Risk Mitigation Strategies for Operations and Maintenance Activities

CMAT
CONSTRUCTION MANAGEMENT AND TECHNOLOGY

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16. Abstract

The objective of this research was to investigate the application of integrated risk modeling to operations and maintenance activities, specifically moving operations, such as pavement testing, pavement marking, painting, snow removal, shoulder work, mowing, and so forth. The ultimate goal is to reduce the frequency and intensity of loss events (property damage, personal injury, and fatality) during operations and maintenance activities.

This report includes a literature review that identifies the current and common practices adopted by different state departments of transportation (DOTs) and other transportation agencies for safe and efficient highway operations and maintenance (O/M) activities. The final appendix to the report includes information for eight innovative O/M risk mitigation technologies/equipment and covers the following for these technologies/equipment:

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April 2012

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EXECUTIVE SUMMARY

Problem Statement

Previous research on construction work-zone safety found that moving operations represent the highest-risk activity when considering both frequency of occurrence and crash severity (Shane et al. 2009). The research further determined that using an integrated risk model that assesses risk over the project life cycle could mitigate the risk of moving operations (among others) during the construction phase.

Hence, this research examines how an integrated risk-modeling approach could be used to reduce the frequency and intensity of loss events (property damage, personal injury, fatality) during highway operations and maintenance (O/M) activities.

Objective

The objective of this research is to investigate the application of integrated risk modeling to O/M activities, specifically moving operations such as pavement and structures testing, pavement marking, painting, shoulder work, mowing, and so forth.

Research Description

The methodologies that were adopted in this research are as follows:

- Identification of current O/M processes through expert input
- Literature review
- Analysis of crash data
- Validation survey
- Identification of mitigation strategies

Identification of Current O/M processes through Expert Input

The research started with an expert panel session/brainstorming workshop with the technical advisory committee (TAC) aimed at mapping the O/M process as currently utilized by state, county, and local agencies. The objective was to categorize the activities, environments, tools/equipment, and relationships involved with different O/M functions.

This session was followed up by in-depth interviews with three members of the expert panel.

Literature Review

The researchers performed an extensive literature search compiled a preliminary list of risk factors and loss events during O/M activities. The search mainly included results from academic

journals, trade publications, transportation research technical reports, and state departments of transportation (DOT) web sites.

The literature review reveals several studies on the impacts of weather on the roadways and, hence, its effects on work-zone safety, along with specific research on the interaction of traffic and O/M and mobile work-zone-related safety. However, these studies did not specifically address risk assessment and mitigation strategies for the O/M activities on highways.

The literature search also gave insight into how the identified factors play a role in mobile work-zone crashes, specifically work zones that involve O/M activities on highways.

Analysis of Crash Data

The analysis of the crash database provided by the Iowa DOT played a very important role in the development of the Integrated Risk Management Model. To obtain information about the relevant crashes, a query was created to gather data for all severity level of crashes from 2001 through 2010 that involved two types of work zones: intermittent or moving work and work on shoulder or median.

The suitable variables in the crash database that were able to explain the effect of the previously-identified factors (activities, environment, tools/equipment, and relationships) were queried to analyze their effect on crash severities and the frequency with which they occur within the database.

The Integrated Risk Management Model consists of two parts: factors contributing to the severity of the crash and the frequency of the factors involved in the crashes. In this research study, the significance of the factors contributing to the severity of the crash was assessed by developing a statistical model and the frequency of those factors that were found to be significant in the model was assessed through descriptive statistics of the crash database.

The researchers examined weather (environment), equipment, activities, and related factors to develop a risk severity matrix to indicate the relative severity of each factor on a Likert scale of 1 to 5. By performing an analysis of the crash database, the researchers generated a model (and refined it) to show the relationships between the various factors and the severity and frequency of crashes in mobile work zones.

Validation Survey Data Analysis Results

The loss events identified in the literature review and crash data analysis were validated in a short survey that was administered to state, county, and local O/M personnel, as well as to traffic safety professionals in the private sector, including both office and field personnel. The survey assisted the research team in ranking loss events in order of risk (frequency and severity).

The survey questions included the O/M activities identified from the expert panel session. The participants were asked to rank those activities from their experience according to their severity

and likelihood of occurrence (frequency), both of which were measured with a Likert scale rank value from 0 to 5.

The number of responses obtained was 24. Because of the small sample size, no statistical tests were performed with the survey results. These results were used only to validate the results obtained through the statistical analysis of the crash database.

Identification of Mitigation Strategies

After identifying potential risk factors, establishing proximate causes, and estimating frequency and severity, the research team identified risk mitigation strategies that could be used to reduce the frequency and/or severity of losses during O/M activities. The potential mitigation strategies were identified after a meeting with the TAC members.

Key Findings

After identifying potential risk factors and evaluating loss severity, the research team identified the following risk mitigation strategies that can be used within integrated teams to reduce the frequency and/or severity of losses during O/M activities.

1. Revise and integrate the Iowa DOT Instructional Memorandums (IM), Traffic and Safety Manual, and Standard Road Plans – TC Series (traffic control diagrams) and related notes to provide clear guidance on placement of traffic control measures for mobile work zones.

2. Consider expanding traffic-control options to include proven technologies such as the Balsi Beam, portable rumble strips, blue strobe lights, and other innovations. Traffic-control specifications and associated allocation of risk between contractors and state/local agencies would also need to be revised to encourage adoption of new traffic-control measures. This is an area where a follow-up study would prove beneficial.

3. Investigate new delivery technologies (such as Skype, webinars, and remote conferencing) to allow for improved training within the flattened structure of the Iowa DOT. The training should include both formal programs for centralized functions and informal weekly programs for supervisory personnel to discuss issues with field crews. The Local Technical Assistance Program (LTAP) at the Institute for Transportation (InTrans) may be of assistance in developing such a safety-training program. The safety-training program will be particularly helpful for new and temporary employees working in mobile operations.

4. Written manuals and training programs should focus on the importance of worker and equipment visibility and advance warning systems, especially in high-speed environments (interstates and US highways) and those where drivers may be distracted more easily by pedestrians, traffic signals, bicyclists, etc., such as municipal streets.

5. Schedule Best Practices meetings regularly within divisions. Encourage shop management to meet with division managers and other shop managers to discuss best practices that are discovered in the field, especially when it comes to safety. Division managers should also hold meetings periodically to encourage this type of information sharing. The alternative delivery technologies mentioned above may also be helpful in disseminating best practices.

6. Certain environments should be reviewed to ensure that the minimum number of workers and vehicles are used in the traffic-control system. Specifically, two lane two-way highways, work at railroads and other utility sites, overhead work, and work on bridges are likely high-risk environments where additional vehicles and workers increase the risk of crashes. The value of impact attenuators should be researched to determine the safety benefits of such equipment. The analysis of the crash database did not find any reports of impact attenuators associated with mobile work-zone crashes.

7. Policies and safety training programs should emphasize the need for locating traffic controls at the appropriate distance from the work site to allow for driver reactions, and traffic controls should be moved at the same pace as the mobile operations whenever possible.

This report includes a comprehensive discussion of findings beyond what's included in this summary.

Research Limitations

The limitations of this research study are as follows.

- Not all of the factors/hazards that were studied in this research could be described by the crash database variables queried. Representative variables were selected and analyzed from the crash database, which indirectly explained the effect of the required variables/factors/hazards. The data entered on the responding officer's report does not always match the variable of interest.
- The crash data were drawn from the Iowa crash database, but the survey and literature review was national in scope. This made the research study somewhat biased.
- To get a good sample size, crash data from the last 10 years (2001 through 2010) were analyzed. This may have included information about several crashes that occurred after changes in work-zone signage practices and other infrastructure development.
- The response rate for the validation survey was low. Because of the sample size, no statistical analysis could be performed.

Implementation Readiness

The possible mitigation strategies developed as a result of this research are not field-tested, as that was outside of the scope of this research project. If further research on the implementation ideas is needed, a separate research study can be conducted focusing on the implementation of the risk-mitigation techniques found as a result of this study. Testing may include evaluation of the risk-mitigation strategies in simulators or actual field situations to determine effectiveness.

Implementation Benefits

The research findings are intended to provide a process map or guidebook outline for use by the Iowa DOT, Iowa county engineers, and municipal transportation agencies to assess the risk potential of various O/M activities and develop team-based risk-mitigation strategies.

The primary benefits of this research are the reduced risk of injury, fatality, and property damage for O/M and the traveling public. The research results can be implemented by the Iowa DOT staff, county engineers, municipal transportation directors, and any other transportation professionals responsible for O/M activities, including field personnel.

The results can also be used as a standard process for identifying highest-risk O/M activities and developing mitigation strategies to reduce those risks. However, it should be noted that the risk-mitigation processes developed and envisioned in this research are highly inclusive, involving state, local, and regional professionals from both field and office positions.

Intuitively, any process that decreases risk should improve worker safety, lower agency costs, improve service to the traveling public, and lead to more-efficient procedures over the long-term, although these specific performance benefits are not assessed directly as part of this research project.

INTRODUCTION

Problem Statement

Previous research on construction work-zone safety found that moving operations represent the highest-risk activity when both frequency of occurrence and severity of loss are considered (Shane et al. 2009). The research further determined that using an integrated risk model that assesses risk over the project life cycle could mitigate the risk of moving operations (among others) during the construction phase.

Although designed specifically to examine risk and safety for work-zone applications, the research indicated that construction activities that involve moving operations (e.g., painting, guardrail placement) represented the highest risk. This finding suggests that the risk-modeling process could be applied beneficially to operations and maintenance (O/M) functions outside of static construction work-zone applications.

Hence, this research examines how an integrated risk-modeling approach could be used to reduce the frequency and intensity of loss events (property damage, personal injury, fatality) during highway O/M activities.

Objectives

The objective of this research is to investigate the application of integrated risk modeling to O/M activities, specifically moving operations such as pavement and structures testing, pavement marking, painting, shoulder work, mowing, and so forth.

The ultimate goal is to reduce frequency and severity of loss events (property damage, personal injury, and fatality) during O/M activities. Potential risk factors to explore included the following issues:

- Traffic level/congestion
- Number of roadway lanes
- Posted speed limit
- Inadequate/improper signage
- Inadequate/improper vehicle lighting and marking
- Insufficient worker training
- Proximity of obstructions (equipment) to traveled roadway
- Physical limitations of crash attenuators
- Limitations of equipment due to the specialized nature of the fleet
- Weather (condition of road surface, visibility, etc.)
- Work under traffic (inadequate separation or lack of detours/lane shifts)

After identifying potential risk factors and evaluating loss severity, the research team identified risk mitigation strategies that can be used within integrated teams to reduce the frequency and/or severity of losses during O/M activities.

LITERATURE REVIEW

The literature review is intended to identify the current and common practices for safe and efficient highway O/M that have been adopted by different state departments of transportation (DOTs) and other agencies throughout the world. The review also attempted to find out some of the factors that increase the likelihood of vehicle crashes during any type of mobile operations on highways, like testing, painting, repairing and replacement of guardrails, etc., and how the different agencies take precautionary measures to mitigate the chance of crashes due to these factors.

However, it has been found that most of the research has been done on the impacts of weather and different climatic changes on highways and other surface transportation systems with only a few studies focusing on the identification of traffic control devices and safety for mobile and short-duration work zones. Much less focus has been given to a comprehensive examination of risk factors and mitigation strategies for mobile operations, which is the focus of this research project.

Weather/Environment

The National Research Council estimated that drivers endure more than 500 million hours of delay annually on the nation's highways and principal arterial roads because of fog, snow, and ice, excluding delays due to rain and wet pavement (Qin et al. 2006). Furthermore, 1.5 million vehicular crashes each year, accounting for approximately 800,000 injuries and 7,000 fatalities, are related to adverse weather and the injuries, loss of lives, and property damage from weather related-crashes cost an average of 42 billion dollars in the US annually (Qin et al. 2006).

Weather and climate changes have a great impact on surface transportation safety and operations. In the future, with the increase in global warming, transportation managers would need to modify the advisory, control, and treatment strategies to an appropriate level and implement several modern risk mitigation strategies to limit the weather impacts on roadway safety and operations (Pisano et al. 2002).

Moreover, weather also acts through visibility impairments, precipitation, high winds, temperature extremes, and lightning to affect driver capabilities, vehicle maneuverability, pavement friction, and roadway infrastructure. According to the National Center for Statistics and Analysis in 2001, the combination of adverse weather and poor pavement conditions contributes to 18 percent of fatal crashes and 22 percent of injury crashes annually (Pisano et al. 2002).

The crash risk increases during the rainfall, especially if rain is followed after a period of dry weather. In fact, the crash risk during rainfall was found to be 70 percent higher than the crash risk under clear and dry conditions (Pisano et al. 2008). In winter, however, the drivers adjust their behaviors sufficiently to reduce the crash severity during snowfall but not enough to lower the crash frequency.

The traffic volumes during snow events were also found to be 30 percent lower than volumes in clear weather signifying that the drivers themselves become cautious and reluctant to travel during a snow event *(*Pisano et al. 2008). Furthermore, on analysis of the 10 years of winter crash data on Iowa interstates, the crash risk was found to be 3.5 times higher at the start of the winter than it was at the end. Another interesting result propounded by Pisano et al. (2008) was wet weather being much more dangerous when compared to winter weather in terms of both crash frequency and severity.

The combination of high traffic volumes, relatively high speeds, and low traction likely explains why most of the weather-related crashes occur during rainfall and on wet pavement. In fact, 47 percent of weather-related crashes happen in the rain and the annual cost of these crashes is estimated nationally between $22 billion (for only those crashes that are reported) and $51 billion (for both the reported and unreported crashes, because about 57 percent of the crashes are not reported to police, according to the National Highway Traffic Safety Administration/NHTSA report by Blincoe et al. (2002)) (Pisano et al. 2008).

The different strategies recommended in the research to mitigate these kinds of weather-related risks are advisory (announcing the road weather information prior to the actual event so motorists can take precautionary measures), control (access control, speed management, and weather-related signal timing are the three different types of control that increase road safety), and treatment strategy (includes fixed and mobile anti-icing/deicing systems, chemical sequences, etc.).

Several road-weather-management research programs targeted toward traffic, emergency, and winter maintenance management would help to increase the safety, mobility, and productivity of the nation's roadways and would also benefit national security and environmental quality (Pisano et al. 2008). Research by Goodwin (2003) on best practices for road weather management contained 30 case studies of systems in 21 states that improve the roadway operations under inclement weather conditions including fog, high winds, snow, rain, ice, flooding, tornadoes, hurricanes, and avalanches.

This research also mentioned three types of mitigation strategies in response to the control threats: advisory (provide information on prevailing and predicted conditions to both transportation managers and motorists), control (restrict traffic flow and regulate roadway capacity), and treatment strategies (apply resources to roadways to minimize or eliminate weather impacts).

The Alabama DOT (ALDOT) developed and installed a low-visibility warning system integrated with a tunnel management system to reduce the impact of low visibility due to fog. The California DOT (Caltrans*)* developed a motorist warning system for use during low visibility caused by windblown dust in summer and dense localized fog in the winter.

Goodwin (2003) reports that in Aurora, Colorado, a maintenance-vehicle management system (MVMS) was implemented to monitor the operation of maintenance vehicles including snowplows and street sweepers. Vehicles were outfitted with MVMS equipment and a global

positioning system (GPS), which tracked the location of the vehicles. This information was controlled centrally, allowing for the transmission of pre-programmed, customized messages to a single vehicle, a selected group of vehicles, or to all vehicles.

The MVMS could also monitor road treatment activities. With the MVMS monitoring system, transportation managers could easily provide information to citizens about operations and maintenance activities on a particular street or roadway. In addition, treatment costs were minimized and productivity increased 12 percent.

Qin et al. (2006) conducted research to investigate the impact of snowstorms on traffic safety in Wisconsin. The temporal distribution of crash occurrences showed that a large percentage of the crashes occurred during the initial stages of the snowstorms, indicating that to be the most risky time of travel on the highways during a snowstorm. The factors responsible for the risks were low friction pavement, which makes operating and maneuvering vehicles difficult, impaired visibility due to blowing snow or fog, which limits drivers' sight distance, accumulating or drifting snow on the roadway, which covers pavement markings and obstructs vehicles, drivers' inadequate perception and comprehension of the snowstorm event, and high traffic volumes.

The researchers also found that the highest risk of crashes occurred at traffic flow rates from 1,200 to 1,500 vehicles per hour per lane under snow conditions. In the same study, the researchers also found that higher wind speeds/gusts pose high risks causing more severe crashes than higher snowfall intensity.

The mitigation strategies suggested by the researchers to render a "passable roadway" (roadway surface free from drifts, snow ridges, ice, and snowpack and can be traveled safely at reasonable speeds without losing traction by the vehicles) were proper winter maintenance operations such as snow plowing and de-icing techniques, like salting and sanding.

In the US, the crash frequency was eight times higher on a two-lane highway and 4.5 times higher on a multilane freeway before the deicing techniques were applied than that after the application; the crash frequency was nine times and seven times higher on two-lane highways and multi-lane freeways, respectively, before the application of salt than that after the application, with a crash severity reduction of 30 percent (Qin et al. 2006).

The outcomes of this research were as follows: (1) snow plowing and spreader trucks should be sent out prior to the start of the storm event to reduce the number of crashes, (2) the winter maintenance crews should be deployed earlier to significantly reduce crash occurrence, (3) severity of snowstorm and snowfall will increase crash occurrence, and (4) higher wind speed causes more severe crashes (Qin et al. 2006). An interesting result from this study was that freezing rain does not cause more crashes than non-freezing rain, which is counter intuitive given the notoriety of the "black ice" phenomenon pavements.

Research by Shi (2010) recommended several best practices for winter road-maintenance activities, including the use of a software tool for computer-aided design of passive snow control

measures to reduce maintenance costs and closure times, use of anti-icing and pre-wetting techniques, and use of improved weather forecasts through several modern technologies:

1. Road Weather Information Systems/Environmental Sensor Stations (RWIS-ESS), which is an aggregation of roadside sensing and processing equipment used to measure the current weather conditions and road environment such as pavement temperature and pavement conditions in addition to atmospheric conditions and thus aid in winter maintenance decisions

2. Mesonets, which are used as regional networks of weather information integrating the observational data from a variety of sources and thus provide a more comprehensive and accurate picture of the current weather conditions and great potential for improved weather forecasts

3. Fixed Automated Spray Technology (FAST) that is used for anti-icing at key locations enabling the winter maintenance personnel to treat potential conditions before snow and ice problems arise; coupled with RWIS and other reliable weather forecasts, the technology promotes the paradigm shift from being reactive to proactive in fighting winter storms

4. Advanced snowplow technologies, such as automatic vehicle location (AVL), which are vehicle-based sensors, surface-temperature measuring devices, freezing point and ice presence detection sensors, salinity measuring devices, visual and multispectral sensors, and millimeter wavelength radar sensors that have immense importance in winter road-maintenance procedures

5. Maintenance Decision Support Systems (MDSS), which are computer-based systems that integrate current weather observations and forecasts to support maintenance agency response to winter weather events and provides real-time road treatment guidance for each maintenance route

Mobile and Short-Duration Operations/Maintenance Activities and Equipment

As the highway system reaches the end of its serviceable life, it becomes necessary for transportation agencies to focus on the preservation, rehabilitation, and maintenance of these roads. With the significant increase in the number of work-zone activities, transportation officials and contractors are challenged with finding ways to reduce the impact of maintenance activities on driver mobility. In addition, agency leaders are sorting out ways to mitigate risks posed by obstructions to vehicles in work zones.

A study by Sorenson et al. (1998) on maintaining customer-driven highways focused on the efforts by the Federal Highway Administration (FHWA) to minimize traffic backups and travel delays caused by highway maintenance, rehabilitation, and reconstruction. The study also investigated traffic management practices and policies intended to cut down on work-zone

congestion and minimize crash risks. Finally, the study identified contracting and maintenance procedures to cut the time from start to finish in pavement rehabilitation projects.

Through extensive interviews with 26 state highway agencies, the research formulated the best traffic management practices and policies that most of the states use to cut down on work-zone congestion and to minimize crash risks for drivers and highway workers. Specific examples of state DOT practices identified in the study are discussed as follows:

1. The Oregon DOT (ODOT) used an innovative contracting technique, awarding contracts based not on the lowest bid, but on a combination of price and qualifications. The innovative contracting introduced a system of awarding incentives if the work is done earlier or a penalty if it is delayed. The use of "lane rental" charged a rental fee to the contractor based on the road user costs for those periods of time when the traffic is obstructed through the lane or shoulder closures.

2. The New Jersey DOT (NJDOT) recommended performing work at night and providing the public with shuttle buses and other transportation alternatives during the construction/rehabilitation of the highways to mitigate the negative impact of the project on the traffic flow. They also assigned a state patrol unit full time to state DOT construction projects to assist with traffic control and increase work-zone safety.

3. The North Carolina DOT (NCDOT) initiated a public information program that informs motorists, businesses, and residents of upcoming road construction and encourages them to use alternate routes. The researchers also interviewed the road users regarding optimizing highway performance and the findings were noteworthy. For example, in addition to reducing traffic congestion caused by work zones, the public demanded the following things:

    - Increased public awareness of the highway construction process
    - Longer lasting pavements
    - Non-traditional work schedules such as evening and weekend road closures
    - Upgraded product performance
    - Improved communications with the public—with the help of portable traffic management systems consisting of video detection cameras and a series of variable message signs
    - Educating drivers about how to navigate safely through work zones by using videotapes and other media to describe the construction and rehabilitation process
    - High-performance hot-mix asphalt (HMA) to increase the lifetime of the highways and thus minimize disruptions caused by construction and maintenance work

Moriarty et al. (2008) examined the impact of preservation, rehabilitation and maintenance activities on traffic. The researchers developed several simulation models to estimate delays, queues, and delay-related costs associated with traffic impacts created by work zones. The simulation results provided a low-risk, low-cost environment and helped in improving the planning and design of work zones; however, these simulation results only provided guidance to the users who must have a fundamental understanding of the highway capacity analyses and traffic flow fundamentals.

A study by Paaswell et al. (2006) on traffic control devices for mobile and short-duration operations was conducted to focus on the following:

- Identification of state-of-the-art work-zone safety technologies to improve worker safety in the mobile work zones
- Methods for improving the information systems for work-zone traffic control to reduce delays and crashes
- Introduction of best practices for the use of law enforcement to improve work-zone safety along with identifying the key issues to be considered from public outreach and information systems

The study was done in New Jersey for NJDOT and the team found that most of the NJDOT mobile and short-duration work-zone crashes were caused by careless driving, speeding, and motorist inattention. Hence, safety devices should be selected based on their ability to reduce traffic speed through work zones, improve motorists' recognition of work-zone hazards, and improve motorists' attention to signs in the work zone.

The researchers also noted the Texas DOT (TxDOT) had found operational problems with mobile work-zone configurations that included the improper use of arrow-boards, the lack of uniform procedures for freeway entry and exit, large spacing between caravan vehicles, and unnecessary lane blockage by the caravan.

Also included in the report, Caltrans conducted the Caltrans Worker Safety Program, which included construction and maintenance-worker safety orientation and a District Driver Training Program to eliminate employee preventable vehicle accidents (Paaswell et al. 2006).

The FHWA recommended the use of automated enforcement and intrusions alarms as well as uniformed police officers to improve traffic safety at highway work zones. Motorists' information about the work zones, education and outreach systems, and proper training of the workers were mentioned as important factors responsible for decreasing the risks of crashes in mobile work zones.

The review of work operations found that safety for mobile operations of pothole patching, sweeping, spraying and mobile patching was in accordance with Manual on Uniform Traffic Control Devices (MUTCD) requirements, but workers requested improved devices such as strobe lights and improved reflective materials for signs to get drivers' attention (Paaswell et al.

2006). The Paaswell study is very thorough and helps provide several informative findings, which are summarized in Tables 1a, 1b, 2, and 3.

Table 1a. Effective technologies/safety devices for mobile operations

Institution or Agency	**Special Lights/Signs/Indicators/Markers**													
	Fluorescent/bright lights (yellow/green gives best visibility)	Advanced warning signs	Variable message signs (VMS)	Flashing lights	Dancing diamonds (lights)	Rotating lights/strobe lights	Flashing Stop/Slow paddle	All-terrain sign and stand	Drone radar/speed indicator	Radar-triggered speed displays	Dynamic message signs	Direction indicator barricade	Lighted raised pavement markers	Robotic highway safety markers
New Jersey DOT	**X**								**X**					
Kansas DOT										**X**			**X**	
New York State DOT									**X**		**X**			
Strategic Highway Research Program							**X**	**X**				**X**		**X**
FHWA Research Program	**X**	**X**	**X** (includes flip disk, light-emitting diode, fiber-optic, etc.)	**X** (series of synchronous flashing lights)	**X**	**X** (attracts drivers' attention)			**X**					

Table 1b. Effective technologies/safety devices for mobile operations

Institution or Agency	Special Instruments/Technologies																	
	Reflectorized/bright suits and vests	Remotely-operated auto flagger	Truck-mounted attenuators and message boards	CB Wizard alert system	Rumble strips	Lane merger system	White lane drop box	Shadow vehicles	Barrier vehicles	Advance warning vehicles	Cone shooter	Automated pavement crack sealers	Automated debris removal vehicle	Balsi Beam	Automated enforcement and intrusion alarms	Vehicle intrusion alarms (both audio and visual)	Salt spreader truck-mounted attenuator (TMA)	Queue detector
New Jersey DOT	X	X	X	X	X	X												
Missouri DOT				X	X orange		X											
Kansas DOT				X														
California DOT (Caltrans)								X	X	X				X				
New York State DOT					X													
Strategic Highway Research Program				X	X portable						X	X longitudinal and random crack sealers	X	X		X	X	X
FHWA Research Program			X		X										X	X		

Table 2. Techniques adopted for safer mobile work zones

Institution or Agency	Uniformed Police Enforcement in Work Zone	Reduced Channelization Spacing	Enhanced Flagger Stations	Reduced Speed Limits	Education and Outreach Systems for Training of Workers
New York State DOT	X	X	X	X	
FHWA Research Program	X				X

Table 3. Criteria satisfied by selected work-zone device/equipment

Work Zone Device	Criteria 1	Criteria 2	Criteria 3	Criteria 4	Criteria 5
Truck-mounted attenuator	Partly satisfy	Fully satisfy	Partly satisfy	Partly satisfy	Fully satisfy
Vehicle intrusion alarm	Does not satisfy	Fully satisfy	Partly satisfy	Does not satisfy	Does not satisfy
Rumble strips	Does not satisfy	Fully satisfy	Does not satisfy	Does not satisfy	Does not satisfy
All-terrain sign and stand	Does not satisfy	Fully satisfy	Does not satisfy	Does not satisfy	Partly satisfy
Directional indicator barricade	Does not satisfy	Fully satisfy	Does not satisfy	Does not satisfy	Fully satisfy
Flashing Stop/Slow paddle	Does not satisfy	Fully satisfy	Does not satisfy	Does not satisfy	Fully satisfy
Opposing traffic lane divider	Does not satisfy	Fully satisfy	Does not satisfy	Does not satisfy	Partly satisfy
Queue detector	Partly satisfy	Fully satisfy	Does not satisfy	Does not satisfy	Partly satisfy
Remotely-driven vehicle	Partly satisfy	Fully satisfy	Partly satisfy	Partly satisfy	Fully satisfy
Portable crash cushion	Partly satisfy	Does not satisfy	Fully satisfy	Partly satisfy	Does not satisfy
Cone shooter	Fully satisfy	Does not satisfy	Partly satisfy	Does not satisfy	Partly satisfy
Pavement sealers	Fully satisfy	Does not satisfy	Partly satisfy	Partly satisfy	Partly satisfy
Debris removal vehicle	Fully satisfy	Does not satisfy	Does not satisfy	Fully satisfy	Partly satisfy
Balsi Beam	Fully satisfy	Partly satisfy	Fully satisfy	Fully satisfy	Partly satisfy
Robotic highway safety marker	Fully satisfy	Does not satisfy	Does not satisfy	Partly satisfy	Does not satisfy

Does not satisfy Partly satisfy Fully satisfy

Criteria:

1. Reduce exposure to the motorists/crew
2. Warn motorists/crew to minimize the likelihood of crash
3. Minimize severity of crashes once they occur
4. Provide separation between work crew and traffic
5. Improve work zone and traffic control device visibility

The evaluation criteria for device functionality in mobile operations would provide assistance in selecting appropriate traffic control devices for worker safety and the safe and efficient movement of traffic through mobile and short-duration work zones, as shown in Table 3, based on the utility and effectiveness of the devices mentioned in the study. Selected innovative technologies discussed by Paaswell et al. (2006), which show promise for operations and maintenance activities, are discussed in more detail below. Appendix D provides additional information on innovative technologies.

Balsi Beam

Developed by Caltrans, the Balsi Beam has great potential for protecting exposed workers in short-duration work operations (See Figure 1).

Figure 1. The Balsi Beam being rotated from side to side

The beam provides positive protection from errant vehicles and is crashworthy as tested by National Cooperative Highway Research Program (NCHRP) criteria. Unlike portable concrete median barriers, which are labor/equipment intensive to set up and require a 42 in. clear zone between the barrier and the worker, the Balsi Beam can be set up in less than 10 minutes and requires no clear zone between the beam and workers.

Caltrans is presently implementing the barrier for specialized concrete construction and bridge repair operations on high-speed interstate highways. The beam can be used in maintenance operations wherever workers are exposed to traffic in a limited area for several hours. Caltrans uses the beam for median barrier repairs, bridge deck patching and repairs, slab replacement and joint repairs, installation of bridge sealers, and guide rail and parapet repairs. The beam is used in conjunction with other safety equipment, such as truck-mounted attenuators, trucks, signs, and safety set up.

Dancing Diamonds (light panels)

These signs (Figure 2) use a dancing-diamond panel, which is a matrix of light elements capable of either flashing and/or sequential displays and act as an advance caution device.

Figure 2. Dancing diamonds (lights)

Rotating Lights/Strobe Lights

Rotating/strobe lights were effective in getting drivers' attention but not as useful in providing speed and closure rate information, especially when the service vehicle has stopped.

Portable Rumble Strips

Portable rumble strips (Figure 3) are placed temporarily on the road surface at a distance of about 100 meters (250 ft) in advance of the work zone and cause a vibration in the steering wheel and a rumble as vehicles pass over them, alerting drivers of changing conditions ahead and are best suited for low-speed roads that carry few heavy trucks.

Figure 3. Flagger stopping traffic (left) and portable temporary rumble strips being field tested near Perry, Kansas (right)

Portable rumble strips are very easy to use as the device weighs only 34 kg (75 lbs) and one or two workers can deploy them from the back of a pick-up truck.

Cone Shooter

A cone shooter (Figure 4) is a machine that can automatically place and retrieve traffic cones and, thus, open and close busy lanes safely and quickly without exposing workers to traffic.

Figure 4. Cone shooter (AHMCT Research Center - UC Davis)

Typical lane configurations use 80 traffic cones for each 1.5 miles of lane closure and the cones generally come in the 36 in. size. Manually, only three cones can be carried by a worker at a time, so the cone shooter helps in reducing both the cost and injury involved in a mobile work zone in a busy lane.

Automated Pavement Crack Sealers

Given that one of the most frequent maintenance operations involves pavement crack sealing and it is done by mobile operations, the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center has developed two automated crack sealers (Figure 5).

Figure 5. Automated pavement crack sealer

The longitudinal and random crack sealers perform the operation with greater efficiency and in less time.

Robotic Highway Safety Markers

The Mechanical Engineering Department at the University of Nebraska-Lincoln has developed a mobile safety barrel robot (Figure 6) for efficient use in mobile work zones.

Figure 6. Robotic safety barrel (RSB)

The Robotic Safety Barrel (RSB) replaces the heavy base of a typical safety barrel with a mobile robot. The mobile robot can transport the safety barrel and robots can work in teams to provide traffic control.

The robotic highway safety markers have been tested in field environments. Each robot moves individually. A single lead robot (the "General") provides global planning and control and issues commands to each barrel (the "troops"). All robots operate as a team to close the right lane of a highway.

The robotic safety barrels can self-deploy and self-retrieve, removing workers from exposure to moving traffic. The robots move independently so they can be deployed in parallel and reconfigure quickly as the work zone changes. These devices would be of great advantage in the mobile work zone where the cones or barrels could be programmed to move along with the working crew, saving time and increasing safety to workers.

CB Wizard Alert System and Program

CB Wizard is a portable radio that broadcasts real-time work-zone information and safety tips through radio channels. The advanced warning gives drivers the opportunity to moderate their speed and become observant of the need to slow, stop, or maneuver before they reach the work zone or encounter queues of halted vehicles.

Truck-Mounted Changeable Message Signs

Research at Texas A&M University has identified truck-mounted changeable message signs (TMCMS) (Figure 7) as an innovative technology that improves safety for both drivers and workers (Sun et al. 2011).

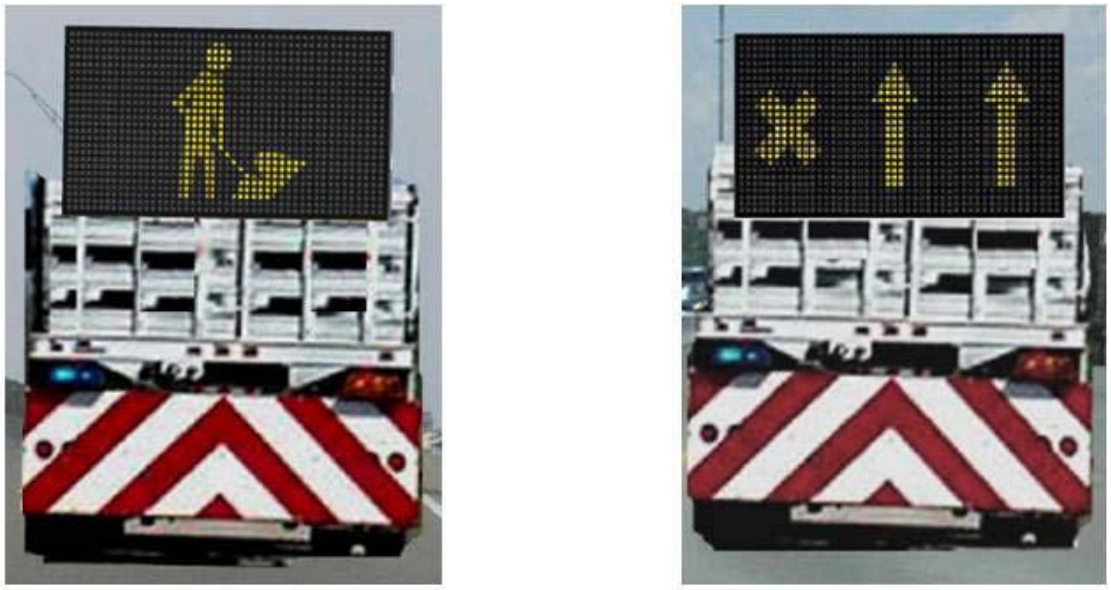

Figure 7. Truck-mounted changeable message signs (event example, left, and lane-blocked example, right) (photos Texas A&M University-Kingsville)

TMCMS can provide information to drivers in both symbols and text, and the truck-mounted deployment allows the information to be delivered to the driver at the closest possible point to the actual work site.

Driver Behavior and Impacts on Truck-Mounted Attenuators

Research by Steele and Vavrik (2010) explored driver behavior and identified some specific challenges that pose a risk for mobile work zones and lane closures such as providing adequate advance warning to motorists, decreasing driver speeds and heightening motorist awareness approaching the work zone, getting drivers to change lanes at a safe distance upstream of the work zone, and maintaining traffic in the open lane until a safe distance beyond the work space.

The researchers observed that the return distance of the vehicles in the closed lane on urban expressways (high- and low-traffic during daytime) was as early as 25 ft in congested and 50 ft under free-flowing traffic, while the rural interstate traffic was more relaxed, returning to the closed lane 100 ft beyond the lead traffic control truck. However, in all cases, traffic came back into the closed lane at distances where workers would normally be present.

It was also observed that increasing the visibility of the work crew by placing a lead truck downstream is an effective means of extending the buffer space at least by 200 ft and deterring drivers from returning to the closed lane too soon.

Observation was also made about the workspace length. The analysis of predicted roll-ahead distances for truck-mounted attenuators (TMAs) impacted by vehicles of different sizes and speeds showed that for typical highway speeds, single- and multiple-unit trucks were capable of pushing the TMA into the work space creating a dual threat of lateral intrusions. So, the impacts on TMAs must be considered when developing traffic control standards.

An important conclusion was made regarding nighttime mobile lane closure, which created hazardous conditions due to increased traffic speeds, decreased visibility, and increased numbers of impaired drivers. However, the addition of a flashing vehicle on the shoulder of the closed lane and 500 ft upstream reduced the number of vehicles approaching the work zone closely from 18.1 to 3.6 percent.

Lighting

Effective lighting is very important for service and maintenance vehicles. Although this is not included in the scope of this research work, a summary of three major studies regarding warning lights for service vehicles is provided in Appendix A.

Literature Review Conclusions

The literature review reveals several studies on the impacts of weather on the roadways and, hence, its effects on work-zone safety, along with specific research on the interaction of traffic and O/M and mobile work-zone-related safety. However, these studies did not specifically address risk assessment and mitigation strategies for the O/M activities on highways.

This research study examines weather (environment), equipment, activities, and related factors to develop a risk severity matrix to indicate the relative severity of each factor on a Likert scale of 1 to 5. An analysis of the crash database is also performed to generate a model showing the relationships between the various factors and the severity and frequency of crashes in mobile work zones.

RESEARCH METHODOLOGY

The purpose of this section is to describe the research methods used to develop the Integrated Risk Management Model and identify, assess, and respond to the risks associated with highway O/M activities, such as pavement testing, pavement marking, painting, shoulder work, mowing, and so forth.

As mentioned earlier, the ultimate goal of this research is to reduce the frequency and severity of loss events (property damage, personal injuries, and fatalities) during O/M activities. After potential risk factors were identified and loss frequency and severity had been evaluated, the research team identified risk mitigation strategies that can be used within integrated teams to reduce the frequency and/or severity of losses during O/M activities. The methodologies that were adopted in this research are as follows:

- Identification of current O/M processes through expert input
- Literature review
- Analysis of the crash data
- Validation survey
- Identification of mitigation strategies

Identification of Current O/M processes through Expert Input

The research started with an expert panel session aimed at mapping the O/M process as currently utilized by state, county, and local agencies. The objective was to categorize the activities, environments, tools/equipment, and relationships involved with different operations and maintenance functions. The outcomes of the expert panel (technical advisory committee or TAC) session are described in Appendix B.

Appendix C contains in-depth follow-up interviews with three members of the expert panel (Bob Younie, Mark Black, and Jeff Koudelka).

Literature Review

An extensive literature search was performed and a preliminary list of risk factors and loss events during O/M activities was identified. The search mainly included results from academic journals, trade publications, transportation research technical reports, and state DOT web sites.

The primary websites used to facilitate the search for relevant publications were Google Scholar, the Transportation Research Board (TRB), Parks Library at Iowa State University, and the Iowa DOT Library. The literature search also gave insight into how the identified factors play a role in mobile work-zone crashes, specifically work zones that involve O/M activities on highways.

Analysis of the Crash Data

The analysis of the crash database provided by the Iowa DOT played a very important role in the development of the Integrated Risk Management Model. To obtain information about the relevant crashes, a query was created to gather data for all severity level of crashes from 2001 through 2010 that involved two types of work zones (given we were focused on moving operations and not static work): intermittent or moving work and work on shoulder or median.

The suitable variables in the crash database that were able to explain the effect of the previously-identified factors (activities, environment, tools/equipment, and relationships) were queried to analyze their effect on crash severities and the frequency with which they occur within the database. Table 4 shows the variables selected from the crash database to analyze the risk posed by each of the factors in O/M activities.

Table 4. Variables queried from the Iowa crash database

Data Field (crash data) and Field Description	**Categories**
Crash Severity	
CSEVERITY: Crash severities as measured	Fatal
	Major Injury
	Minor Injury
	Possible or Unknown Injury
	Property Damage Only (PDO)
Activity	
WZ_Type: Type of work activities involved	1. Work on shoulder or median 2. Intermittent or moving work
Equipment	
FIRSTHARM: What the first harmful event is collision with	Impact Attenuator (fixed object)
SEQEVENTS1: In the sequence of events, what the first event is collision with	Impact Attenuator (fixed object)
EmerVeh: Emergency vehicle type	Maintenance Vehicle
EmerStatus: Emergency status of the vehicle considered	1. In emergency 2. Not in emergency
VCONFIG: Vehicles involved in the crash	1. Passenger car 2. Four-tire light truck 3. Van or mini-van 4. Motor home /recreational vehicle 5. Motorcycle and sport utility vehicle 6. Mopeds/Motorcycle 7. Trucks and tractors (Single-unit truck two-axle, Single-unit truck ≥ three axles, Truck/trailer, Truck tractor, Tractor/semi-trailer, Tractor/doubles, Tractor/triples and other heavy trucks) 8. Bus (School bus > 15 seats, Small school bus nine to 15 seats, Other bus > 15 seats, and Other small bus nine to 15 seats) 9. Maintenance or construction vehicle

Data Field (crash data) and Field Description	Categories
Environment	
LIGHTING: Derived light conditions	1. Daylight 2. Darkness 3. Morning Twilight 4. Evening Twilight
VISIONOBS: What the vision is obstructed by	1. Moving vehicles 2. Frosted windows/windshield 3. Blowing snow 4. Fog/smoke/dust
TRAFCONT: Where the traffic control signs are in the accident zone	Work-zone signs
RAMP: Crash location	Mainline or ramp
ROADCLASS: Road classification	1. Interstate 2. US Route 3. Iowa Route 4. Secondary Route 5. Municipal Route 6. Institutional Road
RCONTCIRC: What the contributing circumstances in the roadway are	1. Work zone (construction/maintenance/utility) 2. Traffic control device inoperative/missing/obscured
WEATHER1: Weather conditions	1. Cloudy 2. Fog, smoke 3. Rain 4. Sleet, hail, freezing rain 5. Snow 6. Blowing sand, soil, dirt, snow
WZ_LOC: Work zone crash location	1. Before work-zone warning sign 2. Between advance warning sign and work area 3. Within transition area for lane shift 4. Within or adjacent to work activity 5. Between end of work area and End Work Zone sign 6. Other
Driver Characteristics	
DAGEBIN1: Age of the driver (in years)	1. Driver ≤18 years 2. Driver > 18 and <25 years 3. Driver ≥ 25 and <45 years 4. Driver ≥ 45 and <65 years 5. Driver ≥ 65 years
DRIVERGEN: Driver's gender	1. Male 2. Female
DL_STATE: Driver's license state	1. Iowa – In state 2. Other – Out of State

The Integrated Risk Management Model consists of two parts: factors contributing to the severity of the crash and the frequency of the factors involved in the crashes. In this research study, the significance of the factors contributing to the severity of the crash is assessed by developing a statistical model (as described in the next section) and the frequency of those factors that are found to be significant in the model is assessed through descriptive statistics of the crash database.

Assessment of Severity

The data collected from the Iowa DOT crash database consists of 55,042 crashes that occurred during the years 2001 through 2010 due to intermittent and moving work zones or work on the shoulders or median. The severity of the crashes, which are discrete but ordered, is the dependent variable for the analysis.

We assumed the disturbance terms $\varepsilon \sim N(0, 1^2)$. Hence, the model that was suitable for this type of data analysis was an ordered probit model. The severities as obtained from the crash database include five categories: Fatal, Major Injury, Minor Injury, Possible or Unknown Injury, and Property Damage Only (PDO).

It was observed that the categories Fatal and Major Injuries do not have significant numbers of observations and so it was decided to combine these into one category as Fatal/Major Injury while the others are kept the same. The new percentage frequencies for the categories are as follows: Fatal/Major Injury [y=3] = 2.40%; Minor Injury [y=2] = 14.96%; Possible/Unknown Injury [y=1] = 20.80%; and PDO [y=0] = 61.84%.

The number of threshold parameters ($\mu 1$ and $\mu 2$) for the probit analysis will be two, the lowest threshold being set at zero. The desired outcome of the ordered probit model is to obtain an optimized linear function that determines the factors that are having an effect on the severity of the crashes (y) under the intermittent and moving work-zone situation and work on shoulder or median situation.

The statistical significance of the different variables in the model is estimated using a one-tailed t-test and 90 percent confidence (α=0.10). The critical cut-off value for the t-statistic is 1.28 for large sample sizes (e.g., sample size >100).

After the significant factors are identified along with their relationship to fatal or major injury crashes, they are ranked on a scale of 1 to 5, with 1 being the least severe and 5 being the most severe according to their probabilities of contributing to a fatal/major injury crash.

Assessment of Frequency

The frequency of the factors involved in the crashes is determined from their descriptive statistics and is expressed as the percentage of the total crashes. This was then categorized evenly on a scale of 1 to 5, with 1 being very rarely occurring and 5 meaning very frequently occurring. The entire analysis was performed using the LIMDEP transportation data analysis software.

Validation Survey

The loss events identified in the literature review and crash data analysis were validated in a short survey that was administered to state, county, and local O/M personnel, as well as to traffic safety professionals in the private sector, including both office and field personnel. The survey assisted the research team in ranking loss events in order of risk (frequency and severity).

The survey questions included the O/M activities identified from the expert panel session. The participants were asked to rank those activities from their experience according to their severity and likelihood of occurrence (frequency), both of which were measured with a Likert scale rank value from 0 to 5. The Frequency Likert scale was defined as follows:

0 – Unable to answer
1 – Very unlikely
2 – Unlikely
3 – Neutral
4 – Probable
5 – Very probable

The Severity Likert scale was defined as follows:

0 – Unable to answer
1 – No loss
2 – Property Damage Only (PDO)
3 – Minor Property Damage/Minor Injuries
4 – Major Property Damage/Major Injury
5 – Catastrophic Loss/Fatality

The number of responses obtained was 24. Because of the small sample size, no statistical tests were performed with the survey results. These results were used only to validate the results obtained through the statistical analysis of the crash database.

Identification of Mitigation Strategies

After identifying potential risk factors, establishing proximate causes, and estimating frequency and severity, the research team identified risk mitigation strategies that could be used to reduce the frequency and/or severity of losses during O/M activities. Potential mitigation strategies were identified after a meeting with the TAC and are discussed in the last section of the report.

DATA ANALYSIS

This section explains the results of the statistical analysis of the crash database and descriptive analysis of the survey data. It also presents the Integrated Risk Management Model developed from the analyses.

Crash Database Analysis Results

Data Description

In order to perform a statistical data analysis to get an overall idea about the severities and frequencies of the factors involved in mobile work-zone crashes, a query was created to gather data for all the severity levels of crashes for the years 2001 through 2010, as provided in the Iowa DOT Saver Crash Data from the Office of Traffic and Safety.

From the data collected, crashes pertaining to intermittent and moving work zones and work on the shoulder or median were extracted. The relevant factors affecting the crashes were selected based on the information obtained from the expert panel meeting (and described in Table 4).

Table 5 shows that 55,042 crashes have occurred in mobile work zones that involve intermittent or moving work or work on the shoulders or medians. The table shows the number of crashes according to the severity levels over the 10 years from 2001 through 2010.

Table 5. Iowa statewide work-zone crash statistics

Year	Fatal/Major Injury Crashes	Minor Injury Crashes	Possible Injury Crashes	Property Damage Only Crashes	Total
2001	113	1,156	469	982	2,720
2002	320	68	3,471	1,212	5,071
2003	65	101	524	9,454	10,144
2004	54	341	1,294	4,825	6,514
2005	117	683	680	2,376	3,856
2006	17	4,424	957	1,923	7,321
2007	118	133	358	2,123	2,732
2008	304	804	521	1,972	3,601
2009	84	195	2,594	1,290	4,163
2010	131	329	579	7,881	8,920
Total	**1,323**	**8,234**	**11,447**	**34,038**	**55,042**

The rows in Table 5 show the number of crashes according to the different severity levels in each year as well as the total number of crashes. The total number of crashes of a particular severity

level that occurred over the 10 years is displayed in the columns. The percentage distribution of the number of crashes according to the crash severity levels is shown in Figures 8 and 9.

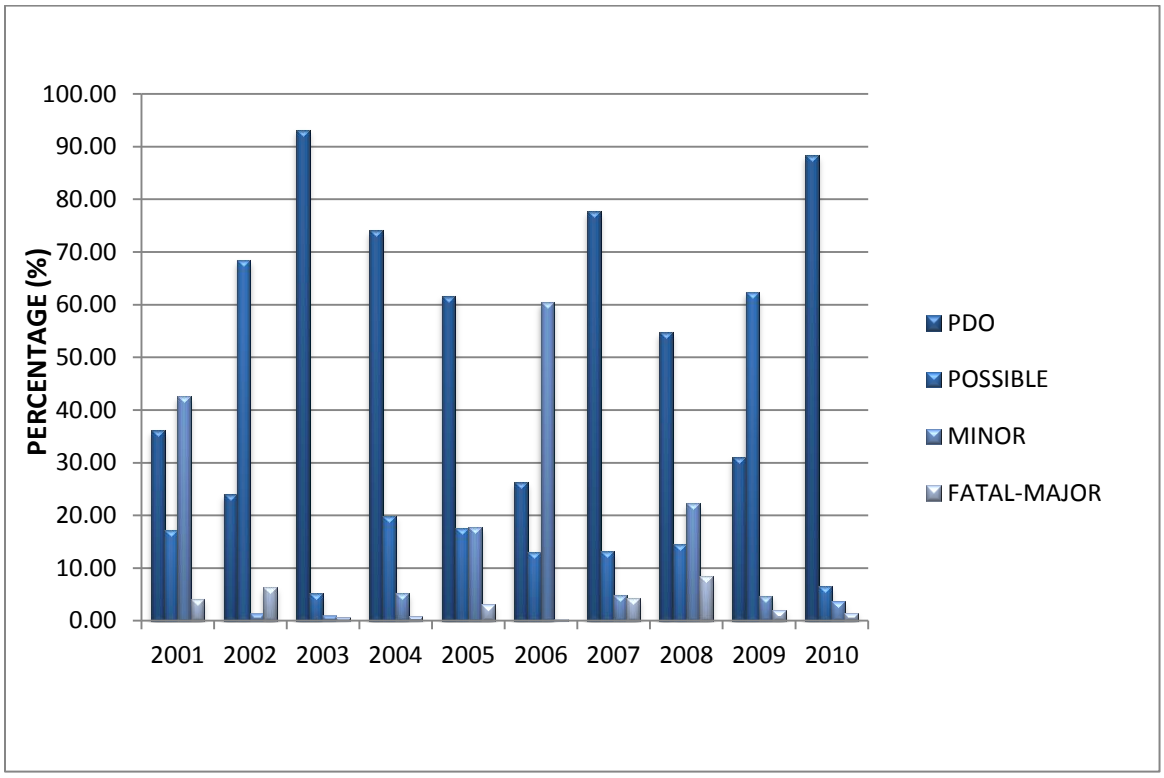

Figure 8. Percentage distribution of statewide work-zone crashes according to severity over 10 years (2001–2010)

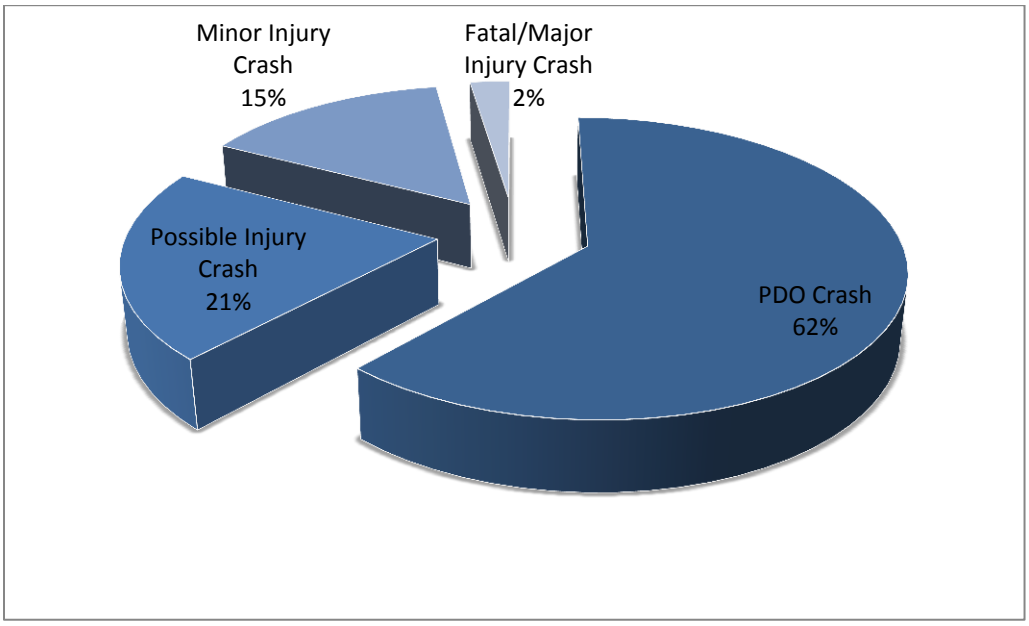

Figure 9. Statewide work-zone crash severity distribution—total crashes (2001–2010)

Severity Analysis and Factor Rating According to Severity

The crash severity is categorized into five types as defined by the Iowa DOT (2001). The categories can be defined as follows:

1. **Fatal** – Any injury that results in death within 30days of the motor vehicle accident

2. **Incapacitating/Major Injury** – Any injury, other than a fatal injury, which prevents the injured person from walking, driving or normally continuing the activities the person was capable of performing before the injury occurred; inclusions are severe lacerations, broken or distorted limbs, skull, chest, or abdominal injuries, unconsciousness, unable to leave the accident scene without assistance

3. **Non-Incapacitating/Minor Injury** – Any injury, other than a fatal injury or an incapacitating injury, which is evident to observers at the accident scene; inclusions are lump on head, bruises, abrasions, and minor lacerations

4. **Possible/Unknown Injury** – Any injury reported or claimed, which is not a fatal, incapacitating, or a non-incapacitating injury; inclusions are momentary unconsciousness, claim of injuries not evident, limping, complaint of pain, nausea, and hysteria

5. **Property Damage Only (PDO)** – Uninjured

Variables Created for Analysis along with Definitions

The variables that were created to build the model are listed in Table 6. All of the variables created were indicator variables and they were created in such a way that they can portray the effect of the activities, equipment, environment, driver characteristics, and some other factors on the crash severities.

The variable description along with their frequencies is given in Table 6. Those variables that are marked red were found to be statistically significant (α=0.10) during the analysis and were used in the model; whereas, those marked in black were found not to be statistically significant during the analysis and thus were not used in the model.

Table 6. Descriptive statistics and significance of the indicator variables created or used in the model

Variables	Variable Description	Frequency	Significance Indicator
Equipment			
FIRSTHAR	First harmful event is collision with impact attenuator	0.0004	
SEQEVENT	In the sequence of events, first event is collision with impact attenuator	0.0001	
EMRMNTN	Emergency vehicle type is maintenance vehicle	0.0068	
MVEHEM	Maintenance vehicle in emergency	0.0016	
MVHNOEM	Maintenance vehicle not in emergency	0.0052	
PSVEH	Passenger vehicle	0.54293085	
PCKTRK	Four-tire light truck/pick-up truck	0.139875	
VAN	Van or minivan	0.10264889	
SUV	Sport utility vehicle	0.11316813	
TRCKTRAC	Trucks and tractors (Single-unit truck two-axle, Single-unit truck ≥ three axles, Truck/trailer, Truck tractor, Tractor/semi-trailer, Tractor/doubles, Tractor/triples and other heavy trucks)	0.0772	
BUS	Bus (School bus > 15 seats, Small school bus with nine to 15 seats, Other bus > 15 seats, and Other small bus with nine to 15 seats)	0.0049	
VCNFIGCO	Vehicle configuration involved in crash is a maintenance/construction vehicle	0.0077	
Environment			
DAYLIT	Daylight crash	0.8821	
NODAYLIT	Crash when no daylight, i.e., during Darkness, Morning Twilight, or Evening Twilight	0.1180	
VNOBSCUR	Vision not obscured by anything	0.9164	
VOFROSTW	Vision obstructed by frosted windows or windshield	0.0002	
VOMOVVEH	Vision obstructed by moving vehicle	0.0116	

Variables	Variable Description	Frequency	Significance Indicator
VOWEATHE	Vision obstructed by weather like blowing snow, fog, smoke, or dust	0.0068	
NOTFCONT	No traffic control present near the work zone where the crash occurs	0.7293	
TRAFCONW	Traffic control present near the crash work zone involves work-zone sign	0.0912	
LOCRAMP	Crash location is near the ramp	0.0545	
LOCMAIN	Crash location near the mainline	0.9455	
INTERSTA	Interstate route	0.6305	
USROUTE	US route	0.1306	
IOWAROUT	Iowa route	0.068	
SECROAD	Secondary road	0.0545	
MUNIROAD	Municipal road	0.1137	
INSTROAD	Institutional road	0.0009	
RCNTCIRC	Contributing circumstances of the crash involves work-zone (construction/ maintenance/utility)	0.9509	
CNTNCRCTC	Contributing circumstances of the crash involves inoperative/obscured/missing traffic control device	0.0006	
BLOWSNOW	Weather condition has blowing snow	0.0027	
CLOUDY	Weather condition is cloudy	0.1129	
FOGSMOKE	Weather condition is foggy or smoky	0.0026	
RAIN	Weather condition has rain	0.1633	
SNOW	Weather condition has snow	0.0024	
BETAWWRK	Crash location is between the advance warning sign and work area	0.1663	
WTHWRKZN	Crash location is within or adjacent to the work activity	0.6921	
Driver Characteristics			
UNDDRI	Driver ≤ 18 years	0.0594	
YONDRI	Driver > 18 and < 25 years	0.2244	

Variables	Variable Description	Frequency	Significance Indicator
MDDRI	Driver ≥ 25 and < 45 years	0.3499	
OLDRI	Driver ≥ 45 and < 65 years	0.3304	
VOLDRI	Driver ≥ 65 years	0.0641	
IOWALCNC	Iowa driver's license	0.7904	
X16	Driver gender (male = 1, female = 0)	0.5124	
OFSMLDR	Out-of-state male driver	0.1587	
OFSFMDR	Out-of-state female driver	0.1002	

The final model of the crash severities was selected after a reiterative selection of the different independent variables through the LIMDEP software, which are shown in Table 7 with their beta coefficient and statistical significance.

Table 7. Variable description and results

ID	Indicator/Variable Description	Variable Mnemonic	Estimated Coefficient	T-Statistic
1	Constant	Constant	-1.984366***	-15.004
2	Crash Location Indicator 1 (1 if the crash location is between the advance warning sign and work area; 0 if otherwise)	BETAWWRK	.91979447***	45.373
3	Crash Location Indicator 2 (1 if the crash location is within or adjacent to the work activity; 0 if otherwise)	WTHWRKZN	.340550***	19.633
4	Crash Location Indicator 3 (1 if the location of the crash is near the ramp; 0 if otherwise)	LOCRAMP	.107263***	4.445
5	Cloudy Weather Indicator (1 if the weather condition is cloudy; 0 if otherwise)	CLOUDY	.8491091***	49.481
6	Under-Aged Driver Indicator (1 if driver ≤ 18 years; 0 if otherwise)	UNDDRI	-.419101***	-9.814
7	Young-Aged Driver Indicator (1 if driver > 18 and < 25 years; 0 if otherwise)	YONDRI	-.507994***	-12.772
8	Middle-Aged Driver Indicator (1 if driver ≥ 25 and < 45 years; 0 if otherwise)	MDDRI	-.2448169***	-6.439
9	Old-Aged Driver Indicator (1 if driver ≥ 45 and < 65 years; 0 if otherwise)	OLDRI	-.2721166***	-7.067
10	Very Old-Aged Driver Indicator (1 if driver ≥ 65 years; 0 if otherwise)	VOLDRI	.1761806***	8.132
11	Time of Day Crash Indicator (1 if no daylight, i.e., either in darkness, morning twilight, or evening twilight; 0 if otherwise)	NODAYLIT	.4889586***	28.701
12	Out-of-State Male Driver Indicator (1 if out-of-state male driver; 0 if otherwise)	OFSMLDR	.1177997***	6.898
13	Out-of-State Female Driver Indicator (1 if out-of-state female driver; 0 if otherwise)	OFSFMDR	-.235061***	-9.695
14	Rain Indicator (1 if rain; 0 if otherwise)	RAIN	-.292615***	-15.717
15	Interstate Route Indicator (1 if Interstate; 0 if otherwise)	INTERSTA	.551989***	4.393

ID	Indicator/Variable Description	Variable Mnemonic	Estimated Coefficient	T-Statistic
16	US Route Indicator (1 if US Route; 0 if otherwise)	USROUTE	1.191032***	9.434
17	Secondary Road Indicator (1 if Secondary Route; 0 if otherwise)	SECROAD	1.43160***	11.252
18	Municipal Route Indicator (1 if Municipal Route; 0 if otherwise)	MUNIROAD	1.112705***	8.800
19	Iowa Route Indicator (1 if Iowa Route; 0 if otherwise)	IOWAROUT	1.18880***	9.367
20	Traffic Control Sign Indicator (1 if traffic control present near the crash work zone involves work-zone sign; 0 if otherwise)	TRAFCONW	.02326043*	1.28
21	Passenger Vehicle Indicator (1 if Passenger vehicle; 0 if otherwise)	PSVEH	.432212***	25.049
22	Pick-up Truck Indicator (1 if four-tire light truck/pick-up truck; 0 if otherwise)	PCKTRK	.353129***	16.581
23	Van Indicator (1 if Van or Minivan; 0 if otherwise)	VAN	.437940***	19.581
24	Truck and Tractor Indicator (1 if Single-unit truck two-axle, Single-unit truck ≥ three axles, Truck/trailer, Truck tractor, Tractor/semi-trailer, Tractor/doubles, Tractor/triples and other heavy trucks; 0 if otherwise)	TRCKTRAC	.535388***	21.932
25	Vision Not Obscured Indicator (1 if vision not obscured by any of the hindrances like moving vehicles, weather, etc., during the crash; 0 if otherwise)	VNOBSCUR	.328564***	14.660
26	Gender Indicator (1 if male driver; 0 if female driver)	X16	-.035858***	-3.008
Threshold Parameter				
27	μ 1		.7617741***	125.083
28	μ 2		1.915051***	158.255
	NO. OF OBSERVATIONS	55042		
Overall fit by ρ - Square	Log likelihood function [LL(β)]	-49179.94		
	Restricted log likelihood [LL(C)]	-54910.88		
	ρ - Square = 1-LL(β)/LL(C)	0.104368023		
	adjusted ρ - Square = 1-(LL(β)-k) /LL(C)	0.103858106		

	k= number of parameters in the model	28
Overall fit by X2 estimate	K (No. of parameters in the unrestricted – No. of parameters in the restricted model]	28-3=25
	-2 [LL(βc) – LL(β)]	11461.88
	X2critical [25 d.f.]	60.1403
Given that -2 [LL(βc) – LL(β)] > $X^2_{critical}$ at α=0.0001, we can state that the entire model is significant at 99.99 percent.		

***, **, * = Significance at 1%, 5%, 10% level, respectively
For detailed statistical analysis, refer to Sayanti (2011) master's thesis upon publication/distribution of it

The marginal effects for each response category are interpreted as a change in the outcome probability of each threshold category P(y=j) given a unit change in a continuous variable x (Washington et al. 2010). These values are dimensionless and relative and also do not carry any specific meaning.

There are in fact two ways of estimating how much the event probability changes when a given predictor is changed by one unit. The marginal effect of a predictor is defined as the partial derivative of the event probability with respect to the predictor of interest. A more direct measure is the change in predicted probability for a unit change in the predictor.

Being a derivative, the marginal effect is the slope of the line that is drawn tangent to the fitted probability curve at the selected point. Note that the marginal effects depend on the variable settings that correspond to the selected point at which this tangent line is drawn, so the marginal effect of a variable is not constant.

Table 8 depicts the marginal effects of the factors. Marginal effect of any factor can be defined as the effect a positive or a negative coefficient has on the probabilities of the crash severity. For example, if we consider BETAWWRK (the crash location is between the advance warning sign and work area), the probability of the crash being fatal/major is 0.0595 higher (on average), the probability for the crash being a minor injury is 0.203 higher (on average), and the probability for the crash being a probable or unknown injury is 0.0917 higher (on average); whereas, the probability of the crash being a PDO is 0.3541 lower (on average). Thus, marginal effects portray the impact each factor has on the potential severity of the crash.

Table 8. Marginal effects of the factors along with their severities

Significant variables affecting severity	Probability of the factors causing fatal-major crashes	Probability of the factors causing minor crashes	Probability of the factors causing possible/ unknown injury crashes	Probability of the factors causing PDO	Weighted Average of the Probabilities of the factors causing several severe crashes
BETAWWRK	0.0595	0.203	0.0917	-0.3541	0.0672**
CLOUDY	0.0564	0.1904	0.082	-0.3288	0.0629
UNDDRI	-0.0087	-0.064	-0.0716	0.1443	-0.0219
YONDRI	-0.0119	-0.0815	-0.0851	0.1784	-0.0276
MDDRI	-0.007	-0.0436	-0.0398	0.0905	-0.0144
OLDRI	-0.0076	-0.0481	-0.0445	0.1002	-0.0159
VOLDRI	0.0065	0.0348	0.0264	-0.0677	0.0113
NODAYLIT	0.0233	0.1039	0.0635	-0.1907	0.0336
OFSMLDR	0.004	0.0225	0.0183	-0.0448	0.0074
OFSFMDR	-0.0059	-0.0396	-0.0394	0.0849	-0.0133
RAIN	-0.0073	-0.0491	-0.049	0.1054	-0.0165
INTERSTA	0.0152	0.0948	0.0895	-0.1995	0.0316
USROUTE	0.102	0.2655	0.0793	-0.4468	0.0921
SECROAD	0.1719	0.3069	0.0288	-0.5076	0.1185
MUNIROAD	0.0924	0.2503	0.0781	-0.4208	0.0859
IOWAROUT	0.1145	0.2679	0.06	-0.4423	0.0949
PSVEH	0.0132	0.0782	0.0687	-0.1601	0.0258
PCKTRK	0.0147	0.0723	0.0499	-0.1368	0.0234
VAN	0.0202	0.0924	0.0581	-0.1708	0.0298
TRCKTRAC	0.0278	0.1164	0.0653	-0.2095	0.0377
TRAFCONW	0.0007	0.0043	0.0037	-0.0088	0.0014
VNOBSCUR	0.0075	0.0529	0.0557	-0.1161	0.0179
WTHWRKZN	0.0092	0.059	0.056	-0.1242	0.0196
LOCRAMP	0.0037	0.0207	0.0165	-0.0409	0.0067
X16	-0.0011	-0.0066	-0.0057	0.0135	-0.0022
Weighting Factors	4.5	3	2	1	
Total Weighting	10.5				

Calculation of the Weighted Average of the Probability (example):
0.067242857** = (0.0595 × 4.5 + 0.203 × 3 + 0.917 × 2 - 0.3541 × 1) ÷ 10.5

To rank the factors in terms of their impact on severity, a weighted average technique was adopted. The weighted average of the probabilities of the factors is calculated to give an overall severity value. The different categories of the crashes are assigned ranking factors based on their importance and impact and they are as follows:

- Fatal – 5
- Major Injury – 4
- Minor Injury – 3
- Probable/Unknown Injury – 2
- PDO – 1

Given the fatal and major injury crashes have been combined, the average of the ranking factors 5 and 4 (4.5) is assigned to the Fatal/Major Injury crash category. Therefore, for this research, the ranking factors are as follows:

- Fatal/Major Injury – 4.5
- Minor Injury – 3
- Probable/Unknown Injury – 2
- PDO – 1

The calculation of the weighted average for the probabilities is shown in Table 8.

Figure 10 shows the distribution of the factors according to the weighted average of the probabilities for the occurrence of the different types of crashes, which is referred to as the severity of the factors in this report.

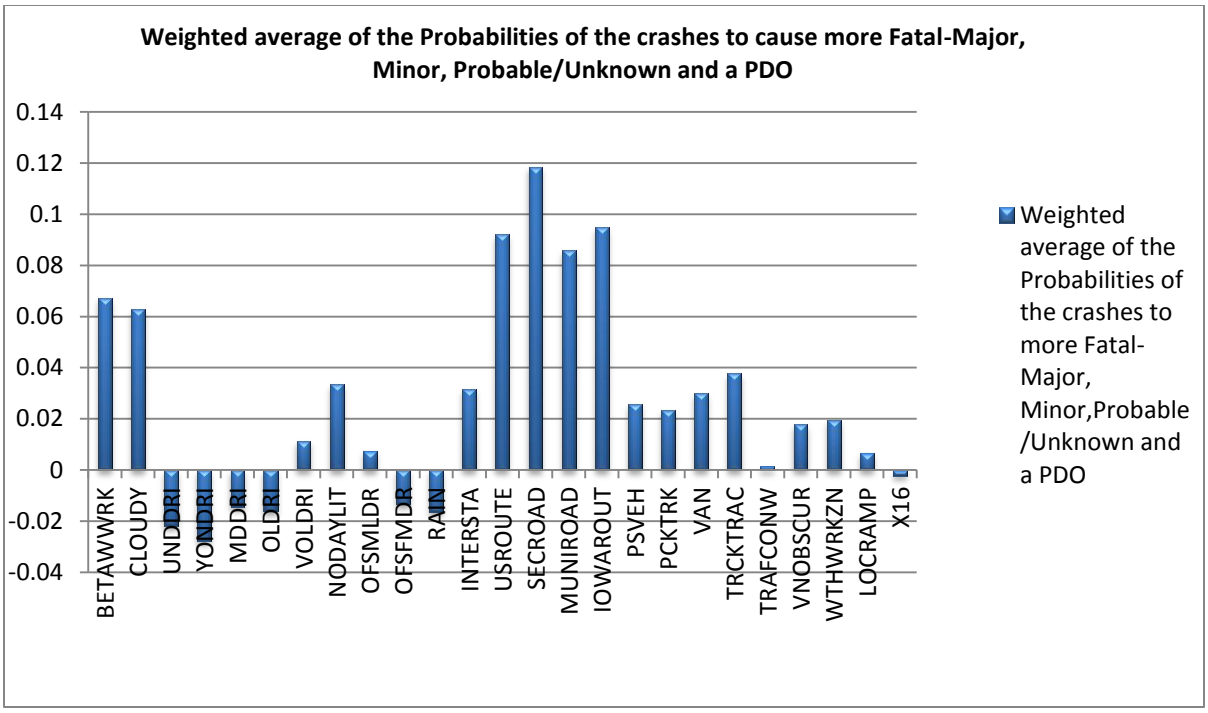

Figure 10. Distribution of the weighted average for the probabilities of the factors for the occurrence of the different types of crashes

The factors showing higher positive probabilities are more likely to cause a Fatal/Major Injury crash; whereas, those showing a negative probability indicate they are more likely to cause a PDO crash.

To rank the factors on a scale of one to five based on the severity (5 being the most severe and 1 being the least severe), the probability distribution is categorized into five distinct levels:

- Less than 0 = 1
- 0 - 0.02 = 2
- 0.02 - 0.04 = 3
- 0.04 - 0.08 = 4
- Greater than 0.08 = 5

Following this scale, the significant factors are ranked from most severe to least severe (generally from top to bottom) as shown in Table 9.

Table 9. Ranking of the factors according to severity

Variable	Severity Ranking
USROUTE	5
SECROAD	5
MUNIROAD	5
IOWAROUT	5
BETAWWRK	4
CLOUDY	4
NODAYLIT	3
INTERSTA	3
PSVEH	3
PCKTRK	3
VAN	3
TRCKTRAC	3
VOLDRI	2
OFSMLDR	2
TRAFCONW	2
VNOBSCUR	2
WTHWRKZN	2
LOCRAMP	2
UNDDRI	1
YONDRI	1
MDDRI	1
OLDRI	1
OFSFMDR	1
RAIN	1
X16	1

Frequency Analysis and Factor Rating According to Frequency

Risk is defined as the combined effect of the severity (i.e., the impact) and frequency (i.e., the likelihood of occurrence). Therefore, the impact the factors have on severity cannot by itself predict the magnitude of risk that those factors possess for O/M activities on the highways.

Frequency of the factors plays a major role in determining the risk value of the factors and develops the Integrated Risk Management Model. The number of times that the factors are involved in each type of crash is illustrated in Table 10.

Along with the frequencies of occurrence of the factors shown in Table 10, the frequency distribution is shown in Figure 11.

Table 10. Frequency distribution of the factors

Significant Variables Affecting Severity	Fatal/ Major Injury Crashes	Minor Injury Crashes	Possible Injury Crashes	PDO Crashes	Total	Frequency Distribution (%)
BETAWWRK	97	2,345	3,038	3,675	9,155	16.63
CLOUDY	83	2,835	1,131	2,165	6,214	11.29
UNDDRI	26	928	458	1,859	3,271	5.94
YONDRI	51	1,969	1,615	8,715	12,350	22.44
MDDRI	491	2,428	4,516	11,825	19,260	34.99
OLDRI	485	2,794	4,687	10,220	18,186	33.04
VOLDRI	146	582	1,277	1,525	3,530	6.41
NODAYLIT	117	2,916	562	2,897	6,492	11.79
OFSMLDR	336	913	1,529	5,956	8,734	15.87
OFSFMDR	263	178	850	4,224	5,515	10.02
RAIN	99	1,379	359	7,154	8,991	16.33
INTERSTA	600	3,242	6,798	24,065	34,705	63.05
USROUTE	455	1,624	1,474	3,633	7,186	13.06
SECROAD	184	268	1,513	1,035	3,000	5.45
MUNIROAD	19	1,828	1,144	3,268	6,259	11.37
IOWAROUT	64	1,272	486	1,922	3,744	6.80
PSVEH	433	6,097	5,652	17,702	29,884	54.29
PCKTRK	294	756	1,721	4,928	7,699	13.99
VAN	189	587	1,540	3,334	5,650	10.26
TRCKTRAC	323	385	910	2,630	4,248	7.72
TRAFCONW	311	641	1,125	2,941	5,018	9.12
VNOBSCUR	1,038	7,933	10,551	30,919	50,441	91.64
WTHWRKZN	1,056	5,189	6,857	24,995	38,097	69.21
LOCRAMP	17	164	877	1,941	2,999	5.45
X16	865	3,766	6,163	17,412	28,206	51.24
Total					**55,042**	

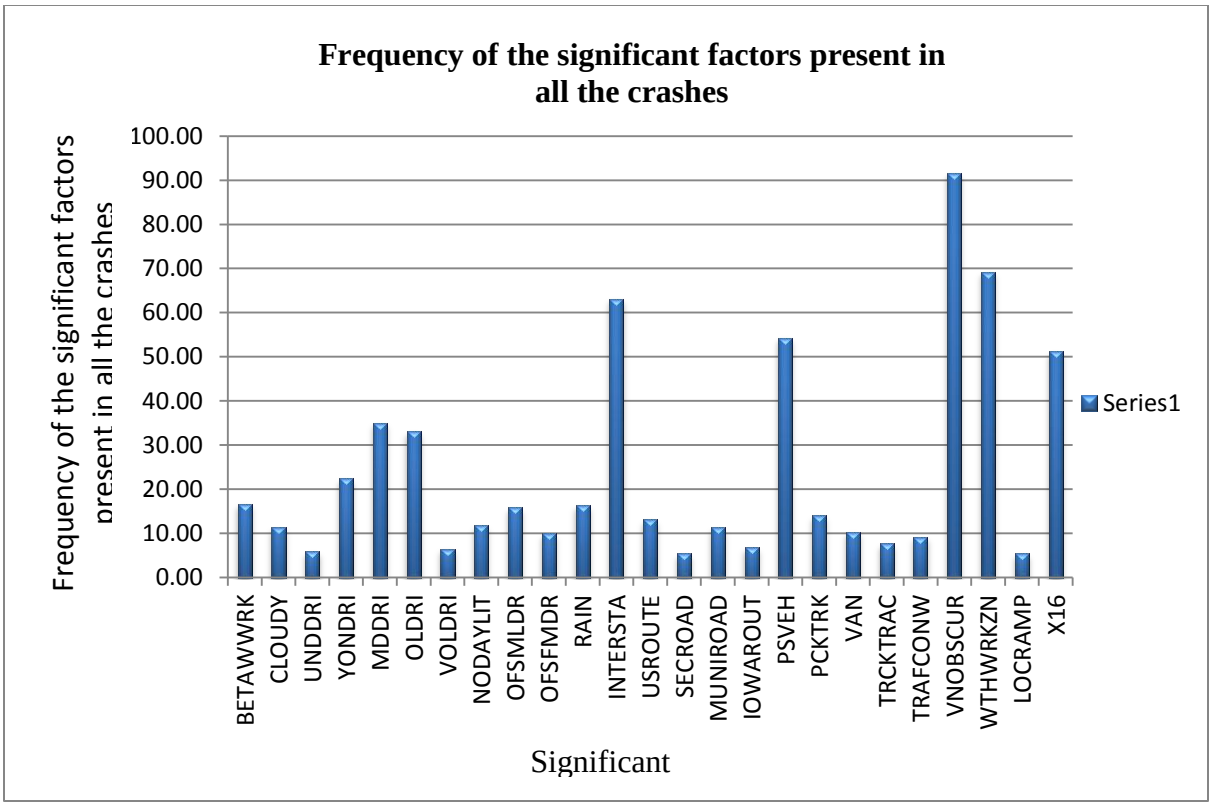

Figure 11. Distribution of the percentage frequency of the factors (crash database) present in all crashes involving intermittent and moving work zones and work on the shoulders and median

To rank these significant factors according to their frequency of occurrence on a scale of one to five (1 being the least frequently occurring factor and 5 being the most frequently occurring factor), the percentage frequency scale is categorized into five levels as follows:

- 0 - 9.99 = 1
- 10.00 - 19.99 = 2
- 20.00 - 39.99 = 3
- 40.00 - 59.99 = 4
- Greater than 60.00 = 5

Following this categorization protocol, the factors can be ranked according to their frequency of occurrence as shown in Table: 11.

Table 11. Ranking of significant factors according to their frequency of occurrence

Variables	Frequency Ranking
INTERSTA	5
VNOBSCUR	5
WTHWRKZN	5
PSVEH	4
X16	4
YONDRI	3
MDDRI	3
OLDRI	3
BETAWWRK	2
CLOUDY	2
NODAYLIT	2
OFSMLDR	2
RAIN	2
USROUTE	2
MUNIROAD	2
PCKTRK	2
UNDDRI	1
VOLDRI	1
OFSFMDR	1
SECROAD	1
IOWAROUT	1
VAN	1
TRCKTRAC	1
TRAFCONW	1
LOCRAMP	1

Risk Rating of the Factors

Risk can be defined mathematically as the product of the severity or impact of the factors and the frequency of occurrence of the factors. This combined estimate of the severity and frequency of occurrence gives an assessment of risk posed by the hazard and helps decision makers prioritize which hazards to address, assists in safety planning, and facilitates the development of risk mitigation strategies. Risk values are assigned to the significant factors as shown in Table 12.

Table 12. Risk values of the significant factors

Variables	Severity Ranking	Frequency Ranking	Risk Assessment
INTERSTA	3	5	15
PSVEH	3	4	12
USROUTE	5	2	10
MUNIROAD	5	2	10
VNOBSCUR	2	5	10
WTHWRKZN	2	5	10
BETAWWRK	4	2	8
CLOUDY	4	2	8
NODAYLIT	3	2	6
PCKTRK	3	2	6
SECROAD	5	1	5
IOWAROUT	5	1	5
OFSMLDR	2	2	4
X16	1	4	4
YONDRI	1	3	3
MDDRI	1	3	3
OLDRI	1	3	3
VAN	3	1	3
TRCKTRAC	3	1	3
VOLDRI	2	1	2
RAIN	1	2	2
TRAFCONW	2	1	2
LOCRAMP	2	1	2
UNDDRI	1	1	1
OFSFMDR	1	1	1

Validation Survey Data Analysis Results

In the validation survey, 33 responses were obtained, of which 24 were complete responses and nine were partial responses but missing answers to the open-ended questions. The responses were compiled in the form of percentages of participants selecting that particular category of a particular question.

Table 13 illustrates the levels of probable severities and Table 14 illustrates the probable frequency of occurrence of the different factors (i.e., hazards), under activity, environment, equipment, and other, which the participants anticipated from their experiences.

Table 13. Severity levels of the factor

		Severity					
ID		**No Loss**	**Potential Property Damage**	**Minor Property Damage and/or Minor Injuries**	**Major Property Damage and/or Major Injuries**	**Catastrophic Loss/Fatality**	**Weighted Average of the Severity**
Activity		**1**	**2**	**3**	**4**	**5**	
1	FWD structural testing on pavement and subgrade	0.06	0.16	0.22	0.22	0	0.1280
2	Ride quality testing on pavement or bridge surface	0.16	0.16	0.16	0.06	0	0.0800
3	Core drilling on pavements	0.03	0.16	0.16	0.26	0.03	0.1347
4	Manual condition surveys for pavement section	0.12	0.09	0.06	0.22	0.06	0.1107
5	Bridges and culvert repair and inspection	0.06	0.12	0.16	0.28	0.06	0.1467
6	Mowing	0.12	0.16	0.34	0.16	0.03	0.1500
7	Movement of street sweeper/street cleaner	0.16	0.22	0.16	0.19	0.03	0.1327
8	Straddling painting (centerline painting)	0.06	0.26	0.26	0.26	0.06	0.1800
9	Offset painting (edge-line painting) on four-lane divided highway	0.09	0.28	0.25	0.19	0.03	0.1540
10	Offset painting (edge-line painting) on two-lane two-way traffic roadway	0.06	0.32	0.23	0.19	0.06	0.1633
11	Pavement markings	0.03	0.25	0.28	0.22	0.06	0.1700
12	Crack filling/patch work	0.09	0.12	0.25	0.31	0.06	0.1747
13	Curb and surface repairs	0.06	0.19	0.32	0.16	0.03	0.1460
14	Flagger operations	0.16	0.06	0.25	0.34	0.16	0.2127
15	Replacing/repairing the signals and signage	0.15	0.22	0.33	0.11	0.07	0.1580
16	Loading/unloading material for maintenance operations on four-lane divided highway	0.15	0.22	0.19	0.26	0.07	0.1700
17	Loading/unloading material for maintenance operations on two-lane two-way road	0.12	0.23	0.19	0.27	0.08	0.1753

		Severity					
ID		**No Loss**	**Potential Property Damage**	**Minor Property Damage and/or Minor Injuries**	**Major Property Damage and/or Major Injuries**	**Catastrophic Loss/Fatality**	**Weighted Average of the Severity**
18	Shoulder grading	0.12	0.31	0.27	0.15	0	0.1433
19	Repair, maintenance, and installation of guardrails, cable rails, and barrier rails on four-lane divided highway	0.04	0.22	0.19	0.33	0.07	0.1813
20	Repair, maintenance, and installation of guardrails, cable rails, and barrier rails on two-way two-lane road	0.04	0.31	0.12	0.27	0.12	0.1800
21	Repair, maintenance, and installation of centerline guardrails, cable rails, and barrier rails on four-lane divided traffic roadway	0.11	0.22	0.19	0.26	0.07	0.1673
22	Maintenance of sanitary and storm sewer and water main	0.07	0.41	0.04	0.19	0.04	0.1313
23	Ditch cleaning	0.23	0.35	0.04	0.15	0	0.1100
24	Cleaning storm sewer intakes and structures	0.24	0.28	0.08	0.08	0.04	0.1040
25	Survey work	0.3	0.19	0	0.19	0.11	0.1327
26	Ingress and egress from construction site	0.15	0.04	0.33	0.37	0	0.1800
27	Electric/power system maintenance and street lighting	0.04	0.35	0.12	0.23	0.04	0.1480
28	Snow removal	0	0.22	0.3	0.22	0	0.1480
Environment							
29	Nighttime operations	0.04	0.08	0.16	0.4	0.24	0.2320
30	Presence of small towns or schools nearby	0.2	0.24	0.24	0.08	0.04	0.1280
31	Improper signs and signage at ramps and roadway intersections near work zones	0.08	0.08	0.28	0.28	0.2	0.2133
32	Pavement markings at intersections at nighttime	0.12	0.08	0.24	0.36	0.08	0.1893

		Severity					
ID		**No Loss**	**Potential Property Damage**	**Minor Property Damage and/or Minor Injuries**	**Major Property Damage and/or Major Injuries**	**Catastrophic Loss/Fatality**	**Weighted Average of the Severity**
33	Pavement markings at intersections at daytime	0.12	0.2	0.4	0.16	0	0.1573
34	Work zones on roads in hilly areas	0.08	0.04	0.36	0.32	0.16	0.2213
35	Peak traffic hours	0.08	0.04	0.2	0.6	0.08	0.2373
36	Lack of knowledge about variable peak traffic time in local regions near work zone (e.g., variable travel patterns near institutions like the Iowa DOT, University, and Animal Disease Lab in Ames, Iowa)	0.08	0.04	0.33	0.33	0.08	0.1913
37	Work near railway crossings	0.12	0.16	0.08	0.36	0.12	0.1813
38	Clearing roadway for emergency vehicles	0.16	0.12	0.32	0.2	0.04	0.1573
39	Unforeseen weather conditions	0.12	0.28	0.16	0.28	0.12	0.1920
40	Fog and mist	0.08	0.08	0.32	0.4	0.12	0.2267
41	Different rules in shared jurisdictions	0.16	0.24	0.08	0.2	0	0.1120
42	Special events such as parades, races, and fairs in local cities and towns	0.16	0.24	0.36	0.08	0	0.1360
Equipment							
43	Falling-weight deflectometer	0.17	0.13	0.13	0.13	0	0.0893
44	Straddling painters	0.05	0.23	0.32	0.18	0.05	0.1627
45	Maintainers on gravel roads	0.04	0.35	0.13	0.09	0	0.0993
46	Cold-mix patchwork	0.09	0.26	0.22	0.22	0.09	0.1733
47	Friction testing	0.22	0.13	0.13	0.09	0	0.0820
48	Media trucks	0.3	0.3	0	0.17	0	0.1053
49	Trucks carrying rock/ aggregate	0.04	0.22	0.3	0.26	0	0.1613
50	Boom trucks	0.13	0.22	0.17	0.26	0.04	0.1547
51	Pick-up trucks	0.22	0.22	0.17	0.22	0	0.1367

		Severity					
ID		**No Loss**	**Potential Property Damage**	**Minor Property Damage and/or Minor Injuries**	**Major Property Damage and/or Major Injuries**	**Catastrophic Loss/Fatality**	**Weighted Average of the Severity**
52	Street sweepers/street cleaners	0.13	0.22	0.26	0.17	0	0.1353
53	Jet vac	0.17	0.22	0.17	0.13	0	0.1093
54	Paint carts (hauled on trailers)	0.13	0.3	0.04	0.22	0	0.1153
55	Absence of proper signage near work zone	0.09	0	0.23	0.36	0.27	0.2380
56	Absence of fluorescent diamond signs	0.13	0.09	0.26	0.3	0.13	0.1960
57	Not using lights/blinkers in work zone	0.09	0.17	0.17	0.26	0.22	0.2053
Other							
58	Lack of coordination with municipalities	0.26	0.13	0.26	0.17	0.04	0.1453
59	Work done under full closure	0.57	0.13	0.13	0.04	0.13	0.1353
60	Lack of coordination between state and local agencies	0.26	0.09	0.26	0.17	0.04	0.1400
61	Lack of work safety and training programs	0.09	0.04	0.26	0.22	0.35	0.2387
62	Absence of train-the-trainers philosophy	0.17	0.04	0.22	0.22	0.22	0.1927
63	Lack of coordination between DOT and utilities regarding control of ROW	0.35	0.09	0.17	0.13	0.04	0.1173
64	Improper third-party interaction	0.18	0.14	0.27	0.14	0	0.1220
65	Not imposing speed limit fines on public	0.09	0.09	0.26	0.3	0.22	0.2233

Table 14. Frequency distribution of the factors

		Frequency					
ID		**Very Unlikely**	**Unlikely**	**Neutral**	**Probable**	**Very Probable**	**Weighted Average of Likelihood of Occurrence**
Activity		**1**	**2**	**3**	**4**	**5**	
1	FWD structural testing on pavement and subgrade	0.12	0.12	0.28	0.12	0	0.1120
2	Ride quality testing on pavement or bridge surface	0.12	0.19	0.16	0.16	0	0.1080
3	Core drilling on pavements	0.09	0.25	0.16	0.22	0	0.1300
4	Manual condition surveys for pavement section	0.1	0.19	0.06	0.23	0	0.1053
5	Bridges and culvert repair and inspection	0.07	0.23	0.13	0.3	0	0.1413
6	Mowing	0.19	0.29	0.19	0.13	0	0.1240
7	Movement of street sweeper/street cleaner	0.12	0.19	0.19	0.25	0	0.1380
8	Straddling painting (centerline painting)	0.03	0.26	0.1	0.45	0.06	0.1967
9	Offset painting (edge-line painting) on four-lane divided highway	0.1	0.19	0.23	0.32	0.03	0.1733
10	Offset painting (edge-line painting) on two-lane two-way traffic roadway	0.06	0.25	0.25	0.25	0.03	0.1640
11	Pavement markings	0.06	0.16	0.31	0.28	0.03	0.1720
12	Crack filling/patch work	0.12	0.09	0.22	0.41	0	0.1733
13	Curb and surface repairs	0.03	0.23	0.3	0.23	0	0.1540
14	Flagger operations	0.12	0.12	0.34	0.31	0.06	0.1947
15	Replacing/repairing the signals and signage	0.11	0.3	0.33	0.11	0.04	0.1560
16	Loading/unloading material for maintenance operations on four-lane divided highway	0.07	0.3	0.22	0.19	0.11	0.1760
17	Loading/unloading material for maintenance operations on two-lane two-way road	0.08	0.23	0.23	0.31	0.08	0.1913

		Frequency					
ID		**Very Unlikely**	**Unlikely**	**Neutral**	**Probable**	**Very Probable**	**Weighted Average of Likelihood of Occurrence**
18	Shoulder grading	0.07	0.37	0.33	0.04	0	0.1307
19	Repair, maintenance, and installation of guardrails, cable rails, and barrier rails on four-lane divided highway	0.07	0.22	0.37	0.19	0	0.1587
20	Repair, maintenance, and installation of guardrails, cable rails, and barrier rails on two-way two-lane road	0.07	0.22	0.3	0.26	0	0.1633
21	Repair, maintenance, and installation of centerline guardrails, cable rails, and barrier rails on four-lane divided traffic roadway	0.11	0.11	0.48	0.15	0	0.1580
22	Maintenance of sanitary and storm sewer and water main	0.11	0.33	0.19	0.11	0	0.1187
23	Ditch cleaning	0.22	0.33	0.11	0.07	0	0.0993
24	Cleaning storm sewer intakes and structures	0.15	0.35	0.19	0.08	0	0.1160
25	Survey work	0.22	0.15	0.26	0.11	0.04	0.1293
26	Ingress and egress from construction site	0.04	0.15	0.19	0.48	0.04	0.2020
27	Electric/power system maintenance and street lighting	0.12	0.19	0.23	0.19	0	0.1300
28	Snow removal	0	0.11	0.15	0.48	0	0.1727
Environment							
29	Nighttime operations	0	0.04	0.17	0.58	0.17	0.2507
30	Presence of small towns or schools nearby	0	0.32	0.28	0.16	0.04	0.1547
31	Improper signs and signage at ramps and roadway intersections near work zones	0.12	0	0.08	0.56	0.16	0.2267
32	Pavement markings at intersections at nighttime	0	0.08	0.16	0.48	0.16	0.2240
33	Pavement markings at intersections at daytime	0.04	0.04	0.52	0.24	0.04	0.1893

		Frequency					
ID		**Very Unlikely**	**Unlikely**	**Neutral**	**Probable**	**Very Probable**	**Weighted Average of Likelihood of Occurrence**
34	Work zones on roads in hilly areas	0	0	0.29	0.54	0.12	0.2420
35	Peak traffic hours	0	0	0.08	0.68	0.24	0.2773
36	Lack of knowledge about variable peak traffic time in local regions near work zone (e.g., variable travel patterns near institutions like the Iowa DOT, University, and Animal Disease Lab in Ames, Iowa)	0.08	0.04	0.21	0.46	0.12	0.2153
37	Work near railway crossings	0.12	0.16	0.28	0.24	0.04	0.1627
38	Clearing roadway for emergency vehicles	0	0.17	0.17	0.33	0.17	0.2013
39	Unforeseen weather conditions	0.04	0.08	0.28	0.4	0.16	0.2293
40	Fog and mist	0.04	0.08	0.16	0.48	0.24	0.2533
41	Different rules in shared jurisdictions	0.12	0.08	0.16	0.24	0.12	0.1547
42	Special events such as parades, races, and fairs in local cities and towns	0.08	0	0.48	0.2	0.12	0.1947
Equipment							
43	Falling-weight deflectometer	0.04	0.13	0.17	0.17	0	0.0993
44	Straddling painters	0.04	0.13	0.26	0.39	0	0.1760
45	Maintainers on gravel roads	0	0.26	0.3	0.04	0	0.1053
46	Cold-mix patchwork	0.09	0.22	0.39	0.17	0	0.1587
47	Friction testing	0.17	0.09	0.26	0.04	0	0.0860
48	Media trucks	0.3	0.09	0.22	0.17	0	0.1213
49	Trucks carrying rock/ aggregate	0.13	0.13	0.26	0.26	0.04	0.1607
50	Boom trucks	0.13	0.17	0.35	0.17	0	0.1467
51	Pick-up trucks	0.17	0.39	0.17	0.13	0	0.1320
52	Street sweepers/street cleaners	0.13	0.22	0.17	0.26	0	0.1413
53	Jet vac	0.14	0.14	0.36	0.09	0	0.1240
54	Paint carts (hauled on trailers)	0.13	0.13	0.3	0.17	0.04	0.1447

		Frequency					
ID		**Very Unlikely**	**Unlikely**	**Neutral**	**Probable**	**Very Probable**	**Weighted Average of Likelihood of Occurrence**
55	Absence of proper signage near work zone	0.04	0	0.04	0.61	0.26	0.2600
56	Absence of fluorescent diamond signs	0.09	0.05	0.27	0.36	0.14	0.2093
57	Not using lights/blinkers in work zone	0.04	0.04	0.26	0.43	0.17	0.2313
Other							
58	Lack of coordination with municipalities	0.04	0.13	0.39	0.3	0.04	0.1913
59	Work done under full closure	0.39	0.48	0	0.04	0.09	0.1307
60	Lack of coordination between state and local agencies	0.04	0.17	0.35	0.22	0.09	0.1840
61	Lack of work safety and training programs	0.09	0	0.26	0.17	0.43	0.2467
62	Absence of train-the-trainers philosophy	0.05	0.14	0.14	0.32	0.23	0.2120
63	Lack of coordination between DOT and utilities regarding control of ROW	0.13	0.13	0.35	0.22	0.04	0.1680
64	Improper third-party interaction	0	0.14	0.23	0.41	0.05	0.1907
65	Not imposing speed limit fines on public	0	0.05	0.23	0.45	0.23	0.2493

Analysis of Severity and Ranking of the Factors

The severity is analyzed by calculating a weighted average of the five levels of severity. The weight is assigned to the factors based on their importance and level of severity as follows:

- No Loss = 1
- Potential Property Damage = 2
- Minor Property Damage and/or Minor Injuries = 3
- Major Property Damage and/or Major Injuries = 4
- Catastrophic Loss/Fatality = 5

The weighting is used to create a severity index score that can be used to rank the factors according to the associated severity of the crashes.

The weighted average of the severity is calculated in the following way:

Weighted average of severity (FWD Structural Testing on Pavement and Subgrade)
= (0.06 × 1 + 0.16 × 2 + 0.22 × 3 + 0.22 × 4 + 0.0 × 5) ÷ 15 = 0.1280

Figure 12 shows the distribution of the factors graphically according to the weighted average of the severity levels. According to this distribution, the factors are ranked on a Likert scale from 1 to 5 (with 1 being the least severe and 5 being the most severe):

- Less than 0.1 = 1
- 0.10 - 0.15 = 2
- 0.15 - 0.20 = 3
- 0.20 - 0.25 = 4
- 0.25 - 0.30 = 5

Based on the distribution of the factors according to the severity levels as shown in Figure 12 and the categories as defined above, the factors were ranked according to severity, which is shown in Table 15.

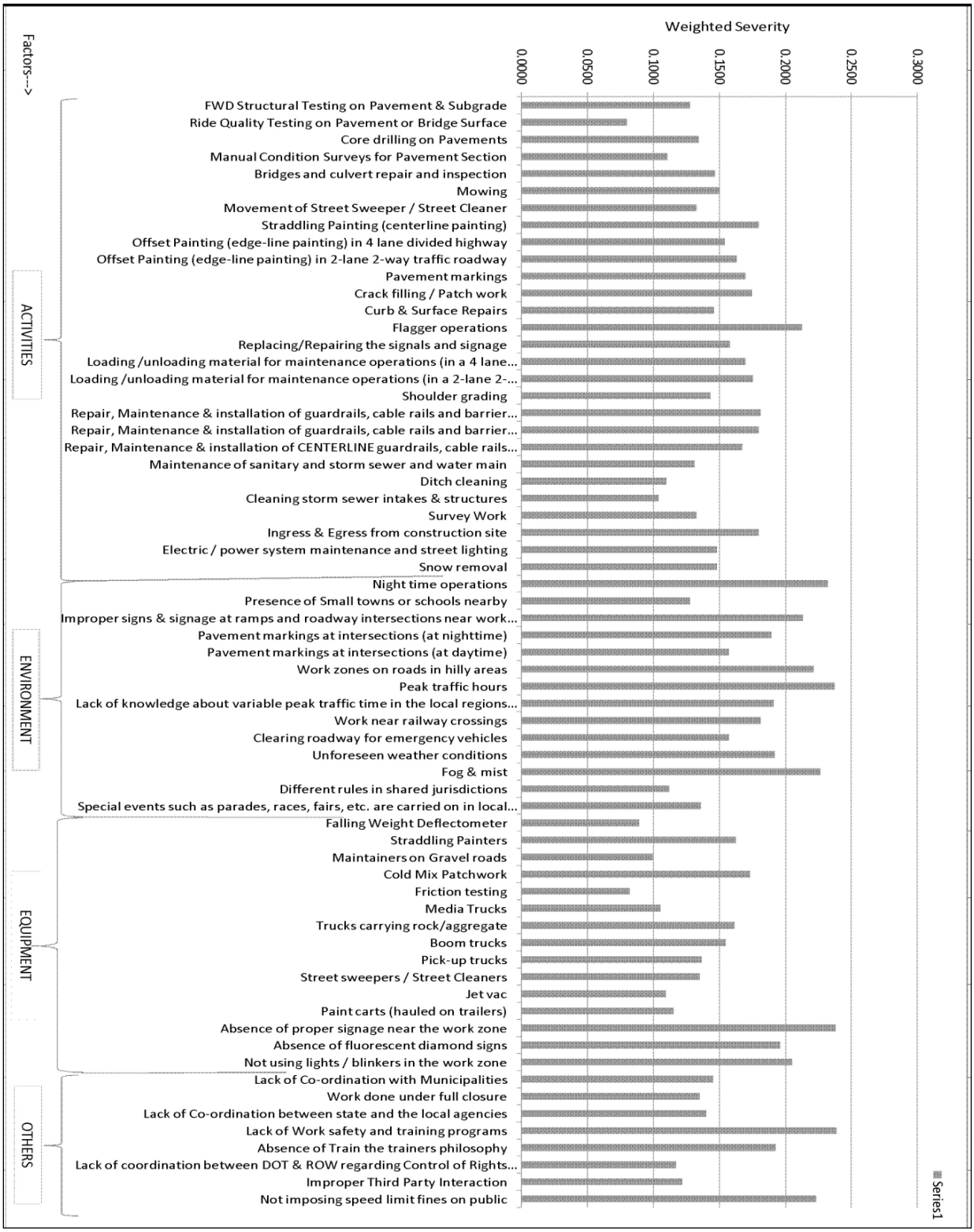

Figure 12. Distribution of the severity levels of the factors (crash database) present in all crashes involving intermittent and moving work zones and work on the shoulders and median

Table 15. Ranking of the factors according to severity

Activity	Severity
Flagger operations	4
Mowing	3
Straddling painting (centerline painting)	3
Offset painting (edge-line painting) on four-lane divided highway	3
Offset painting (edge-line painting) on two-lane two-way traffic roadway	3
Pavement markings	3
Crack filling/patch work	3
Replacing/repairing the signals and signage	3
Loading/unloading material for maintenance operations on four-lane divided highway	3
Loading /unloading material for maintenance operations on two-lane two-way road	3
Repair, maintenance, and installation of guardrails, cable rails, and barrier rails on two-lane two-way road	3
Repair, maintenance, and installation of guardrails, cable rails, and barrier rails on four-lane divided highway	3
Repair, maintenance, and installation of centerline guardrails, cable rails, and barrier rails on four-lane divided traffic roadway	3
Ingress and egress from construction site	3
FWD structural testing on pavement and subgrade	2
Movement of street sweeper/street cleaner	2
Core drilling on pavements	2
Manual condition surveys for pavement section	2
Bridges and culvert repair and inspection	2
Curb and surface repairs	2
Shoulder grading	2
Maintenance of sanitary and storm sewer and water main	2
Ditch cleaning	2
Cleaning storm sewer intakes and structures	2
Survey work	2
Electric/power system maintenance and street lighting	2
Snow removal	2
Ride quality testing on pavement or bridge surface	1
Environment	**Severity**
Nighttime operations	4
Improper signs and signage at ramps and roadway intersections near work zones	4
Work zones on roads in hilly areas	4
Peak traffic hours	4
Fog and mist	4
Pavement markings at intersections at nighttime	3
Pavement markings at intersections at daytime	3

Lack of knowledge about variable peak traffic time in local regions near work zone (e.g., variable travel patterns near institutions like the Iowa DOT, University, and Animal Disease Lab in Ames, Iowa)	3
Work near railway crossings	3
Clearing roadway for emergency vehicles	3
Unforeseen weather conditions	3
Presence of small towns or schools nearby	2
Different rules in shared jurisdictions	2
Special events such as parades, races, and fairs in local cities and towns	2
Equipment	**Severity**
Absence of proper signage near the work zone	4
Not using lights/blinkers in the work zone	4
Absence of fluorescent diamond signs	3
Straddling painters	3
Trucks carrying rock/aggregate	3
Cold-mix patchwork	3
Boom trucks	3
Media trucks	2
Pick-up trucks	2
Street sweepers/street cleaners	2
Jet vac	2
Paint carts (hauled on trailers)	2
Falling-weight deflectometer	1
Maintainers on gravel roads	1
Friction testing	1
Other	**Severity**
Lack of work safety and training programs	4
Not imposing speed limit fines on public	4
Absence of train-the-trainers philosophy	3
Lack of coordination with municipalities	2
Work done under full closure	2
Lack of coordination between state and local agencies	2
Lack of coordination between DOT and utilities regarding control of ROW	2
Improper third-party interaction	2

Analysis of Frequency

Weighted average of the frequency of occurrence of the different factors is also calculated to rank the factors on the same scale according to their likelihood of occurrence. The weighted average of the frequency/likelihood of occurrence is calculated as follows:

Weighted average of frequency (FWD Structural Testing on Pavement and Subgrade)
$$= (0.12 \times 1 + 0.12 \times 2 + 0.28 \times 3 + 0.12 \times 4 + 0.0 \times 5) \div 15 = 0.1120$$

Figure 13 shows the distribution of the factors graphically according to the weighted frequency. According to this distribution, the factors are ranked on a Likert scale from 1 to 5 (with 1 being the least frequent and 5 being the most frequent):

- Less than 0.1 = 1
- 0.10 - 0.15 = 2
- 0.15 - 0.20 = 3
- 0.20 - 0.25 = 4
- 0.25 - 0.30 = 5

Based on the distribution of the factors according to the frequencies shown in Figure 13 and the categories defined above, the factors are ranked according to frequency as shown in Table 16.

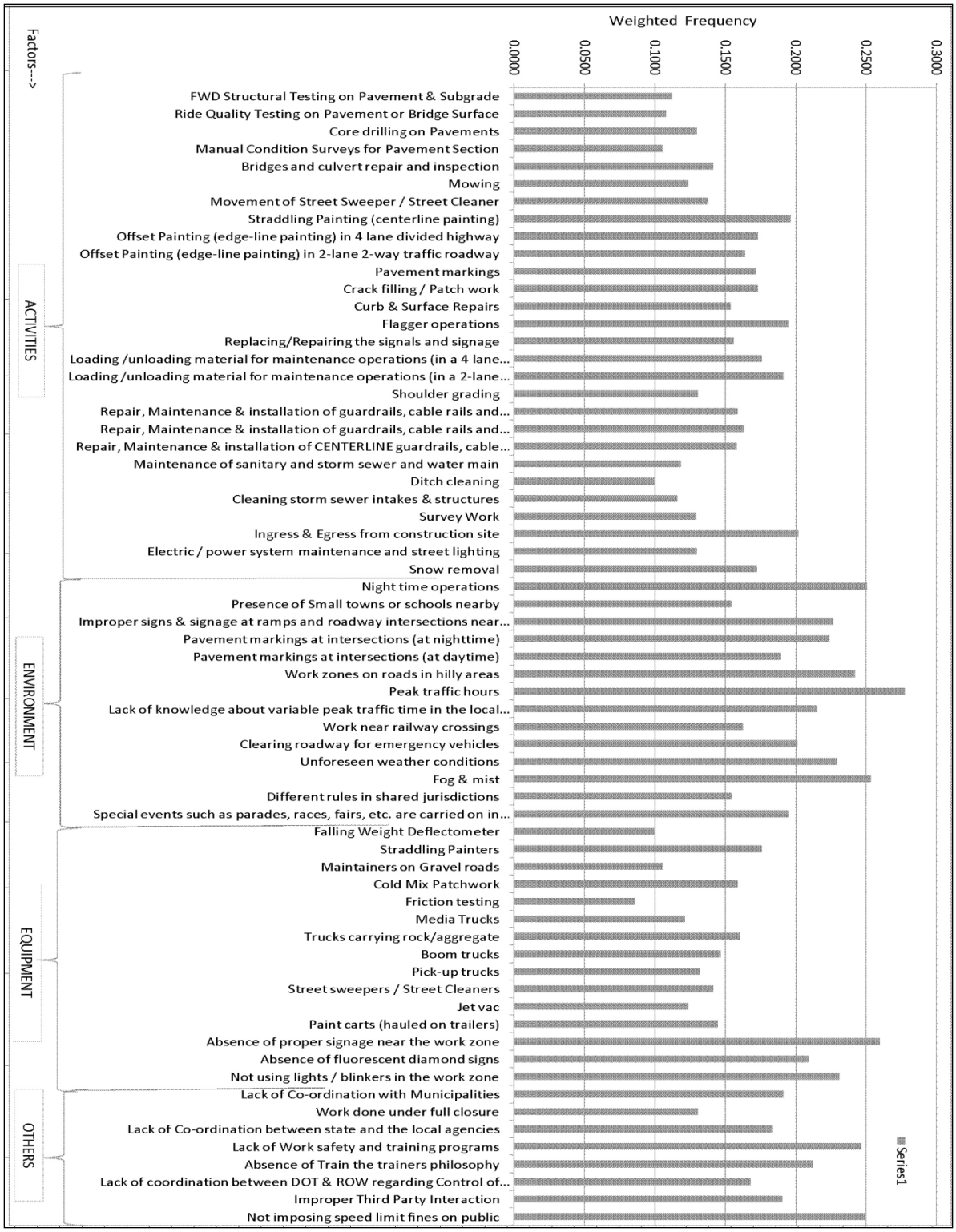

Figure 13. Distribution of the percentage frequency of the factors (crash database) present in all crashes involving intermittent and moving work zones and work on the shoulders and median

Table 16. Ranking of the factors according to frequency

Activity	Frequency
Ingress and egress from construction site	4
Straddling painting (centerline painting)	3
Offset painting (edge-line painting) on four-lane divided highway	3
Offset painting (edge-line painting) on two-lane two-way traffic roadway	3
Pavement markings	3
Crack filling/patch work	3
Curb and surface repairs	3
Flagger operations	3
Replacing/repairing the signals and signage	3
Loading /unloading material for maintenance operations on four-lane divided highway	3
Loading /unloading material for maintenance operations on two-lane two-way road	3
Repair, maintenance, and installation of guardrails, cable rails, and barrier rails on four-lane divided highway	3
Repair, maintenance, and installation of guardrails, cable rails, and barrier rails on two-way two-lane road	3
Repair, maintenance, and installation of centerline guardrails, cable rails, and barrier rails on four-lane divided traffic roadway	3
Snow removal	3
FWD structural testing on pavement and subgrade	2
Ride quality testing on pavement or bridge surface	2
Core drilling on pavements	2
Manual condition surveys for pavement section	2
Bridges and culvert repair and inspection	2
Mowing	2
Movement of street sweeper/street cleaner	2
Shoulder grading	2
Cleaning storm sewer intakes and structures	2
Survey work	2
Electric/power system maintenance and street lighting	2
Maintenance of sanitary and storm sewer and water main	2
Ditch cleaning	1
Environment	**Frequency**
Nighttime operations	5
Peak traffic hours	5
Improper signs and signage at ramps and roadway intersections near work zones	4
Pavement markings at intersections at nighttime	4
Work zones on roads in hilly areas	4
Lack of knowledge about variable peak traffic time in local regions near work zone (e.g., variable travel patterns near institutions like the Iowa DOT, University, and Animal Disease Lab in Ames, Iowa)	4
Clearing roadway for emergency vehicles	4

Unforeseen weather conditions	4
Fog and mist	4
Presence of small towns or schools nearby	3
Pavement markings at intersections at daytime	3
Work near railway crossings	3
Different rules in shared jurisdictions	3
Special events such as parades, races, and fairs in local cities and towns	3
Equipment	**Frequency**
Absence of proper signage near the work zone	5
Absence of fluorescent diamond signs	4
Not using lights/blinkers in the work zone	4
Straddling painters	3
Cold-mix patchwork	3
Trucks carrying rock/aggregate	3
Maintainers on gravel roads	2
Media trucks	2
Boom trucks	2
Pick-up trucks	2
Street sweepers/street cleaners	2
Jet vac	2
Paint carts (hauled on trailers)	2
Falling-weight deflectometer	1
Friction testing	1
Other	**Frequency**
Lack of work safety and training programs	4
Absence of train-the-trainers philosophy	4
Not imposing speed limit fines on public	4
Lack of coordination with municipalities	3
Lack of coordination between state and local agencies	3
Lack of coordination between DOT and utilities regarding control of ROWs	3
Improper third-party interaction	3
Work done under full closure	2

Risk Rating of the Factors

Similar to crash data analysis, the risk assessment value of the hazards/factors identified in the survey is calculated by multiplying the frequency rating and the severity rating of the hazards.

Thereby, the risk assessment value of the factors ranges from 1 (1×1) to 25 (5×5), which is the same as that of the risk assessment value range obtained from the crash data analysis. Thus, the same Integrated Risk Management Model can be used to assess the identified risks obtained from both the crash data and the survey data as shown in Table 17.

Table 17. Ranking of the factors according to risk assessment value

Activities	Frequency 1	Severity 2	Risk Value 1×2
Flagger operations	3	4	12
Ingress and egress from construction site	4	3	12
Straddling painting (centerline painting)	3	3	9
Offset painting (edge-line painting) on four-lane divided highway	3	3	9
Offset painting (edge-line painting) on two-lane two-way traffic roadway	3	3	9
Pavement markings	3	3	9
Crack filling/patch work	3	3	9
Replacing/repairing the signals and signage	3	3	9
Loading /unloading material for maintenance operations on four-lane divided highway	3	3	9
Loading /unloading material for maintenance operations on two-lane two-way road	3	3	9
Repair, maintenance, and installation of guardrails, cable rails, and barrier rails on four-lane divided highway	3	3	9
Repair, maintenance, and installation of guardrails, cable rails, and barrier rails on two-way two-lane road)	3	3	9
Repair, maintenance, and installation of centerline guardrails, cable rails, and barrier rails on four-lane divided traffic roadway)	3	3	9
Mowing	2	3	6
Curb and surface repairs	3	2	6
Snow removal	3	2	6
FWD structural testing on pavement and subgrade	2	2	4
Shoulder grading	2	2	4
Core drilling on pavements	2	2	4
Manual condition surveys for pavement section	2	2	4
Bridges and culvert repair and inspection	2	2	4
Maintenance of sanitary and storm sewer and water main	2	2	4
Movement of street sweeper/street cleaner	2	2	4
Cleaning storm sewer intakes and structures	2	2	4
Survey work	2	2	4
Electric/power system maintenance and street lighting	2	2	4
Ride quality testing on pavement or bridge surface	2	1	2
Ditch cleaning	1	2	2
Environment	**Frequency 1**	**Severity 2**	**Risk Value 1×2**
Night time operations	5	4	20
Peak traffic hours	5	4	20
Improper signs and signage at ramps and roadway intersections near work zones	4	4	16

Work zones on roads in hilly areas	4	4	16
Fog and mist	4	4	16
Pavement markings at intersections (at nighttime)	4	3	12
Lack of knowledge about variable peak traffic time in local regions near work zone (e.g., variable travel patterns near institutions like the Iowa DOT, University, and Animal Disease Lab in Ames, Iowa)	4	3	12
Clearing roadway for emergency vehicles	4	3	12
Unforeseen weather conditions	4	3	12
Pavement markings at intersections at daytime	3	3	9
Work near railway crossings	3	3	9
Presence of small towns or schools nearby	3	2	6
Different rules in shared jurisdictions	3	2	6
Special events such as parades, races, and fairs in local cities and towns	3	2	6
Equipment	**Frequency 1**	**Severity 2**	**Risk Value 1×2**
Absence of proper signage near the work zone	5	4	20
Not using lights/blinkers in the work zone	4	4	16
Absence of fluorescent diamond signs	4	3	12
Straddling painters	3	3	9
Cold-mix patchwork	3	3	9
Trucks carrying rock/aggregate	3	3	9
Boom trucks	2	3	6
Media trucks	2	2	4
Pick-up trucks	2	2	4
Street sweepers/street cleaners	2	2	4
Jet vac	2	2	4
Paint carts (hauled on trailers)	2	2	4
Maintainers on gravel roads	2	1	2
Friction testing	1	1	1
Falling-weight deflectometer	1	1	1
Other	**Frequency 1**	**Severity 2**	**Risk Value 1×2**
Not imposing speed limit fines on public	4	4	16
Lack of work safety and training programs	4	4	16
Absence of train-the-trainers philosophy	4	3	12
Lack of coordination with municipalities	3	2	6
Lack of coordination between state and local agencies	3	2	6
Lack of coordination between DOT and utilities regarding control of ROWs	3	2	6
Improper third-party interaction	3	2	6
Work done under full closure	2	2	4

The results are analyzed and explained in the final section of this report (Discussion and Implications of the Results.)

Development of the Integrated Risk Management Model

A risk matrix was developed as part of the risk assessment process as a metric representing the association of significant factors to severity and frequency of crashes. In the development of the Integrated Risk Management Model, the significant factors were termed hazards to be consistent with prior research on risk.

A hazard is a condition (e.g., blowing snow or excessive speed) that contributes to a loss event, either as the proximate cause of the loss or as a contributing factor. A risk of loss can be represented as the total of each of the hazards (factor) that contribute to it. The risk associated with any particular hazard, H, can be defined as its probability or likelihood of occurrence (i.e., the frequency), p, multiplied by its severity, c.

Stated simply, the risk associated with any single hazard is the product of how likely it is to happen and how bad it would be if it did happen, as represented in the following equation.

$$Hazard = P_H \times C_H$$

The total risk, R, of a loss event, e, is the sum of the *n* potential hazards that would result in that event:

$$R_e = \sum_{i=0}^{n} H_i$$

The severity of the factors is obtained from the weighted average of the marginal effects of the statistical model, and, the frequency or likelihood of occurrence of the factors is obtained from the descriptive statistics.

The best tool to assess the risk of the hazards in such a scenario is to develop a risk assessment matrix. A risk assessment matrix is a two-dimensional representation of the frequency or likelihood of occurrence of the hazards on one scale (frequency scale) and the severity or consequence of those hazards on the other scale (severity scale).

The frequency scale is on the vertical axis and the severity scale is on the horizontal axis. Both the scales are marked from 1 to 5. Thus, the risk assessment matrix (Figure 14) measures the risk of the hazards on a scale of 1 (1×1) to 25 (5×5).

Frequency						
5	5	10	15	20	25	
4	4	8	12	16	20	
3	3	6	9	12	15	
2	2	4	6	8	10	
1	1	2	3	4	5	
	1	2	3	4	5	
	Severity					

1 to 3	Negligible Risk Potential
4 to 5	Marginal Risk Potential
6 to 9	Moderate Risk Potential
10 to 12	Critical Risk Potential
15 to 25	Catastrophic Risk Potential

Figure 14. Risk assessment matrix

As shown, this scale is categorized into five levels, depending on the magnitude or overall effect of the risk:

- Negligible Risk Potential – Risk value ranging from 1 to 3
- Marginal Risk Potential – Risk value ranging from 4 to 5
- Moderate Risk Potential – Risk value ranging from 6 to 9
- Critical Risk Potential – Risk value ranging from 10 to 12
- Catastrophic Risk Potential – Risk value ranging from 15 to 25

The color-coded risk assessment matrix is a very useful technique to determine the potential risk of the hazards already identified from the crash database analysis. This matrix should be used in conjunction with Tables 12 and 17, which contain the identified significant factors generated from the Iowa DOT statewide crash data analysis along with the combined hazard value and also the factors identified from the survey data analysis, respectively.

Any hazard present in a risk event can be assessed in the following way: Say, for example, the factor BETAWWRK, from the crash database, has a hazard value of 8, which means the location between the advance warning sign and work area bears a moderate risk potential and a crash occurring within this region would likely be a moderately severe crash. On the other hand, the factor WTHWRKZN has a hazard value of 10, which means the location within or adjacent to the work activity bears critical risk potential and the crashes occurring within this zone is more likely to be severe than the other location. Hence, the second location needs to be closely monitored and proper traffic control measures need to be taken to avoid crashes within this location.

The risk assessment matrix helps in prioritizing the different hazards and thereby helps in planning risk mitigation strategies.

Given that a “typical” crash is assumed to have both the frequency and severity ranked as 3, the combined value of 9 (3×3) marked the boundary for moderate risk potential. Anything greater than this value was considered as having critical or catastrophic risk potential.

DISCUSSION OF KEY FINDINGS

Crash Data Analysis

Six factors were assessed with a hazard value greater than 9 as follows:

- Interstate route
- US route
- Municipal route
- Passenger vehicle
- Vision not obscured by moving vehicles or frosted windows/windshield, blowing snow, or fog/smoke/dust
- Region located within or adjacent to the work activity

The researchers found that the routes of travel are extremely critical from the overall risk point of view. According to the methodology of this research, these hazards should be determined to have the top-most priority while planning for mitigation strategies. Some reasons for significance of the routes of travel are likely higher speeds on interstates and US highways and inadequate/improper traffic control systems not coordinated with the actual location of the mobile operations.

The analysis shows interesting results in terms of location of the crash. It describes the region located within or adjacent to the work activity bears critical or catastrophic risk potential and severe crashes are more likely to occur within this zone. This indicates that proper traffic control measures may not be in use near or within the mobile work zones, or that traffic control may be keeping pace with the moving operations. Proper safety rules need to be followed in those regions.

In addition to the above mentioned factors, those hazards having a value of 5 on either the severity scale or the frequency scale need attention.

Four factors were assessed with a value of 5 in the severity scale as follows:

- US route
- Secondary route
- Municipal route
- Iowa route

On these routes, the crashes that are occurring are mostly severe crashes.

Three factors are assessed with a value of 5 in the frequency scale as follows:

- Vision not obscured by moving vehicles or frosted windows/windshield, blowing snow, or fog/smoke/dust
- Interstate route
- Region located within or adjacent to the work activity

Most of the crashes related to the maintenance and mobile operations work zone occur when vision is not obscured by moving vehicles or frosted windows/windshield, blowing snow, or fog/smoke/dust. This is because, if the vision is not obscured by any obstruction, most likely the vehicles will drive at a higher speed. If coming upon a mobile work zone like lane painting or guardrail repairs, it may then happen that the vehicles are unable to control their speed and end up traveling into the work zone causing a crash.

The Interstate route is also another important factor in terms of frequency of crashes taking place. About 63 percent of the crashes take place on the interstates. Because crashes on virtually all types of routes were determined to be severe by the model, the researchers suspected the model may be over-specified in terms of route types.

Therefore, the model was re-run (model 2) eliminating state and local routes from the analysis. The most interesting change is in the severity result related to the Interstate route, which went down from a severity ranking of 3 in the first model to a severity ranking of 1 in model 2. The frequency ranking (of 5) remained the same.

When state and municipal routes were deleted from the final model, the Interstate route had a negative marginal effect instead of a high positive value, as was the case in the initial model. This change suggests that a crash on an interstate is actually more likely to be a PDO crash and contrasts with the results from the initial model, which suggested that crashes on all routes were likely to be severe. Thus, the initial observation that higher speed limits on interstates were causing more severe work-zone crashes appears to be in doubt.

An alternative explanation is that, given the study focused on work-zone crashes only, where speeds are reduced, and variation in travel speeds are likely to be minimized, interstates are actually safer due to their superior design parameters compared to other routes and are also better maintained, generally speaking. Interstate mobile work zones almost always maintain a minimum of two divided lanes in each direction, whereas, other routes are frequently head-to-head traffic. In other words, the interstates provide more space (in terms of number of lanes) for the vehicles to pass by the mobile work zone than that of other routes.

Similarly, the region located within or adjacent to the mobile work activity is critical in terms of the frequency of the crashes. Most of the crashes are likely to occur within or adjacent to the work activity, indicating that proper traffic control systems and safety rules are important.

Validation Survey Data Analysis

In the validation survey, factors (or hazards) were categorized as follows:

- Activity
- Environment
- Equipment
- Other

The factors within each category are ranked in the descending order of the magnitude of the severity, frequency, and risk assessment value in Tables 14, 16 and 17, respectively. The Integrated Risk Management Model helps in prioritizing the different identified factors (or hazards) when used in conjunction with the risk assessment values of the factors as shown in Table 17.

The hazards with a risk assessment value (i.e., the combined value of severity and frequency) greater than 9 (i.e., hazards bearing critical or catastrophic risk potential) are as follows:

Activity
- Flagger operations
- Ingress and egress from construction site

Environment
- Nighttime operations
- Peak traffic hours
- Improper signs and signage at ramps and roadway intersections near work zones
- Work zones on roads in hilly areas
- Fog and mist
- Pavement markings at intersections at nighttime
- Lack of knowledge about variable peak traffic time in local regions near work zone (e.g., variable travel patterns near institutions like the Iowa DOT, University, and Animal Disease Lab in Ames, Iowa)
- Clearing roadway for emergency vehicles
- Unforeseen weather conditions

Equipment
- Absence of proper signage near the work zone
- Not using lights/blinkers in the work zone
- Absence of fluorescent diamond signs

Other
- Not imposing speed limit fines on public
- Lack of Work safety and training programs
- Absence of train-the-trainers philosophy

The nine hazards that are in the red zone with catastrophic risk potential (among all the factors and under all the categories) are as follows:

- Nighttime operations
- Peak traffic hours
- Absence of proper signage near the work zone
- Improper signs and signage at ramps and roadway intersections near work zones
- Work zones on roads in hilly areas
- Fog and mist
- Not using lights/blinkers in the work zone
- Not imposing speed limit fines on public
- Lack of work-safety and training programs

According to the validation survey results, the hazards mentioned above are most likely to cause very serious (or catastrophic) crashes due to the operations and maintenance activities.

Of the 65 hazards that were identified from the expert panel discussion, only three hazards have been assessed in the survey with a frequency score of 5:

- Nighttime operations
- Peak traffic hours
- Absence of proper signage near the work zone

None of the hazards scored 5 for severity.

The survey respondents appear to perceive that most of the crashes due to O/M activities occur when the operations are carried out during nighttime and during peak traffic hours. Absence of proper signage near the work zone is perceived as another major cause of crashes.

The potential hazards related to crash risks during O/M activities were identified through expert panel discussions and literature reviews, analyzed through statistical modeling of quantitative crash data and determination of perceptual data obtained through a national survey, and assessed by developing an integrated risk model and risk value assignments.

Identification of Risk Mitigation Strategies

The final step in the research study was to develop relevant mitigation strategies for potential adoption in mobile work zones.

The results of the expert-panel brainstorming workshop, follow-up in-depth interviews with three members of the panel, analysis of the crash database, and perceptions from a national survey suggest the following risk mitigation strategies may be helpful in reducing the severity and frequency of crashes in mobile work zones associated with O/M activities.

1. Revise and integrate the Iowa DOT Instructional Memorandums (IM), Traffic and Safety Manual, and Standard Road Plans – TC Series (traffic control diagrams) and related notes to provide clear, comprehensive, and easily-accessible guidance on placement of traffic control measures for mobile work zones.

2. Consider expanding traffic-control options to include proven technologies such as the Balsi Beam, portable rumble strips, blue strobe lights, and other innovations. (Appendix D provides additional information on innovative technologies.) Traffic-control specifications and associated allocation of risk between contractors and state/local agencies would also need to be revised to encourage adoption of new traffic-control measures. This is an area where a follow-up study would prove beneficial.

3. Investigate new delivery technologies (such as Skype, webinars, and remote conferencing) to allow for improved training within the flattened structure of the Iowa DOT. The training should include both formal programs for centralized functions and informal weekly programs for supervisory personnel to discuss issues with field crews. The Local Technical Assistance Program (LTAP) at the Institute for Transportation (InTrans) may be of assistance in developing such a safety-training program. The safety-training program will be particularly helpful for new and temporary employees working in mobile operations.

4. Written manuals and training programs should focus on the importance of worker and equipment visibility and advance warning systems, especially in high-speed environments (interstates and US highways) and those where drivers may be distracted more easily by pedestrians, traffic signals, bicyclists, etc., such as municipal streets.

5. Schedule Best Practices meetings regularly within divisions. Encourage shop management to meet with division managers and other shop managers to discuss best practices that are discovered in the field, especially when it comes to safety. Division managers should also hold meetings periodically to encourage this type of information sharing. The alternative delivery technologies mentioned above may also be helpful in disseminating best practices.

6. Certain environments should be reviewed to ensure that the minimum number of workers and vehicles are used in the traffic-control system. Specifically, two lane two-way highways, work at railroads and other utility sites, overhead work, and work on bridges are likely high-

risk environments where additional vehicles and workers increase the risk of crashes. The value of impact attenuators should be researched to determine the safety benefits of such equipment. The analysis of the crash database did not find any reports of impact attenuators associated with mobile work-zone crashes.

7. Policies and safety training programs should emphasize the need for locating traffic controls at the appropriate distance from the work site to allow for driver reactions, and traffic controls should be moved at the same pace as the mobile operations whenever possible.

Research Limitations

The limitations of this research study are as follows.

- All of the factors/hazards that were studied in this research could not be described by the crash database variables queried. Representative variables were selected and analyzed from the crash database, which indirectly explained the effect of the required variables/factors/hazards. The data entered on the responding officer's report does not always match the variable of interest.

- The crash data were drawn from the Iowa crash database, but the survey and literature review was national in scope. This made the research study somewhat biased.

- To get a good sample size, crash data from the last 10 years (2001 through 2010) were analyzed. This may have included information about several crashes that occurred after changes in work-zone signage practices and other infrastructure development.

- The response rate for the validation survey was low. Because of the sample size, no statistical analysis could be performed.

Implementation Readiness

The possible mitigation strategies developed as a result of this research are not field-tested, as that was outside of the scope of this research project. If further research on the implementation ideas is needed, a separate research study can be conducted focusing on the implementation of the risk-mitigation techniques found as a result of this study. Testing may include evaluation of the risk-mitigation strategies in simulators or actual field situations to determine effectiveness.

Implementation Benefits

The research findings are intended to provide a process map or guidebook outline for use by the Iowa DOT, Iowa county engineers, and municipal transportation agencies to assess the risk potential of various O/M activities and develop team-based risk-mitigation strategies.

The primary benefits of this research are the reduced risk of injury, fatality, and property damage for O/M workers and the traveling public. The research results can be implemented by the Iowa DOT staff, county engineers, municipal transportation directors, and any other transportation professionals responsible for O/M activities, including field personnel.

The results can also be used as a standard process for identifying highest-risk O/M activities and developing mitigation strategies to reduce those risks. However, it should be noted that the risk-mitigation processes developed and envisioned in this research are highly inclusive, involving state, local, and regional professionals from both field and office positions.

Intuitively, any process that decreases risk should improve worker safety, lower agency costs, improve service to the traveling public, and lead to more-efficient procedures over the long-term, although these specific performance benefits are not assessed directly as part of this research project.

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APPENDIX A. LIGHTING STUDIES

This appendix includes a summary of three major service vehicle lighting studies with relevance to our study for risk mitigation in mobile and maintenance operations.

Study 1: Effect of Warning Lamps on Pedestrian Visibility and Driver Behavior

University of Michigan, Transportation Research Institute

This study examined how warning lighting has an adverse effect on drivers' ability to see workers outside of their vehicles. The three areas of the study cover nighttime glare from warning lamps, effects on driving performance, and nighttime photometry.

The study was done on a closed course track with a mannequin set up near a vehicle that was at a standstill and a panel of warning lights set to various settings, where drivers were asked to identify at exactly what point they were able to see the mannequin. The horizontal passing distance between the mobile car and stationary car was also measured in each trial.

The major findings in this study showed that the only major deterrent from the driver's ability to see the mannequin standing near the parked vehicle was the level of reflective clothing that the mannequin was wearing.

Study 2: Recommendations for Service Equipment Warning Lights

Texas Department of Transportation (TxDOT)

This study was part of a larger research project about maintenance activities. According to TxDOT operation manuals, blue lights are to be used by maintenance vehicles that travel less than 5 mph slower than operating traffic in a travel lane or 30 mph less than operating traffic when not in a traveling lane.

Results show people have learned a hierarchy about flashing warning lights. Yellow conveys the least degree of danger, a combination of yellow and blue conveys the second least, a combination of blue and red represents the highest perception of danger to drivers, and red is perceived to represent more danger than any of the other lights individually. People also believe there is less of a need to slow down when yellow warning lights are used compared to other colors.

This study also reviewed which types of vehicles drivers associate with different color of warning lights. Yellow lights are associated with the most basic service vehicles, including maintenance and motorist-assistance vehicles, such as tow trucks. People most associated blue and red lights with police and law enforcement vehicles. Red warning lights were most likely to be associated with ambulances, fire trucks, and emergency-response vehicles.

A set of warning lights was placed on a roadway to monitor the average speed of vehicles as they related to the color of warning lights. The only two lights that were compared in this study were yellow and blue. The color combination of yellow and blue showed the only statistically significant speed difference in this study. The blue or yellow lights alone did not show any significance in speed reduction.

This study also explored the effect of warning light colors on brake light activations. The only lighting set-up that did not show a statistically significant increase in brake applications was yellow only. The researchers believed that this portion of the study was the most important and showed the best indicators of how people actually respond to warning lights. They also stated evidence of an incremental benefit to implement a combination of blue and yellow lights rather than yellow alone.

Study 3: LED Warning Lights for DOT Vehicles

CTC and Associates, Wisconsin Department of Transportation (WisDOT)

Studies on the use of LED lighting have come with mixed results from several different applications. Wiring these LED systems, when compared to standard strobe lights, is cheaper. However, the overall startup has higher associated costs. Differing colors have presented cost issues as well. LEDs present far fewer maintenance problems over the long term so, in many cases, LEDs have been less expensive overall.

LEDs have been found to have a running life under field conditions of around 100,000 hours and only draw about 10 percent of the amperage of normal incandescent lighting systems. LEDs are able to turn on and off much more quickly so their ability to “punch” signals rather than turning on from a slow glow is better. LEDs will likely be an extremely economic alternative to the systems in use currently.

Another advantage of the LED’s ability to turn on faster is the capability for trailing drivers to see a vehicle that is breaking in front of them. According to the study, the extra time saved in signaling presents one extra car length of room for drivers to react at 65 mph.

When retrofitting fleets, it is important to consider how many phases it will take to equip all of the vehicles. It can be a problem if too many vehicles are taken out of commission at one time and take away from the day-to-day duties of the fleet. For example, it would be most economical to fit snowplows during the summer when the equipment is not being used.

APPENDIX B. EXPERT PANEL SUMMARY REPORTS

TAC Kick-Off Meeting

Moving operations is a common term used for construction activities that involve mobile work zones, such as painting and pavement marking, guardrail replacement, repair of the signage, pavement inspection, structural testing, and so forth. These activities fall under the general heading of operations and maintenance (O/M). The basic objective of this research is to develop an integrated risk modeling approach, which could be used to reduce the frequency and intensity of loss events (property damage, personal injury, fatality, etc.) during highway O/M activities.

The first task of the research plan is to identify the current O/M processes used by state, county, and local agencies. To begin this task, a meeting was held at the Institute for Transportation (InTrans) with the expert technical advisory committee (TAC) on December 10, 2010 to identify those current O/M processes.

During the panel discussion/brainstorming workshop, identified O/M activities were classified into four broad categories per the activities, environments, and tools/equipment used and the different relationships involved with O/M functions. The potential risk factors involved in the categories that were identified during this meeting include the following:

- Traffic level/congestion
- Number of roadway lanes
- Posted speed limit
- Inadequate/improper signage
- Inadequate/improper vehicle lighting and marking
- Insufficient worker training
- Proximity of obstructions (equipment) to traveled roadway
- Weather (condition of road surface, visibility, etc.)
- Work under traffic (inadequate separation or lack of detours/lane shifts)

Moving operations involve mainly the following four types of work zones:

- Short-term work zones
- Intermediate work zones
- Overnight work zones
- Work zones within 15 ft of the moving traffic

Current O/M Processes and Practices

A detailed, edited report of current O/M processes and practices follows.

A. Activity

1. **Material testing**: The methods generally used for roadway and pavement testing are as follows.

   Falling-weight deflectometer (FWD) structural testing - A non-destructive test performed to evaluate the strength properties of the pavement and subgrade layers. Information is used in the pavement management system as well as in the pavement design process. The equipment stops in the lane and the loading instrument is lowered to contact the pavement.

   Ride-quality testing – A non-destructive test conducted with either a 25 ft profilograph or a lightweight inertial profiler to measure the ride quality of a pavement or bridge surface. The profilograph is pushed at about 3 mph. A lightweight profiler operates at 10 to 20 mph.

   Core drilling – A destructive process used to drill and cut out a pavement core for laboratory analysis. The drill is truck mounted. The truck stops in the lane and the drill is lowered to contact the pavement.

   Manual condition surveys – A non-destructive process to obtain condition data for a pavement section.

   The FWD and core drilling operations involve stopping in the lane of travel. Depending on the distance between stops or the length of time stopped, these operations will be either a moving operation or a temporary lane closure. Once the test is taken or the core is drilled, the equipment can move to the shoulder to allow traffic to proceed.

   Ride-quality testing involves a machine/equipment mounted on a moving vehicle and thus belongs to the moving operations work zone. The testing is continuous and the equipment must stay in the lane and at test speed for the duration of the test section.

   The condition survey process is done from the shoulder when there is a wide enough shoulder. Staff may have to enter the lane to take measurements, normally at traffic gaps. These testing operations can often block the main roadway and disrupt/slow down the normal flow of the traffic.

   The risks posed by these types of operations include, but are not limited to, distract the drivers' attention, force the vehicles to move toward the roadway edge, loss of control, and infringe on sidewalk or bike path.

2. **Bridges and culvert repair and inspection**: These types of operations are also moving work-zone operations, as most of the inspection activities are of short duration. These activities also pose risks including, but not limited to, blocks the main roadway, slows down the traffic, distracts the drivers' attention toward the work zone, forces vehicles to move adjacent to the testing equipment, forces vehicles to move toward the roadway edge, loss of control, and collision with guardrails of the bridges or the culverts. Therefore, these types of inspection activities also pose risk.

3. **Mowing**: This activity doesn't typically affect the traffic but would be considered a work zone when it occurs within 15 ft of the roadway. However, while mowing a sloped embankment on the side of a pavement or a roadway, the equipment may block the traffic to some extent and the same risks as mentioned above may occur.

4. **Movement of street sweeper**: A street sweeper or street cleaner refers to a variety of mobile equipment that cleans streets, usually in an urban area. This type of activity slows down traffic to less than the normal traffic speed and may distract drivers' attention.

5. **Painting**: Painting constitutes the major portion of moving O/M activities. About 90 percent of the painting activities belong to the moving operation category. Painting has a big impact on traffic. It is extremely dynamic and depends on several factors. Roadway/pavement painting is of two types: straddling (for centerline painting) and offset (for edge-line painting). The straddling type doesn't affect the traffic much compared to offset. However, the riskiest situation is the edge-line painting on two-lane two-way traffic roads, because the traffic is moving in the opposite direction of the operation. The most difficult situation arises when the traffic has to be maintained in both lanes. In some situations, the traffic coming from one direction may need to let the traffic from the other direction pass by temporarily when the painting operation blocks a roadway (especially during edge-line painting).

6. **Pavement markings**: Pavement markings are very important as a guide to drivers and are also included as a moving operation as it involves marking the pavement by blocking the traffic in that zone for a short duration. This also blocks and slows down the traffic and creates similar problems as that of painting. However, in this case, care should be taken about the safety of the unprotected (not inside a vehicle) workers working on the roadways, as sometimes vehicles coming at high speeds may lose control.

7. **Crack filling/patch work**: Crack filling/patch work is a really "hectic" maintenance operation of the roadways and the roadway may be blocked for up to half a day in the case of a high-volume road. This type of work involves flagger operations, which act as a signal for the moving work zone. In addition, high-strength materials are used here so that the road track becomes usable after a short while. However, workers are responsible for guiding the public to stop and move off to the shoulder and also make them stop until the work is done. In other situations, O/M workers may simply wait for a break in traffic and walk out into the traveled path to fill a crack.

8. **Curb and surface repairs**: Curb and surface repairs are usually done by smaller trucks and equipment (e.g., pick-up trucks and even golf-cart-type buggies), which do not have as much protection or visibility when positioned next to moving vehicles. Therefore, curb and surface repairs can become a risky operation in a busy roadway. This type of repair work also blocks the traffic road for a while and thus makes the normal traffic flow slower and may distract drivers.

9. **Flagger operations:** Flagger operations take place generally on a two-way two-lane highway where the roadway is partially blocked for a moving O/M activity. The portion that is blocked is guarded by two flaggers or signals on either side, which stops the flow of traffic on the lane where work is going on, letting the traffic move on the other lane and, then, the flow is reversed (opposite lane traffic is halted and the disrupted lane traffic is allowed to pass). This is a timed activity and attention is given to the fact that traffic is affected by the O/M activity.

10. **Replacing/repairing the signals and signage:** Many sign-replacement and repair tasks occur at the side of the road and most times do not disrupt the traffic flow. If the work is on the shoulder, it is safer than in the traveled lane, but workers who are very close to the track (within 15 ft) are at risk. Special precautions are needed so that workers do not mistakenly enter the traveled roadway/street. In some instances, barricades need to be put up to keep the traffic flow from the work-zone. In case of repairing or removal of the signage over the roadway, boom trucks are generally used, which also block the roadway and disrupt the traffic to a great extent.

11. **Loading/unloading material for maintenance operations**: This is an activity where the trucks may block traffic while unloading/loading material, for maintenance of signals and signage, for instance. If it is a low-volume road, the problem is not as significant compared to a high-volume road. However, the associated risk events are quite dangerous. On a two-lane two-way road, loading/unloading material can block the vision of the vehicle operators. Moreover, the vehicles trying to pass the obstructing truck may move onto the side lane and cross the centerline where vehicles are coming from the opposite direction. Pedestrians, on finding that the sidewalk is blocked, may also try to pass the truck by coming onto the roadway.

12. **Shoulder grading**: Shoulder grading involves the shaping and stabilizing of unpaved roadway shoulder areas. This maintenance activity can be completed year-round, but is usually programmed between April and November in Iowa. A shoulder-grading crew utilizes about 10 workers on the road, in addition to graders, dump trucks, a belt loader, a roller, and usually a street sweeper. Therefore, this activity has a significant impact on the traffic as it involves several types of equipment that block the roadway and slows down traffic.

13. **Repair, maintenance, and installation of guardrails, cable rails, and barrier rails**: Guardrails and cable rails may be very close to the traveling lanes, just at the edge of the shoulder, and these rails frequently need repair or replacement when they are hit by a vehicle. Many times, if their damage is projected outside the roadway, they may be replaced or

repaired without blocking traffic. However, if the shoulder width is not enough or the damage is projected toward the traveling lane, it becomes a mobile work-zone condition. In these cases, a portion of the road needs to be closed temporarily. In addition, drivers tend to move toward the centerline of the road while passing the short length of the temporary work zone, which can pose risks if it is a two-lane two-way roadway.

On the other hand, the repair and maintenance of barrier rails (mainly at the center of the road) and some guardrails and cable rails that are at the center of the road (such as for many bridges) present different work-zone conditions. Here, the risk is more for the safety of the workers rather than the traveling public. If a vehicle loses control and crosses the centerline, bridge deck crews have limited time or routes to escape from that situation, particularly vehicles coming from the opposite direction.

14. **Maintenance of sanitary and storm sewer and water main**: In this case, the equipment is kept on the shoulder, but if the space is not adequate, some parts of the roadway need to be blocked, which, again becomes a moving work zone.

15. **Ditch cleaning**: Similar to sanitary and storm sewer and water main maintenance, ditch cleaning is not a high- risk event in most cases, except for potential driver distraction and that traffic may become a little slower if a part of the roadway is blocked.

16. **Cleaning storm sewer intakes and structures**: This activity is similar to sewer and water main maintenance and ditch cleaning.

17. **Survey work**: Survey work is a moving operation that often needs to block the roadway for a short while. One of the main problems is that survey work uses minimum work-zone signage, which creates several problems, particularly on two-way highways. In many cases, drivers do not understand what the survey crew is doing. Moreover, vehicles moving at high speeds need time to lower their speeds, for which proper signage should be installed at a certain distance from the work zone.

18. **Ingress and egress from construction site**: Ingress and egress from the construction site is a risk event created when trucks load and unload materials needed for repairs and maintenance jobs for signals and signage, among others. The trucks need to slow their speed when they ingress the work-zone site and need to separate themselves from the moving traffic. This often creates a problem on high-volume roads, as the traffic behind the truck also needs to slow down. Again, the same problem arises at the time of the egress from the work-zone site. The trucks need to come back to the normal traffic flow by entering the right lane and gaining the required speed. This activity also blocks moving traffic to some extent and proper signals need to be given so that accidents and head-on collisions can be avoided.

19. **Electric/power system maintenance and street lighting**: In many states, the electric/power system is overhead, above the traveled lane, so repair or maintenance of such overhead lines requires the use of boom trucks, which may block the roadway and disrupt the normal traffic

flow. These activities can also distract driver attention and force drivers to move toward the centerline of the road. Proper attention should also be given to the safety of the crews working in these kinds of work-zones as workers in overhead buckets have little mobility or protection.

20. **Snow removal**: Generally, snow plows are used to move snow from the roads and streets, but they may be unobserved by drivers, which can lead to accidents. In addition, removing snow frequently requires end-loaders to back into traveled lanes, especially in urban areas (streets). Because of the unique characteristics of snow removal, it is excluded from this study.

B. Environment

1. **Nighttime operations**: To avoid the high volume of traffic in rush hours, some operations are done at night. However, night operations on bridges are risky for both materials testing and maintenance operations. Coring, painting, some patching work, debris pick-up, and different barrier rail repairs are done at night rather than in the daylight. In all these cases, the major issue is lighting of the work zone. If the work zone is properly illuminated, problems are minimized. However, most of the mobile work zones require portable lights, as many of the working regions may not have proper street lighting.

2. **Rutted roadways**: Due to weathering effects, the roadway tracks in the traveled lanes can become deteriorated and the middle of the tracks may have potholes. This often affects driver behavior as, to avoid the potholes, drivers try to move toward the edge of the road and may hit signs or guardrails. Sometimes, drivers are forced to move toward the centerline and therefore shift lanes to where vehicles are moving at a different speed (divided four-lane) or vehicles are coming from the opposite direction (two-lane two-way). Unanticipated movements such as these can create risks in mobile work zones.

3. **Small towns or schools nearby**: If the work zone is near a small town or a school, the work in that area needs to be scheduled according to the timing of the local peak traffic flows. For instance, in the case of a school, the work needs to be stopped near the time when school starts or ends. Roadways cannot be blocked at those peak hours as that causes real inconvenience to the public and also increases the risk factor to a higher degree.

4. **Ramps and roadway intersections**: If work is at intersections or ramps, proper signals and signage are often not installed for the drivers coming from the other lanes where no work is being performed. Proper attention should be given to the movement of these vehicles (on the intersecting or merging roads/streets), so those motorists know of the work zone ahead. Without such configurations, entrance to the work zone cannot be controlled. Signage and warnings are needed on both sides of the ramps. Again, all signage should be pertaining to the current work situation and thus needs to be updated according to the progress of the work.

5. **Pavement markings**: This type of work is done generally in the morning hours to avoid disruption of traffic, especially at intersections.

6. **Roads in hilly areas**: In hilly areas, sight distance is problematic. In any hilly work-zone area, flaggers may be employed ahead of stoplights to make sure information about the work zone is communicated to the public at the appropriate time and distance and to make sure convoys stay together.

7. **Peak traffic hours**: Work should be scheduled in moving work zones according to the traffic hours. Generally, in peak traffic hours on high-volume roads, the work is stopped for a while and is again resumed after the peak hours.

8. **Variable travel pattern**: In some areas, different institutions (like the Iowa DOT, University, and Animal Disease Lab in Ames, Iowa). create different and variable peak travel times. Therefore, some decisions on moving operations require local knowledge or input.

9. **Work near railway crossings**: Work near railway crossings should be done very carefully and also needs to be stopped when a train is approaching. Therefore, this work should be coordinated as much as possible with train schedules.

10. **Responding to emergency vehicles**: In these cases, the work is brought to a temporary halt and the emergency vehicle is allowed to pass by.

11. **Unforeseen weather conditions**: The weather conditions in Iowa can be quite variable and difficult to predict, especially in the last three years. Flexibility to move to another site for O/M work is needed if the weather is bad in the region where work was originally planned. For instance, if a large area is experiencing heavy rain or dense fog, the scheduled operation needs to be shifted to a different area.

12. **Fog and mist**: Fog or mist is a temporary weather situation that affects visibility for a short time (usually early mornings) and/or in a small area (river valleys). In this situation, either special signals are used to warn drivers of a mobile work zone nearby or, if the situation worsens, work is brought to a temporary halt.

13. **Different rules in shared jurisdictions**: Different rules can apply when work moves “across the street” in a shared jurisdiction, which mainly includes city streets, DOT routes, and institutional routes (such as within Iowa State University). This sometimes creates confusion among drivers, contractors, utility companies, etc. and may cause inconvenience (permits, notifications, coordination, etc.) to the working crews in the different mobile work zones.

14. **Special events**: Different special local events such as parades, races, and fairs are carried on in local cities and towns, which may block the road for a while. These also stop the work in the O/M work zone for a while to give space for the events to take place.

C. Equipment

1. **Falling-weight deflectometer**: This type of equipment is used to test the strength properties of the pavement and subgrade. This equipment is mounted on a moving vehicle, which stops in the lane to test at different locations. Because it is stop-and-go, it hinders the normal traffic flow to some extent.

2. **Straddling painters**: These are mobile painting machines used to paint the centerline of roads. Usually, they do not block traffic but will slow traffic flow in both directions.

3. **Maintainers on gravel roads**: No signage is used during this operation. Most work is on low-volume roads with local traffic only that is knowledgeable of the operation.

4. **Cold-mix patchwork**: Generally, when cold mix is put in a hole on the roadway, traffic is not affected and no signage is used for this activity.

5. **Friction testing**: This machine can disrupt traffic because of the water that is applied to the roadway surface during the three-second test at 40 mph.

6. **Media trucks**: Although the work is for a short duration, these vehicles and their operators frequently lack safety protocols while working. They may block the road for more than two hours and often do not use any proper signage, which can disrupt the movement of traffic.

7. **Trucks carrying rock/aggregate**: Many times, rocks and other aggregate may fall on the roadway while being hauled, sometimes cracking the windshields of the following vehicles. Proper signage should be used and precaution should be taken.

8. **Boom trucks**: These trucks are mounted with long booms, which are used to maintain and repair signage and signboards across the road lanes and also help to repair the overhead electric lines at times.

9. **Pick-up trucks**: This is a light-weight motor vehicle used to carry light material, tools, and equipment from one place to another or during inspections.

10. **Street sweepers**: A street sweeper or street cleaner refers to a machine that cleans streets, usually in an urban area.

11. **Jet vac**: This equipment is used for cleaning the leaves out of storm or sanitary intakes and structures.

12. **Paint carts (hauled on trailers)**: Paint carts are usually used when painting roads and pavements in urban areas (e.g., turn arrows and crosswalks).

13. **Proper signage**: Proper signage at different types of moving work zones is a necessity in preventing accidents and warning drivers in advance about the work zone. The signage should be changed as the work progresses so that current information can be conveyed to the public.

14. **Fluorescent diamond signs**: These types of signs should be used at the back of the vehicles and equipment to notify the drivers coming from behind that a moving work zone is ahead.

15. **Use of lights/blinkers**: Several types of lights and blinkers are used in the mobile O/M work zone with little standardization.

16. **Fluorescent borders**: In some mobile work zones where work is conducted mainly at night or equipment is stored overnight, fluorescent-colored indicators form borders on signs to signal that a mobile work zone is ahead.

17. **Speed limit fines**: Fines for mobile operations generally do not exist as they do for other construction activities, so drivers may not be as aware or as careful in these types of operations.

D. Relationships

1. **Coordination with municipalities:** Many times due to lack of communication, local events have an impact on O/M activities. This is probably a bigger problem for centralized state activities than for local (e.g., county) activities.

2. **Advantage of closed roads**: For many types of O/M activities, preference of work should be given to roads that are temporarily closed. However, due to lack of coordination and information, static and mobile operations often run into each other.

3. **Coordination between state and local agencies:** Sometimes due to lack of information, state and local agencies may come to work at the same place at the same time, which may create a problem.

4. **Worker safety and training programs:** Younger and temporary O/M workers are not given enough training, which may lead to inefficient work and an unsafe work zone.

5. **Train the trainers:** This philosophy is used to train all the employees of the organization to the extent required only for performing their particular work. Supervisors are given training, which they in return deliver to the employees in their team. If any additional problems occur, it is generally escalated to the supervisor.

6. **Control of right-of-way (ROW):** Frequently, ROW managers are not aware of O/M activities occurring in the ROW. While the DOT tries to coordinate ROW permits, they don't always get a copy of the final permit. In some local and institutional situations,

communication or coordination is lacking when control of the ROW changes. Private utilities and contractors making taps or upgrades in streets or ROWs should get a new ROW permit form, which contains a requirement for traffic-control planning, but this doesn't always happen.

7. **Third-party interaction:** There is subcontracted maintenance and repair work on some major utility repairs, especially directional drilling for electrical conduit. There are also O/M activities on shared jurisdiction roads. Neighborhood groups often do not communicate upcoming activities. O/M also tries to coordinate with law enforcement on issues such as missing signs or placement of stop signs. O/M also needs to coordinate with railroads and utilities on maintenance of rail crossings and utilities under the railroad.

APPENDIX C. EXPERT INTERVIEWS

This appendix includes information from three in-depth follow-up interviews with experts.

Follow-Up Interview with Bob Younie, State Maintenance Engineer

Discussions with Bob Younie mostly included an overview of the chain of command in the Iowa DOT and what can be done internally to help mitigate risk.

In more recent years, the Iowa DOT has decided to flatten their chain of command in an attempt to cut back on overhead expenses. The overhead costs have been diminished, but so have other portions of operations that maybe should not have been.

For example, the total number of man hours spent in training in 2000 was roughly 103,000 hours, compared to 2010, when roughly 44,000 man hours were allocated to training, which includes safety training.

Included in this interview summary are organizational charts for Iowa DOT staff and their positions in the Highway Division and the District 2 Highway Division for reference on how the organization is currently set up (Figures C.1 and C.2).

One of the main points of concern that Bob brought up was the lack of emphasis on coordination of training and safety programs. Bob expressed that he was more concerned with managerial operations that addressed safety and risk mitigation than with dangerous working conditions. In short, the problems in executing safety procedures come from poor training strategies and that, if strategies were adjusted, the outside (worksite) risk factors would become less of a problem.

Because of the flattening of operations, more work has been assigned to division and shop managers, which means less time in the work week for managers to hold training sessions. At one point in time, most garages were managed by a single supervisor. Today, the trend is that an individual manager now is responsible for two to four maintenance garages, cutting their ability to supervise all operations or O/M crews directly and effectively.

Along with not being able to hold as many training sessions, shop managers, as well as division managers, are not available to hold “Job Box Talks” or to have daily safety reminders. Because of the increased span of control (two to four garages instead of one), managers also find it difficult to schedule face-to-face meetings with O/M field crews to discuss things that are unique to a certain job or area they are working on for that day.

These daily reminders are often the best line of defense when it comes to safety for an individual operator, because they are hearing from their direct supervisors and can know that their safety is in their supervisor’s best interest. Shop managers likely have the most experience when it comes to jobsite safety, especially when it comes to a regional or local problem area.

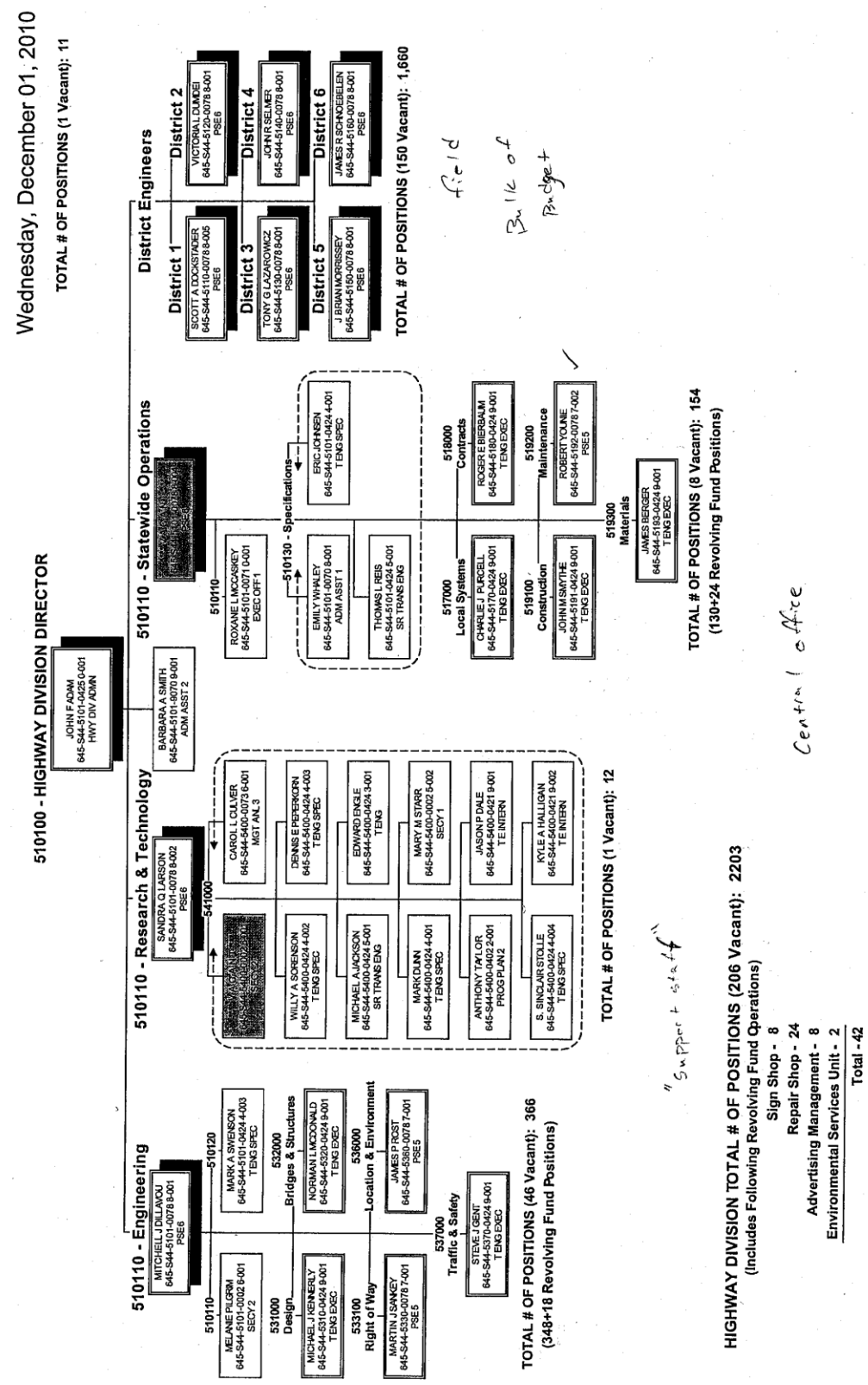


Figure C.1. December 2010 Iowa DOT Highway Division organizational chart

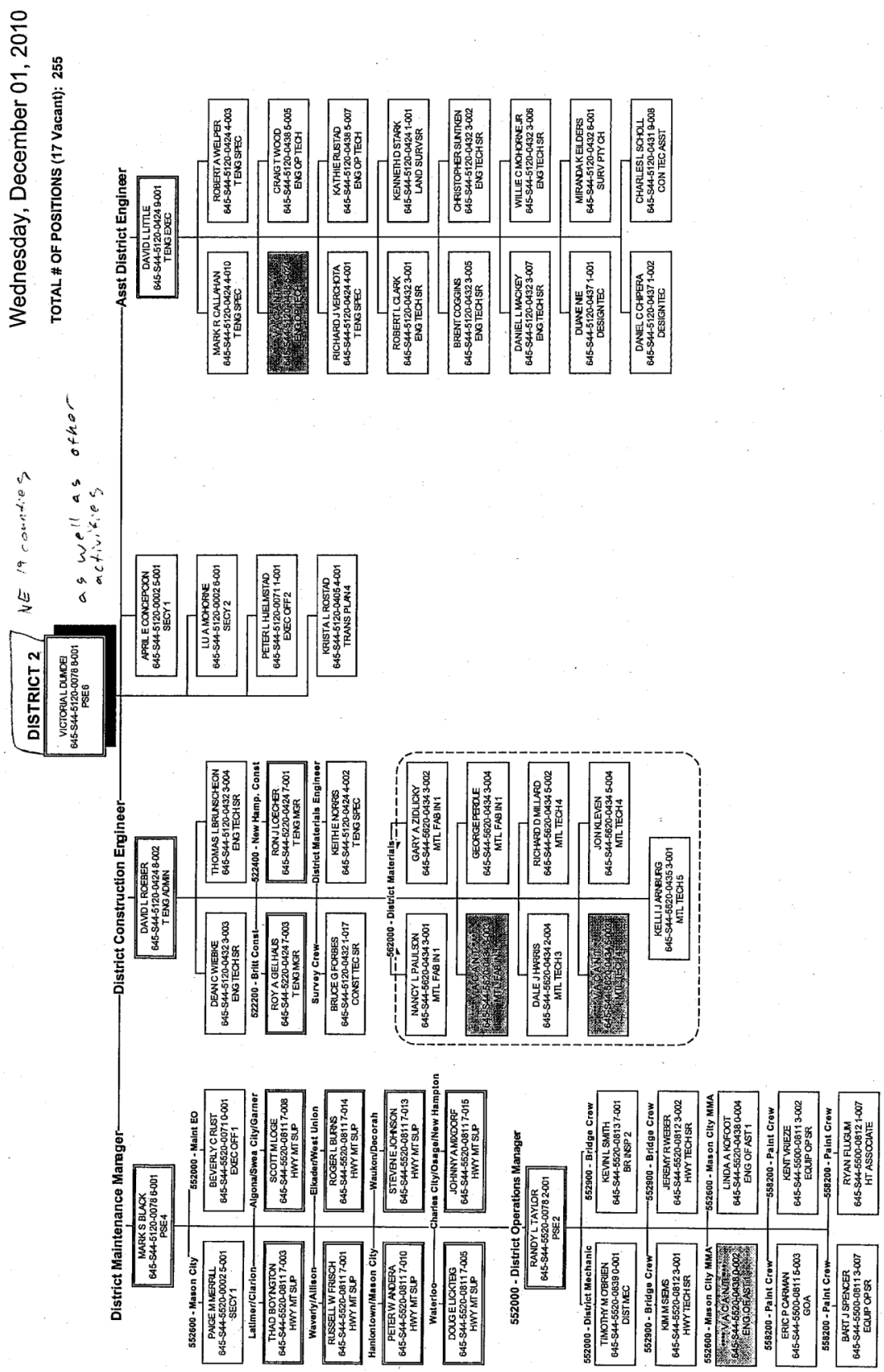


Figure C.2. December 2010 Iowa DOT District 2 Highway Division organizational chart

Another point of emphasis that Bob brought up is that there may not be enough Best Practices meetings held within divisions. If a local garage or division finds that a certain process works better than another does, it does not seem to filter out to other garages as quickly as it should. It was suggested that shop managers be encouraged to meet with division managers and other shop managers to discuss best practices that are discovered in the field, especially when it comes to safety. It was also encouraged that division managers call meetings periodically to encourage this type of information sharing.

In further discussion about safety training, Bob was not convinced that adequate training was being taught on all levels, especially at the supervisory level. He felt the DOT currently is not doing enough to prepare its garage supervisors to manage safety in their local regions and, in turn, their operators are not receiving a well-rounded safety training background. The amount of formal training does not seem to be translating into peer training or the ability for one operator or laborer to identify a safety problem and show another why they are working unsafely.

Interview with Mark Black, Iowa DOT District 2 Engineer

After review of the Maintenance Instructional Memorandum (IM) there were a few suggestions that Mark Black discussed maybe should be changed on a broad level that their garage has already implemented. On top of the IM review, Mark also suggested that the Traffic Control Manual be reviewed, as well as the Flagger's Handbook. (The researcher's later discovered this Traffic Control Manual is a reference that the district put together and updates each April and October to coincide with revisions to the Standard Road Plans, which are available at http://www.iowadot.gov/erl/index.html.)

The Traffic Control (TC) Manual at one point in time was included in the Maintenance IM as an appendix but grew over time to include a wide variety of differing work-zone set-ups. At some point, recently, the traffic control diagrams (labeled Traffic Control Standard Road Plans – TC Series online) were removed and compiled into a separate standalone binder.

Following are the issues that Mark Black would like us to consider in our study.

At the point in time when the TC Manual became a separate publication, the references from the Maintenance IM to the diagrams in the TC Manual never changed. When these diagrams were included as references in the in the Maintenance IM they were annotated as RC diagrams (RC-1, RC-3). The RC designations are no longer used, but are still referenced in some places. Now that traffic control diagrams are in a separate TC Manual, the titles of the diagrams have changed (e.g., TC-1). This makes referencing diagrams from the Maintenance IM difficult.

Another problem with the references to the traffic control diagrams is that the Maintenance IM still refers to an appendix that once included these diagrams, indicating that a section of the Maintenance IM is missing, rather than recognizing that there is now a separate manual for Traffic Control. This causes problems for crew foremen, because they are confused as to which

diagram to use. The result is that neither the TC Manual nor the Maintenance IM is used as efficiently and thoroughly as intended.

The second problem that should be considered is the location of diagram-specific notes in the TC Manual and how they should be referenced. As it stands now, the diagram-specific notes are still located in the Maintenance IM , indicating they did not travel with the diagrams, as they should have when the TC Manual became a separate publication. The required cross-referencing between the Maintenance IM and the TC Manual was never completed.

Mark indicated that the notes included in the diagrams were just as important as the diagrams themselves, because they have control standards that vary from job to job. For example, for a certain working activity, if the work zone is less than a quarter of a mile, certain safety measures are used and, if the work zone is longer than a quarter of a mile, a different set of standards are used.

Without reading the notes that are associated with a traffic control diagram, a crew foreman may miss these operational standards completely. Mark indicated that not reading through these notes for specific traffic control setups could be extremely hazardous and hinder the ability to protect the workers of the operation properly.

An example of a traffic control diagram is included as Figure C.3. This would be the only reference for a crew foreman. The diagram has no indication of the supplemental notes that should be evaluated in this work zone. Also note the title of TC-202 in the bottom right corner, which was not always the standard title.

The traffic control diagrams (Standard Road Plans – TC Series) can be found at http://www.iowadot.gov/design/stdplne_tc.htm.

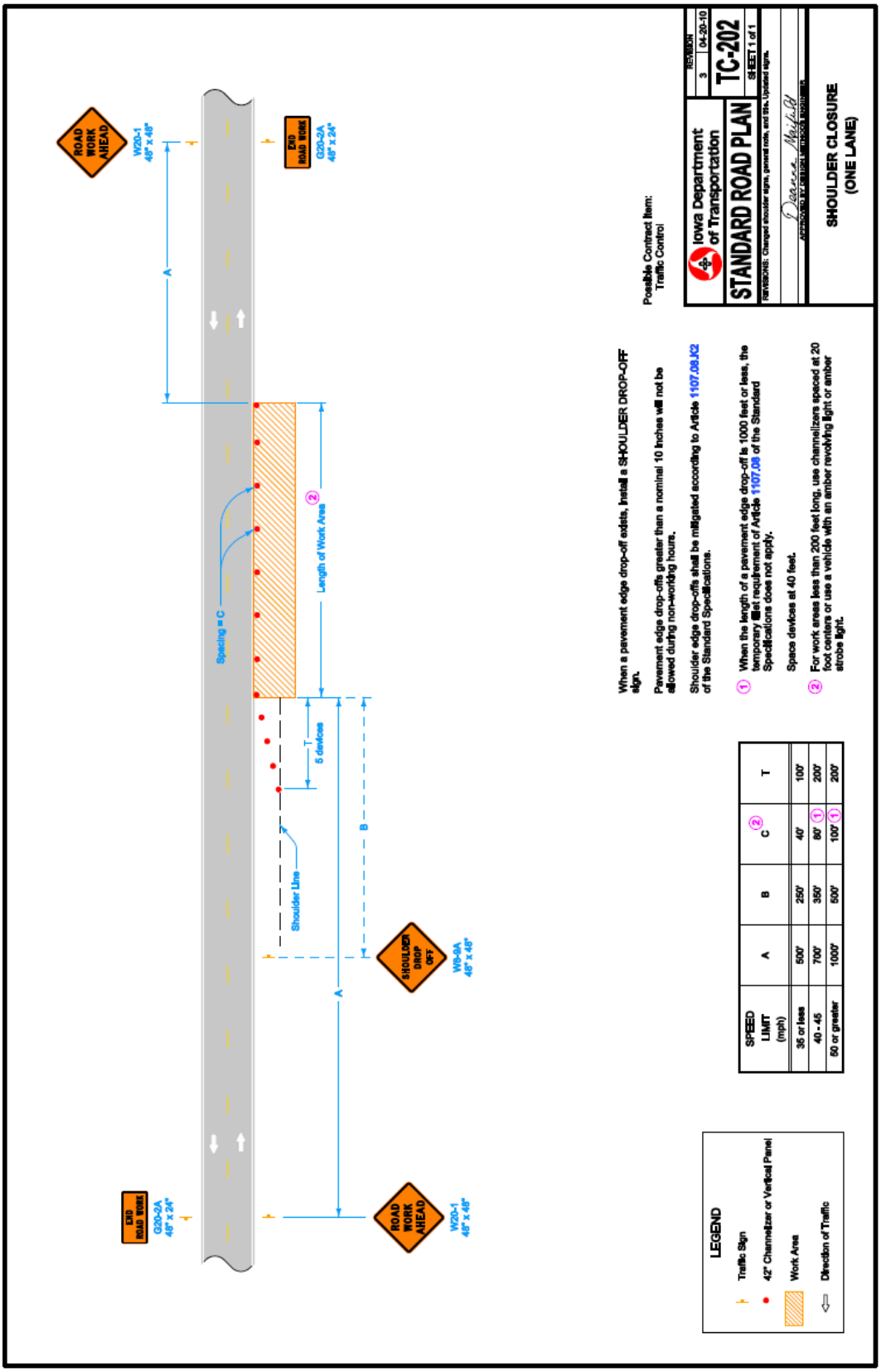


Figure C.3. Sample traffic control diagram for a shoulder closure

The third topic discussed by Mark is the use of truck-mounted attenuators (Figure C.4).

Figure C.4. Truck-mounted traffic attenuator

Mark indicated that these types of vehicles in a mobile operation are the first piece of equipment that actually is in the lane of traffic. He indicated there are inherent problems when using this equipment. The problem with this type of equipment is that it is designed to push traffic over to another lane, but it is not designed to handle the impact of being struck by a moving vehicle.

The single biggest threat, Mark said, was that vehicles such as semi-trucks and trailers did not have the ability to stop and have caused catastrophic damages including loss of life and extreme property damage. The incidents Mark discussed also showed that references to the diagram-specific notes could have been reviewed more thoroughly as conditions such as traffic volume had changed over the course of several years of work.

Interview with Jeff Koudelka, Vice President of Iowa Plains Signing, Inc.

Iowa Plains Signing does many different types of work involving mobile operations including line striping and installing temporary barrier rails and is often accountable in other mobile operations for many other safety measures. About 95 to 97 percent of their work is subcontract work.

The primary concern that Jeff expressed with relation to mobile operations is the ability to attract driver attention and drivers' abilities to identify and respect the mobile work zone. He feels driver distraction causes many more incidents than any failure of their own to adhere to safety standards. To help curb this problem of drivers' not paying attention to changing roadway conditions, strobe-type warning lights have been installed on every vehicle used in their mobile fleets. This is not a DOT safety standard; rather, it is a practice implemented by Iowa Plains Signing that goes above and beyond the typical standard.

Another point of concern was the inability to keep vehicles from changing lanes between vehicles in the operation rather than passing all of the vehicles in the line at once (Figure C.5).

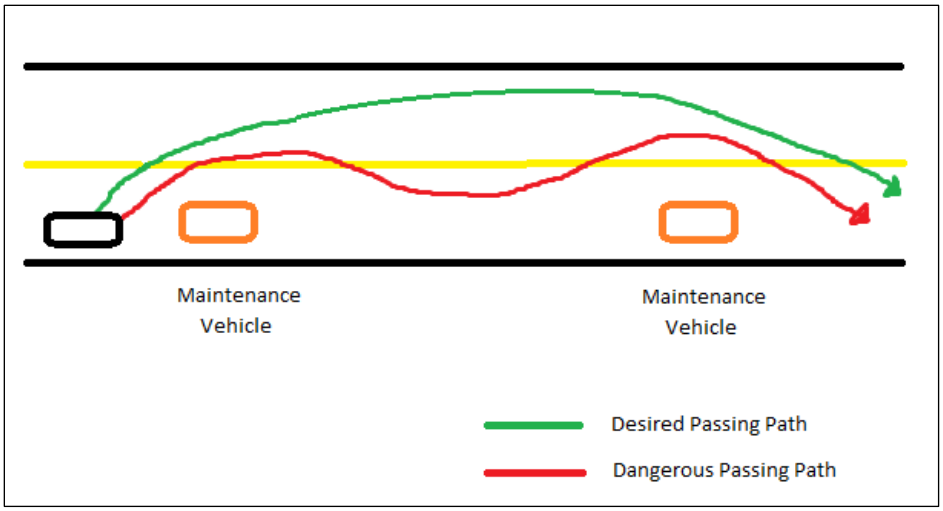


Figure C.5. Desired versus dangerous passing path

The dangerous passing path around and between the O/M vehicles poses two major issues in that the contractor is no longer able to control the entire work zone that the passenger vehicles are traveling through and presents two points where drivers potentially cut off maintenance vehicles too closely when passing rather than one.

Passenger vehicles often do not allow enough space when returning to the traveling lane between themselves and the maintenance vehicle. This poses a major threat to persons who are on equipment that does not enclose the operator. A source of this danger often comes from too many maintenance vehicles in a fleet that is operating on a two lane-two way highway.

In addition, the Iowa DOT Traffic Control standards do not seem to take into account that fewer vehicles are better for two-lane work, whereas more vehicles are better for multilane and interstate highway work.

The third point of emphasis discussed in this conversation was the clarity of diagrams in the traffic control diagram and the inability to go above and beyond the standards shown. In several of the diagrams (such as TC-431) graphics of vehicles to be used in the fleet but near them is an indicator that the piece of equipment is optional. Jeff felt that if it is included in the road standard, the piece of equipment should not be optional and should always be included.

Jeff stated that Iowa Plains Signing never allows a piece of equipment to be optional in an operation if it is shown as so on the DOT Traffic Control Standard. In addition, oftentimes the vehicles that are depicted in the diagrams do not accurately show the realistic footprint of a piece of equipment. For example a rumble-strip grinder may be shown to be working outside of the traveling lane on the diagram but, in reality, the grinder may be sitting a few feet into the lane or even entirely in the lane of travel.

The second part of this concern is that because Iowa DOT standards are very specific in how they should be implemented (number of signs, number of trucks), contractors feel they cannot go above and beyond the standards without being liable for damages outside of their work zone.

Therefore, standards often constrict the contractor to perform to a standard that does not allow for additional safety measures. Because of all the past litigation Iowa Plains Signing has faced for not adhering strictly to the Traffic Control Standards over seemingly meaningless regulations, they are not willing to provide additional signage and other safety equipment.

The last main topic of discussion was the lack of willingness to accept new safety products and implement them in Iowa DOT standards. One item that was specifically talked about is temporary rumble strips (Figure C.6).

Figure C.6. Temporary rumble strips

Temporary rumble strips have the ability to grab the attention of drivers and alert them to the potential hazardous situations ahead and can be included in operations that require temporary set up in a specific area.

Finally, some innovative items have been adopted in the Iowa DOT standards as recently as 2011. The latest equipment being used in traffic control are automated signal lights, which replace standard flagging controls. These signal lights allow for two fewer laborers to be outside of a vehicle and exposed to moving traffic.

APPENDIX D. INNOVATIVE TECHNOLOGIES/EQUIPMENT

About the References for this Appendix

The researchers created a separate reference list of sources for this appendix, loosely using the endnotes system, where the number assigned to each source citation appears in italics and parentheses in the text. The researchers then grouped the source information by each technology/equipment category in the Appendix D References for your convenience.

Introduction

A work zone traffic control system influences driver perception of risk, and affects driver performance through the work zone. A properly designed work zone provides drivers with information regarding the potential hazards in the work zone, enabling them to respond safely to a given situation.

If drivers do not perceive risk associated with a work zone/work area, they are less likely to respond as intended to the traffic control measures. This may pose severe danger, given that hazards and other risks may be present even if and when a driver does not perceive them.

One example includes drivers who disregard reduced speed limits through work zones. In such cases, any error on the part of the driver may have a catastrophic result.

This study identified eight innovative technologies that show promise for operations and maintenance activities as listed in Table D.1 (*11*).

Table D.1. Overview of innovative technologies/equipment covered in this appendix

Technology/Equipment	Use
Mobile Barrier Trailers	Channelizing device/positive protection
Dancing Diamonds (lights)	Advance warning
Rotating Lights/Strobe Lights	Advance warning
Portable Rumble Strips	Advance warning
Cone Shooters	Channelizing device
Automated Pavement Crack Sealers	
Robotic Highway Safety Marker	Channelizing device
CB Wizard Alert System	Advance warning

The Strategic Highway Research Program (SHRP) has supported research on a number of these technologies/equipment, including mobile barrier trailers (the Balsi Beam in particular), cone shooters, automated pavement crack sealers, and robotic highway safety markers (*11*). These technologies have the potential to increase work efficiency and improve worker safety by eliminating direct worker exposure to traffic and by mitigating errant vehicles (*11*).

Innovative technologies can help ensure that driver expectations are met. Meeting driver expectations also helps to reduce driver frustration and aggressive driving behavior.

According to the Manual on Uniform Traffic Control Devices (MUTCD) 2009 Edition, Section 6G.02: "Work duration is a major factor in determining the number and types of devices used in [temporary traffic control or] TTC zones. "The duration of a TTC zone is defined relative to the length of time a work operation occupies a spot location… The five categories of work duration and their time at a location shall be:

A. Long-term stationary is work that occupies a location more than three days.
B. Intermediate-term stationary is work that occupies a location more than one daylight period up to three days, or nighttime work lasting more than one hour.
C. Short-term stationary is daytime work that occupies a location for more than one hour within a single daylight period.
D. Short duration is work that occupies a location up to one hour.
E. Mobile is work that moves intermittently or continuously."

The innovative technologies discussed in this appendix are suitable for intermediate term stationary work zones, such as those for altered pavement markings, placement of temporary traffic barriers, and temporary roadways, short-term stationary work zones, which include mostly the maintenance and utility operations, and short-duration work zones.

In completing this study, the researchers explored the following areas further for the eight innovative technologies/equipment in this appendix:

- Appropriate conditions for deployment
- Performance/effectiveness depending on hazard/activity
- Cost to purchase
- Cost to operate and maintain
- Availability (including resources and references)

Mobile Barrier Trailers

Mobile barrier trailers are basically of two types: the Balsi Beam and the Mobile Barriers Trailer (MBT-1). The Balsi Beam was invented first and it was followed by the MBT-1, which is a modification of the Balsi Beam that provides significantly higher walls for greater physical and visual protection, with an improved lighting system.

Balsi Beam

The Balsi Beam is considered a highly-portable positive protection technology, which means that it contains and redirects errant vehicles from intruding into a workspace in spite of driver error. It deflects the vehicle away from the work zone when it strikes the barrier.

Barrier and shadow vehicles positioned behind the workers on foot provide some protection from vehicles entering from "upstream," but due to vehicle spacing, may not provide adequate protection from errant vehicles entering from the side (*1, 2*). However, the Balsi Beam has been proved to provide a very strong lateral protection by the virtue of its design and construction.

The equipment was named after a Caltrans District 4 maintenance employee named Mark Balsi who was severely injured in January 2001 when a motorist crashed into the work zone, where he and others were picking up trash along I-280 in Santa Clara County, California (*1*).

Traditionally, positive protection has been achieved through complete diversion of traffic to another roadway or use of a portable concrete barrier. By providing protection cost-effectively and quickly, the highly-portable Balsi Beam increases safety in work areas where a concrete barrier is not feasible.

The Balsi Beam actually consists of a tractor-trailer combination, with the trailer converting into a 30 ft long work space in between the rear axles and tractor, shielded on one side with two steel beams (*1*).

The equipment is also called "shield of steel" because of its structural make-up and mode of working (*3*). The beams on the trailer have a dedicated truck to transport them to the worksite at normal highway speed without the need for any permits (*4*).

The Balsi Beam was developed by the Caltrans Division of Equipment based on the concepts and ideas provided by the Caltrans Division of Research and Innovation and then was delivered to the Caltrans Division of Maintenance in August 2003 for field trials and crash tests. The results were very good for both the Balsi Beam and the impacted vehicles (*4*), improving the safety of both the construction field workers and motorists (*5*).

Caltrans has a patent pending on this equipment and research is still going that focuses on which mobile work zone activities would actually benefit the most by using this system.

The Balsi Beam works well for jobs that are particularly localized, such as deck repairs, bridge rail repairs, and bridge joint maintenance. Caltrans is currently using the Balsi Beam and they have found it to be a very valuable safety asset, as it provides a high level of confidence in protecting workers from potential intruding vehicles, while working within a few feet of live traffic (*1*).

Balsi Beam Mode of Working

The Balsi Beam can be set up easily at the mobile work zone site. Once it reaches the site as a normal tractor-trailer truck, one of the telescope beams from one side (the side facing the work zone) is rotated to overlap with the beam on the other side (the side facing the moving traffic) to provide a double-beam protection and provides 30 ft of protected workspace.

The trailer is designed so that each side is built of high-strength steel box section beams that are able to extend an additional 15 ft. With the use of hydraulic power, the beams rotate left or right, depending on where protection is needed in the work zone (*5*).

The trailer beams form a solid wall of protection that deflects vehicles away from workers. This equipment can be used both for work on shoulders and on medians, as either of the beams can be rotated to the other side.

The equipment set-up procedures are shown in three simple stages in Figures D.1, D.2, and D.3.

Stage 1: Positioning the barrier
Tractor-trailer in its initial or at-rest position; the two beams form the two sides of the trailer.

Figure D.1. First stage of Balsi Beam installation at worksite

Stage 2: Deploying the barrier
Beam on the side of the work zone is being rotated to overlap with the beam on the other side to provide dual beam protection from moving traffic; rotation of the beam is fully automated and equipment can be set up in less than 10 minutes.

Figure D.2. Second stage: rotating one of the beams to the other side

Stage 3: Fully deployed barrier
Tractor-trailer in its final position with the two beams overlapping each other, providing the required work zone space for both field crews and moving traffic.

Figure D.3. Final stage: the two beams are overlapped on one side

Balsi Beam Physically-Protected Areas

The Balsi Beam provides a much larger protected space than a traditional truck-mounted attenuator for both single-lane and two-lane closures as shown in Figure D.4 (*4*).

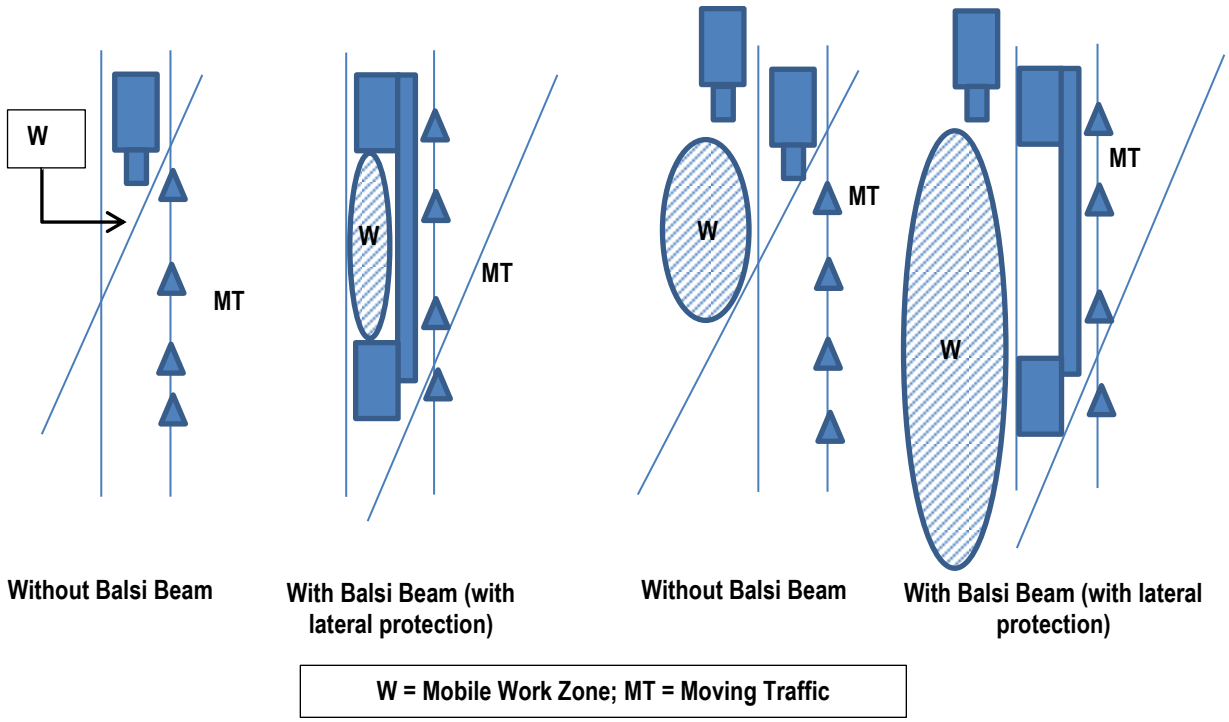


Figure D.4. Single-lane closure (left) and two-lane closure (right)

Successful Balsi Beam Applications

Caltrans designed the Balsi Beam and subcontracted it to the Murray Trailer Company in 2003 to build a prototype and it showed successful results in protecting both field crews and motorists (*4*, *5*).

Currently, Caltrans is conducting a risk assessment and cost/benefit analysis to assess how the equipment can be assigned for the most beneficial impact.

Some of the activities where the Balsi Beam could be used efficiently, as found in some of the existing literature, are listed in Table D.2.

Table D.2. Literature review for efficient uses of the Balsi Beam

Use	Determination/Potential (*source*)
Litter Pickup	Maybe (*4*)
Geotechnical Work, such as drilling and pavement core sampling	Maybe, depending on the size of the core sample needed, given the present equipment used may not fit into the work zone (*4*, *6*)
Pothole Patching	Maybe, given operations within the bridge deck or in limited areas with median barrier and guardrails require evaluation of the Balsi Beam (*4*)
Edge/Guardrail Repair	Maybe, given the present equipment used limits where the use of the Balsi Beam is of benefit (*4*, *6*)
Signal/Lighting Installation/Maintenance	Maybe, with the most appropriate use being installation of foundations, given maintenance of existing lights being problematic due to the size of lift trucks and positioning of the Balsi Beam within intersections where it creates a greater hazard (*4*)
Bridge Seal/Deck Repair	Yes (*4*, *6*)
Irrigation Repair	Yes (*4*, *5*)
Culvert Repairs	Maybe, depending on the scope of work, site location and equipment requirements (*4*, *5*)
Bridge Inspections	Yes (*4*, *5*)
K Rail Concrete Barriers, Median repair	Yes (*4*, *5*, *6*)

Currently, the Balsi Beam is primarily used by Caltrans bridge maintenance crews, but evaluation of different maintenance activities such as sign repair, manhole work, highway patrol assistance, setting of blasting materials, and landscaping is required as suggested by the 13 DOTs where the Balsi Beam tour was conducted to give demonstrations (*4*, 7). The Balsi Beam can also be used for surveying and maintenance operations with restricted escape routes and areas with high accident history (*6*).

Balsi Beam Drawbacks

The Balsi Beam has several drawbacks for which it is not accepted by the accepted by FHWA under and in accordance with NCHRP 350 (or the Manual for Assessing Safety Hardware/MASH) at any test level. The drawbacks can be listed as follows:

- It occupies 8 ft of lane width and does not allow large equipment access into the work zone directly from the rear. An adjacent lane or shoulder must be available for vehicles to access the protected work area. This is a problem on two-lane conventional highways or freeways with very narrow shoulders (*1*).
- It has a fixed length of 30 ft and the length cannot be extended, which may be required in some types of mobile work and this marks a limitation for the equipment.

- It does not have a good warning light system installed in the equipment and therefore additional warning lights and cautions need to be used in addition to this mobile equipment.
- Configuration of the equipment to work on either the left side or the right side of a lane involves rotating a beam from one side to the other, which, although being controlled and operated remotely, it is quite difficult to perform the rotation of the beams all the time.
- The cost of the prototype device is too high and it is about $217,000 to build (for each truck and trailer), but its price is expected to drop significantly when other models are produced. This cost is insignificant when compared to the loss of life or traumatic injury that highway workers are exposed to on the job (*2*, *8*).

Mobile Barrier Trailers (MBT-1)

Given the drawbacks of the Balsi Beam, the Colorado DOT (CDOT) developed similar equipment that has been accepted by the FHWA called Mobile Barrier Trailers (MBT-1). The equipment is currently in use in the mobile work zones in Colorado.

The MBT-1 can be easily configured from 42 to 102 ft, is easier to deploy (just pull in place), more mobile (no jack stands to deploy or arms to rotate), can be easily configured to the right or left (the tractor can attach to either end without rotating the beam as in the Balsi Beam) and also is less expensive.

Mobile Barriers Trailers MBT-1 provides state-of-the art protection and efficiency for work-zone construction and mobile applications. MBT-1 is the only such mobile device that has been tested and accepted by FHWA for use on the National Highway System (NHS) and on Federal Aid Projects.

MBT-1 is accepted for Test Level 2 (TL-2) and Test Level 3 (TL-3) use under both NCHRP 350 and MASH criteria, which contain revised criteria that include a safety-performance evaluation of virtually all roadside safety features (*48*).

The FHWA has clarified that states can use it on the NHS and Federal Aid Projects relatively easily with only a simple certification and no Public Interest Finding (PIF) or Finding In the Public Interest (FIPI) is required.

The MBT-1 looks like an 18-wheeler flatbed trailer, which is hooked to a semi-tractor and can be driven down the road and parked in the work zone to operate as a rigid, strong, one-piece work-zone barrier, functioning in much the same way as a concrete barrier (*49*).

The barriers can be configured from 42 to more than 100 ft and can be set up to protect to the right or left side of the road, just by changing the location of the semi truck's head from one end to the other. Moreover, the mobile barrier trailers use onboard generators and onboard lights for night work, which is a unique feature that is very helpful for advance warnings to motorists.

MBT-1 increases the efficiency of the mobile work. For example, in a normal intermittent/mobile work zone where the MBT-1 is not used, in an eight-hour lane closure, only six to eight guardrail pieces could be repaired, because of the time consumed to shift the work zone from one place to the other along the road while repairing the guardrails. When CDOT used the MBT-1 in Colorado in the same eight-hour duration of the lane closure, more than 42 pieces of guardrail were replaced/repaired (*50*).

Thus, instead of a week of lane closures, the work was completed over one night, reducing the equipment and labor costs, safety exposure, and traffic congestion.

Likewise, costs can be also saved for activities like concrete bridge deck slab replacements, concrete barrier and bridge rail repairs, bridge inspections, roadway repairs, information technology services (ITS) maintenance, and other activities.

Successful Applications of Mobile Barrier Trailers (MBT-1)

The MBT-1 can be used in all the types of activities where the Balsi Beam can be used (described earlier) and, in fact, more efficiently than the Balsi Beam can. An article by Tyler Graham, Ted Phillips, and Darren Waters on the Mobile Barrier Trailer states that the contractor schedule is advanced due to use of the trailers in different types of maintenance and operational activities on highways. Different repair works, saw cutting, concrete removal, dowel installation, concrete placement, and curing were all done as a single operation.

The device (Figures D.5 and D.6) can be used for providing work zone barriers for pothole filling; crack sealing; pavement testing; bridge repairs, investigations, and washing; accident scene investigations and cleanup; guide rail and barrier repairs; illumination repairs and maintenance; and other pre-engineering activities (*51*).

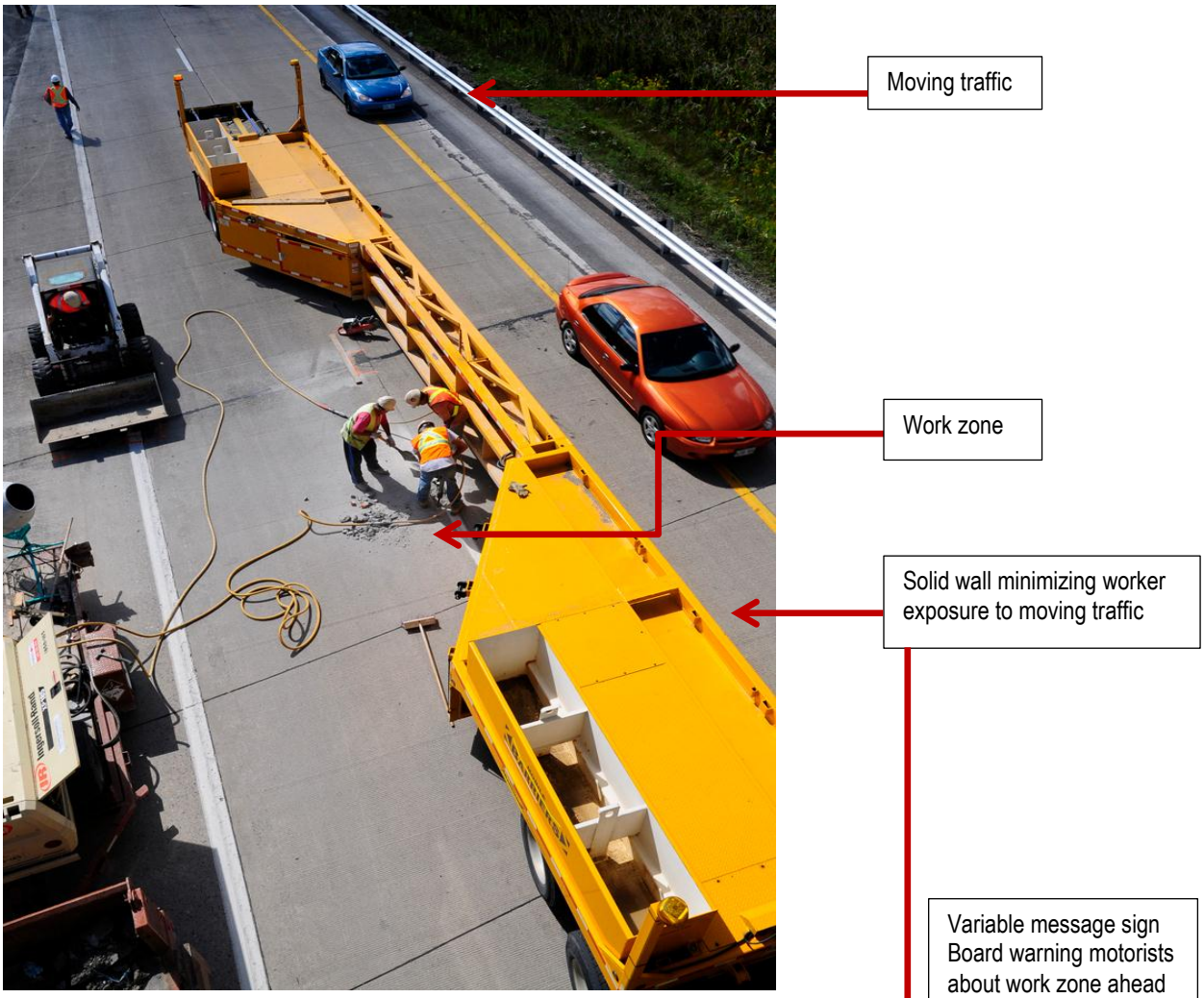


Figure D.5. Top view of the MBT-1

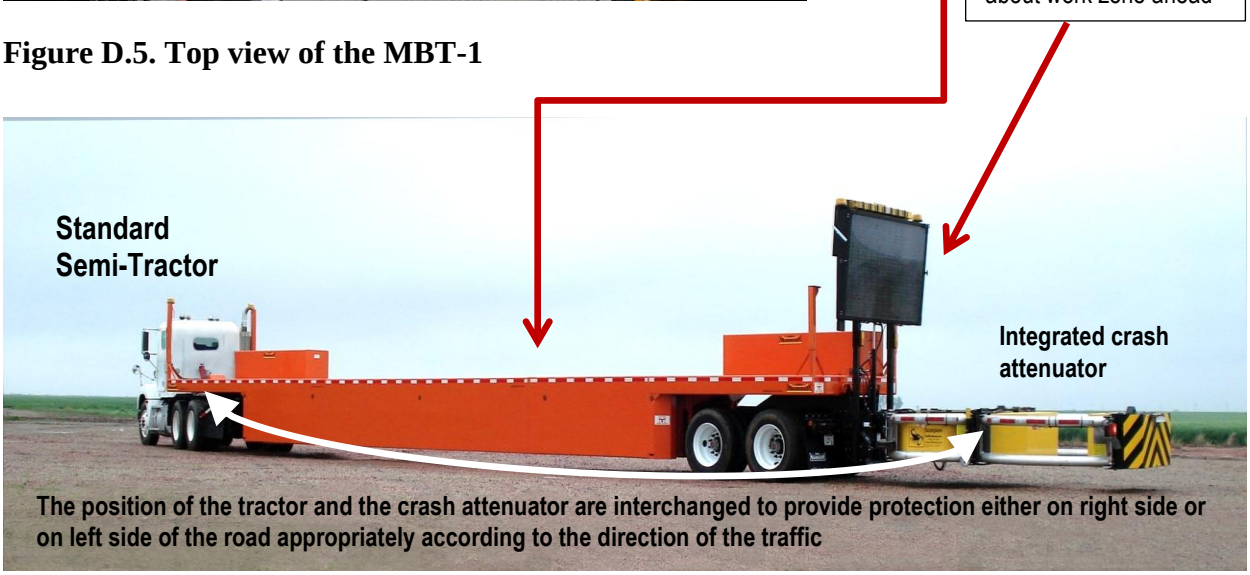


Figure D.6. Side view of the MBT-1

Mode of Working of the Mobile Barrier Trailer (MBT-1)

The rigid trailer (main body of the MBT-1) is towed into place by a standard semi-tractor at the front and includes an integrated crash attenuator at the rear as shown in Figures D.5 and D.6.

The attenuator and tractor trailer provide approximately 40 ft of protection, but the MBT-1 also includes three removable 20 ft panels, which allows users to select 60, 80, or 100 ft of protection based on the area and accessibility of the worksite and the comfort and competence of the driver (*52*).

Apart from providing a physical and visual barrier, the MBT-1 includes other unique features that mitigate the risks within the enclosed work zone, such as an integrated three-line message board, vertical lift, usable power, portable air, welder, storage and supply areas, radar, safety lighting, and work lighting.

Along with all of these features, the equipment was also crash tested for 5,135 lbs with a 2002 Dodge Ram 1500 Quad Cab pickup truck at a speed of 62 mph at an angle of 25 degrees with no structural damage and a maximum dynamic deflection of two ft (*52*).

All said, the MBT-1 appears to be a unique and effective mobile barrier system for intermittent and mobile activities on highways.

Dancing Diamonds

Non-directional arrow panel displays are used as an early warning caution on highways near a work zone. Non-directional caution displays, such as Dancing Diamonds or Double Diamonds and Flashing Diamonds, are used in addition to directional caution signage, such as Flashing Arrows and Sequential Chevrons, to maximize the safety-per-dollar of investment (*10*).

The MUTCD designates the non-directional arrow panel display as the Flashing Caution. The caution display signs are panels consisting of a matrix of lights that convey additional warnings and directions to motorists symbolically.

This matrix of lights is capable of flashing directional displays as well as non-directional displays that provide additional warning to motorists so they may exercise caution while traveling through an upcoming work zone.

Directional arrow panel displays mostly help motorists to shift lanes in a multilane highway near a work zone, safely slow down, and be more alert of a work zone ahead.

Non-directional displays, which are signs with a matrix of light elements capable of either flashing and/or sequential displays, are only meant to alert drivers and attract their attention to

other traffic control devices. Non-directional signs never require drivers to change lanes, but alert them of some form of work zone ahead so they have sufficient time to slow down.

The Flashing Box with dancing diamond pattern of displays had been widely used in the western US (such as in Utah and Oregon), because the Dancing Diamonds display is associated with cautious driving and attracted driver attention more when compared to the Flashing Box.

The Oregon Department of Transportation (ODOT) uses Dancing Diamond panel displays as an advance caution device for mobile and short-duration maintenance operations. A study conducted by ODOT in 2001 found the "+ ACI-dancing diamonds" are better than the other caution displays (like the Flashing Box) and that local citizens preferred the Dancing Diamonds to other caution displays (*11*).

A study by Turley et al. (*9*) found little difference in driver comprehension between Dancing Diamonds, Flashing Diamonds, and Flashing Box displays. However, the Dancing Diamonds are the best-prompted safety sign near the highway work, as they are associated with a statistically-significant 2 mph (3 km/h) reduction in mean speeds of the vehicles (whereas, the Flashing Box was not associated with any significant decrease in the mean speeds of the vehicles). Thus, it is evident that Dancing Diamonds cause drivers to slow down cautiously and is considered by drivers to be better at promoting safe driving near highway work zones (*10*).

Figures D.7 and D.8 show Dancing Diamond displays and panel setup.

Figure D.7. Dancing diamond displays

Figure D.8. Panel with 25 lamps used as a dancing diamond display by customizing the lamp-flashing sequence (TrafCon Industries Inc.)

Rotating Lights/Strobe Lights

Visibility and proper protection of the maintenance vehicles is very important, especially those involved in moving operations such as snow removal and shoulder operations, crack sealing, and pothole patching (*20*). It is evident that procedures or devices used in intermediate or short-term work zones are much different from those for long-term work zones.

Sometimes, the time taken to set up short-duration or intermediate work zones is more than the actual duration of the work and it is also quite hazardous for the workers. Proper selection of work-zone devices is very important to increase the efficiency of the short duration or intermediate works and devices with greater mobility, such as lights or signage mounted on the trucks, are much more effective than larger, more imposing or more visible equipment that are good choices for stationary work-zone alert systems (*12*).

Although maintaining reasonably-safe work and road user conditions are a paramount goal in carrying out mobile operations, they are very difficult to maintain as the work zone frequently changes location. Appropriately-colored or -marked vehicles with high-intensity rotating, flashing, oscillating, or strobe lights may be used in place of signs and channelizing devices for short-duration or mobile operations (MUTCD 2009 Edition Section 6G.02) (*15*, *17*).

These devices, such as high-intensity rotating, flashing, oscillating, or strobe lights on work vehicles, help to reduce the number of warning devices used in mobile work zones and help maintain work-zone mobility, which is one of the very important criteria for these work zones; however, the other vehicle hazard warning signs can supplement the rotating lights, but cannot replace them (*13*). In fact, these strobe lights are used the most in short-term stationary work zones (more than an hour, but within the same daylight period), in short-duration work zones

(one hour or less duration), and during mobile operations, which are similar to short-duration work zones (at a particular place), but involve frequent stops and moves within a region, such as litter cleanup, pothole patching, or utility operations (*14*, *15*).

As a standard, Michigan, for example, uses appropriate devices such as high-intensity rotating, flashing, oscillating, or strobe lights, signs, or special lighting on equipment, or a separate vehicle with appropriate warning devices, for mobile operations that move at speeds greater than 20 mph, such as pavement marking operations (*12*).

Pulsar LED Lights: A pulsar light-emitting diode (LED) lamp is a white pre-flash light that produces a flash of white light before the flashing of amber lights in an arrow panel. These lights improve the visibility of drivers to a great extent in adverse weather conditions, such as rain, snow, fog, mist, or nightfall, when the visibility of amber lights also decreases (*53*).

This pre-flash white light can be integrated easily into flashing light panels (Dancing Diamonds/Double Diamonds or directional Arrow signs) and immediately attracts driver attention under any weather circumstances.

The MUTCD does not restrict the use of white pre-flash lights, so they can be used without any hindrance. These lights are manufactured by TrafCon Industries Inc. and have been used successfully in several states including Minnesota and Delaware (*53*).

However, no one light is maximally effective in both transmitting information and gaining attention (*11*, *19*). Rotating and strobe lights have proven effective in getting driver attention, but not as useful in providing speed and closure rate information, particularly when the service vehicle is stopped. Conversely, flashing lights, which work really well for giving speed information, are not effective in providing clear clues of the work zone to drivers from long distances. Therefore, several of the lighting recommendations combine the two types of lighting cues to ensure optimum information transmission and conspicuity (*11*, *19*).

Blue Strobe Lights: There is considerable growing pressure in several DOTs to incorporate lighting technologies into maintenance and service vehicles that are visually similar to those implemented on police and other emergency vehicles, such as light bars or blue flashers or blue strobe lights (*19*).

However, blue strobe lights are not permissible for highway maintenance and operational activities in many states, as they are used and reserved for police-patrol services, ambulance, and emergency vehicles. Still, some DOTs use blue strobe lights, along with standard amber lights, in certain situations for mobile and short-duration work.

The Texas DOT (TxDOT) recommends using blue strobe lights in some nighttime conditions as follows (*16*):

- Road snow and ice removal
- Mobile operations in a traffic lane with speeds less than 3 mph or with speeds less than 30 mph of the posted speed of the traffic lane
- Maintenance vehicle response to or parked at an incident place
- Employees out of equipment and in a lane of traffic and channeling devices, such as cones, tubular markers, or drums, not present upstream of the equipment to close the lane

However, TxDOT also advises that care should be taken to turn off blue strobe lights when the maintenance vehicle is not involved in any one of the above operations (*16*).

A study conducted by the Texas Transportation Institute (TTI) and TxDOT found the color of the light has some effect on its conspicuity and its effect on motorists. In daylight conditions, red lights have been shown to be more conspicuous than blue lights; whereas, the opposite is true under nighttime conditions. Meanwhile, the conspicuity of yellow lights generally falls between that of blue and red lights in both daytime and nighttime viewing conditions (*19*).

The use of blue strobe lights/blue flashing lights are beneficial because the flashing blue light grabs the attention of drivers, especially at night, and checking or reducing vehicle speed is a natural reaction (*18*, *21*).

A MnDOT study concluded that the 85th percentile speed in work zones was reduced 8 to 11 mph when police officers were present with vehicle lights and flashers activated (*21*). However, if police patrols are not possible in the mobile operations, use of blue lights on maintenance vehicles would also help to decrease the speeds of vehicles as motorists would instinctively reduce speeds upon seeing blue flashing lights (*21*).

Figure D.9. Amber strobe lights (normally used on work vehicles) (left) and blue strobe lights (recommended for use on work vehicles) (right)

Portable Rumble Strips

Portable or temporary rumble strips are used in TTC to generate awareness among drivers through audible cues and a "feel" caused due to vibration through the tires and through the steering wheel.

Portable rumble strips are placed temporarily across the road surface at certain distances away from the start of the work zone to make drivers cautious and aware of the work zone ahead, helping to give them enough time to decrease their speed near the work zones.

These strips are mobile yet stable, durable, withstanding both the impact of high-speed traffic and adverse weather, and very handy, enabling quick manual installation and removal (*22*).

The two different types of portable rumble strips are plastic rumble strips and adhesive rubberized polymer rumble strips. The plastic rumble strip configurations have been found to be more effective for both cars and trucks and only four plastic rumble strips placed at a distance of 12 to 18 inches apart is sufficient, instead of six adhesive rubberized polymer rumble strips similarly placed apart from each other (*24*).

Plastic rumble strips are so portable, they do not require any adhesives or fasteners to place them on the road surface and their shape conforms to the surface of the road, as shown in Figures D.10 and D.11.

Figure D.10. Portable rumble strips

Figure D.11. Two people placing portable rumble strips

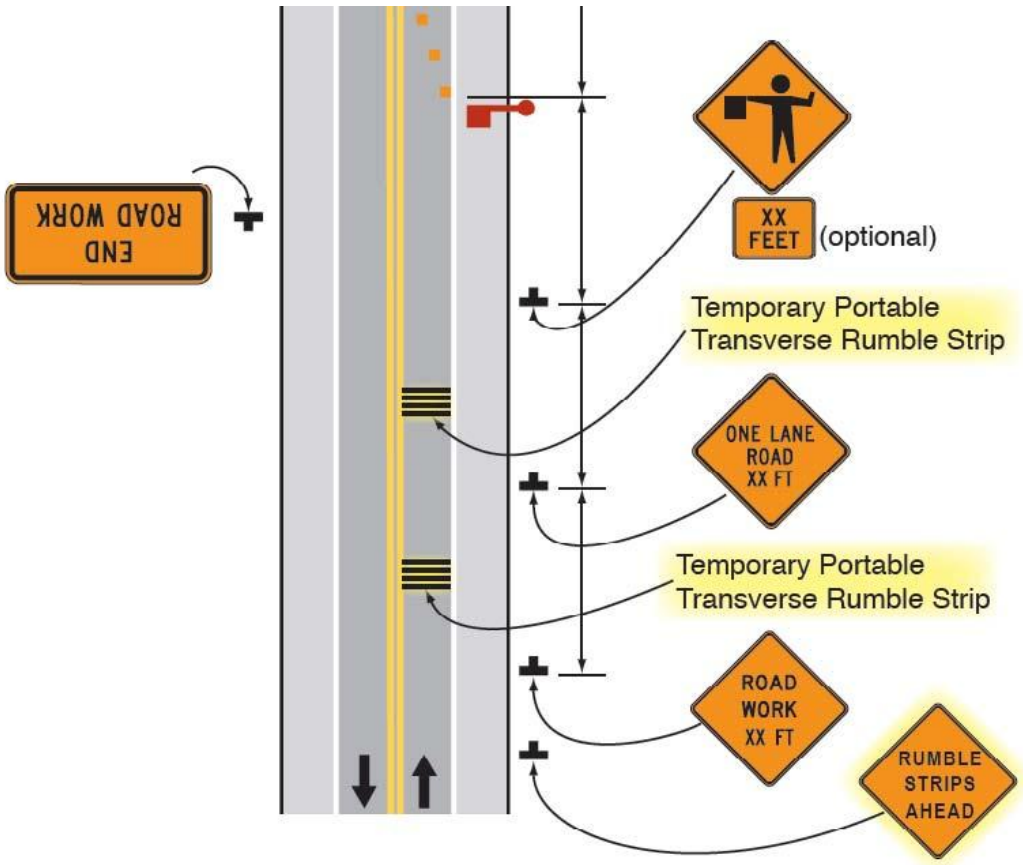
Plastic rumble strips are relatively stable, observing movement of about two inches over several hours on a 5,000 ADT high-speed route (*22*). Generally, plastic rumble strips are installed by removing the protective backing, placing the rumble strip on the road surface, and using a weighted roller to firmly adhere the strip to the pavement (*23*). Fourth-generation plastic rumble strips are also resistant to vertical and horizontal movements, particularly at vehicle speeds of 60 mph (*24*).

A Missouri DOT (MoDot) research study found the strips were best used on clean surfaces regardless of treads (*22*).

Portable rumble strips are very useful for intermittent work zones (duration more than a day but less than three days) and also short-duration work zones (duration more than an hour but within the same daylight).

Each strip is 10 ft long and weighs 120 lbs, requiring only two people to set them up on the road surface with three or four rumble strips one ft from each other at the beginning of the work zone (*22*). However, this configuration may vary based on the type of road where used and also on the quality and brand of the rumble strips. Figure D.12 shows a sample design configuration.

Portable rumble strip installation needs to follow the specifications (either the Department's or the manufacturer's) closely for both air and pavement temperatures, presence of moisture, cleaning of pavement, and method of adhesion to survive the anticipated duration in service, although specifications can be deviated from a little (*25*). Sound engineering judgment is paramount in placing temporary rumble strips to ensure they are necessary for that particular type of work zone, will be effective, and are properly installed.



http://www.modot.org/tsc/2011documents/Chris_PortableRumbleStripsD9WorkZones.pdf

Figure D.12. Portable rumble strip placement design

A TTI study found that portable rumble strips reduced speeds 1.4 to 4 mph with trucks decelerating more than the cars (*23*). This might be attributed to the wider viewing angles of the trucks for which they could see the rumble strips from quite a distance ahead and take proper measures accordingly.

This TTI study found rumble strip installation took a three-person crew 40 minutes under light traffic and that maintenance crews were concerned that time would be excessive for many short-term work zones. The authors concluded that portable rumble strips may be better suited to intermediate work zones or short-term stationary work zones (as defined earlier), but not quite suitable for short-duration or mobile operations (*23*).

Many states, including California, Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, Missouri, Pennsylvania, Ohio, New Mexico, and South Dakota are using different types of temporary rumble strips as a TTC method near an intermediate or short-duration work zone and they have proved to be a successful tool to attract driver attention to reduce their speeds while approaching a work zone (*25*).

RoadQuake Temporary Rumble Strip: This is the most commonly used portable rumble strips, manufactured by Plastic Safety Systems, Inc. RoadQuake rumble strips are ideal for use where daily installation and removal of the work zone is required and are suitable for posted speed limits of 60 mph or less and temperatures above 40 degrees Fahrenheit (*54*).

Cost-related information for RoadQuake is given in the table at the end of this appendix.

MoDOT has started to use RoadQuake temporary rumble strips with quite positive results. The rumble strips have reduced speeds five to 10 mph, as well as increased attentiveness given the audible and vibratory alert, increasing safety in work zones (*27*).

Cone Shooters

Laying cones near a road maintenance and construction work zone is hazardous to workers who work in the back of a truck to place and retrieve the cones. Handling the cones is also physically strenuous and can cause injuries. In addition, exposure to fast-moving traffic creates a tremendous worker hazard.

To mitigate this hazard, Cone Shooters were developed by the Advanced Highway Maintenance and Construction Technology Research Center (AHMCT), which is a project-oriented research center at the University of California (UC)-Davis. The center partners with Caltrans to manufacture concept vehicles and equipment (*28*).

The Cone Shooter, as shown in Figure D.13, was developed to meet the Caltrans need for cone-laying operations that would increase worker safety and efficiency for short-duration and mobile maintenance operations on California highways.

Figure D.13. AHMCT Cone Shooter

While, manually, a worker can carry only three cones at a time, the Cone Shooter can automatically place and retrieve traffic cones and, thus, open and close busy lanes safely and quickly without exposing workers to traffic. In this way, the Cone Shooter helps in reducing both the cost and injury involved in mobile work in a busy lane.

The typical lane configuration uses 80 traffic cones for each 1.5 miles of lane closure and the cones generally come in the 36 in. size. Several modifications are being made to improve the Cone Shooter, including development of a multi-stack cone machine to maximize the number of cones carried by the equipment. The original Cone Shooter carries up to 80 cones; whereas, the multi-stack equipment can carry up to 300 cones (*32*).

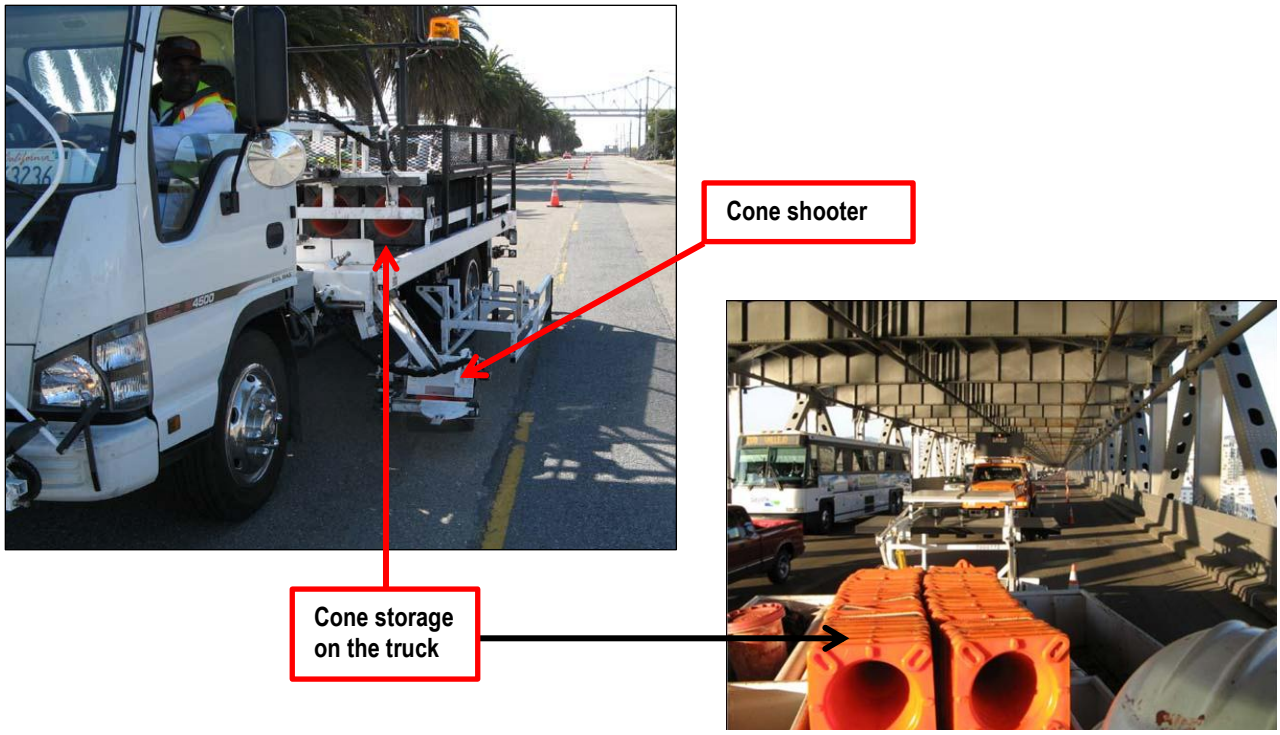
The concept and design of the Cone Shooters has been transferred by AHMCT to a California-based start-up company called Traf-tech, which has licensed the technology and is marketing a machine that closely copies the AHMCT design. The first Traf-tech design had the features of full automation and was optimized for carrying 250 cones, which was more versatile and compact (*29*).

Cone Shooter features are generally as follows (*30*):

- By default, handles the generic 28 in. highway cone, but can be readily modified to handle other sizes and cones with heavier bottoms that don't easily tilt
- Controlled using simple switches by the driver
- Automated equipment occupies minimal space on standard trucks and standard vehicle configuration is maintained when not handling cones
- By default, can store 80 cones in stacks lying on side and carrying capacity can be readily modified as already modified by AHMCT and Traf-tech
- Cones can be placed in the forward direction, on either the left or right side
- In the default configuration, cones can be spaced automatically every 25, 50, or 100 ft, while traveling at a speed of 10 mph, and spacing choices can be readily modified
- Easy retrieval of upright or knocked-over cones on either the left or right side while traveling either in a forward or reverse direction

Cones are stacked at the back of the Cone Shooter truck and placed on the road or retrieved from the road through a conveyor belt system, which is completely automated, as shown in Figure D.14 (*31*).

Driver interactions with the machine are minimal and workers are not exposed to moving traffic while placing the cones near the work zones. The equipment is very easy to handle and is compatible with the Caltrans cone body.



http://ahmct.ucdavis.edu/wp-content/uploads/pdf/ahmct_cone_machine_05-2007.pdf

Figure D.14. Storage and placement of cones with an AHMCT Cone Shooter

The equipment includes four switches that the driver uses and cones are automatically dropped off the vehicle onto the road with the pre-defined spacing as the vehicle moves forward. The driver controls the spacing. Similarly, the driver retrieves the cones back onto the vehicle when the maintenance work is done.

Automated Pavement Crack Sealers

A frequent mobile maintenance operation involves pavement crack sealing, including longitudinal cracks or joints between concrete lanes and random cracks along the pavement. About $200 million dollars of government expenditures per year go toward crack sealing (with two-thirds on labor costs, one-fourth on equipment, machinery, and its maintenance, and the remaining on materials) (*38*).

Hand sealing longitudinal and random cracks consumes significant time and involves workers, safety concerns, and lane closures. Typical longitudinal crack sealing operations involve a large crew sealing 1.5 to 3 km per day with workers exposed to moving traffic in adjacent lanes (*34*).

To help mitigate the problem and the hazards, AHMCT has developed (Figure D.15) automated pavement crack sealers for both longitudinal and random crack sealing. The machines perform crack sealing operations with greater efficiency and less time than manual sealing (*11*).

Figure D.15. AHMCT SHRP H107A automatic crack sealing machine, fully operational in 1993

The first AHMCT automatic crack sealing machine (ACSM) was developed in 1991 at the University of California-Davis. Caltrans and SHRP contracted with AHMCT to design and build a fully automated, self-contained crack sealing machine (*34*).

The ACSM was developed to identify and seal all types of highway pavement cracks. It was a self-contained vehicle that could both seal cracks entirely within a highway lane and seal longitudinal cracks alongside the vehicle (*33*). The ACSM integrated system was completely modular, allowing various combinations of sub-assemblies for sealing procedures.

The three-axle truck with line scan vision (video) systems mounted on the front and side, had a robot positioning system mounted at the rear of the vehicle and also computer systems housed on the truck bed, as were peripheral support systems (*34*).

The ACSM performs the following functions automatically: senses the occurrence and location of cracks, prepares the pavement surface, prepares and dispenses sealant and forms the sealant into the desired configuration. In addition to the support vehicle, the machine includes seven subsystems: Integration and Control Unit, System Display Unit, Vision Sensing System, Local Sensing System, Vehicle Orientation and Control System, Robot Positioning System, and Applicator and Peripherals System (*33*).

During ACSM development, AHMCT quickly found that automated crack sealing needed to be divided into two categories, longitudinal and random, given altogether different accessibility and technology requirements.

The longitudinal sealing system was spun-off as the Longitudinal Crack Sealing Machine (LCSM) (Figure D.16) and the random crack sealing system was spun-off as the Operator Controlled Crack Sealing Machine (OCCSM).

Figure D.16. AHMCT Transfer Tank Longitudinal Sealer (TTLS)/Sealzall

The LCSM is remote-controlled by the in-cab crew and can fill cracks at a speed of up to 5 mph, this can be done without a fixed lane closure (*37*). This compares to a manual sealing operation that would take a large crew all day to complete two miles (*35*).

The LCSM shown in Figure D.16 is ideal for sealing joint cracks between Portland cement concrete (PCC) slabs as well as transitions between PCC slabs and asphalt cement (AC) shoulders (*36, 37*). On the other hand, the Random Crack Sealing Machine has a robot arm that can reach across a full lane and seal random cracks in the pavement (*35*). However, sealing of longitudinal cracks is relatively simpler and consists of only 25 percent of the total crack sealing operations, whereas the random and meander crack sealing operation includes the remaining 75 percent of the total crack sealing operation (*38*).

Caltrans is conducting several research studies to modify the ACSM to improve it further in terms of productivity, ease of handling, and cost effectiveness. The District 11 Chula Vista Travelway Crew reported the data in Table D.3 when comparing their use of one of the first automated longitudinal crack sealing (ALCS) machines (the LCSM) deployed to Caltrans Maintenance crews to hand-applied operations (*36*).

Table D.3. Distance compared: 32 miles along I-5

Parameters Reported	LCSM	Hand-Applied
Number of employees	3	4
Average miles per day	3.5	0.8
Work days	9	40
Bare rate cost	$4,017	$23,820
Closures	No	Yes
Employees on foot	No	Yes

Robotic Highway Safety Markers

Proper traffic control is essential near all types of construction work zones and channelizing devices, such as signs, barricades, cones, and plastic safety barrels, are often used. Placement of channelizing devices in traffic, and particularly on highways where traffic moves at high speeds, is a very hazardous activity for road workers exposed to the traffic.

Again, accidents can occur because of improper work-zone design, improper work-zone housekeeping, such as covering and uncovering signs and moving traffic control devices, and driver negligence (*40*). Automated safety devices can improve work-zone design and housekeeping and therefore increase the safety for both workers and motorists.

Moreover, these improvements can help reduce traffic congestion in the work zone. The cost of traffic congestion to US motorists in lost productivity is estimated to be at least $100 billion annually, not including the cost of wasted fuel and environmental damage (*42*).

Thus, although deployment of Robotic Safety Barrels (RSBs), shown in Figure D.17, clearly has a higher equipment cost than traditional systems (*42*), this technology could help to effectively reduce maintenance and operations labor costs and traffic congestion costs and increase worker safety.

Figure D.17. Robotic Safety Barrel

Developed by the Mechanical Engineering Department at the University of Nebraska-Lincoln, the RSB replaces the heavy base of a typical safety barrel with a mobile robot. RSBs can self-deploy and self-retrieve, removing workers from exposure to moving traffic (*11*).

The robots move independently, so they can be deployed in parallel and quickly reconfigured as the work zone changes. Hence, these devices would be of great advantage in the mobile work

zone where the cones or barrels can be programmed to move along with the working crew, saving time and increasing worker safety.

RSBs are the first elements of a team of robotic safety markers (RSMs), which includes signs, cones, barricades, and arrestors (*39*). The mobile robot can transport the safety barrel and robots can work in teams to provide traffic control.

Generally, safety barrels are placed on the periphery of the work zone to guide traffic and serve as a visible barrier between traffic and work crews. Basically, they act as the channelizing device between the work zone and moving traffic.

These barrels consist of a brightly-colored plastic drum (approximately 50 in. tall and 20 in. in diameter) attached to a heavy base (*41*). Often, hundreds of barrels are manually placed in a typical work zone.

There are several advantages of the independent, autonomous motions of the barrel. First, the barrels can self-deploy, eliminating the dangerous task of manually placing barrels in busy traffic. Second, the barrel positions can be quickly and remotely reconfigured as the work zone changes and hence it is very suitable for the intermittent and short duration work zones. The barrels can continuously follow work crews to maintain optimal placement for safety.

Figure D.18 shows how the robotic safety barrel works to place the barrels to channelize or close the lanes.

http://www.engineering.unl.edu/research/robots/publicationdocs/robotic_safety_markers.pdf

Figure D.18. Lane closure with five barrel robots

CB Wizard Alert System

The Wizard Work Zone Alert and Information Radio was designed and patented by Highway Technologies Inc. and built and marketed by TRAFCON Industries Inc. The CB Wizard Alert System is a device, shown in Figure D.19, that continuously broadcasts a warning message over Citizens' Band (CB) radio channel 19 to warn drivers of work zones (*43*).

Figure D.19. CB Wizard Alert System (*44*)

This warning system is mostly used and effective for warning truck drivers on interstate highways about mobile maintenance operations (such as painting). An evaluation study conducted by the Iowa DOT and the Center of Transportation Research and Education (CTRE) as a part of the Midwest Smart Work Zone Deployment Initiative (SWZDI) (with Iowa, Kansas, Missouri, Nebraska, and Wisconsin involved as of 2001), found that this warning system was very effective and efficient in warning and controlling traffic along moving work zones on interstate highways.

The advanced warning gave drivers the opportunity to moderate their speed and become observant of the need to slow, stop, or maneuver before reaching the work zone or encountering either queues of halted vehicles or slow-moving work vehicles. About 41percent of the truck drivers stated that CB alert was their first warning. This system was also found to be very effective in alerting truck drivers at night (*43*, *45*).

The system was found to be very useful in reducing the speeds of trucks, particularly in rural mobile work zones given heavy trucks typically represent 30 percent or more of the traffic on rural interstates. (*43*).

The primary costs of the CB Wizard Alert System include the system itself and staff time for installation, recording messages, and removal. No lane closures are required as the system is completely unmanned and is installed, operated, and removed without traffic disruption (*44*). Messages can be pre-recorded or recorded on site (Figure D.20), and can be transmitted every 30, 60, or 90 seconds. To avoid interfering with other CB users, the device monitors transmissions on the selected frequency and, when it detects a lull, the safety message is broadcast (*46*).

Figure D.20. Inside of a CB Wizard Alert System

The Maryland State Highway Administration summarized the advantages of using the CB Alert System as follows (*46*):

- Very effective communication tool for disseminating up-to-the minute work-zone related information to truck drivers approaching the work zone on interstates
- Allows drivers to receive advance warning before static signs or Portable Changeable Message Signs (PCMS) messages become visible
- Advance notifications help truck drivers to lower their speed and change lanes before reaching the work zone
- Truck operators are typically tuned to a CB radio frequency, so no further driver action is required to become aware of the advance warning
- Non-hazardous, portable, low-cost, and easy-to-deploy work-zone safety tool
- No traffic disruption involved in installation, operation, or removal of the system
- Unlike the traditional Highway Advisory Radio (HAR), use of CB frequencies do not require a Federal Communications Commission (FCC) permit

Moreover, an evaluation study by Kamyab et al. (2000) found that among the three warning systems, the CB Wizard Alert System was most effective in terms of its usage as an early warning system (*47*). The other two systems evaluated for effectiveness were the Safety Warning System (SWS), or electronic displays of warning messages near work zones, and the Speed Monitor Display (SMD), or electronic devices that display vehicle speeds digitally.

Effectiveness of the Technologies/Equipment

Table D.4 ranks the performance or effectiveness of each of the innovative technologies/ equipment for various activities related to the following hazard categories, which were found to bear critical or catastrophic risk potential both from the crash data analysis and survey data for this study:

- Worker exposure to traffic
- Inadequate visibility of workers, work zone, and traffic control devices
- Inadequate advance driver warning
- Driver behavior in or near the work zone
- Inadequate worker training (not ranked or scored in Totals, but listed)

Given the hazards related to improper training cannot be mitigated by any of the technologies/ equipment, their effectiveness is not ranked in this table.

The color key for the rankings shown in the table are as follows:

Yes – Fully satisfied

Maybe – Satisfies with some condition/criteria or effectiveness is still being researched

No – Not at all effective or not applicable

Not all the red rankings mean the technologies/equipment do not work for the respective activities; some of the red rankings signify that the technologies/equipment are not really applicable for the listed activity.

Summary of Effectiveness Rankings

From the rated activities/hazards, MBT-1, Dancing Diamonds, Rotating Lights/Strobe Lights, Portable Rumble Strips, the CB Wizard Alert System, and the Balsi Beam are most effective. All of the technologies/equipment reviewed in this appendix have proven effective in mitigating the O/M risks for the hazards in the targeted area that they were designed and developed to address.

Table D.4. Effectiveness ranking of innovative technologies/equipment by hazard/activity

Activity/Hazard	Innovative Technology/Equipment								
	Balsi Beam	MBT-1	Dancing Diamonds	Rotating lights/ Strobe lights	Portable Rumble Strips	Cone Shooters	Automated Pavement Crack Sealers	Robotic Highway Safety Markers	CB Wizard Alert System
Hazards related to worker exposure to traffic									
Region located within or adjacent to the work activity									
Flagger operations in a two-way, two-lane highway where one of the lanes is partially blocked due to O/M activity									
Peak traffic hours									
Pavement markings at intersections (at nighttime)									
Hazards related to inadequate visibility of workers, work zone, and traffic control devices									
Cloudy weather (lesser visibility)									
Foggy / misty / partly cloudy weather (lesser visibility)									
Night time operations									
Work zones on roads in hilly areas									
Fog and mist									
Unforeseen weather conditions									

Activity/Hazard	**Innovative Technology/Equipment**								
	Balsi Beam	MBT-1	Dancing Diamonds	Rotating lights/ Strobe lights	Portable Rumble Strips	Cone Shooters	Automated Pavement Crack Sealers	Robotic Highway Safety Markers	CB Wizard Alert System
Hazards related to inadequate advance driver warning									
Region located between the advance warning sign and work area									
Improper signs and signage at ramps and roadway intersections near work zones									
Absence of proper signage near the work zone									
Not using morning lights in the work zone									
Absence of fluorescent diamond signs									
Hazards related to driver behavior in or near the work zone									
Passenger vehicle									
Vision not obscured by moving vehicles or frosted windows/ windshield (speed increases)									
Ingress and egress from the mobile (O/M) work zone									
Lack of knowledge about variable peak traffic time in the local regions near work zone (e.g., variable travel patterns near institutions like the Iowa DOT, University, and Animal Disease Lab in Ames, Iowa)									

Activity/Hazard	**Innovative Technology/Equipment**								
	Balsi Beam	MBT-1	Dancing Diamonds	Rotating lights/ Strobe lights	Portable Rumble Strips	Cone Shooters	Automated Pavement Crack Sealers	Robotic Highway Safety Markers	CB Wizard Alert System
Clearing roadway for emergency vehicles									
Not imposing speed limit fines on public									
Hazards related to inadequate worker training									
Lack of worker safety and training programs	–	–	–	–	–	–	–	–	–
Absence of "train-the-trainer" philosophy	–	–	–	–	–	–	–	–	–
Totals									
	11	15	17	18	18	6	2	5	14
	3	3	2	1	0	1	3	2	4
	7	3	2	2	3	14	16	14	3

Innovative Equipment/Technology Costs

Any equipment cost is associated with the cost of owning and operating the equipment/ technology. Equipment costs are traditionally stated on an hourly basis.

The most significant cash flows affecting ownership cost include purchase expense, salvage value, major repairs and overhauls, property taxes, insurance and storage, and miscellaneous. Operating costs involve costs for fuel, oil, and grease (*55*).

The three methods to deploy equipment are purchase, lease, or rent. The hourly cost for use is lowest with purchased equipment, but keeping the equipment fleet busy can be challenging. With leasing, the hourly charge is higher than on owned equipment, but the risk involved is much less. When renting equipment, the hourly charge is the highest, so equipment rentals are best for relatively- or very-short periods of time.

Before procurement of any equipment for work-zone use, it is very important to evaluate the types of equipment to use for particular types of work zones and to select the best means of equipment employment to optimize and help reduce ownership and operating costs.

In Table D.5, the ownership cost, operating cost, and lifetime or salvage value of the top six ranked technologies in Table D.4 are provided, along with some information about the respective products and the manufacturers and commercial distributers of the products. (The ones not included in this table are Cone Shooters, Automated Pavement Crack Sealers, and Robotic Highway Safety Markers.)

Table D.5. Cost information for six effective technologies/equipment

Equipment/ Technology	Types Commercially Available	Manufacturers	Ownership Cost	Operation Cost	Lifetime/ Salvage Value	Reference
Rotating Lights/ Strobe Lights	• Strobe Warning Lights; LED Warning Lights • Portable Strobe Lights • Rotating and Flashing Lights • UL listed warning lights (http://northamericansignalc.thomasnet.com/category/strobe-warning-lights-strobe-lights?&bc=100)	• North American Signal Company, Wheeling, IL (http://www.nasig.com/) • Peterson: Vehicle Safety Lighting Systems and Accessories (http://www.pmlights.com/products.cfm?cId=7&fId=29); Distributer-Foxtaillights (http://www.foxtaillights.com) • Signaworks: Industrial Signal Products (http://www.signaworks.com/signaworks.com/rotary/)	Prices vary according to the type of lights Price of Emergency warning lights and equipment range from $30 - $350 per light (Foxtaillights)	Not Applicable	Bulb can be replaced if not working	Peterson Iowa rep: Jim Rowe at jrowe@nawilliams.com or 770-433-2282 Distributer of Peterson Products is Foxtaillights at http://www.foxtaillights.com/emergency--warning.html or 877-476-5444
Dancing Diamonds/ Double Diamonds	25 light arrow board with one solar panel and two batteries (6 Volts each)	TRAFCON Industries, Inc. 81 Texaco Road Mechanicsburg, PA 17050 717-691-8007	$3,785	Solar energy operated: $300/year Diesel operated: $4,000/year	Varies from 20 days to indefinite days depending on the combination	Used by Oregon DOT

Equipment/ Technology	Types Commercially Available	Manufacturers	Ownership Cost	Operation Cost	Lifetime/ Salvage Value	Reference
Portable Rumble Strips	Temporary Rumble Strip Tape (with adhesive for inclement weather)	Barco products: A Geneva Scientific Company at http://www.barcoproducts.com/ manufactures temporary rumble strips with adhesive	Temporary Rumble Strip Tape (with adhesive for inclement weather): $420 for a 4 in. wide, 50 ft roll ($8.40/linear ft) and removable primer (covers 200 ft_2) at $39.85/gal or permanent primer (covers 166 ft_2) at $43.85/gal	Negligible	Depends on traffic volume and road type	www.barcoproducts.com/store/item.asp?ITEM_ID=685or 1-800-338-2697
	RoadQuake: Temporary rumble strip for speed limits of 60 mph or less, and temperatures above 40° F. (www.plasticsafety.com/road-quake-construction-rumble-strips)	Plastic Safety Systems, Inc. (www.plasticsafety.com/road-quake-temporary-portable-rumble-strips) – manufactures RoadQuake and RoadQuake2 Rumble Strips (without adhesive)	RoadQuake Portable Rumble Strips 11 ft x 1 ft x 13/16 in. thick with a 12 degree bevel on the leading edge ≈ $1,375 each	Negligible	All Roadquake products have an average lifespan of 3-5 years depending on use	http://library.modot.mo.gov/RDT/reports/ad09153/orb10000.pdf http://www.ktc.uky.edu/kytc/kypel/prodDetail.php?proID=10932; http://www.tapconet.com or Jeff Tidaback – Plastic Safety Systems Inc. Office: 800-662-6338 Cell: 216-409-6842 Fax: 216-231-2702

Equipment/ Technology	Types Commercially Available	Manufacturers	Ownership Cost	Operation Cost	Lifetime/ Salvage Value	Reference
Portable Rumble Strips (continued)	RoadQuake 2: Temporary rumble strip for speed limits of 65 mph or less, and temperatures from 0° to 180° F. (www.plasticsafety.com/road-quake-2-rumble-strips)	See above	RoadQuake 2 Portable Rumble Strips retail cost of 44 in. strip is $495 each (11 ft strip assembled from three 44 in. strips is $1,485)	Negligible	All Roadquake products have an average lifespan of 3-5 years depending on use	See above
Mobile Barrier Trailer (MBT-1)	Only one type but can be configurable from 42-102 ft wide or 0-3 wall sections	Mobile Barriers	Base value: $250,000 (price may increase for additional components); cost for the equipment is flexible based on the specification of the equipment as required by various agencies	Negligible (described below)	Life: 20 years; Salvage value: value of scrap steel	http://www.mobilebarriers.com Walt Black, email: walt@iwapi.com cell: 303-551-5354
CB Wizard Alert System	1. Handheld Unit 2. Trailer-Mounted Unit	Designed and patented by Highway Technology Inc. and built and marketed by TRAFCON Industries, Inc. 1-717-691-8007	Handheld Unit: ≈ $4,300 Trailer-Mounted Units: ≈ $7,500	No such except replacement of batteries	5 years for the Plug-in type	www.sha.maryland.gov/OOTS/07CBWizardAlertSystemW-Summary.pdf
Balsi Beam	Only one type and provides 30 ft of protected workspace	Murray	Average original cost: $310,764 Average capitalized cost: $347,224	Improvement cost: $36,459.74 Maintenance cost: $49,767.61	Not sold yet. But estimated salvage value is $20,000	Information obtained from Coco Briseno, Acting Chief, Division of Research and Innovation March 21, 2012

Additional Cost Information

Dancing Diamonds

The information below was obtained from John Hawkins, Sales Manager, TRAFCON Industries, Inc.

Dancing Diamonds (also known as Double Diamonds) are actually an arrangement of arrow board lamps they are used only for warning purposes without any directional attributes. The sequence of the flashing of the lights is decided by the respective state's DOT and according to the arrow panel manufactured.

Ownership cost for customers (mostly DOTs) depends on the initial layout of the lamps and maintenance of the batteries. The arrow panel can be either solar powered or diesel powered. However, the typical Dancing Diamond display is a 25 light arrow board operated by a solar panel and two batteries (6 Volts each).

The operation cost is minimal for the solar-powered arrow panels. The only maintenance required is to check the water levels in the batteries frequently and keep the panels clean. Operation costs increase greatly with diesel-powered arrow panels due to fuel costs and EPA standards.

On average, the maintenance cost for a solar-powered panel is $300 per year, including shifting the equipment from one place to the other. The diesel-powered panel maintenance cost is about $4,000 a year, most of which is attributed to the fuel and maintenance such as changing the air filters and maintaining the batteries.

The lifetime of the arrow panel depends on the lifetime of the batteries and the energy type used for recharging the batteries. For the unit with only batteries but no solar- or fuel-recharging facility, the arrow panels have a lifetime of 28 days. With a solar panel, the lifetime could be indefinite dependent on the location where used.

For example, if the arrow panel is used in Florida where the solar intensity is very high, the arrow panels can work 24 hours a day seven days a week (24/7)for an entire year. Conversely, in Alaska or northern parts of the US in the severe winter months, the panels cannot work so efficiently with solar energy.

The diesel-powered arrow panels can work for 20 days at a stretch before refueling and air filter replacement. However, the same arrow panel can have a dual system of solar-operated or diesel-operated.

Portable Rumble Strips

The following information about Roadquake and RoadQuake2 Portable Rumble Strips was obtained from Jeff Tidaback, Sales Representative of Plastic Safety Systems, Inc. in Iowa.

The retail cost of RoadQuake is $1,250 per 11 ft strip and that of RoadQuake2 is $495 per 44 in. segment, with three segments required to make an 11 ft strip ($1,485 for an assembled 11 ft strip). No related property taxes are known and the strips are currently being used across the country without any additional insurance riders.

It is also very easy to store the strips when they are not in use because any type of shelter is fine and storage does not need to be temperature controlled. In addition, there are no associated repair, maintenance, or overhaul costs with these rumble strips.

Installation cost is minimal just to place the units on the roadway and remove them at the end of the work. The manufacturer recommends that the units be checked on the same schedule as the channelizers/at least twice per shift.

The RoadQuake units have an expected lifespan of 3 to 5 years, potentially more, depending on the amount of use. Salvage value at the end of their usable life would be minimal.

Mobile Barrier Trailer (MBT-1)

The base price ownership cost of the MBT-1 trailer with the front and rear platform and two wall sections is approximately $250,000. Additional options include a wall section generator, air compressor, rear steer, variable message system (VMS) signage, and crash attenuator. These options can total up to $150,000.

Operating costs were based on minimal driving and included tires and brakes on the trailer over the life of the trailer. Depending on mileage, tires and brakes would last up to 10 years for an average cost of replacement around $1,500. Other costs would include diesel fuel for the air compressor and/or generator of approximately 10 to 15 gal per 10 hr shift, depending on the rate of usage (i.e., 50 percent load versus 75 percent).

As far as salvage cost goals, it would totally be based on the price of scrap metal at the time that the equipment is retired you, but you would have roughly 50,000 lbs of scrap steel.

CB Wizard Alert System

The information below was obtained from John Hawkins, Sales Manager, TRAFCON Industries, Inc.

The CB Wizard Alert System is a battery-operated system that can be either solar-energy-driven or a plug-in type. The battery is recharged by DC power input, which can be obtained either from solar energy panels or from DC input from the vehicle or trailer or from any type of plug-in through a converter that converts AC to DC.

The CB Wizard Alert System can be handheld or trailer-mounted. The ownership cost of the handheld unit is about $4,300, as it includes only the wizard without solar panels, batteries, antenna, and other relevant accessories. The trailer-mounted unit is $7,500 and includes the solar panels, batteries, and all other relevant accessories.

Operating and maintenance costs for the CB Wizard Alert System is minimal given, after recording the necessary messages, the equipment can be placed on the trailer unattended.

With the solar-energy-powered system, the solar panel needs to be maintained properly and cleaned regularly. The batteries in this case are generally replaced every two or three years at about $200 per battery x 6 or $1,200.

The batteries usually operate between negative (-) 40 degrees to positive (+) 110 degrees Fahrenheit. Therefore, for a solar-operated battery where the temperature varies from place to place more than that, there is a much higher chance that the battery's lifetime is reduced.

Generally, the lifetime of the CB Wizard System depends on the lifetime of the battery and for a unit that draws its power directly from the AC to DC power input converter continuously, the unit can work for five years. However, for the solar-energy-powered unit, the lifetime of the unit is completely dependent on the location and solar intensity for battery recharging.

The repair cost of the unit varies from $300 to $500.

Appendix D References

The researchers created a separate reference list of sources for this appendix and organized it by technology/equipment. While not exactly in sequence by order of appearance in the text of this appendix (as is customary when numbering references/citations with endnotes), the number for each source citation appears in italics and parentheses in the text. The researchers grouped the source information by technology/equipment for your convenience in this final section of the appendix.

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