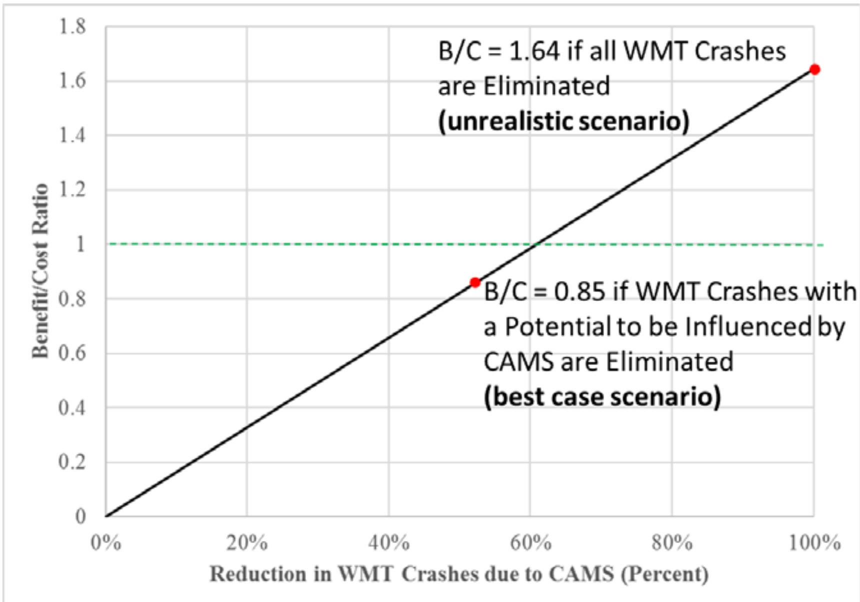


Figure 8-4 Benefit/Cost Ratio for CAMS installation

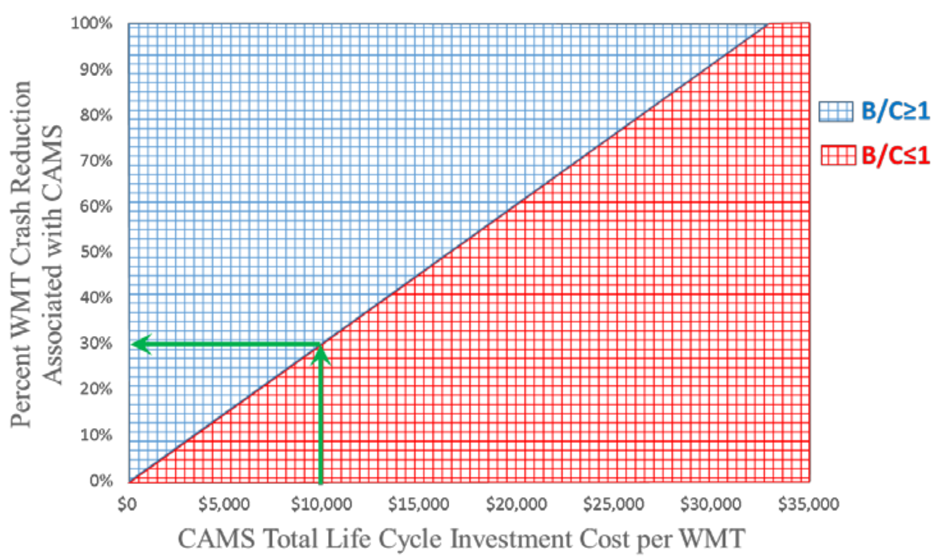


Figure 8-5 Minimum required percent reduction in WMT crashes to ensure profitability of the CAMS for any given life cycle investment cost

CHAPTER 9 – SUMMARY AND RECOMMENDATIONS

A study was performed to determine the potential safety and economic impacts associated with a vendor-developed prototype rear-facing collision avoidance and mitigation system on winter maintenance trucks in Michigan. This study evaluated both the operational performance of CAMS and the extent to which CAMS modifies the behavior of drivers encroaching to the rear of the WMT. The effect of CAMS warning light on driver behavior was evaluated during actual winter maintenance operations on select freeways and arterials in Livingston and Washtenaw counties using the same two CAMS-implemented trucks with and without the CAMS warning alert light connected. These field studies also allowed for evaluation of the operational performance of the CAMS radar and cleaning/washing system. To identify key issues and challenges with using the system, feedback was obtained from winter maintenance personnel across Michigan and nationwide, including WMT drivers with and without experience using CAMS-equipped vehicles. The study also investigated the potential of CAMS to reduce WMT-involved crashes, and estimated the economic viability associated with widespread deployment across Michigan.

This chapter summarizes all collective findings of this study and also includes discussion of the study limitations. Recommendations are provided to improve the CAMS performance and overcome the limitations that were encountered, including further evaluation of the system.

9.1 Summary of Findings

The findings of this study can be summarized as follows.

<u>System Performance</u>

1. Blockage/occlusion of the camera/radar box caused by the accumulation of debris inhibited system performance. This was typically a result of issues with the cleaning/washing system.
2. The warning alarm did not always activate precisely at the pre-specified relative headway thresholds. In many cases, a vehicle encroached beyond the warning alert threshold, but activation of the warning system was either delayed by as much as 2-seconds or not triggered at all. Although this issue was exacerbated by accumulation of debris on the camera/radar box, it also occurred when the box was clear.

3. A substantial number of cases were observed, where the warning light was triggered by a vehicle traveling in an adjacent lane.

Driver Behavior Impacts

1. The rate of vehicular encroachments in close proximity to the WMT was found to be lower when the warning light alert system was enabled versus disabled. Although this suggests that the CAMS warning light has potential to be effective in improving driver behavior, more data is needed, particularly for the disabled case and on curve segments, before definitive conclusions can be drawn.

2. The response time, defined as the time gap between when the warning alert is triggered and when the minimum relative headway is observed, was 20% lower when the warning system was enabled versus disabled suggesting a reduced risk of rear-end crashes with WMTs. However, the low number of observations during the disabled periods may reduce the significance of this conclusion. Thus, an expanded comparison of behavior during the enabled and disabled conditions is needed before definitive conclusions can be drawn.

Feedback from Winter Maintenance Staff

3. A survey of staff from 21 Michigan county road commissions and 14 state DOTs suggested that properly implemented technological improvements on WMTs, including collision avoidance systems, have the potential to improve safety during winter maintenance operations. However, there are practical concerns regarding the ability to design a cleaning/washing system that can keep the CAMS equipment clean and fully operational during adverse winter weather conditions.

4. According to MDOT WMT drivers, tailgating and the speed differential between WMTs and other road users are major issues regarding safety during winter maintenance operations. Drivers felt that a well-designed warning system could potentially address these issues. Similar feedback was received during surveys of Michigan county road commissions and other state DOTs.

5. The WMT drivers with CAMS experience did not believe the CAMS system to be effective in its current format. Changes in the behavior of the following vehicle drivers in response

to the CAMS warning alert were considered by the truck drivers to be too small in magnitude to have relevance for safety benefits.

6. The surveyed drivers recommended additional changes to the system, including using a warning light color that is distinct from the other warning lights on the WMTs, improving the washing system performance, and improving the in-vehicle display to improve blind-spot monitoring.

<u>Estimated Safety Impacts and Economic Analysis</u>

7. A review of statewide UD-10 crash reports from 2012 through 2017 revealed an average of 225.7 WMT-involved crashes per year. A secondary assessment of the narratives and diagrams within these crash reports revealed that 117.2 annual WMT crashes would potentially be influenced by the proposed CAMS operation.

8. A benefit/cost (B/C) analysis was performed assuming the following: i.) statewide implementation of CAMS on all 800 WMTs operating in Michigan, ii.) current implementation and maintenance life-cycle costs for the CAMS system, iii.) 117.2 average annual WMT-involved crashes statewide that would potentially be influenced by the CAMS (representing 51.9% of all WMT crashes), and iv.) estimated average cost of $26,206 per WMT-involved crash. Based on these assumptions, elimination of all such crashes would result in a benefit-cost (B/C) ratio of 0.85. In order for the CAMS to be cost-effective (i.e., B/C > 1.0), the number of WMT-involved crashes during the CAMS life-cycle must be reduced by at least 61 percent. As this is an unrealistic crash reduction target, reducing the implementation cost is essential to economically justify incorporating the CAMS into winter maintenance operations. To that end, this study also provided a required crash reduction percentage for any given investment cost per WMT to ensure a B/C ratio of 1.

9.2 Study Limitations

Reviewing the study findings based on the different analyses provided in the previous section, one should note that there are certain limitations associated with these analyses:

1. The number of observed true positive warning light activations (i.e., when vehicles traveling in the same lane of the WMT cross the activation threshold and the warning light is activated), is not large enough to draw statistically valid conclusions regarding the effects of the CAMS on drivers' behavior.

2. The behavioral analysis might be biased due to different weather conditions during the light enabled (heavy snow events including low visibility periods) and light disabled (light snow events mostly high visibility) cases.
3. The washing system failure during the heavy snow conditions interferes with operation of the CAMS radar unit and obstructs the camera view. This prevents assessment of the performance of the CAMS during periods when the CAMS unit would typically be most beneficial.

9.3 Recommendations

Overall, this study suggests that there may be potential safety benefits associated with broad deployment of the CAMS system. However, the current prototype CAMS system requires additional modification and testing prior to widespread deployment. This is largely due to the operational issues for both the CAMS radar system and the associated cleaning/washing system that persisted during field testing and inhibited reliability. The following list of recommendations should be considered prior to further CAMS implementation. After these changes have been made, a follow up study is recommended to further evaluate the performance of the modified CAMS system.

1. The cleaning/washing system requires significant modifications to keep the CAMS equipment (radar/camera housing box and warning light) clean during operations, particularly during severe weather conditions when the warning alert is most needed. The fluid container of the washing system needs to be enlarged and placed in a better location to facilitate the refilling. If possible, it may be advisable to connect the CAMS washing system to the switch for the windshield wipers.
2. Consider using a different color for the CAMS light relative to already used lights in WMTs. A combination of amber and green colors is suggested. Modification to the colors may also necessitate modification to the flash patterns. Note that using red or blue is not currently allowed for maintenance purposes in Michigan.
3. Resolve issues with the inconsistency/imprecision of the CAMS warning light activation. Although the data log suggests that the radar was properly identifying the location and speed of vehicles, the warning light was often activated at inappropriate times or not activated when it should have been. The specific issues included: warning light activated by an

adjacent lane vehicle, delays in warning light activation of up to 2 seconds, and warning light not activated at all.

4. Collect additional driver behavior data during comparable weather events with the warning light enabled vs. disabled. To evaluate the performance of the system in as unbiased manner as possible, it is suggested to alternate between enabled and disabled data collection during each maintenance operation (e.g. alternating between enabled and disabled operation hourly). This would make the conditions as consistent as possible during enabled and disabled data collection in terms of weather, roadway, and traffic conditions, and result in a more accurate assessment of the impacts of the warning light on driver behavior.

5. Modify the CAMS to better assist WMT drivers during winter maintenance operations. This may include better blind spot coverage, which would require inverting the mirrored camera view. Providing an improved driver assistive component would further motivate the drivers to maintain the system during the winter maintenance operations. Alternatively it may also be appropriate to remove the camera and in-cab display, as doing so has no impact on CAMS operations.

6. In addition to the time headway thresholds currently used to activate the warning alert, incorporate an absolute distance-based threshold for warning alert activation. This would help to prevent tailgating and keep vehicles away from the rear zone of the WMT, regardless of the speed differential with the WMT.

REFERENCES

Atkins, J., Dierckman, J., & O'Bryant, K. (1990). A real snow job. *The UMAP Journal,* 11:231–9.

Battelle. (2007). *Evaluation of the Volvo Intelligent Vehicle Initiative Field Operational Test Version 1.3.* Washington D.C.: US Department of Transportation, DTFH61-96-C-00077.

Bureau of Management Consulting. (1975). *Improving snow clearing effectiveness in Canadian municipalities.* Catalogue No. T48-9/1975. Canada: Transportation Development Agency, Ministry of Transport.

Camden, M. C., Medina-Flintsch, A., Hickman, J. S., Bryce, J., Flintsch, G., & Hanowski, R. J. (2018). Prevalence of Operator Fatigue in Winter Maintenance Operations. *Accident and Analysis & Prevention*, on-line.

Chapman, L., Young, D., Muller, C., Rose, P., Lucas, C., & Walden, J. (2014). *Winter Road Maintenance and the Internet of Things.* Birmingham: SIRWEC.

Chernak, R., Kustiner, L., & Phillips, L. (1990). The snowplow problem. *The UMAP Journal*, 11:241–50.

Cranson, J., & Donohue, D. (2016). When Green Means Slow: Winter maintenance vehicles getting green lights to improve visibility, http://www.michigan.gov/mdot/0,4616,7-151-9620-398805--,00.html.

Georgi, A., Zimmermann, M., Lich, T., Blank, L., Kickler, N., & Marchthaler, R. (2009). *New Approach of Accident Benefitn Analysis for Rear End Collision Avoidance and Mitigration Systems.* Stuttgart: Robert Bosch Corporation.

Gorjestani, A., Alexander, L., Newstrom, B., Cheng, P., Sergi, M., Shankwitz, C., & Donath, M. (2003). *Driver assistive systems for snowplows.* Minnesota Department of Transportation.

Harper, C. D., Hendrickson, C. T., & Samaras, C. (2016). Cost and Benefit Estimates of Partially-Automated Vehicle Collision Avoidance Technology. *Accident Analysis and Prevention 95*, 104-115.

Hartman, C., Hogenson, K., & Miller, J. (1990). Plower power. *The UMAP Journal* , 11:261–72.

Heqimi, G., Kay, J., & Gates, T. (2017). Using Spatial Interpolation to Determine Effects of Snowfall on Traffic Crashes: A Case Study of Interstate-94 in Southwest Michigan. *Proceedings of the 96th Annual Transportation Research Board Annual Meeting.* Washington, DC.

Iowa DOT. (2017). *Driving Maneuvers.* https://iowadot.gov/maintenance/pdf/driving_maneuvers.pdf.

IOWADOT. (2017). *Safe Travel Around Snowplows,.* https://iowadot.gov/maintenance/pdf/SafeTravelAroundSnowplows.pdf.

Kocianova, A. (2015). The Intelligent Winter Road Maintenance Management in Slovak Conditions. *Procedia Engineering 111*, 410-419.

Lemieux, P., & Campagna, L. (1984). The snow ploughing problem solved by a graph theory algorithm. *Civil Engineering Systems*, 1:337–41.

McLaughlin, S. B., Hankey, J. M., & Dingus, T. A. (2008). A method for evaluating collision avoidance systems using naturalistic driving data. *Accident Analysis and Prevention, 40*, 8-16.

MDOT. (2017). *Michigan NETS Winter Driving Safety Tips.* https://www.michigan.gov/documents/Nov05_144130_7.pdf.

Michigan Office of Highway Safety Planning. (n.d.). *Michigan Traffic Crash Facts Data Query*

Tool, https://www.michigantrafficcrashfacts.org/querytool.
Michigan Vehicle Code Section 257.698. (n.d.). http://www.legislature.mi.gov/%28S%28qezohfdta14btdnide0ygl1g%29%29/mileg.aspx?page=getObject&objectName=mcl-257-698.
Moss, C. (1970). *A routing methodology for snow plows and cindering trucks.* PennDOT project 68-5, Pennsylvania Transportation and Traffic Safety Center, Pennsylvania State University.
Perrier, N., Langevin, A., & Campbell, J. (2007). A survey of models and algorithms for winter road maintenance. Part IV: Vehicle routing and fleet sizing for plowing and snow disposal. *Computers & Operations Research*, 258-294.
Riaz, F., Jabbar, S., Sajid, M., Ahmad, M., Naseer, K., & Ali, N. (2018). A collision avoidance scheme for autonomous vehicles inspired by human social norms. *Computers and Electrical Engineering 69*, 690-704.
Robinson, J., Ogawa, L., & Frickenstein, S. (1990). The two-snowplow routing problem. *The UMAP Journal* , 11:251–9.
Schneider, W. H., Maistros, A. R., Crow, M. J., Holik, W. A., & Gould, Z. T. (2017). *Evaluation of the GPS/AVL Systems for Snow and Ice Operations Resource Managment.* Columbus: Ohio Department of Transportation.
Tucker III, W. (1977). A computer model of municipal snow removal. *Cold Regions Research and Engineering Lab Hanover MH*, (No. CRREL-77-30).
Usman, T., Fu, L., & Miranda-Moreno, L. F. (2010). Quantifying Safety Benefits of Winter Road Maintenance: Accident Frequency Modeling. *Accident Analysis and Prevention 42*, 1878-1887.
Vahidi, A., & Eskandarian, A. (2003). Research Advances in Intelligent Collision Avoidance and aDaptive Cruise Control. *IEEE Transactions on Intelligent Transportation Systems*, 143-154.
Wang, H., Tota, A., Aksun-Guvenc, B., & Guvenc, L. (2018). Real time implementation of soically acceptable collision avoidance of a low speed autonomous shuttle using the elastic and method. *Mechatronics 50*, 341-355.
Weingarten, D. (2016). *Superior Stick: Innovative lighting system makes wing plows more visible, http://www.michigan.gov/mdot/0,4616,7-151-9620-377797--,00.html.* MDOT.

APPENDIX A – SURVEY OF WMT DRIVERS

A.1. The survey for drivers of WMTs equipped by CAMS:

<u>*Safety Issues:*</u>

1. Do you feel the CAMS system improves safety during winter maintenance activities?

   a) It helps the drivers of following vehicles to more easily detect WMTs
   Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐
   Comment:
   ………………………………………………………………………………………
   ………………………………………………………………………………………
   ………………………………………………………………………………………

   b) It reduces the possibility of rear-end and sideswipe crashes
   Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐
   Comment:
   ………………………………………………………………………………………
   ………………………………………………………………………………………
   ………………………………………………………………………………………

   c) It reduces the number of sharp braking or other evasive maneuvers by motorists following the WMT
   Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐
   Comment:
   ………………………………………………………………………………………
   ………………………………………………………………………………………
   ………………………………………………………………………………………

   d) Other factors
   ………………………………………………………………………………………
   ………………………………………………………………………………………
   ………………………………………………………………………………………

2. Is the CAMS system distracting to you while driving?
   Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐
   Comment:
   ………………………………………………………………………………………
   ………………………………………………………………………………………
   ………………………………………………………………………………………

Washing System Performance:

3. How well does the automated washing system perform?

   a) Turning on/off at appropriate time

   Excellent ☐ Good ☐ Average ☐ Fair ☐ Poor ☐

   Comment:

   ……………………………………………………………………………………
   ……………………………………………………………………………………
   ……………………………………………………………………………………

   b) Keeping the camera clear

   Excellent ☐ Good ☐ Average ☐ Fair ☐ Poor ☐

   Comment:

   ……………………………………………………………………………………
   ……………………………………………………………………………………
   ……………………………………………………………………………………

   c) How often it needs to be refilled?

   ……………………………………………………………………………………
   ……………………………………………………………………………………
   ……………………………………………………………………………………

4. Are there any improvements to the washing system that you would recommend?

   ……………………………………………………………………………………
   ……………………………………………………………………………………
   ……………………………………………………………………………………

CAMS Performance:

5. The CMAS performance (i.e., turns on at appropriate times, etc.) is different for plowing versus deicing operation.

   Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐

   Comment:

   ……………………………………………………………………………………
   ……………………………………………………………………………………
   ……………………………………………………………………………………

6. The CMAS performance is in day versus night time operations.

   Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐

   Comment:

   ……………………………………………………………………………………
   ……………………………………………………………………………………
   ……………………………………………………………………………………

7. The CMAS performance is different for various weather conditions.
   Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐
   Comment:
   …………………………………………………………………………………………
   …………………………………………………………………………………………
   …………………………………………………………………………………………

8. CAMS is helpful for U-turn and stopping maneuvers.
   Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐
   Comment:
   …………………………………………………………………………………………
   …………………………………………………………………………………………
   …………………………………………………………………………………………

<u>*Maintenance:*</u>

9. Is there any issue associated with the durability of the CAMS sensors or any of its components?
   …………………………………………………………………………………………
   …………………………………………………………………………………………
   …………………………………………………………………………………………

10. How often the CAMS view box needs to be cleaned (in garage)?
    …………………………………………………………………………………………
    …………………………………………………………………………………………
    …………………………………………………………………………………………

<u>*General:*</u>

11. What do you like most about CAMS?
    …………………………………………………………………………………………
    …………………………………………………………………………………………
    …………………………………………………………………………………………

12. What would you most like to change about CAMS?
    …………………………………………………………………………………………
    …………………………………………………………………………………………
    …………………………………………………………………………………………

A.2. The survey for drivers of regular WMTs:

1. What are the safety issues you face during winter maintenance activities?
   a) Conflicts between WMT and following or adjacent vehicles
   ……………………………………………………………………………………………
   ……………………………………………………………………………………………
   ……………………………………………………………………………………………

   b) Conflicts between following or adjacent vehicles because of WMT presence
   ……………………………………………………………………………………………
   ……………………………………………………………………………………………
   ……………………………………………………………………………………………

   c) Conflicts due to the infrastructure design (roadway condition, shoulder, signs, …)
   ……………………………………………………………………………………………
   ……………………………………………………………………………………………
   ……………………………………………………………………………………………

2. Do you feel a collision avoidance system on the rear of a WMT that is designed to detect potential rear-end collisions and alert the following motorists would improve safety?

a) It can help the following vehicles to more easily detect WMTs
Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐
Comment:
…………………………………………………………………………………………
…………………………………………………………………………………………
…………………………………………………………………………………………

b) It can reduce the possibility of rear-end and sideswipe crashes
Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐
Comment:
…………………………………………………………………………………………
…………………………………………………………………………………………
…………………………………………………………………………………………

c) It can reduce the number of sharp braking or other evasive maneuvers by motorists following the WMT
Comment:
…………………………………………………………………………………………
…………………………………………………………………………………………
…………………………………………………………………………………………

d) Other factors
…………………………………………………………………………………………
…………………………………………………………………………………………
…………………………………………………………………………………………

3. Do you think that tailgating of WMTs is a significant safety issue? What do you suggest to decrease the number of tailgaters of WMT?
…………………………………………………………………………………………
…………………………………………………………………………………………
…………………………………………………………………………………………

4. What types of warning systems would you like to see installed on WMTs?
a) Green warning lights (a visual warning light installed on the WMT to be detected easier by other vehicle drivers)
Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐
Comment:
…………………………………………………………………………………………
…………………………………………………………………………………………
…………………………………………………………………………………………

b) Back up alarms (a simple sound alert when the vehicle is backing up)
Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐
Comment:
……………………………………………………………………………………………
……………………………………………………………………………………………
……………………………………………………………………………………………

c) Lane Departure Warning (a system to warn the driver when the vehicle starts to move out of its lane)
Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐
Comment:
……………………………………………………………………………………………
……………………………………………………………………………………………
……………………………………………………………………………………………

d) Forward Collision Warning (a safety system that monitors the distance and speed variations between the WMT and the vehicles traveling in front of it to issue warning if it is needed to the WMT driver)
Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐
Comment:
……………………………………………………………………………………………
……………………………………………………………………………………………
……………………………………………………………………………………………

e) Side collision warning (similar to Forward Collision Warning for vehicles traveling in the adjacent lanes)
Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐
Comment:
……………………………………………………………………………………………
……………………………………………………………………………………………
……………………………………………………………………………………………

f) Blind Spot Warning (a system to detect other cars in the driver’s side and rear)
Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐
Comment:
……………………………………………………………………………………………
……………………………………………………………………………………………
……………………………………………………………………………………………

g) Adaptive Cruise Control (a cruise control system that automatically control the vehicle speed to keep a safe distance from vehicles ahead)
Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐
Comment:
……………………………………………………………………………………………
……………………………………………………………………………………………
……………………………………………………………………………………………

h) Infrastructure Assisted Hazard Warning (such as sensors, cameras, and road-side units to inform drivers with the possible conflicts)
Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐
Comment:
……………………………………………………………………………………………
……………………………………………………………………………………………
……………………………………………………………………………………………

i) Other
……………………………………………………………………………………………
……………………………………………………………………………………………
……………………………………………………………………………………………

5. Is there any other equipment that would help you perform snow plowing activities?
……………………………………………………………………………………………
……………………………………………………………………………………………
……………………………………………………………………………………………