Cost-Benefit Analysis & Justification

Mobile Barriers MBT-1

June 2017

Executive Summary

by

Gary C. Price, P.E.

with FEMA/DHS justification and additional analysis by CO, CA and others

About the author – *Gary C. Price, P.E. is a transportation consulting engineer with over sixteen years of public experience with the Florida Department of Transportation (FDOT) and twenty six years of private experience as a consulting engineer. His last four years with FDOT was as the State Traffic Operations Engineer. For several different engineering consulting firms he has served as a Senior Transportation Engineer, the Director of Traffic Engineering and Planning, and Assistant Regional Manager where he was a Project Manager and Engineer of Record on highway design and maintenance of traffic (MOT) plans, and Project Engineer on construction engineering and inspection (CEI) projects. Presently he is an independent consulting engineer working on specific projects for several firms.*

During his career, Mr. Price has been the Engineer of Record for the MOT on many highway widening and resurfacing projects on interstate, multi-lane and two lane roadways. Additionally, he has been the Engineer of Record for roadway, signing and marking, signalization and lighting plans.

While at FDOT Mr. Price worked directly with many manufacturers and construction contractors in the development of standards and specifications for the certification and installation of work zone traffic control devices. As a consulting engineer he has been involved in numerous roadway Design-Build and Public-Private-Partnership projects where he worked directly with roadway contractors regarding the "means and methods" to be provided by the contractors. Through his involvement with construction contractors and manufacturers of work zone traffic control devices, Mr. Price is knowledgeable regarding their expertise and capabilities, and the relationship between design and construction related issues.

Gary has been a member of the TRB Freeway Operations Committee and was a member of the High Occupancy Vehicle (HOV) Task Force. He served on the AASHTO Highway Lighting Task Force, Traffic Engineering Subcommittee and Operations Subcommittee prior to joining private practice. Gary was a NCHRP panel member for a freeway incident management project and an urban interchange design project. Gary was a technical advisory panel member for an update of the Traffic Systems Handbook published by FHWA.

Mr. Price has been involved as an Expert Witness in over 100 cases throughout the southeast and has provided court testimony in over 30 cases. He has been qualified as an expert in transportation engineering, accident reconstruction, standards of practice for roadway construction, and maintenance of traffic for roadway projects. Testimony has been provided for plaintiff and defense clients in civil and criminal cases.

Gary has been an adjunct professor at FAMU/FSU College of Engineering since 1988 where he has taught classes in Transportation Engineering, Traffic Engineering Studies, Traffic Systems, Traffic Flow Theory and Geometric Design. Gary was involved in several research projects with the university including Minimum Speeds on Interstate Highways and Truck Lane Restrictions on Interstate Highways.

COST BENEFIT ANALYSIS & JUSTIFICATION
re
MOBILE BARRIERS MBT-1

EXECUTIVE SUMMARY

Every year tens of thousands of people are involved in work zone crashes which result in fatalities, personal injuries and property damage. Millions of people and commerce are affected by the disruptions and congestion delays associated with such crashes and work zone related lane closures. As stated in the Federal Highway Administration's (FHWA) web site, "the loss of nationwide capacity on the National Highway System (NHS) each day during the summer construction season is about 180 million vehicles." The cost of work zone lane closure congestion delay, on roadways in heavily traveled areas, can quickly exceed $500,000 per day. With America's aging infrastructure and increasing traffic flows, the ability to work safely, while maintaining mobility for the public and commerce, is an increasing challenge. Transportation agency applications for highly mobile barriers are for construction, maintenance, and utility/permit work activities, and for Traffic Incident Management programs. Positive protection for these work activities and programs are highly beneficial since they occur in the highway median, on the shoulder, stationary in a highway lane(s), and moving or intermittent in a highway lane.

Likewise, millions of people and commerce are affected by the disruptions and congestion delays associated with large-scale emergencies (wild fires, severe weather, national security threats) and special events with terrorist warnings (sporting, entertainment, political, tourist, and commercial activities). The Department of Homeland (DHS) and the Federal Emergency Management Agency (FEMA, part of DHS) applications for highly mobile barriers deal primarily with traffic diversion at check points or gates, roadway or ramp closures, and the shielding of emergency workers and the public from hazards created by the event.

Only within the last ten years or so, has the private sector responded to these challenges with the development of new movable (or temporary) barrier (movable concrete, movable steel, and movable water filled plastic) and new, highly mobile steel barrier. These advancements in the industry can and have helped improve work zone safety to the benefit of both workers and the traveling public. For work zones of long duration and long work area lengths, movable concrete or other types of barrier to provide positive protection, may be a great option. Work zones for short duration work activities, short work area lengths and moving operations, a new, highly mobile steel barrier may be the better option for positive protection – Mobile Barriers MBT-1. To appreciate the cost and benefits of this option, some background is helpful.

Mobile Barriers MBT-1

Mobile Barriers MBT-1 was originally conceived following a tragic incident in which two Colorado maintenance workers were killed in a work zone incursion. The MBT-1 underwent four years of development and refinement before being initially deployed in 2008. After further in-service testing and evaluation, it was introduced at a trades show in 2009 where it received the first of several innovation awards. The MBT-1 has since received national and international accolades for improving safety, efficiency and traffic flows in and around work zones.

Efficiently enabling the impractical

A highly mobile steel barrier has made it possible to efficiently provide protection where it has historically been impractical – particularly for short duration work activities and slow moving operations. It had not been practical to provide lateral protection for many of these types of work activities. There is not time to set out movable (or temporary) concrete or other types of barrier, and then do meaningful work over night or between rush hours.

The MBT-1 highly mobile barrier is, essentially, a truck tractor and specially designed steel trailer with a trailer-mounted attenuator (TMA). The steel trailer is the barrier, and can drive at speed with traffic to site, or from site to site, for stationary or slow moving operations. The barrier can be switched to left or right configurations at lengths of 42 to 102 feet. Wall heights of the steel trailer are 5, 7 or 9 feet high. Preparation of the site and assembly of barrier components is not required as in other types of movable and temporary barriers.

For transportation agency applications, it provides both longitudinal and lateral protection for road workers and improves safety and traffic flows for road users. For DHS/FEMA applications it provides traffic diversion or "slow approaches" to check points or gates, secure roadway closures, and the shielding of emergency personnel and the public from risk event hazards.

Benefits for workers, the public and commerce

For work crews, the MBT-1 protects against (1) work zone incursions (front, back and side); (2) reduces the number of vehicles and equipment otherwise needed on site (reducing clutter and congestion in the work area); and (3) improves lighting and ambient conditions (reduces noise, fatigue, and generally, improves the ability to communicate within the work area so workers can focus on the work at hand). Each of these three areas has been shown, in applicable research, to be significant contributors to accidents and injuries within work zones if mitigation measures are not implemented.

For the traveling public and commerce, the barrier helps reduce the number and duration of lane closures and improve safety. Research has found that the barrier allows traffic to pass at higher and more uniform speeds. "Buffer lanes", typically, are not required, and lanes can be quickly reopened for peak traffic hours. These factors in turn help reduce disruption and congestion delay in and around work zones to the benefit of both workers and the public.

A former Deputy Executive Director of the Texas Department of Transportation (TxDOT) said, ***"There's no better way to reduce work zone accidents and improve conditions for everyone than to safely complete the work as quickly as possible and reopen the roadway to normal traffic flow."***

Benefits to the public for DHS/FEMA applications are realized in their goals and mission to be prepared for, respond to and recover from all hazards. This requires the application and use of state-of-the-art equipment to "continuously strengthen operations" and "improve upon its operational core competencies" (see MBT-1 Applications for Inclusion in DHS/FEMA Funding Request attached).

20 year life - likely to save someone

In justifying one of their barriers, the Colorado Department of Transportation ("CDOT") noted that ***if the barrier saves just one life in its 20 year life, it pays for itself (many times over).*** The odds are good that a MBT-1 will save someone's life over its estimated 20 year useful life.

In the last several years, barriers have been credited with saving several lives. Barriers have, repeatedly, turned and redirected errant drivers (even semi trucks - see *Semi Crashes*). Such incidents would have been much worse if the work area had been only coned off. As a result, the interstate was not closed in what, otherwise, could have been a disaster. Risks all too common today are turned into "non-events" with the use of MBT-1.

Nominal annualized hard cost

Continuing its justification, CDOT noted "On average the CDOT Applied Research Branch conducts 17 lane closures per year using private traffic control companies and on occasion CDOT maintenance forces. The cost of providing traffic control, which includes equipment as well as manpower, is paid by the Research Branch using SPR funds. This cost will be significantly reduced through deployment of the MBT which comes equipped with truck mounted attenuator, arrow board, electrical power and worksite lights, on-board air for jackhammer and tools. The amount of time it takes to set up, move and remove lane closure is also expected to be reduced with deployment of MBT. Additionally reduction in duration of lane closure will reduce delays and crash potential for the traveling public. ***Amortized over useful life of 20 years at $17,000 annually MBT will pay for itself just in savings in the cost of traffic control in addition to providing positive protection to workers and the traveling public.***" *(excerpt from CO Cost Benefit Analysis attached)*

Estimated $1.9 Million cost benefit per year per barrier

The forgoing cost benefit was based solely on hard costs. If any one of the factors in associated or "soft" costs to workers, the public or commerce are considered, ***the barrier can pay for itself very quickly – many times over!***

The USDOT has valued a life at over $9 Million (*link*). Such estimates may vary, but they are surely significant. In addition to fatalities, we have the additional costs of injuries, property damage, accidents, disruptions, and congestion delay to workers, the traveling public, and commerce, and the impact these costs have on families, friends, businesses and others.

In a detailed analysis, ***California research found a cost benefit of $1.9 Million per year, per barrier*** (see CA Cost Benefit Analysis attached – pg 59). One of the researchers involved noted that the cost benefit is at least, if not even more, applicable to Mobile Barriers MBT-1.

The Hard Truth about "Soft" Costs

Soft costs (fatalities, injuries, accidents, delay, congestion, wasted time, fuel and resources) are real and significant. They need to be considered. They impact workers. They impact the public. They impact commerce. They impact us all. Mobile Barriers MBT-1 can make a difference – improvements in work zone safety, efficiency and traffic flows can help many.

But even if one looks at it solely in terms of hard costs, it is still easy to justify Mobile Barriers MBT-1.

EXHIBITS:

1. **MBT-1 Applications for Inclusion in DHS/FEMA Funding Request**

2. **CO Cost Benefit Analysis re Mobile Barriers**
   Kononov, et. al., Deployment and Evaluation of Mobile Barrier in CDOT Research Branch (Justification)

3. **CA Cost Benefit Analysis re Mobile Barriers**
   Arico & Ravani, A Risk Assessment and Cost Benefit Analysis for the Balsi Beam Mobile Work Zone Crash Protection System.
   (pg 59 - $1.9 million cost benefit per year, per barrier)

For articles, videos and other information, see www.mobilebarriers.com
or click:

- **WorkZoneSafety Blog – Some will not work without it**
- **TxDOT Facebook Post & Comments – We love this barrier! So much safer…**
- **Mobile Barriers Helping Save Lives – Driver 32 Counts Reckless Endangerment**
- **Navigating the I-495 Express Lanes (Capital Beltway)**
- **Big Barriers for Boosting Road Work Safety (FleetOwner)**
- **45% of Contractors Had Vehicles Crash Into Work Zones (AGC)**
- **NBC-DFW News (TxDOT)**
- **Dallas TV 33 News (NTTA)**

Mobile Barriers MBT-1
www.mobilebarriers.com
June 2017

MBT-1 APPLICATIONS FOR INCLUSION IN DHS/FEMA FUNDING REQUEST

Positive Protection

There comes a time in almost every community when unanticipated events create an immediate, critical need for a temporary physical barrier – to protect people, property and public safety. This need can arise from a man-made event, such as an active shooter situation, a potential IED or an act of terrorism, or it could come from a weather-related event such as a tornado, hurricane or wildfire. First Responders including emergency personnel, police, fire and public works officials, need to act quickly to protect themselves and others in order to mitigate the impact of the event giving rise to the need for a protective barrier. They need something that is portable, requires minimal human intervention, is cost effective and is easy to install and maintain. They need the positive protection that a highly mobile barrier system can provide.

Temporary concrete barriers (TCB) (also known as “Jersey walls”) are commonly used devices to provide barriers in long-term highway work zones or at building construction sites, but these kinds of barriers are ill-suited to a rapid-response requirement. For short term public safety activities, TCB or other similar devices may require much more time to install than authorities have to respond to an unfolding incident. They are labor-intensive to set up, not cost-effective and generally do not provide the level of personal protection to the setup crews that other types of barrier systems provide.

Because TCBs and similar devices were not designed for rapid-response situations, communities have previously resorted to such work-around techniques as staging large dump trucks, garbage trucks, police cars and even empty school busses to form a temporary protective barrier. Not only is this a misuse of valuable government vehicles, it is still labor intensive and expensive to set up each of these vehicles in a barrier-like formation, especially where the risk of damage to the vehicle is very high.

However, with the introduction of portable positive protection, and especially highly mobile barriers which became available in 2008, providing immediate protection for a rapid-response need is now available. Plus, these portable barriers provide the kind of cost efficient, highly effective capability that law enforcement and first responders need.

Highly Mobile Barriers for Positive Protection

A highly mobile barrier system is, essentially, a standard truck tractor and a specially designed steel trailer with a trailer-mounted attenuator (TMA) which is configured to provide both longitudinal and lateral protection for personnel and property. The steel trailer is the barrier and can be driven by a single individual to the site where the protection is to be provided. The steel trailer can be switched to left or right configurations at lengths of 42 to 102 feet. Wall heights of the steel trailer are 5, 7 or 9 feet high. Preparation of the site and assembly of barrier components is not required so that there is nearly instant set-up and deployment. This provides a significant advantage in rapid response situations over TCBs and other types of temporary barriers. It is not a stretch to suggest that time saved in deploying a highly mobile barrier system could easily equate to lives saved in an emergency response.

DHS/FEMA Applications

As the nation's lead emergency management and preparedness agency, FEMA constantly strives to improve upon its operational core competencies and capabilities and those of state, local and regional emergency preparedness and response organizations. To serve disaster victims and communities more quickly and effectively, FEMA builds on experience, applies lessons learned and best practices from field operations. Best practices for providing positive protection where needed, in the shortest response time possible, is with the deployment of highly mobile barriers in situations where, for example, severe storms wash out a road or bridge; trees or active power lines are down over roadways; or, a wildfire changes direction and creates a probable traffic danger. Mobile barriers can also be used for crowd control purposes and vehicle stand-off protection zones.

Homeland security users can, in many respects, benefit from the experience of transportation agencies use of mobile barriers. Transportation agencies use highly mobile barriers to separate workers from traffic passing by a work zone or incident location. Some transportation applications are similar to the needs of law enforcement and emergency responders, but some are unique. Homeland security applications deal primarily with personnel protection, traffic diversion at check points or gates, roadway or ramp closures, and the shielding of emergency workers and the public from hazards created by the event.

Many state transportation agencies have established Traffic Incident Management (TIM) programs which are composed of many of the same partners and stakeholders that law enforcement and first responders utilize to carry out their mission. Although their focus is primarily on managing highway traffic incidents, many of the same equipment assets, coordination, communication and manpower needs are the same as those for successfully managing large-scale emergencies (wild fires, severe weather, national security threats) and special events with terrorist warnings (sporting, entertainment, political, tourist, and commercial activities).

The availability of highly mobile barriers to provide positive protection improves the ability to prepare for, respond to, and recover from all hazards (natural risks, terrorists, or man-made disaster).

> **Check Points, Road or Ramp Closures & Traffic Diversions -** For warnings or alerts of terrorist and man-made events, highly mobile barriers can be used for highly mobile temporary check points which can be positioned and repositioned as needed. Vehicles can be either stopped off the wall, or pulled inside the lighted internal area for better examination or random inspections.
>
> Highly mobile barriers can be used to support short term roadway/lane closure or moving applications such as security checks and clearances of underground facilities and bridges. These are typical activities along roadway routes prior to presidential or dignitary visits and special events parades.
>
> Highly mobile barriers can be used to restrict or close access to public events, critical infrastructure or government facilities following DHS or law enforcement warnings of potential vehicle-born attacks.

The barriers can also be used to further protect security personnel at permanent check points or gates at critical infrastructure facilities such as nuclear power facilities, chemical production facilities, water treatment plants, telecommunications sites and critical government facilities. Multiple barriers can be rapidly arranged to create a "slow approach" to the check point to detour intrusion attacks. A highly mobile barrier can also be used to completely close a check point by occupying a position 90 degrees to the check point or gate roadway, and remaining there until an entering vehicle is cleared to do so. The highly mobile barrier would then be driven just far enough to allow access and then backed to the former position.

For high vehicular volume check points or gates, the highly mobile barrier can be positioned downstream of the existing closure devices without the check point or gate roadway closed. When directed or a potential intrusion vehicle is observed, the tractor driver of the highly mobile barrier immediately repositions to completely close the check point or gate roadway.

Highly mobile barriers can be used in roadways to support other permanent barriers protecting government facilities. These support barriers can be rapidly deployed and positioned based on pre-established plans following DHS or law enforcement warnings of potential truck intrusion attacks like the recent terrorist attacks in Nice, France, and London, England.

Highly mobile barriers can be placed until more traditional barriers (portable or temporary concrete barrier) can be installed should the situation, threat or warning persist.

Incident Preparedness & Cleanup – Highly mobile barriers can be used to support first responders in natural risks, including hurricanes, tropical storms, tornadoes, flooding, ice storms, earthquakes, and wildfires. Responders can use the barriers, for example, prior to various incidents to prepare (for example disconnect power and lights, deploy special signage), during the event to divert traffic and reroute traffic, and after the event to again cleanup and restore functionality and service.

Some applications of a highly mobile barrier for a roadway or ramp closure may not require an enforcement officer and vehicle, which is the typical way such closure is accomplished without a barrier. If placement of the device precludes circumvention, this enforcement officer and vehicle can be used for other duties during the risk event.

Shielding from hazards - Highly mobile barriers can be used by first responders to shield emergency personnel during recovery from damaged infrastructure and drop offs created by the risk event, and then to shield the public from these hazards until more permanent barrier can be provided or the hazard corrected.

Customized Highly Mobile Barriers

Highly mobile barriers can be customized to meet special needs of the user. Highly mobile barriers have a standard sheer strength of approximately 1,000,000 lbs and can stop a car or pickup in a direct 90 degree impact of at least 45 mph. When angled to the approach, the barrier is capable of stopping, turning and/or redirecting even larger vehicles at higher speeds. If the user deems it necessary to exceed this force, then a customized barrier can be provided to meet the user's requirements.

Additionally, highly mobile barriers are rated to 85,000 GVWR and can carry substantial equipment and supplies. They can be customized for the user to carry vehicles, turrets, communication masts and other user needs when deployed to designated locations in accordance with pre-established response plans.

Optional cranes with hook and basket can be mounted for lifting and elevated work.

The outer skin on the barrier can be upgraded at nominal additional cost with special hardened steel capable of withstanding small arms fire. Additional blast protection can also be added.

Summary

A highly mobile barrier system, like the one described above, is eligible for funding under a number of FEMA-administered grant programs, as it fits squarely within the definition of Authorized Equipment List 14SW-01-WALL - Barriers: Fences, Jersey Walls. The highly mobile barrier gives local law enforcement, first responders and critical infrastructure owners and operators a cost-efficient, security-effective way to protect persons and property quickly and with minimal risk.

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Deployment and Evaluation of Mobile Barrier in CDOT Research Branch

(Justification)

Oversight Team

Jake Kononov, Ph.D., P.E.-Director of Research

Charles Meyer, P.E., PTOE – State Traffic and Safety Engineer

Rich Sarchet, P.E. – Region 3 Traffic Operations Engineer

David Wieder, P.E. – State Maintenance Superintendent

Darrel Lingk – Director of Office of Transportation Safety

Steve Hersey, P.E. – Region 6 Traffic and Safety Engineer

David Reeves, P.E. – Safety Research Engineer

Introduction

Deployment and evaluation of Mobile Barrier project in research branch has been selected through a competitive project selection process by the CDOT Research and Implementation Council (RIC) on March 8th, 2012. RIC is comprised of CDOT senior and middle management as well as FHWA staff, representing the multidisciplinary expertise in addition to diverse research needs. Research Implementation Council's decision reflects first and foremost its concern for safety and also its desire to evaluate and deploy new technology which will increase effectiveness and efficiency of setting up traffic control.

Benefits of Implementation

Safety

In the course of the year research staff conducts about 17 lane closures on freeways, bridges and high speed arterials. A significant portion of the work is performed in travel lane or adjacent shoulder while motorists travel by at high speeds and in very close proximity to research staff. The work is generally performed by CDOT research staff and university professors and students. Frequently out of state observers of research initiatives are also present in the work zone. University personnel generally are less sensitized and are less aware of work zone hazards and have limited exposure to work zone safety issues. Work zone traffic control efforts currently consist of a variety of measures to ensure researcher and motorist safety, such as variable message signs, and flaggers. However, current accepted practices for short duration work zones provide limited protection of the workers and separation from vehicles passing through the work zone. Current safety measures such as truck mounted attenuators (TMAs) and spotters typically require additional personnel exposed to the hazards simply to provide these safety measures. Even with TMAs and spotters, the immediate work area remains unprotected adjacent to the functioning travel lanes, allowing errant vehicles and distracted drivers to enter this most vulnerable work area. Lastly, in all locations around Denver metro area and many locations around the state, due to high traffic volumes, lane closure policy requires work activities to be performed at night. Unfortunately the percentage of impaired motorists is substantially higher than during the day.

A recent accident in the research work zone occurred in March of 2012 on Sunday morning when a distracted driver who was using a cell phone ran into the lane closure area at high rate of speed. Even though the lane closure work zone was designed and deployed in full compliance with the Manual on Uniform Traffic Control Devices (MUTCD), and in accordance with Region 4 Lane Closure Policy, the driver's inattention led to loss of control and subsequent crash. Fortunately no one was hurt in this specific accident; however, the outcome could've been much different should the circumstances that lead to loss of control altered only slightly. A definite and extremely valuable benefit of having and using Mobile Barrier Trailer (MBT) is complete isolation and full protection of research staff from errant vehicles. This benefit is proven and demonstrated through the NCHRP 350 testing and acceptance. Societal costs of crashes provided by the FHWA (safety.fhwa.dot.gov) suggest that in addition to obvious importance of ensuring safety of researchers in the work zone (humanitarian and ethical considerations of protecting workers in the work zone) it is also cost-effective.

COMPREHENSIVE COSTS IN POLICE-REPORTED CRASHES
BY ABBREVIATED INJUR SCALE (AIS) SEVERITY
(1994 Dollars)

SEVERITY	DESCRIPTOR	COST PER INJURY
AIS 1	Minor	$ 5,000
AIS 2	Moderate	$ 40,000
AIS 3	Serious	$ 150,000
AIS 4	Severe	$ 490,000
AIS 5	Critical	$ 1,980,000
AIS 6	Fatal	$ 2,600,000

Considering that Mobile Barrier's useful life is 20 years during which time it is likely to prevent one or more crashes the benefits of injury prevention are likely to exceed the cost of the barrier (~$300,000).

Savings on Traffic Control

On the average CDOT Applied Research Branch conducts 17 lane closures per year using private traffic control companies and on occasion CDOT maintenance forces. The cost of providing traffic control, which includes equipment as well as manpower, is paid by the Research Branch using SPR funds. This cost will be significantly reduced through deployment of the MBT which comes equipped with truck mounted attenuator, arrow board, electrical power and worksite lights, on-board air for jackhammer and tools. The amount of time it takes to set up, move and remove lane closure is also expected to be reduced with deployment of MBT. Additionally reduction in duration of lane closure will reduce delays and crash potential for the traveling public. Amortized over useful life of 20 years at $17,000 annually MBT will pay for itself just in savings in the cost of traffic control in addition to providing positive protection to workers and the traveling public.

Research Benefits

Deployment of MBT in research will enable CDOT to quantify the efficiency of deployment and removal of traffic control for lane closures in Colorado specific environment. This question is very important to CDOT because unlike other DOTs CDOT has implemented statewide lane closure policy which provides criteria and authoritative guidance for scheduling lane closures on all state highways and interstates. It was formulated in order to strike an appropriate balance between delays to the traveling public in the work zone and the cost of construction. It is based on extensive data collection and estimates of queues and delays expected during lane closures.

As a result many of the lane closures are now allowed only at night which places a premium on efficiency of setting up and removing traffic control devices. Proposed research aims to evaluate: the efficiency in deploying and removing the system; its impacts on the work operations, worker safety, and worker productivity; perceptions of safety provided by an MBT compared to traditional work zone protective measures; and the types of projects for which it is most suitable. More specifically MBT deployment project will address the following:

1. Evaluate an MBT when used during representative CDOT maintenance activities (case study projects). The performance metrics to be evaluated are: (a) time required to set up and break down the system; (b) limitations and enhancements to the work operations; (c) worker safety and safety perception; (d) worker productivity; (e) motorist safety and safety perception; and (f) system performance based on project/worksite attributes. Determine and assess any adverse effects of transporting the MBS to/from a work zone.

2. Evaluate the same performance metrics of traditional work zone protection practice when used during representative CDOT maintenance activities (comparison projects).

3. Compare the performance of the MBS to that of traditional work zone protection practice based on the identified performance metrics.

4. Develop guidance for CDOT and construction contractors to reference when planning and using an MBT for maintenance activities and potential use on CDOT construction projects.

Additionally preliminary evidence suggests that traffic flow speed and saturation rates around mobile barrier may be higher than next to a cone or barrel delineated work zone. This hypothesis will be tested under field condition as part of MBT deployment. More specifically MBT deployment project will address the following:

5. Identify speed, flow and saturation rates next to lane closure using traditional traffic control devices during typical maintenance operation and compare them with speed, flow and saturation rates next to MBT based lane closure.

Other Benefits

MBT will be controlled and maintained by the Applied Research Branch much like skid-number testing truck currently maintained and operated by research staff. The use of MBT is most effective when a given set of users are allowed to set it up for their specific needs and preferences. There are advantages to having MBT available to research staff to use on research projects and having it configured, loaded and shortened or lengthen as required by site and traffic conditions. Further use and systematic evaluation of MBT by the research branch will pave the way for possible statewide deployment of MBT by maintenance sections. Such deployment is expected to improve safety and efficiency in work zones on CDOT's maintenance and construction projects and is in concert with the intent of the FHWA's Every Day Counts Initiative.

A Risk Assessment and Cost Benefit Analysis for the Balsi Beam Mobile Work Zone Crash Protection System

An AHMCT Technical Report

UCD-ARR-08-09-30-01

Mary C.Arico

Bahram Ravani

For Distribution Within Caltrans Only.

Contents

Chapter 1

Introduction

1.1 Project Overview

The Balsi Beam Crash Protection System has been developed by the California Department of Transportation (Caltrans) to provide positive protection for the highway workers working adjacent to on-going traffic in highway work zones. The system was developed as a mobile work zone protection device to protect Caltrans employees working on highway pavements during highway maintenance operations. It was originally designed by Ms. Angela Wheeler of the Division of Maintenance using research data from Mr. Gary Gauthier of the Division of Research and Innovation.

The Balsi Beam is an innovative concept that allows for rapid deployment of a guardrail type device to provide positive protection for workers within a lane closure. One unit of this system is in use as a form of on-site evaluation. Limited crash testing was performed on the system demonstrating its effectiveness. There was, however, a need for further studies evaluating this system and understanding its safety potential, as well as work zone types that would fully benefit from these safety improvements. In particular, there is a need for a proper risk assessment and safety benefit analysis study for this innovative concept.

The purpose of this work is to perform such an analysis of risks and the potential safety benefits of the Balsi Beam system for working and mobility safety enhancements and improvements. The scope of the work is limited to a paper study involving development of quantitative and qualitative models for such an assessment and a cost benefit analysis. The aim is to develop injury cost models for work zone safety evaluation, and to develop an understanding and prioritization of highway maintenance projects that would receive the most benefit from the Balsi Beam system.

1.2 Task Summary and Approach

Any analysis of safety benefits derived from a crash protection device requires an understanding of crash types and primary injury mechanisms in the type of environment for which the device is designed for, as well as exposure data that would allow determination of crash rates. This information then needs to be combined with injury cost models and statistical evaluation to perform a risk assessment and cost benefit analysis.

In the case of the Balsi Beam, two types of analysis are needed to identify crash types. One is to perform an epidemiological type study of previous work zone type accidents using available databases. The second is to perform an analysis of collision types using predictive models and the existing design of the Balsi Beam system to identify collision angles, workspace boundary movements, and intrusion potentials for the system.

Identification of crash types is an important step in an analysis of risks and benefits derived from any crash protection device. It has been used for seat belts, [6, 21], for head restraints, [25], and for a variety of other automotive related crash protection devices,[14]. A similar type study is needed for work zone accidents. This was performed in Task 1 of this research, where California work zone injury data were evaluated.

Task 2 of this research involved developing injury evaluation criteria for work zones. Development of such criteria is important for proper cost benefit analysis as well as risk assessment. The approach performed here evaluated trends in injury occurrence and severity in highway work zones, using logistic and Poisson regression models. This also involved defining an index to measure the risk of injury, or exposure, a worker experiences in a highway work zone.

The next step in the research involved development of injury cost models for work zone injuries. This was performed under Task 3. Developing injury cost models is an important step in cost benefit analysis of any crash protection device or system. One has to consider both direction economic costs to as well as the total economic cost. These costs cover direct losses and economic costs of motor vehicle crashes as well as the economic value society places on the human life and pain and suffering. In the case of motor vehicle accidents, previous studies have standardized such an evaluation, [4, 17, 33] for the National Highway Traffic Safety Administration (NHTSA) by defining cost estimate criterion. This research used the most updated cost estimate guideline proposed by the Federal Highway Administration (FHWA) as the value of a statistical life (VSL).

Finally, Task 4 was completed, in which a safety benefit analysis was developed, combining the results of the previous tasks. The injury cost model was combined with operational costs to fully evaluate the benefits of Balsi Beam deployment.

Task 5 is completed in this report, as a set of recommendations and guidelines are presented which summarize the results of the study.

1.3 Task List

1. Analyze Crash Data From Work Zone Accidents
    (a) Identify crash types
    (b) Identify primary injury mechanisms
    (c) Identify trends in injury occurrence and severity
2. Develop Injury Risk Evaluation Criteria
    (a) Evaluate work zone injury data
    (b) Develop a method to measure/quantify risk of injury
3. Develop Injury Cost Model
    (a) Identify cost estimates for injuries
    (b) Evaluate costs of evaluated injuries
4. Perform Safety Benefit Analysis
    (a) Perform cost benefit analysis using injury cost model and operational cost estimates
    (b) Perform risk assessment combining injury evaluation and cost benefit analysis
5. Develop Recommendations
    (a) Develop guidelines that can be used for decision making on prioritization for deployment of Balsi Beam for various roadway work zones.
6. Documentation and Reporting

Chapter 2

Injury Analysis of California Work Zone Injury Data

2.1 Introduction

The importance of work zone safety and risk assessment is evident. However, the means of measuring risk in the highway work zone has not been established. The term *work zone exposure* is a commonly used term to quantify exposure to risk of serious and/or fatal injury. Ullman et al.[27], evaluated work zone exposure measures after noting that comprehensive data do not exist on work zone exposure characteristics. Ullman et al. evaluated various work zone exposure measures, including the length, duration and frequency of work zone activity, impact of work zone on available roadway capacity, vehicle exposure to both active and inactive work zones, and the percent of the highway system with at least one day of work zone activity. The purpose of this study was to evaluate the quality and quantity of work zone data in the United States. The most frequent use of *work zone exposure* measures, in research, has been in the study of work zone accidents, and the effect of the work zone on vehicle collisions, focusing, primarily, on the traveling public. Khattak et al.[15], evaluated the effect of the presence of a work zone on injury and non-injury crashes in California. In a similar study, Schrock et al.[23], thoroughly evaluated 77 fatal work zone collisions, in order to develop possible countermeasures to improve work zone safety.

In California, in 2004, there were 109 work zone fatalities, 2 of those were workers working in the work zone [8, 18] (Figure 2.1). While worker fatalities are low despite the high exposure, according to the California Strategic Highway Safety Implementation Plan, *'No worker fatalities in work zones is a reasonable goal'* [9]. However, while some research has been done to evaluate the relationships between various work zone characteristics and the rate of accidents, very little has been done focusing on the risk of injury to the worker.

This portion of the research will accomplish the goal of evaluating work zone parameters and

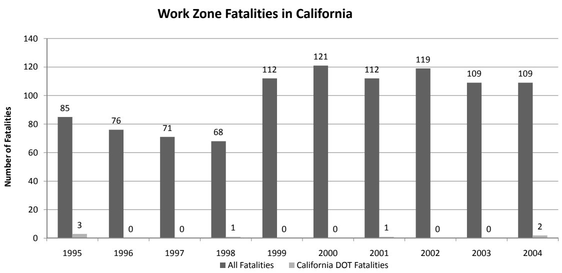


Figure 2.1: Number of fatalities in California work zones. The larger tally represents all fatalities cause by motor vehicle accidents in and around construction and maintenance zones, where the smaller corresponds to Caltrans employees working in the work zone.

how they relate to the risk of injury or fatality for the workers in the work zone. (In the remainder of this research, all injuries considered will be referred to as work zone injury, and they consider only the injuries obtained by the workers in the work zone.) The method for calculation of work zone exposure performed in this research uses the results of work zone injury analysis. Work zone injury data were evaluated to determine evident trends in injuries, and relation to various work zone parameters.

The injury data were evaluated, and the severity of the injury was categorized using the Abbreviated Injury Scale (AIS) [2]. The AIS is an anatomically based, consensus derived global severity scoring system, which classifies an injury in a body region according to its relative importance on a six point scale, [12]. The scale divides the human body into nine regions or groups. These body regions include the head (cranium and brain), face (including eye and ear), neck, thorax, abdomen and pelvic contents, spine (cervical, thoracic, lumbar), upper extremity, lower extremity (including pelvis and buttocks), and external (skin), thermal injuries and other trauma. The injury description defined by AIS assigns a number to each injury, characterizing the severity of the injury. The classes of injury severity are (1) minor, (2) moderate, (3) serious, (4) severe, (5) critical, and (6) maximum injury (currently untreatable).

In addition to the AIS, a second method was used to evaluate the injuries that occurred in the work zone. In many serious accidents the victim is likely to sustain more than one serious injury. The Injury Severity Score, (ISS), is an anatomical scoring system that provides an overall injury score for persons with multiple injuries [3, 13], and is defined as the sum of the squares of the highest AIS grade in each of the three most severely injured body regions. The ISS will be a number in the range of 0 to 75, with any injury assigned an AIS of 6, automatically receiving and ISS of 75. Baker et al.[3], found that persons with an ISS of 10, or less, had high survival rates, where those with an ISS of 50 or greater where much more likely to die as a result of their injuries. Because of its ability to summarize injury severity and good correlation with survival, the Injury Severity Score, is the preferred way to compare both injury severity and rate in different situations.

The object of the work zone injury analysis was two-fold. Evaluation of injury data was performed first to understand the patterns of work zone injuries, and the statistical effects of work zone parameters on the severity of injury. Secondly, using this information, the development of a measure of risk is desired. There are a number of measures used to identify risk, particularly risk to injury in motor vehicle collisions. The metric developed in here, the 'Risk Index', was created as a method to effectively measure risk of injury in a work zone. The index calculates an estimate of the risk of serious or fatal injury in a work zone, which can then be compared between numerous work zones. A 'Risk Index' of this type would be beneficial to work zone protection planning.

This approach has been applied to measure various parameters in other situations, particualy in studies of occupant safety. Viano et al.[32] developed an index, 'Motion Criteria', that considered a number of properties used to determine the relative quality of a lap belt restraint function. By evaluating the 'Motion Criteria' in different situations or crash tests, the restraint function was compared at each different setting. The advantage of an index such as the 'Motion Criteria' is that comparisons can be readily made between seemingly different situations. Viano et al. used the Motion Criteria measure to relate the level of occupant motion, or lap belt restraint, with the probability of abdominal injury.

Analysis of the California work zone injury data began with an epidemiological evaluation of all reported injuries using Microsoft Access and Excel. Following the evaluation, a detailed statistical analysis was performed for those injuries occurring in the work zone in the ten year period from 1998 through 2007. The statistical software package SAS®(SAS Institute, Inc.) was used to perform regression analysis relating injury and accident parameters with the probability and severity of injury.

2.2 Description of Data

California work zone injury data were analyzed to determine injury trends in highway maintenance work zones. The database from which the data were extracted is a collection of accident and injury reports maintained by the California Department of Transportation. These reports included both vehicle accident reports and personal injury accident reports. Overall, the database contained 36,379 injury reports covering the entire state of California, and providing data from the early 1960s through 2007.

During evaluation, the data fields contained in the database were divided into three categories: accident information, work zone information, and injury information. The accident parameters included the date and time of day of the accident (further categorized into peak/rush hours (0700-0900, 1600–1900) or non-peak hours), the weather, roadway and visibility conditions at the time of the accident, the location of the accident, the approximate speed limit at the location, the type of accident (classified as either a motor vehicle collision, struck by object, or struck by motor vehicle), the angle of the work zone intrusion (head on, rear end, sideswipe, or broadside), and the estimated vehicle miles of travel (VMT) for the geographic area where the accident took place. The VMT variable was established using estimates of vehicle miles that motorists traveled on California State Highways in the area of the injury, averaging the yearly estimate from 1999 through 2006. The averages were divided into three categories, low, medium and high, based on the geographic area.

Work zone information included the type of maintenance activity being performed by the worker at the time of the accident, the duration of the work activity (categorized as short-term stationary, short duration, or mobile), and whether or not the victim was wearing personal protective equipment (PPE). The Texas Transportation Institute, [26, 30], defined work zone durations based on the time the workers are occupying the area, as shown in Table 2.1. Since this research only focused on short-term and temporary work zones, the duration category only has three levels, short duration, short-term stationary, and mobile.

Work Zone Duration	Description
Long-term stationary	Occupy a location for more than three days
Intermediate-term stationary	Occupy a location for more than one daylight period, but no more than three days, or at a night location for at least one hour
Short-term stationary	Occupy a location for one hour or more during a single daylight period
Short-duration	Occupy a location for up to one hour
Mobile	Move intermittently or continuously along a roadway segment

Table 2.1: Description of defined work zone durations.

Finally, the injury information incorporated whether or not the incident was fatal, the body region injured, the nature of injury, injury severity (based on AIS and ISS), and the number of lost and modified work days of the victim following the accident. Recall, that ISS is calculated as the sum of the squares of the three most severely injured body regions, which are defined as AIS 1, AIS 2 and AIS 3. A detailed description of the data is shown in Tables 2.2, 2.3 and 2.4.

2.3 Epidemiology of Work Zone Injury Data

Methods

An epidemiological analysis of the Caltrans accident data was carried out in a number of steps. The purpose of this analysis was to identify trends in the injury data, specifically related to Location, Accident Type, VMT, and Activity Type parameters.The entire data set was first evaluated by dividing Accident Type and looking at various accident, work zone and injury parameters including Location of Accident, Activity Type, Lost/Modified Time, Fatal Accident, and VMT. Each

Variable	Class Level	Variable Type
Time of Day	Non-peak Hour Peak/rush Hour	Class variable
Weather	Dry/clear Snow/wet	Class variable
Visibility	$> \frac{1}{2}$ mile $< \frac{1}{2}$ mile	Class variable
Location	City Street Freeway/Highway Freeway Lane Closure Freeway Ramp Moving Lane Closure Shoulder Closure	Class variable
Speed Limit		Continuous
Type of Accident	Motor Vehicle Collision Struck by Motor Vehicle Struck by Object	Class variable
Angle of Intrusion	Head On Rear End Sideswipe Broadside	Class Variable
Vehicle Miles of Travel	Low Medium High	

Table 2.2: Detailed description of accident variables used in analysis of California work zone data.

Variable	Class Level	Variable Type
Activity Type	Driving On Foot	Class variable
Duration	Short-term Stationary Short Duration Mobile	Class variable
PPE	True False	Class variable

Table 2.3: Detailed description of work zone variables used in analysis of California work zone data.

Variable	Class Level	Variable Type
Fatal	True False	Class variable
Body Region	Head Face Neck Thorax Abdomen Spine Upper Extremity Lower Extremity Whole Body/Multiple	Class Variable
Nature of Injury	Abrasion Amputation Bone Fracture Bruise Concussion Crush/Pinch/Cut/Puncture Cumulative Trauma/ Multiple Dislocation Death by Injury Soreness Strain/Sprain Torn Muscle	Class variable
AIS 1	1–6	Class variable
AIS 2	1–6	Class variable
AIS 3	1–6	Class variable
ISS		Continuous
Modified Days		Continuous
Lost Days		Continuous

Table 2.4: Detailed description of injury variables used in analysis of California work zone data.

succeeding analysis evaluated a smaller subset of injury data.

The next step in the accident evaluation was to assess only the reports in which the Accident Type field was either motor vehicle collision, struck by object, or struck by motor vehicle. Data where evaluated, focusing on work zone accidents, including both work zone intrusions and accidents occurring within the work zone. This level of evaluation examined the work zone accidents by Month of accident, Time of Day, and the VMT where the incident took place.

The final level of epidemiological analysis focused on only work zone intrusion data. The data were evaluated based on the type of work zone Intrusion Angle, Body Region of injury, injury severity (measured by AIS and ISS), Maintenance Activity, Visibility, Nature of Injury, number of Modified or Lost Work Days, Weather Conditions, PPE usage, Preventability, and Class Title of Victim. Graphics for each analysis were prepared in Excel, and will be further discussed.

Results

The results of the epidemiological evaluation of the injury data are shown in Table 2.5 through Table 2.10, and Figure 2.3 through Figure 2.13. As described, the analysis started by looking at the general trends of accident reports from the entire dataset. Each step of observations narrowed the analysis until the final analysis only involved incidents which were reported as work zone intrusion accidents.

Table 2.5 below shows the first level of analysis of the overall accident trends, looking at the Accident Type versus Location of Accident. Of the motor vehicle collisions, the top three locations were freeway/highway, city street and freeway ramp, respectively. Similarly, freeway/highway was the most frequent site for struck by motor vehicle accidents, with all other locations averaging around thirteen accidents. The struck by object accident type category has the largest number of accidents occurring in non-roadway locations. The locations, included in the 'non-roadway' category were cafeteria/restaurant, common carrier, crew's quarters, elevator, equipment bay, laboratory, maintenance yard, office building, parking lot, residence, rest area, shop/warehouse, stairway, and unknown (not reported) locations. The 'other*' category of the Accident Type variable was created to encompass those accident types which were not considered to occur in a work zone, or would not be caused by a work zone intrusion. These accidents incorporated: altercation with other, animal/insect bite/sting, repetitive body motion, single event body motion, caught in machinery, caught in non-machinery, chemical exposure, contact with electrical current, contact with flame/fire, contact with hot object, contact with poisonous plant, contact with sharp object, exposure to hazardous material, exposure to dust, exposure to gas/fumes, exposure to high/low temperatures, exposure to infectious material, exposure to irritants, exposure to loud noises, exposure to sun, exposure to virus, fall from ladder/steps, fall from spilled liquid, foreign object in eye, radiation exposure, stress and trip/slip/fall.

	MV Collision	Struck by MV	Struck by Object	Other*
City Street	479	18	91	739
Construction Site	35	18	102	1175
Freeway Lane Closure	35	26	65	513
Freeway Ramp	142	28	196	1668
Freeway/ Highway	1331	121	975	10169
Hwy Structure/ Bridge	54	13	184	1897
Moving Lane Closure	41	2	2	57
Shoulder Closure	21	15	126	1066
Street/ Hwy Lane Closure	26	7	42	414
Sidewalk	1	0	11	171
Tunnel/ Tube	0	0	4	97
Non-Roadway	67	18	1284	13707

Table 2.5: Evaluation of Caltrans injury data by Accident Type and Location of accident. (MV: Motor Vehicle)

The second general analysis of the injury data evaluated the frequency of an Accident Type when taking into account the Activity Type, and is shown in Table 2.6. The most frequent activity type in motor vehicle collision accidents was driving, riding or sitting. For struck by motor vehicle accidents, the most frequent activity is walking, followed closely by standing. The most common work activity being performed during a struck by object incident is the combination of lifting, carrying, pulling, pushing and reaching, and the second most common known activity is using a hand tool. A large portion of the activities in the struck by object incidents were unknown, or classified as not relevant to this analysis. The activity types deemed not relevant include adverse action, altercation with co-worker or supervisor, burning, disciplinary action, enter/leave vehicle, office work, using bench tools, using shop machinery, or unauthorized activity. In further analysis, the Activity Type variable was divided into two categories, driving, or on foot. The activities that were included in the driving level were driving, riding, sitting, and enter/leave vehicle. The on foot level incorporated assigned duties, flagging, inspecting, standing, bending, stooping, shoveling, using hand tools, walking, jumping, running, diving, lifting, carrying, and reaching.

The next overall evaluation assessed the number of Modified and Lost Days required following incidents based on the accident type. Referring to Table 2.7, the majority of reported accidents in all four categories of accident type required less than five days of lost or modified time. The Accident Type requiring the most lost and/or modified time was the struck by motor vehicle category, indicating that these accidents produce more serious injuries. This conclusion in backed up by Table 2.8, in which the number of fatal accidents by Accident Type is shown.

The final general analysis of the complete accident dataset evaluated the Accident Type by the VMT or Vehicle Miles of Travel of the geographic area in which the accident occurred. Of the roadway accidents, the highest percentage of motor vehicle collision and struck by motor vehicle

	MV Collision	Struck by MV	Struck by Object	Other*
Flagging	1	12	5	120
Gardening	1	4	44	657
Inspecting	5	24	84	803
Lifting, Carrying, Pulling, Pushing, Reaching	9	12	1012	8322
Running	4	4	8	194
Shoveling	2	10	26	677
Sitting, Riding, Driving	2092	17	102	1453
Standing	14	58	250	847
Stooping, Bending, Climbing	1	7	145	2358
Using Hand Tool	2	9	513	2754
Walking	4	66	26	3814
Unknown, Not Relevant	97	43	867	9674

Table 2.6: Breakdown of injury data by reported Activity Type. (MV: Motor Vehicle)

Modified Time

Days	MV Collision	Struck by MV	Struck by Object	Other*
0	68.69	65.46	69.23	67.43
1–5	11.44	14.06	14.74	12.37
6–10	8.11	5.62	7.72	8.59
11–20	3.78	2.81	4.51	4.77
21–30	2.84	2.01	1.56	2.41
31–40	0.77	2.01	0.52	0.91
41–100	3.78	5.22	1.53	2.97
Over 100	0.59	2.81	0.19	0.54

Lost Time

Days	MV Collision	Struck by MV	Struck by Object	Other*
0	70.18	51.41	84.71	78.80
1–5	15.90	13.25	9.15	10.40
6–10	3.11	4.42	1.40	2.48
11–20	2.16	5.62	1.27	2.02
21–30	1.58	2.41	0.88	1.38
31–40	0.77	3.21	0.39	0.71
41–100	2.25	4.42	1.27	2.17
Over 100	4.05	15.26	0.94	2.02

Table 2.7: Percent of Modified and Lost Days by Accident Type. (MV: Motor Vehicle)

	MV Collision	Struck by MV	Struck by Object	Other*
Fatal Accidents	12	17	1	27

Table 2.8: Fatal accidents by Accident Type. (MV: Motor Vehicle)

accidents occurred in areas of high VMT, and the highest percentage of struck by object accidents occurred in areas defined as low VMT regions, as shown in Table 2.9. The occurrence of accidents in high and low VMT regions was higher than in areas categorized as having medium VMT levels. While the large quantity of accidents in low VMT areas is unsettling at first, it can be explained by Figure 2.2, which shows the number of California districts in each VMT category. Eight of twelve districts of California are grouped into the 'Low' category based on the division of the VMT range.

	MV Collision		Struck by MV		Struck by Object		Other*	
	#	(%)	#	(%)	#	(%)	#	(%)
Low	805	(36.07)	94	(35.34)	1337	(43.38)	13792	(43.54)
Medium	295	(13.22)	43	(16.17)	393	(12.75)	3892	(12.29)
High	975	(43.68)	113	(42.48)	1173	(38.06)	11672	(36.85)
Unknown	157	(7.03)	16	(6.02)	179	(5.81)	2317	(7.32)

Table 2.9: Spread of injury accidents types throughout the districts of California. (MV: Motor Vehicle)

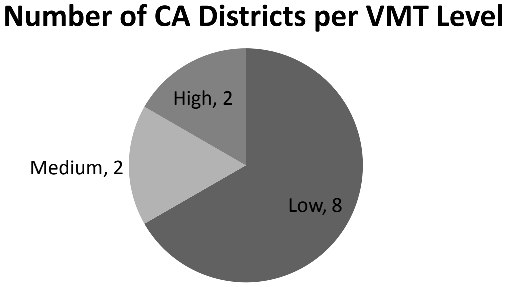


Figure 2.2: Division of California Department of Transportation Districts into Vehicle Miles of Travel (VMT) categories.

The second level of evaluation narrowed the accident data down to accidents that were reported as either motor vehicle collision, struck by motor vehicle, or struck by object. Table 2.10 shows the percent of work zone intrusion and within work zone accidents for each Accident Type. The table shows that 15% of all motor vehicle collisions were work zone intrusions, and only about 3% occurred within the work zone. A total of 80% of the struck by motor vehicle accidents occurred in the work zone, about 50% as work zone intrusions with the remaining 30% occurring within the work zone. Only approximately 1% of the struck by object accidents were a result of a work zone intrusion, but 41% occurred within the work zone. Figure 2.3 shows percentage of the Accident Type of interest for work zone intrusion accidents and within work zone accident types. The majority of the work zone intrusion accidents were classified as motor vehicle collision (68%), followed by struck by motor vehicle (26%), and struck by object incidents (6%). The frequency of accident types of within work zone accidents differed from work zone intrusions, with the majority (88%) classified as struck by object, and the remaining divided equally between motor vehicle collisions (6%) and struck by motor vehicle collision (6%).

	MV Collision		Struck by MV		Struck by Object	
	#	(%)	#	(%)	#	(%)
Work Zone Intrusion	351	(15.41)	132	(49.07)	32	(1.04)
Within Work Zone	83	(3.64)	84	(31.23)	1265	(41.03)

Table 2.10: Work zone accidents broken down by Accident Type. (MV: Motor Vehicle)

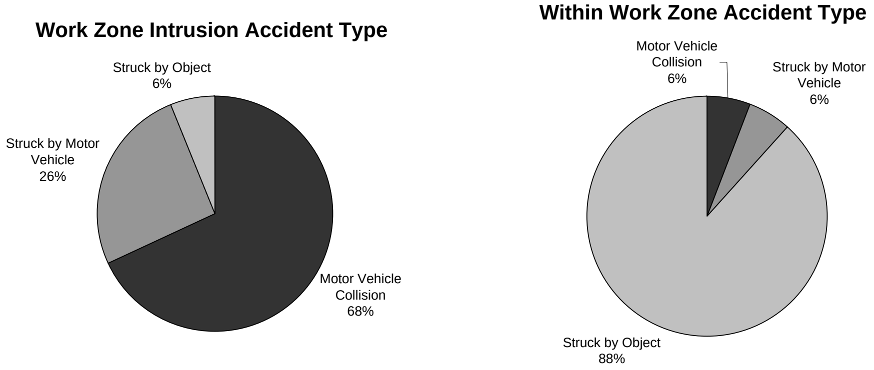


Figure 2.3: Work zone accidents divided by Accident Type.

Figure 2.4 and Figure 2.5 shows the break down of work zone accidents (work zone intrusion and within work zone accidents) by month and time of day. The average number of work zone intrusion accidents was calculated to be 42.92 ± 6.88, compared to the mean number of within work zone incidents, 119.33 ± 17.46. While there is some difference in the number of accidents from month to month in Figure 2.4, the standard deviation is not large. However, there is a large variance across reported time of day graphic. For work zone intrusion accidents, the average number of accidents was found to be 20.38 ± 23.53, and for within work zone accidents the mean was 53.13 ± 74.77. In both cases, the standard deviation is larger than the mean.

The evaluation of work zone incidents based on VMT is shown in Figure 2.6. The graphic shows the highest number of work zone intrusion accidents occurred in areas with high vehicle miles of travel, or heavy traffic. However, the highest number of within work zone accidents occurred in areas of low VMT.

The final step in epidemiological analysis dealt with work zone intrusion accidents only. Figure 2.7 below shows the reported intrusion angle for all work zone intrusion incidents. The most common intrusion angle is entrance from the rear of the work zone, or a rear end intrusion. Figure 2.8 illustrates the injury break down of the reported accidents. These graphics show that the majority of the injuries are considered minor, and the highest percentage of injuries were back injuries. The injury analysis agrees with Figure 2.9, which shows the number of modified and lost days as a result of the injury. Figure 2.10 shows that in most cases, the roadway conditions were

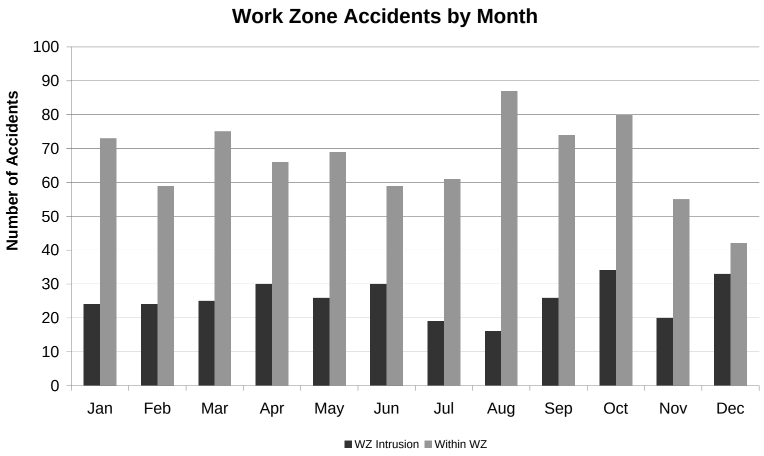


Figure 2.4: Break down of work zone accidents by month.

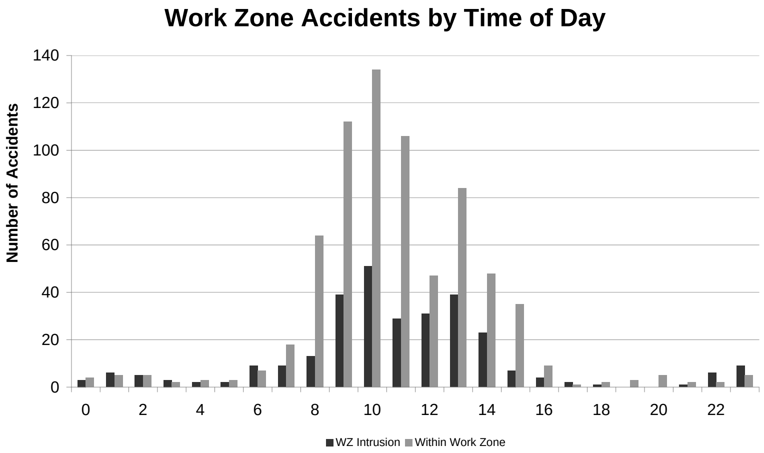


Figure 2.5: Work zone accidents by time of day.

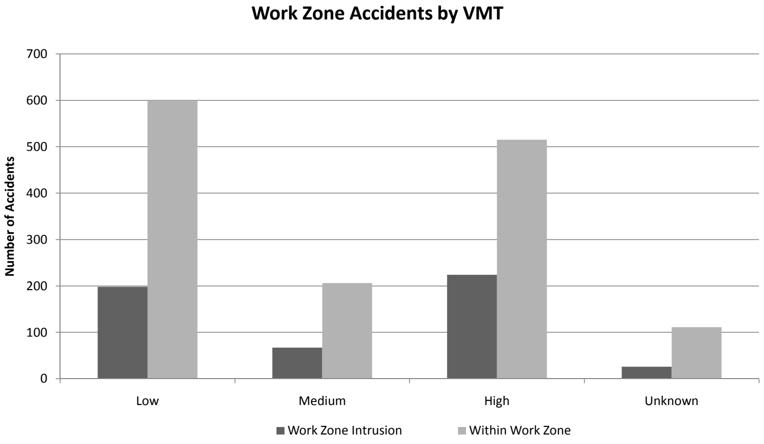


Figure 2.6: Distribution of work zone accidents across Vehicle Miles of Travel (VMT) levels.

ideal for worker safety: clear, dry roadways. The breakdown of work zone intrusions by maintenance activity is illustrated in Figure 2.11. The letter codes for each maintenance activity correspond to an assigned activity code, as described in Table 2.11.

A	Flexible Pavement	J	Other Structures
B	Rigid Pavement	K	Electrical
C	Slope/Drainage/Vegetation	M	Traffic Guidance
D	Litter/Debris/Graffiti	R	Snow/Ice Control
E	Landscaping	S	Storm Maintenance
F	Environment	W	Training/Field Auxiliary Services
H	Bridges	Y	Work for Others

Table 2.11: Description of Caltrans maintenance activity codes.

The two most common activities in which a work zone intrusion occurred were Litter/debris and graffiti clean up, and traffic guidance work. The second graphic describing the breakdown of work zone intrusions, deals with maintenance activities in a more general way, based on the duration of the work zone, (Figure 2.11). In this analysis, work zones were categorized as one of three defined work zone durations, short-term stationary, short duration, or mobile. A short-term stationary work zone occupies a location for one hour or more during a single day. The most common duration in which a work zone intrusion occurred was a moving work zone. Figure 2.12 shows that the majority of workers were wearing personal protective equipment at the time of the accident, and that over 90% of the incidents were not preventable on the part of the worker, as reported by the on-site supervisor. Finally, Figure 2.13 shows the classification title, or job position of the victim. The first figure shows that the most frequently injured workers are those acting as equipment operators, while the second most frequently injured are highway maintenance workers. The second figure shows the level or rank of the injured worker. The highest percentage of victims of work zone intrusions includes landscape and maintenance workers. This result is not surprising, as landscape and maintenance workers make up the largest demographic of the work zone work force.

2.4 Statistical Analysis of Work Zone Injury Data

The procedure used in the statistical analysis of the injury data followed the ‘Model Building Process’ outlined in Kutner et al., [16]. The steps required to build a statistical model are outlined below:

1. Data collection and evaluation using collinearity procedures.
2. Reduction of explanatory or predictor variables using variable stepwise and backward selection methods.

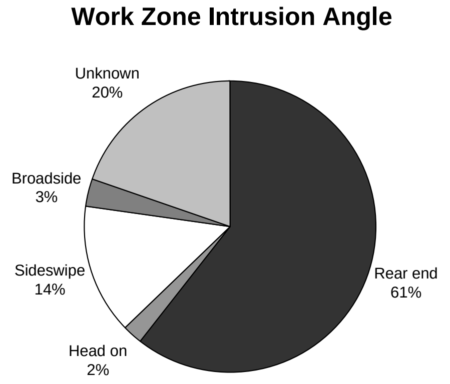


Figure 2.7: Reported intrusion angle of errant vehicles into the work zone.

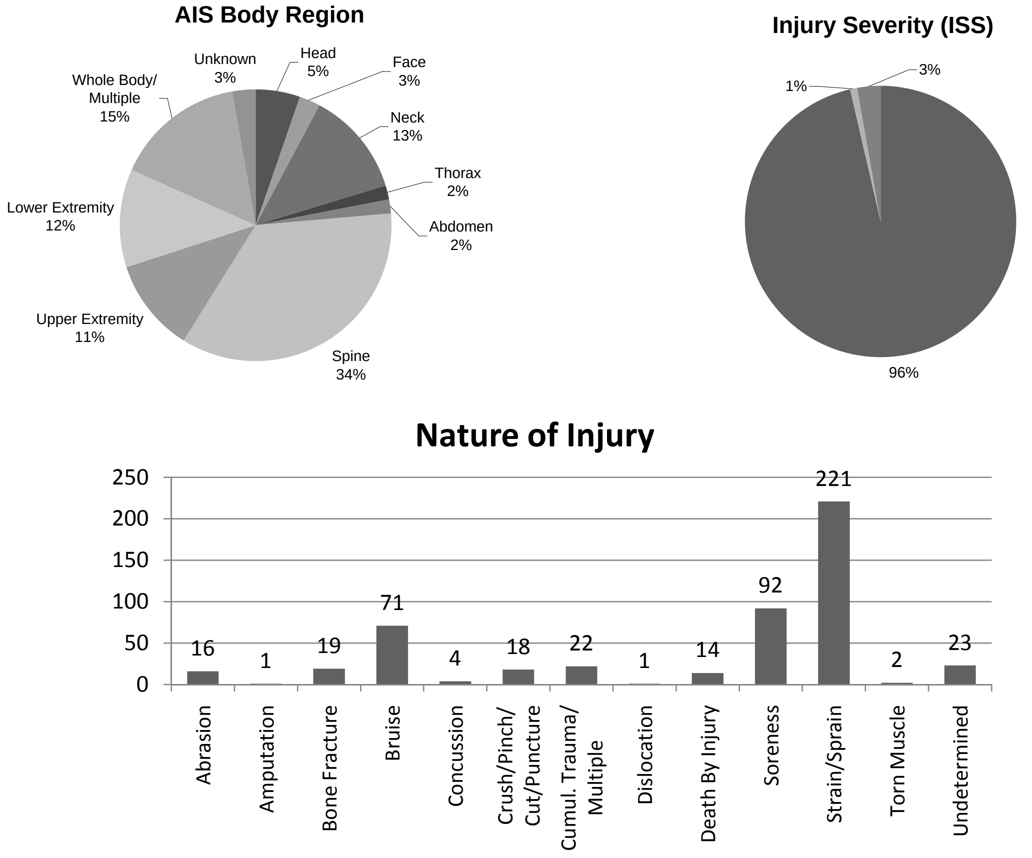


Figure 2.8: Reported body region injured, injury severity and nature of injury in California work zone injuries due to intrusion of an errant vehicle.

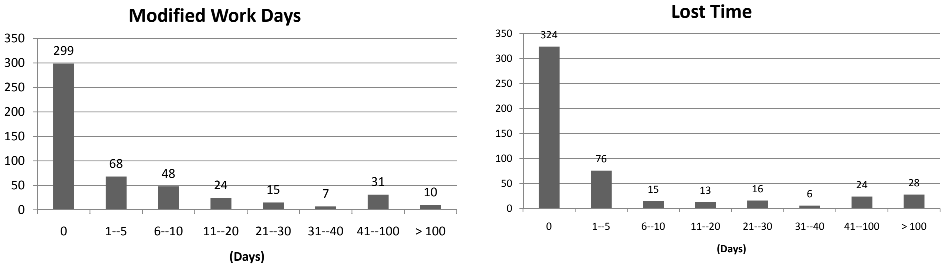


Figure 2.9: Modified and lost time (days) required following injuries in work zone intrusion accidents.

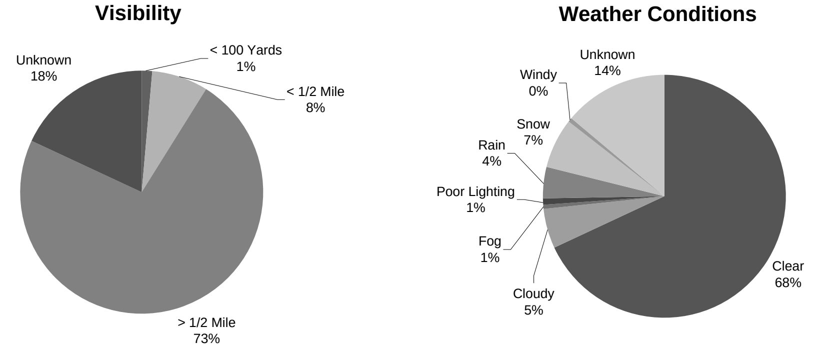


Figure 2.10: Visibility and weather conditions reported at the time of injury in California work zones.

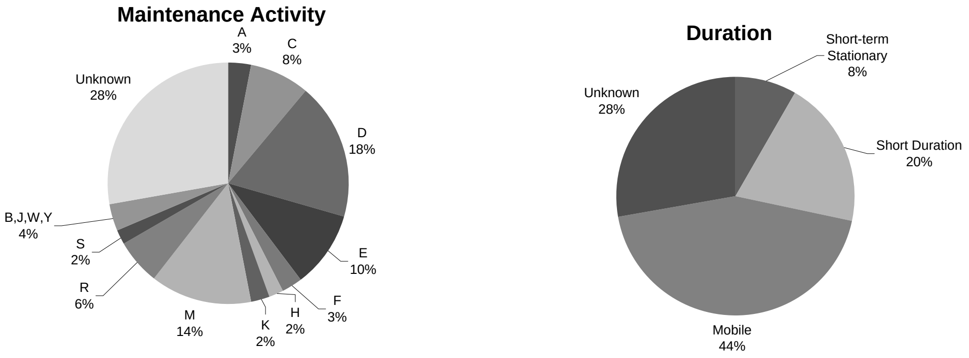


Figure 2.11: Recorded maintenance activity, and corresponding duration of work zone at the time of a work zone intrusion.

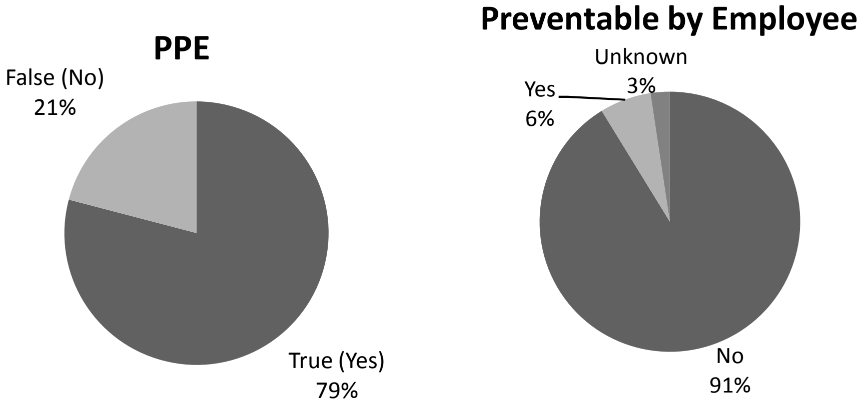


Figure 2.12: PPE usage and whether or not the incident was preventable by the employee, in California work zone injury data.

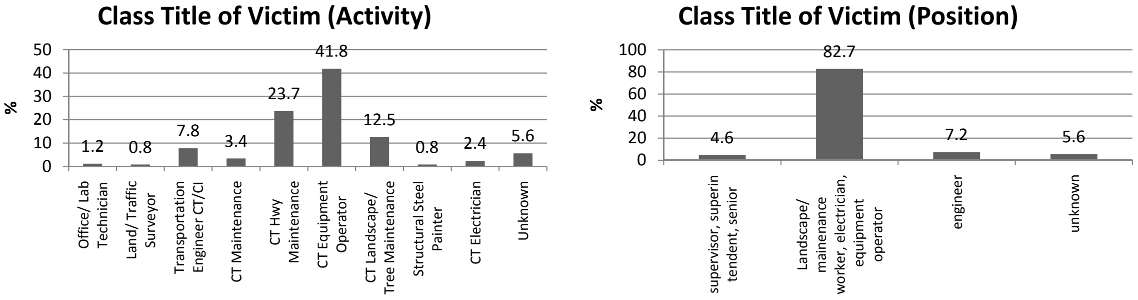


Figure 2.13: Breakdown of job title, and activity of the injured worker.

3. Model refinement and selection using goodness of fit and residual evaluation.

4. Model validation by evaluating predictive power statistics.

The statistical analysis was done using the SAS statistical package (SAS Institute Inc.).

2.4.1 Evaluation of Explanatory Variables

Both the CORR and REG procedures were performed using SAS, on two subsets of explanatory variables, which correspond to the two different regression analyses to be performed.

```
                                 Pearson Correlation Coefficient
                                   Prob > |r| under H0: Rho = 0


                         Time     Weather  Visibility  Activity              Approximate
                 VMT     Code      Code      Code        Type    Location   Speed Limit  Duration     PPE


                1.0000  -0.0396  -0.2281   -0.1075     0.0416   -0.0912     -0.1695     0.0195   -0.0987
     VMT
                         0.4837   <.0001    0.0567     0.4620    0.1062      0.0025     0.7442    0.0803

               -0.0396   1.0000   0.0934    0.0104    -0.0220   -0.0573     -0.0197     0.0730    0.0159
  Time Code
                0.4837            0.0981    0.8541     0.6974    0.3104      0.7274     0.2212    0.7785

   Weather     -0.2281   0.0934   1.0000    0.5293    -0.0445    0.0238      0.0820     0.0778    0.0567
    Code
                <.0001   0.0981             <.0001     0.4313    0.6735      0.1465     0.1919    0.3160

  Visibility   -0.1075   0.0104   0.5293    1.0000     0.0082    0.0221      0.0518    -0.0034   -0.0267
    Code
                0.0567   0.8541   <.0001               0.8853    0.6958      0.3598     0.9550    0.6376

   Activity     0.0416  -0.0220  -0.0445    0.0082     1.0000    0.0908      0.0936    -0.0353    0.0053
    Type
                0.4620   0.6974   0.4313    0.8853               0.1077      0.0972     0.5544    0.9251

               -0.0912  -0.0573   0.0238    0.0221     0.0908    1.0000      0.6385     0.0647   -0.0202
  Location
                0.1062   0.3104   0.6735    0.6958     0.1077                <.0001     0.2778    0.7216

 Approximate   -0.1695  -0.0197   0.0820    0.0518     0.0936    0.6385      1.0000     0.0619    0.0106
 Speed Limit
                0.0025   0.7274   0.1465    0.3598     0.0972    <.0001                 0.2997    0.8508

                0.0195   0.0730   0.0778   -0.0034    -0.0353    0.0647      0.0619     1.0000   -0.0808
  Duration
                0.7442   0.2212   0.1919    0.9550     0.5544    0.2778      0.2997               0.1754

               -0.0987   0.0159   0.0567   -0.0267     0.0053   -0.0202      0.0106    -0.0808    1.0000
     PPE
                0.0803   0.7785   0.3160    0.6376     0.9251    0.7216      0.8508     0.1754
```

Figure 2.14: Summarized PROC CORR output from SAS logistic regression model.

The first variable reduction occurred with the combination of the Visibility and the Weather Code variables into a new explanatory variable named ‘Conditions’. The Pearson correlation coefficient between the two separate variables was equal to 0.5293, with a corresponding $p - value$ of < 0.0001. The new Conditions variable takes a value of 0, 1, or 2, corresponding to the added values

```
                                    Parameter Estimates


                                Parameter     Standard                                        Variance
Variable                  DF     Estimate      Error      t Value  Pr > |t|   Tolerance    Inflation

Intercept                  1     -0.94377     25.84287     -0.04    0.9709         .            0
VMT                        1      0.11666      0.02877      4.06    <.0001      0.86071      1.16184
Time Code                  1     -0.10815      0.11399     -0.95    0.3436      0.95555      1.04652
Weather Code               1      0.24013      0.07846      3.06    0.0024      0.55165      1.81273
Visibility Code            1      0.06277      0.08668      0.72    0.4696      0.60027      1.66593
Activity Type              1      0.30306      0.06729      4.50    <.0001      0.96605      1.03515
Location                   1      0.00454      0.03358      0.14    0.8926      0.93315      1.07164
Approximate Speed Limit    1      0.00825      0.39759      0.02    0.9835      0.99995      1.00005
Duration                   1     -0.01779      0.03594     -0.49    0.6211      0.92542      1.08059
PPE                        1      0.15099      0.06560      2.30    0.0221      0.93512      1.06938
```

Figure 2.15: PROC REG output for SAS logistic regression model.

of the previous two explanatory variables as shown in Table 2.12. The correlation values output for the new Conditions variable are *TOL*= 0.8295 and *VIF*= 1.2056, which show no correlation or collinearity with other variables.

Conditions	Weather/roadway conditions	Visibility	Sum (Weather + Visibility)
C_0	$0 : Clear/dry$	$0 :> \frac{1}{2} mile$	0
C_1	$1 : wet/snowy$	$0 :> \frac{1}{2} mile$	1
	or	or	
C_1	$0 : Clear/dry$	$1 :< \frac{1}{2} mile$	1
C_2	$1 : Wet/snowy$	$1 :< \frac{1}{2} mile$	2

Table 2.12: Definition of new variable Conditions.

The correlation table Figure 2.14 also showed high correlation statistics between Approximate Speed Limit and Location of Accident. This result was not unexpected as, in many cases, where the speed limit data were missing, the speed limit was selected based on the roadway type. Based on the collinearity, and the missing data, the Approximate Speed Limit variable was dropped from the analysis.

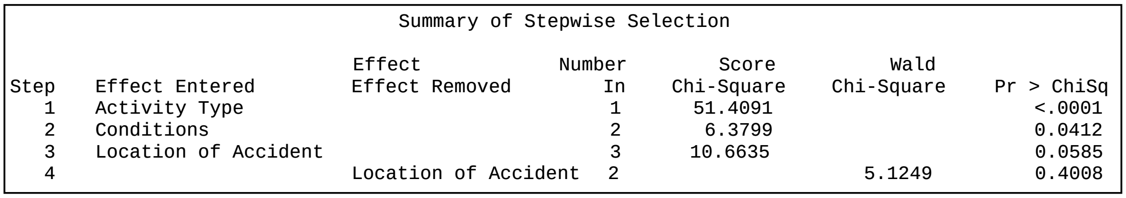
The possibility of multicollinearity existed between the VMT and Conditions variables, based on the correlation table. However, the tolerance values for both variables were large (TOL < 0.4), so both variables remained in the model.

The collinearity analysis for the second group of regression parameters contained similar results to the first. In addition, the variable Accident Type was removed based on the collinearity diagnostics (*TOL*= 0.3959, *VIF*= 2.8910). There was evidence of possible collinearity between other variable pairs existed(VMT–Conditions, Activity Type–Intrusion Angle, Activity Type–ISS), however the variance inflation factors for these variables were not a cause for concern, so the explanatory variables were left in the model.

2.4.2 Logistic Regression

Methods

Following the model building procedure described by Kutner, et al., [16], variable selection for the logistic procedure was performed using a stepwise selection method.



```
                                   Summary of Stepwise Selection

                               Effect             Number        Score         Wald
Step    Effect Entered         Effect Removed         In    Chi-Square    Chi-Square    Pr > ChiSq
   1    Activity Type                                  1       51.4091                      <.0001
   2    Conditions                                     2        6.3799                      0.0412
   3    Location of Accident                           3       10.6635                      0.0585
   4                           Location of Accident  2                      5.1249        0.4008
```

Figure 2.16: Logistic regression variable selection procedure.

The model initiated with an intercept term only, as shown in Figure 2.16. PROC LOGISTIC then selected the most significant explanatory variable, Activity Type to add to the model ($p - value < 0.0001$). Following evaluation, the Wald Chi-square met SLSTAY specifications, so the variable remained in the model. The second step of variable selection began with selecting the most significant of the remaining explanatory variables, Conditions, whose $p - value$ was equal to 0.0412. Again, the Wald Chi-square $p - value$ was within the specified range so the variable remained in the model. In the third step of variable selection, SAS chose Location as the next variable to enter the model, with a $p - value$ equal to 0.0585. However, upon evaluation, the Wald Chi-square $p - value$ for the variable in the model was greater than 0.4 ($p - value = 0.4008$). Therefore, step five involved the removal of the Location variable from the model. Because the same variable was added and removed from the model in successive steps, the selection process was terminated. The final model relates injury to a linear combination of Activity Type and Conditions.

Three additional models were created for predicting injury outcome based on common knowledge of variables understood to influence injury risk on highway work zones. Model A refers to the model created by stepwise selection, where Models B, C and D are the alternate models:

$$\begin{aligned}
&\text{Model A:} && \\
&\textit{Probability of Injury} &=& \ \alpha + \beta_1(\text{Activity Type}) + \beta_2(\text{Conditions}) \\
&\text{Model B:} && \\
&\textit{Probability of Injury} &=& \ \alpha + \beta_1(\text{Activity Type}) + \beta_2(\text{Duration}) + \beta_3(\text{VMT}) \\
&\text{Model C:} && \\
&\textit{Probability of Injury} &=& \ \alpha + \beta_1(\text{Conditions}) + \beta_2(\text{VMT}) + \beta_3(\text{Time Code}) \\
&\text{Model D:} && \\
&\textit{Probability of Injury} &=& \ \alpha + \beta_1(\text{Activity Type}) + \beta_2(\text{Duration}) + \\
& && \ \beta_3(\text{Time Code}) + \beta_4(\text{PPE})
\end{aligned}$$

The explanatory variables chosen to make up Model B were selected to recreate, as closely as possible, the regression model created by Qi et al.,[19], in their study of the frequency of accidents, specifically rear end crashes, in work zones. Qi found that work zone type, traffic control devices, traffic/work zone layout, lane blockage, work zone duration, facility type, and AADT (annual average daily traffic) were associated with the frequency of rear end accidents. Therefore, the independent variables selected that most closely characterize this previous statistical model were Activity Type, Duration, Location, and VMT.

Model C was build using a subgroup of explanatory variables that represent roadway and environmental variables. The non-work zone parameters included Location, VMT, Time Code, and Conditions. Conversely, the variables selected for Model D were selected on the premise that they are variables controllable during work zone planning. Model D contained the explanatory variables representing Activity Type, Duration, Time Code, and PPE. (The variable Location was removed from Models B and C after the first iteration as it caused the models to experience quasi-complete separation.)

By evaluating the available regression diagnostic statistics, comparisons were made between the four models and the 'best' model was selected. Table 2.13 shows the results of the diagnostic statistics. The deviance and Pearsons goodness of fit statistics test the hypothesis that the model is as good as the saturated model, and that the model is appropriate. Based on these two statistics, Models A,B and D provide a better fit to the data. The Hosmer-Lemeshow statistic also tests model goodness of fit by grouping the data into sets based on the estimated probabilities. The statistics support the null hypothesis that the fitted model is adequate, with a more convincing (larger) $p - value$ occurring in Model D, and similar values in all other models.

In addition, predictive power must also be evaluated to ensure that the model both fits the data and does an adequate job of predicting the injury occurrence. The statistics in Table 2.13 reflect that except for Model C, all other models rate equally in their respective predictive power.

The final model evaluation involves examination of model residuals and influence points, shown

Deviance and Pearson Goodness of Fit Statistics

	Model A	Model B	Model C	Model D
Deviance				
Value	62.8743	5.5364	16.8601	3.2852
Pr > ChiSq	1.000	0.9376	0.0510	0.9985
Pearson				
Value	141.7072	5.4623	16.2527	2.4006
Pr > ChiSq	0.2096	0.9407	0.0618	0.9997
Hosmer-Lemeshow Goodness of Fit Test				
Chi-Square	0.8583	4.0106	2.3510	1.2118
Pr > ChiSq	0.6511	0.6752	0.6715	0.9763
Predictive Power				
% Concordant	78.0	84.5	48.9	83.9
% Discordant	3.4	9.6	28.9	8.3
% Tied	18.6	6.0	22.2	7.8
Pairs	7046	7046	7046	7046
Somers' D	0.746	0.749	0.199	0.757
Gamma	0.917	0.797	0.256	0.821
Tau-a	0.120	0.120	0.032	0.121
c	0.873	0.875	0.600	0.878
Max-rescaled R-Square	0.3967	0.3833	0.0501	0.3820

Table 2.13: Logistic regression diagnostic results.

in Figure 2.17. One outlying observation exists; however, all other Pearson and deviance residuals have an absolute value of approximately 2 or less. Evaluation of the *DFBETAS*, (Figure 2.18), shows that the most extreme values are less than 1 in Models B and D. These two diagnostics verify the assumption that the outlying case is not influential.

Overall, Models B and D are similar in goodness of fit, predictive power and treatment of residuals. Model B was chosen as the 'best' model as it agrees with previous research and the fit of the Poisson regression models following in the next section.

Results

The output of the LOGISTIC procedure is very descriptive, giving detailed model information, class level information, frequency distribution of the class variables, deviance and model fit statistics, global null hypothesis tests, Type 3 analysis results, maximum likelihood estimates, odds ratio, and predictive power measures.

Fit statistics and predictive power measures were used to determine which model was the best predictor of injury severity. Figure 2.19 shows the three sections of the SAS output important for model analysis. The first section of interest in Figure 2.19 is the 'Type 3 Analysis of Effects'. This test evaluates the main effects in the model, testing the null hypothesis that the parameter estimate is equal to zero ($H_o : \beta = 0$). These results are similar to those presented in the next

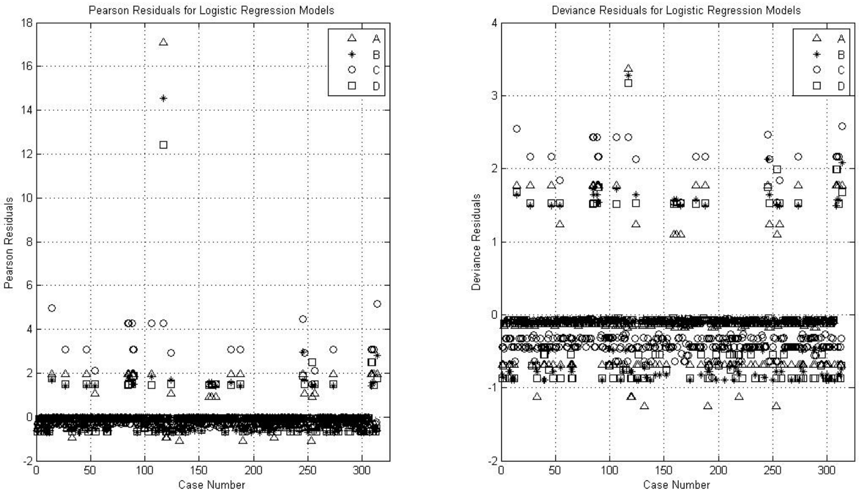


Figure 2.17: Logistic regression residual plots.

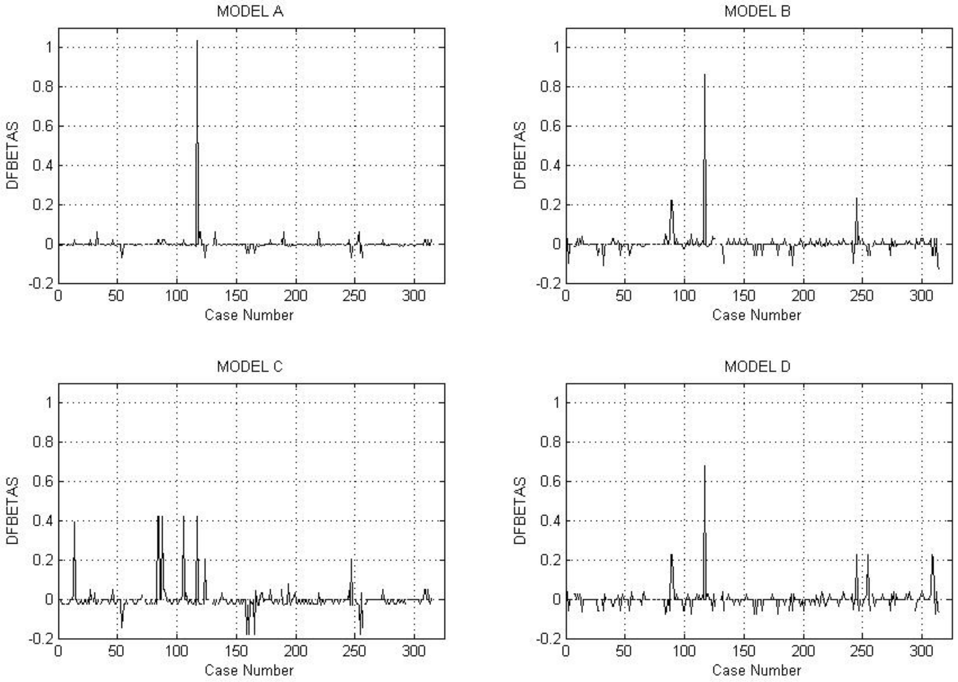


Figure 2.18: DFBETAs plot for logistic regression.

```
                                  Type 3 Analysis of Effects
                                                       Wald
                      Effect             DF    Chi-Square    Pr > ChiSq

                      VMT                 2        2.7384        0.2543
                      Duration            2        0.1168        0.9433
                      Activity Type       1       17.3692        <.0001


                           Analysis of Maximum Likelihood Estimates
                                                           Standard          Wald
Parameter                                DF    Estimate       Error    Chi-Square    Pr > ChiSq

Intercept                                 1     -5.4550      1.2308       19.6439        <.0001
VMT             2                         1     -1.0045      0.8700        1.3332        0.2482
VMT             3                         1      0.3383      0.5040        0.4505        0.5021
Duration        mobile                    1      0.1017      0.7325        0.0193        0.8895
Duration        short duration            1     -0.0763      0.8140        0.0088        0.9253
Activity Type   On Foot                   1      4.2996      1.0317       17.3692        <.0001


                                     Odds Ratio Estimates
                                                                    Point         95% Wald
Effect                                                           Estimate     Confidence Limits

VMT             2 vs 1                                              0.366      0.067      2.015
VMT             3 vs 1                                              1.403      0.522      3.767
Duration        mobile                vs short-term stationary      1.107      0.263      4.652
Duration        short duration        vs short-term stationary      0.927      0.188      4.568
Activity Type   On Foot vs Driving                                 73.673      9.753    556.511
```

Figure 2.19: Condensed output from the SAS LOGISTIC procedure for the model predicting the probability of a worker obtaining a non-minor injury.

output section, 'Analysis of Maximum Likelihood Estimates' in that both test the null hypothesis that $\beta = 0$. However, the maximum likelihood estimate evaluates the significance of each level of the explanatory variable. In addition to testing the significance, the maximum likelihood estimates also lists the parameter estimates and their standard error. Finally, the third section of output shown gives the 'Odds Ratio Estimates', which are derived by taking the exponential of the parameter estimate (e^{β}).

The best way to interpret the parameter estimates produced by the logistic regression is to use the odds ratio. Referring to Figure 2.19, point estimates are available for each level of the three explanatory variables in the regression model. The odds of a worker receiving a non-minor injury are approximately 74 times greater for a worker on foot compared to workers working from a vehicle, conditional on all other variables. The Activity Type is the most significant variable with a Type 3 Analysis $p - value$ of < 0.0001. The second most significant main effect is the VMT variable, ($p - value = 0.2543$), which is not statistically significant. The odds of receiving a non-minor injury are about 1.5 times greater for work taking place in regions declared as high VMT areas compared to low VMT areas. However, the odds of being seriously injured decrease in areas of medium level VMT, compared to areas of low VMT. The odds ratio for a given level is only valid if all other explanatory variables remain constant. The third variable in the model, Duration also does not have a significant effect on the model. However, its inclusion in the model produced better fit statistics and predictability. According to the logistic regression model, workers in mobile work zones are 1.1 times more likely to be severely injured compared to workers in short-term stationary work zones. The likelihood of being severely injured decreases for workers in short duration work zones.

While evaluation of the odds ratio is the preferred way of logistic regression model analysis, the predicted probability can also be determined. The predicted probability of obtaining a non-minor injury based on activity type, and work zone duration, and for three different VMT regions was calculated, and is shown in Figure 2.20.

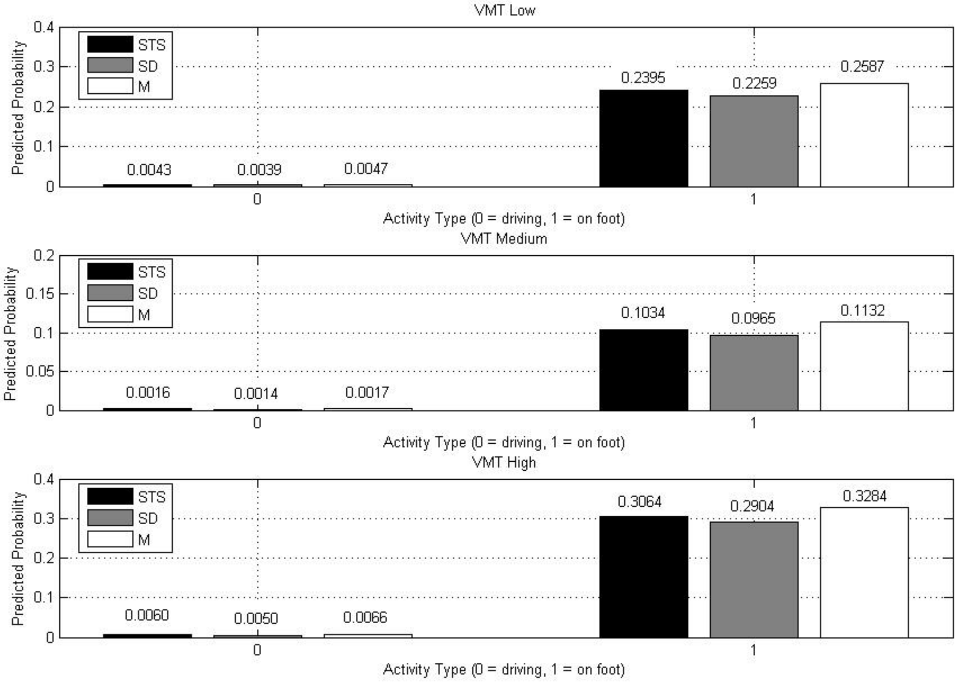


Figure 2.20: Predicted probability of obtaining a serious injury based on Activity Type, work zone Duration and VMT.(STS: Short-term Stationary, SD: Short Duration, M: Mobile)

Interpretation of the first figure, for VMT = 1, or areas of low Vehicle Miles Traveled, is as follows: For short-term stationary work zones, the probability of obtaining a non-minor injury increases from 0.46% to 23.95% when the worker moved from performing work in a vehicle to work on foot. In short duration work zones, the probability of severe injury increases in the same manner as short-term stationary work zones, although not as much (0.39% to 22.59%). The final analysis for areas of low VMT shows that in mobile work zones, the probability of severe injury increases from 0.47% for workers in vehicles to 25.87% for workers on foot. In the two graphs following, for medium and high levels of VMT, the probability of obtaining a non-minor injury increased for all durations when comparing the predicted probability of serious injury for workers working from vehicle to workers performing duties on foot. In all three VMT regions, the largest increase is observed in mobile work zones, followed by short-term stationary work zones, and finally short duration work zones. While there are differences in the predicted probability, the differences between the three work zone durations levels for workers on foot is not significant, as the corresponding $p-values$ forduration are 0.9253 (short duration) and 0.8895 (mobile). Additionally, the predicted probability plots show the change in probability over the three specified levels of VMT. For all categories, the probability of injury is highest in areas of high VMT, or areas of high traffic volume. Conversely, the lowest probabiliyt of non-minor injury occurred, for all variables combinations, in areas rated as medium VMT.

2.4.3 Poisson Regression

Methods

Backward selection was used to select variables for the Poisson regression models. The selection process for both the Modified and Lost Time models is shown in Table 2.14 and Table 2.15.

Modified Time Model

Step	Effect in Model	Effect Removed	$p-value$
1	Location, AIS Body Region, VMT, Time Code, ISS, Conditions, Intrusion Angle, Activity Type, Duration, PPE	None	-
2	Location, AIS Body Region, VMT Time Code, ISS, Conditions, Activity Type, Duration, PPE	Intrusion Angle	Type 1 = 0.8608 Type 3 = 0.8698
3	Location, AIS Body Region, VMT Time Code, ISS, Conditions, Activity Type, PPE	Duration	Type 1 = 0.8100 Type 3 = 0.8100
4	Location, AIS Body Region, VMT Time Code, ISS, Conditions, Activity Type	PPE	Type 1 = 0.6158 Type 3 = 0.6158
5	Location, AIS Body Region, VMT Time Code, ISS, Conditions,	Activity Type	Type 1 = 0.3983 Type 1 = 0.5626

Table 2.14: Steps of backward variable selection for the Modified Time Model.

Three additional models were created for each dependant variable. Construction of the three alternate models occurred in two steps. The first step followed the same procedures used to create alternate models B, C, and D in the logistic regression analysis of the same data set. To reiterate, the three models were created to group together independent variables known to have an effect on work zone safety. Model B (for both Modified and Lost Time models) recreated, using the available variables, the regression model found to influence work zone accident frequency by Qi, et al., [19].

Lost Time Model

Step	Effect in Model	Effect Removed	$p - value$
1	Location, AIS Body Region, VMT, Time Code, ISS, Conditions, Intrusion Angle, Activity Type, Duration, PPE	None	-
2	Location, AIS Body Region, VMT Time Code, ISS, Conditions, Intrusion Angle, Activity Type, Duration	PPE	Type 1 = 0.7567 Type 3 = 0.7567
3	Location, AIS Body Region, Time Code, ISS, Conditions, Intrusion Angle, Activity Type, Duration	VMT	Type 1 = 0.4263 Type 3 = 0.5175

Table 2.15: Steps of backward variable selection for the Modified Time Model.

Model C included predictor variables relating roadway and environmental factors, where Model D evaluated the relationship between the dependent variable and explanatory variables describing parameters that can be controlled by work zone planning. The variables used to make up alternate models B, C and D are shown below. (Separate models were created for each dependent variable, although they are shown together here.)

Model B:

$$\textit{Estimated Modified or Lost Time} = \alpha + \beta_1(\text{Activity Type}) + \beta_2(\text{Duration}) + \beta_3(\text{VMT}) + \beta_4(\text{Location})$$

Model C:

$$\textit{Estimated Modified or Lost Time} = \alpha + \beta_1(\text{Conditions}) + \beta_2(\text{VMT}) + \beta_3(\text{Time Code}) + \beta_4(\text{Location})$$

Model D:

$$\textit{Estimated Modified or Lost Time} = \alpha + \beta_1(\text{Activity Type}) + \beta_2(\text{Duration}) + \beta_3(\text{Time Code}) + \beta_4(\text{PPE})$$

A second step was necessary to add injury and accident parameters into the regression model. However, before more variables were added, Models B, C and D were compared to identify the Poisson regression model with the best fit and residual plots. The diagnostics are shown in Table 2.16.

For both Modified and Lost Time regression models, Model B had the best fit. After selecting the best alternate model, three subgroups of injury and/or accident parameters wee added to the model. The four resulting models, in addition to Model A, are shown below:

Modified Time Model Diagnostics

Criteria for Assessing Goodness of Fit

	Model B	Model C	Model D
Deviance	42.9221	42.7756	48.4693
Scaled Deviance	1.0000	1.0000	1.0000
Pearson Chi-Square	103.2321	97.7065	171.0363
Scaled Pearson	2.4051	2.2842	3.5288

Overdispersion Parameter

Scale	6.5515	6.5403	6.9620

Lost Time Model Diagnostics

Criteria for Assessing Goodness of Fit

	Model B	Model C	Model D
Deviance	52.8147	60.3475	57.7988
Scaled Deviance	1.0000	1.0000	1.0000
Pearson Chi-Square	108.6865	124.6542	126.9927
Scaled Pearson	2.0579	2.0656	2.1972

Overdispersion Parameter

Scale	7.2674	7.7684	7.6026

Table 2.16: Deviance and Pearson's Chi-square goodness of fit statistics for the Modified and Lost time regression models.

Modified Time Model A

$$\begin{aligned}\textit{Estimated Modified Time} &= \alpha + \beta_1(\text{Location}) + \beta_2(\text{VMT}) + \beta_3(\text{Time Code}) + \\ &\quad \beta_4(\text{AIS Body Region}) + \beta_5(\text{ISS}) + \\ &\quad \beta_6(\text{Activity Type})\end{aligned}$$

Lost Time Model A

$$\begin{aligned}\textit{Estimated Lost Time} &= \alpha + \beta_1(\text{Activity Type}) + \beta_2(\text{VMT}) + \\ &\quad \beta_3(\text{Duration}) + \beta_4(\text{Time Code}) + \beta_5(\text{Location}) + \\ &\quad \beta_6(\text{ISS}) + \beta_7(\text{Conditions}) + \beta_8(\text{Intrusion Angle}) + \\ &\quad \beta_9(\text{AIS Body Region}) + \beta_{10}(\text{PPE})\end{aligned}$$

Alternate Model B1

$$\begin{aligned}\textit{Estimated Modified or Lost Time} &= \alpha + \beta_1(\text{VMT}) + \beta_2(\text{Duration}) + \\ &\quad \beta_3(\text{Location}) + \beta_4(\text{Activity Type})\end{aligned}$$

Alternate Model B2

$$\begin{aligned}\textit{Estimated Modified or Lost Time} &= \alpha + \beta_1(\text{VMT}) + \beta_2(\text{Duration}) + \beta_3\ (\text{Location}) + \\ &\quad \beta_4(\text{Activity Type}) + \beta_5(\text{AIS Body Region}) + \\ &\quad \beta_6(\text{ISS})\end{aligned}$$

Alternate Model B3

$$\begin{aligned}\textit{Estimated Modified or Lost Time} &= \alpha + \beta_1(\text{VMT}) + \beta_2(\text{Duration}) + \beta_3(\text{Location}) + \\ &\quad \beta_4(\text{Activity Type}) + \beta_5(\text{Intrusion Angle})\end{aligned}$$

Alternate Model B4

$$\begin{aligned}\textit{Estimated Lost or Modified Time} &= \alpha + \beta_1(\text{VMT}) + \beta_2(\text{Duration}) + \beta_3(\text{Location}) + \\ &\quad \beta_4(\text{Activity Type}) + \beta_5(\text{AIS Body Region}) + \\ &\quad \beta_6(\text{ISS}) + \beta_7(\text{Intrusion Angle})\end{aligned}$$

Recall that Model A was created by backward selection, starting with all explanatory variables, and models B1 through B4 (identical for Modified and Lost Time dependent variables) were created using groups of parameters known to affect work zone safety.

Examination of the Modified Time model, Table 2.17 shows the values of the goodness of fit statistics for each of the five models. Two goodness of fit statistics are available from the GENMOD procedure. These statistics do no provide the same information as logistic regression diagnostics, rather, they are used to determine the adequacy of a model in comparison with another model under consideration. If the model fits the data well, the ratio of the deviance (or Pearson Chi-square) value to the degrees of freedom (Value/DF) should be close to 1, values greater than 1 indicate overdispersion. When this occurs, as it did in the California injury data, an overdispersion parameter, or a free scale parameter, is defined. The scaled deviance is force to equal one by specifying the overdispersion criteria as SCALE = DEVIANCE in the model statement. Allowing for overdispersion has no effect on the regression coefficients, however, it effects the associated $p-values$ and confidence intervals.

Of the five models for Modified Time, Models A, B2 and B4 have similar goodness of fit statistics, and lower dispersion parameters. Evaluation of the influence plots, shown in Figure 2.21, shows the presence of a possible outlier. Upon examination of the data point, certain data fields in case number 203 may have been entered in error, thus, this outlying observation was removed. The model diagnostics for Models A, B2 through B4, with outlying case 203 removed are shown in Table 2.17. The model fit improved with the removal of the observation, however, in general, the fit of the models, relative to one another did not change. Overall, the influence plots show that the studentized residuals are treated well in each model (Figure 2.22). Based on the goodness of fit statistics, and the influence plots, Model B4 was selected to be the best regression model relating Modified Time to selected work zone accident parameters. Model B4 will be a better predictive model, as it considers the effect of more independent variables.

Criteria for Assessing Goodness of Fit

	Model A	Model B1	Model B2	Model B3	Model B4
Deviance	41.4524	42.9221	42.0767	43.1835	42.4715
Scaled Deviance	1.0000	1.0000	1.0000	1.0000	1.0000
Pearson Chi-Square	84.6804	103.2321	81.7773	99.4189	81.2838
Scaled Pearson	2.0428	2.4051	1.9435	2.3022	1.9138

Overdispersion Parameter

Scale	6.4384	6.5515	6.4867	6.5714	6.5170

Criteria for Assessing Goodness of Fit - Outlier Removed

	Model A	Model B1	Model B2	Model B3	Model B4
Deviance	28.1456	30.6654	29.3697	30.9668	29.6721
Scaled Deviance	1.0000	1.0000	1.0000	1.0000	1.0000
Pearson Chi-Square	42.1835	46.4138	43.1022	46.9819	43.4872
Scaled Pearson	1.4988	1.5136	1.4676	1.5172	1.4656

Overdispersion Parameter - Outlier Removed

Scale	5.3052	5.5376	5.4194	5.5648	5.4472

Table 2.17: Poisson regression diagnostics for Modified Time models.

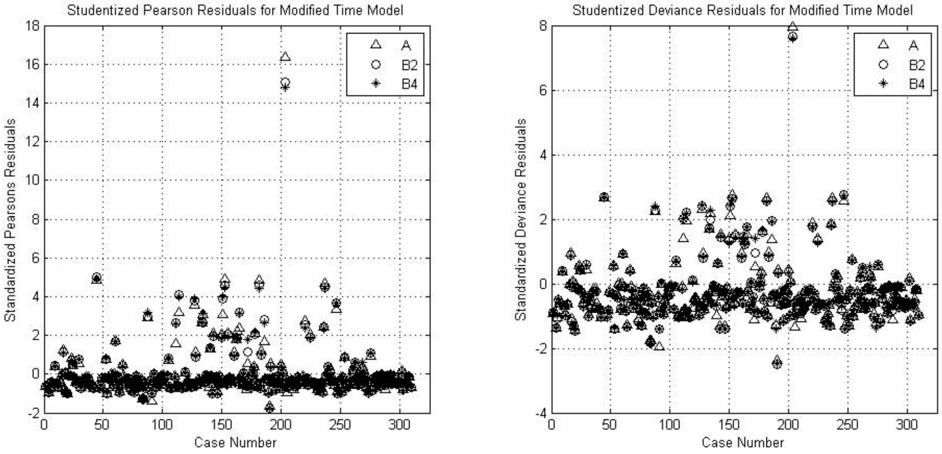


Figure 2.21: Poisson regression studentized residual plots for Modified Time Models A, B2 and B4.

Model selection for the Lost Time regression model was approached in a similar manner. Of the five 'good' models, Model A had the most agreeable goodness of fit statistics, and a slightly smaller dispersion parameter (Table 2.18). The influence plots show that the treatment of the studentized residuals does not differ greatly between the models (Figure 2.23). The outlying observation in the Lost Time data does not appear to be an error in data entry, thus it remains in the model. Since

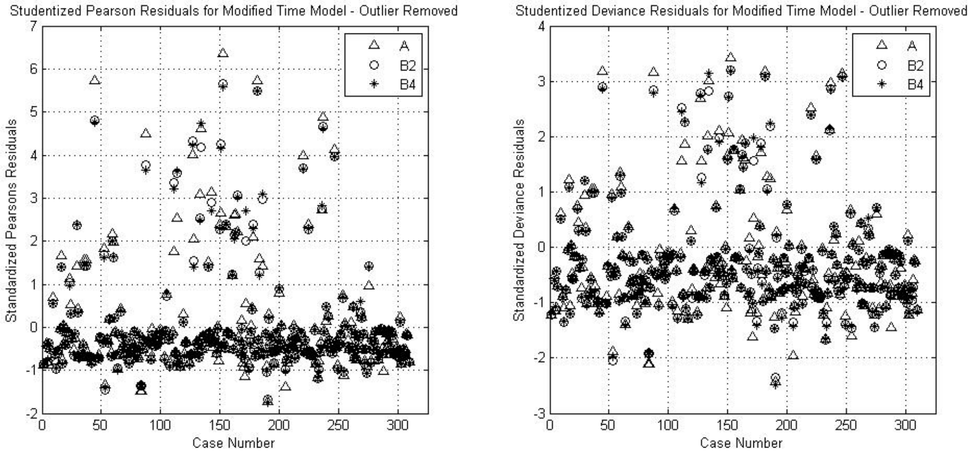


Figure 2.22: Poisson regression studentized residual plots for Modified Time Models A, B2 and B4, with outlying observation removed.

the purpose of this model, similar to those before it, is to predict injury severity (via lost time) based on a number of work zone parameters, Model A was selected, as it was the model including the largest number of explanatory variables, and has good fit and treats the residuals well.

Criteria for Assessing Goodness of Fit

	Model A	Model B1	Model B2	Model B3	Model B4
Deviance	49.5474	52.8147	52.1250	51.9286	51.1817
Scaled Deviance	1.0000	1.0000	1.0000	1.0000	1.0000
Pearson Chi-Square	133.0626	108.6865	109.3724	111.9425	111.2244
Scaled Pearson	2.6856	2.0579	2.0983	2.1557	2.1731

Overdispersion Parameter

Scale	7.0390	7.2674	7.2198	7.2062	7.1541

Table 2.18: Poisson regression diagnostics for Lost Time models.

Results

Abridged Poisson regression outputs produced by the GENMOD procedure for the two regression models (Modified Time, Lost Time) are shown in Figure 2.24, through Figure 2.27. The four important groups of statistical output are listed under the 'Criteria for Assessing Goodness of Fit', 'Analysis of Parameter Estimate', 'LR Statistics for Type 1 Analysis' and 'LR Statistics for Type 3 Analysis' headings. The goodness of fit statistics, described previously, were used in model selection.

The second section of output gives the estimated Poisson regression coefficients for the model, the Wald 95% confidence intervals for each individual regression coefficient, and the chi-square statistic and associated $p - value$. The chi-square statistic tests the null hypothesis that an indi-

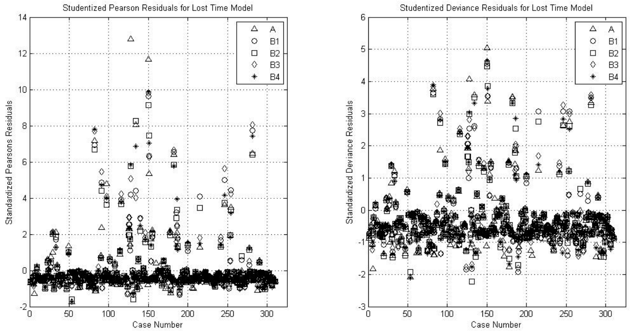


Figure 2.23: Poisson regression studentized residual plots for Lost Time.

```
                                Analysis Of Parameter Estimates

                                             Wald 95%          Chi-                 Odds
Parameter                     Estimate    Confidence Limits   Square   Pr>ChiSq   Ratio

Intercept                       1.4499   -1.2053    4.1051     1.15      0.2845
VMT           (3)              -0.3167   -0.7533    0.1198     2.02      0.1550   0.7285
VMT           (2)              -1.0398   -2.0029   -0.0766     4.48      0.0344   0.3535
VMT           (1)               0.0000    0.0000    0.0000      .          .      1.0000
Duration      (STS)             0.0523   -0.5532    0.6579     0.03      0.8655   1.0537
Duration      (SD)              0.2457   -0.2562    0.7475     0.92      0.3373   0.2785
Duration      (M)               0.0000    0.0000    0.0000      .          .      1.0000
Location      (Shoulder Closure) 1.2188  -1.0662    3.5038     1.09      0.2958   3.3831
Location      (Moving Lane Cl)  1.4759   -0.7868    3.7386     1.63      0.2011   4.3750
Location      (Freeway/Highway) 1.6967   -0.4686    3.8620     2.36      0.1246   5.4559
Location      (Freeway Ramp)   -1.9792   -6.3327    2.3743     0.79      0.3729   0.1382
Location      (Freeway Lane Cl) -0.5363  -3.7285    2.6559     0.11      0.7419   0.5849
Location      (City Street)     0.0000    0.0000    0.0000      .          .      1.0000
Activity Type (On Foot)         0.2598   -0.2665    0.7861     0.94      0.3333   1.2967
Activity Type (Driving)         0.0000    0.0000    0.0000      .          .      1.0000
Body Region   (Whole Body)     -0.7003   -1.8286    0.4279     1.48      0.2238   0.4964
Body Region   (Upper Extremity) -0.6134  -1.7626    0.5358     1.09      0.2955   0.5415
Body Region   (Spine)          -1.1362   -2.1903   -0.0820     4.46      0.0347   0.3210
Body Region   (Neck)           -2.2344   -3.7758   -0.6930     8.07      0.0045   0.1071
Body Region   (Lower Extremity) -0.5170  -1.6208    0.5868     0.84      0.3586   0.5963
Body Region   (Head/Face)      -1.0323   -2.3476    0.2830     2.37      0.1240   0.3562
Body Region   (Abdomen/Thorax)  0.0000    0.0000    0.0000      .          .      1.0000
ISS                             0.1001   -0.0351    0.2353     2.11      0.1467   1.1053
Intrusion Angle(Sideswipe)      0.3527   -0.8708    1.5763     0.32      0.5721   1.4229
Intrusion Angle(Rear end)       0.2483   -0.9181    1.4147     0.17      0.6765   1.2818
Intrusion Angle(Head on)        0.2108   -1.2829    1.7045     0.08      0.7821   1.2347
Intrusion Angle(Broadside)      0.0000    0.0000    0.0000      .          .      1.0000
Scale                           5.4472    5.4472    5.4472

NOTE: The scale parameter was estimated by the square root of DEVIANCE/DOF.
```

Figure 2.24: Partial Poisson regression output for the Modified Time model.

```
                                Analysis Of Parameter Estimates

                                               Wald 95%          Chi-                Odds
Parameter                       Estimate   Confidence Limits   Square   Pr>ChiSq    Ratio

Intercept                         1.2473   -1.8437    4.3382     0.63     0.4260
Activity Type  (On Foot)          1.1736    0.5956    1.7516    15.84     <.0001   3.2336
Activity Type  (Driving)          0.0000    0.0000    0.0000      .        .       1.000
VMT            (3)               -0.0773   -0.5756    0.4210     0.09     0.7610   0.9256
VMT            (2)               -2.9962   -5.0986   -0.8939     7.80     0.0052   0.0500
VMT            (1)                0.0000    0.0000    0.0000      .        .       1.0000
Duration       (STS)              0.6993    0.1546    1.2440     6.33     0.0119   2.0123
Duration       (SD)              -0.7008   -1.4239    0.0223     3.61     0.0575   0.4962
Duration       (M)                0.0000    0.0000    0.0000      .        .       1.0000
Time_Code      (1)                1.0590    0.3578    1.7602     8.76     0.0031   2.8835
Time_Code      (0)                0.0000    0.0000    0.0000      .        .       1.0000
Location       (Shoulder Cl)     -0.1940   -1.7773    1.3893     0.06     0.8102   0.8237
Location       (Moving Lane Cl)   0.7651   -0.7605    2.2906     0.97     0.3257   2.1492
Location       (Freeway/Highway)  0.8162   -0.5404    2.1728     1.39     0.2383   2.2619
Location       (Freeway Ramp)     0.4101   -1.3147    2.1349     0.22     0.6412   1.5070
Location       (Freeway Lane Cl) -2.7248   -7.8097    2.3601     1.10     0.2936   0.0656
Location       (City Street)      0.0000    0.0000    0.0000      .        .       1.0000
ISS                               0.1409   -0.0096    0.2915     3.37     0.0666   1.1513
Conditions     (2)               -1.1508   -2.3208    0.0192     3.72     0.0539   0.3164
Conditions     (1)                0.0975   -0.6297    0.8246     0.07     0.7928   1.1024
Conditions     (0)                0.0000    0.0000    0.0000      .        .       1.0000
Intrusion Angle(Sideswipe)       -0.9685   -1.8577   -0.0793     4.56     0.0328   0.3797
Intrusion Angle(Rear end)        -1.1482   -2.0019   -0.2944     6.95     0.0084   0.3172
Intrusion Angle(Head on)         -0.6564   -2.0443    0.7315     0.86     0.3539   0.5187
Intrusion Angle(Broadside)        0.0000    0.0000    0.0000      .        .       1.0000
Body Region    (Whole Body)       0.8077   -1.9027    3.5181     0.34     0.5592   2.2427
Body Region    (Upper Extremity)  0.1263   -2.6848    2.9374     0.01     0.9298   1.1346
Body Region    (Spine)            1.2927   -1.3546    3.9400     0.92     0.3385   3.6426
Body Region    (Neck)             1.4238   -1.3033    4.1509     1.05     0.3062   4.1529
Body Region    (Lower Extremity)  0.5812   -2.1279    3.2902     0.18     0.6741   1.7882
Body Region    (Head/Face)        1.1176   -1.6755    3.9108     0.62     0.4329   3.0575
Body Region    (Abdomen/Thorax)   0.0000    0.0000    0.0000      .        .       1.0000
PPE            (1)                0.2749   -0.3628    0.9126     0.71     0.3982   1.3164
PPE            (0)                0.0000    0.0000    0.0000      .        .       1.0000
Scale                             7.0390    7.0390    7.0390

NOTE: The scale parameter was estimated by the square root of DEVIANCE/DOF.
```

Figure 2.25: Partial SAS output for the Lost Time Poisson regression model.

vidual predictors regression coefficient is zero ($H_o : \beta = 0$), given that the rest of the predictors are in the model. The probability that any particular chi-square test statistic is as extreme as, or more so, than what was observed under H_o is defined by Pr > ChiSq.

The section entitled 'LR Statistics for Type 1 Analysis' fits a sequence of models, beginning with an intercept only model, and computes likelihood ratio statistics for each iteration. One specified explanatory variable is added at each step. Each entry of the output table gives the deviance and chi-square statistic for the model containing the effect for that row and all the proceeding effects. The statistics evaluate the model under the null hypothesis that the variable is not significant ($H_o : \beta = 0$). Thus, a low $p - value$ supports the alternate hypothesis and denotes a significant variable.

The Type 3 Analysis produces similar results to Type 1 Analysis, however the procedure is slightly different. The analysis produces likelihood ratio statistics, degrees of freedom and chi-square statistics with the corresponding $p - value$ testing the significance of the variable, $H_o : \beta = 0$. However, Type 3 Analysis tests the additional contribution of the variable in the model, given that all other variables remain in the model. Unlike Type 1 Analysis, the resulting statistics do not depend on the order of the variables.

Inferences for Poisson regression were developed in a manner similar to the method used for logistic regression interpretation, using the odds ratio. When evaluating class variables, the variable with an estimate equal to zero represents the reference value for that explanatory variable. The reference variable was chosen by SAS as the level of the classification variable with the lowest (or first, alphabetically) by specifying ORDER = DESCENDING in the CLASS statement.

Evaluation of Figure 2.24 and Figure 2.25 show that many explanatory variables, and their corresponding parameter estimates are statistically significant in the Lost Time model, while few are significant in the Modified Time Model.

The predicted parameter estimates for Activity Type have a significant effect on the mean estimated Lost Time, but not on the mean estimated Modified Time ($p - value < 0.0001$ for Lost Time, 0.3333 for Modified Time). The Lost Time parameter estimate was calculated to be 1.1736 for the 'on foot' Activity Type, and the Modified Time parameter was estimated at 0.2598. One way to interpret the estimate is to follow the log transformation to calculate the odds ratio. After adjusting for all other variables, workers on foot are predicted to experience 3.2 times as many lost work days, or 1.3 as many modified work days due to roadway work zone intrusions, compared to workers working from vehicles.

Each estimate represents the log increase or decrease the variable will have on the estimated mean number modified or lost days. The Activity Type variable is simple to analyze, as it only has two levels. However, class variables with multiple levels are more complex. For example, looking at the Location of Accident variable, we see that the reference level is City Street. Therefore, all levels of analysis will be compared to accidents which occur on city streets. Examining Figure 2.24, it is noticed that the estimated mean number of modified days for injury occurring in a Moving Lane Closure is 4.3750 times the estimated number compared to the reference location, ($p - value = 0.2011$). According to the California data, the most frequently reported location was Freeway/Highway. The Poisson regression model estimates that workers working in work zones located on a highway or freeway are expected to require 5.4559 times more modified work days that a worker involved in an accident in a city street work zone ($p - value = 0.1246$).

Looking at lost time, (Figure 2.25), the same comparisons of Moving Lane Closure and Freeway/Highway accident locations show an increase in lost days as 2.1492 and 2.2619 times the number of lost days, respectively, for the same accident on a city street(Moving Lane Closure $p - value = 0.3257$,Freeway/Highway $p - value = 0.2383$). The significance of the levels of each location are not statistically significant, but the variable is, overall, significant in the model, as will be discussed shortly.

Another type of explanatory variable used in the model was the continuous variable ISS. Figure 2.24 and Figure 2.25 show the parameter estimates and $p - values$ for ISS. The analysis results show that for every 1-unit increase in injury severity (ISS), the estimated modified time will increase by approximately 11% ($p - value = 0.1467$). Keeping with the previous interpretation, this result can be read as the estimated modified days will be 1.1053 times higher for every 1-unit increase in injury level, conditional on all other variables. Evaluating the mean estimated lost time, for every 1-unit increase in ISS, assuming all other variables remain constant, the estimated number of lost days will increase by about 15% (odds ratio = 1.1513, $p - value = 0.0666$).

Evaluation of the Type 1 and Type 3 likelihood ratio statistics provided in the output for the modified and lost time regression models, (Figure 2.26 and Figure 2.27), show that the effect of some of the variables are not significant at the $\alpha = 0.05$ level. However, comparison of the parameter level effect, some variables are significant overall only (Type 1 and Type 3), and some are significant only at specific levels.

For example, in both the Modified and Lost Time models, VMT, Location, and Activity Type are significant overall, but are not statistically significant in every individual level. Conversely, there are predictors that are significant at a specific level, such as the spine and neck body regions in the Modified Time model, or the sideswipe and rear end intrusion angles in the Lost Time model, which do not have statistically significant effects overall.

2.5 Discussion of Work Zone Injury Analysis

A number of conclusions can be drawn from evaluation of the injury analysis. These conclusions will increase the understanding of work zone injuries, and the parameters that may increase or decrease the risk of severe injury. In this section, the effect of each explanatory variable on the predicted probability of injury, or estimated number of modified and lost days will be discussed.

```
                         LR Statistics For Type 1 Analysis
                                                                    Chi-
Source              Deviance   Num DF   Den DF   F Value   Pr > F    Square   Pr > ChiSq

Intercept          9433.8007
VMT                9149.5444        2      253      4.79   0.0091      9.58       0.0083
Duration           9120.3449        2      253      0.49   0.6120      0.98       0.6114
Location           8391.3556        5      253      4.91   0.0003     24.57       0.0002
Activity Type      8064.9909        1      253     11.00   0.0010     11.00       0.0009
AIS Body Region    7582.5023        6      253      2.71   0.0144     16.26       0.0124
ISS                7518.6551        1      253      2.15   0.1436      2.15       0.1424
Intrusion Angle    7507.0470        3      253      0.13   0.9420      0.39       0.9421


                         LR Statistics For Type 3 Analysis
                                                                   Chi-
    Source                 Num DF    Den DF    F Value    Pr > F    Square    Pr > ChiSq

    VMT                         2       253       3.02    0.0503      6.05        0.0486
    Duration                    2       253       0.45    0.6355      0.91        0.6350
    Location of Accident        5       253       5.28    0.0001     26.38        <.0001
    Activity Type               1       253       0.92    0.3377      0.92        0.3368
    AIS Body Region             6       253       2.26    0.0385     13.55        0.0351
    ISS                         1       253       2.01    0.1572      2.01        0.1560
    Intrusion Angle             3       253       0.13    0.9420      0.39        0.9421
```

Figure 2.26: Partial Poisson regression output for the Modified Time model.

```
                         LR Statistics For Type 1 Analysis
                                                                    Chi-
Source              Deviance   Num DF   Den DF   F Value   Pr > F    Square   Pr > ChiSq

Intercept         17743.4707
Activity Type     16573.3691        1      250     23.62   <.0001     23.62       <.0001
VMT               15497.4272        2      250     10.86   <.0001     21.72       <.0001
Duration          14678.3187        2      250      8.27   0.0003     16.53       0.0003
Time Code         14476.2688        1      250      4.08   0.0445      4.08       0.0434
Location          13657.2144        5      250      3.31   0.0066     16.53       0.0055
ISS               13518.3001        1      250      2.80   0.0953      2.80       0.0940
Conditions        13261.8755        2      250      2.59   0.0772      5.18       0.0752
Intrusion Angle   12913.4898        3      250      2.34   0.0736      7.03       0.0709
AIS Body Region   12423.5107        6      250      1.65   0.1344      9.89       0.1294
PPE               12386.8463        1      250      0.74   0.3905      0.74       0.3897


                         LR Statistics For Type 3 Analysis
                                                                   Chi-
    Source                 Num DF    Den DF    F Value    Pr > F    Square    Pr > ChiSq

    Activity Type               1       250      15.32    0.0001     15.32        <.0001
    VMT                         2       250      10.57    <.0001     21.14        <.0001
    Duration                    2       250       6.76    0.0014     13.52        0.0012
    Time Code                   1       250       7.76    0.0058      7.76        0.0053
    Location of Accident        5       250       2.66    0.0232     13.28        0.0209
    ISS                         1       250       3.30    0.0707      3.30        0.0695
    Conditions                  2       250       2.58    0.0781      5.15        0.0761
    Intrusion Angle             3       250       2.08    0.1036      6.23        0.1007
    AIS Body Region             6       250       1.57    0.1571      9.40        0.1521
    PPE                         1       250       0.74    0.3905      0.74        0.3897
```

Figure 2.27: Partial SAS output for the Lost Time Poisson regression model.

The variables found to have a statistical effect on the responses were Activity Type, Duration, Location of Accident, Body Region, ISS, VMT, Time Code, Conditions, and Intrusion Angle.

Primary epidemiological evaluation of the overall California injury data set (Table 2.5, Table 2.6) showed that the majority of work zone injuries were cause by a vehicle, in either a motor vehicle collision, or a struck by motor vehicle accident. Most of the struck by object injuries occurred at non-roadway locations, or during activities not usually occurring in the work zone. Therefore, the most effective way to reduce injuries obtained in the work zone is to focus efforts on protecting workers from traveling and possibly intruding vehicles.

In all three regression models, workers performing duties on foot were predicted to experience a higher rate of serious injury, either by predicting the probability of obtaining a non-minor injury, or by estimating the mean number of modified and lost days. The logistic analysis (Figure 2.20) concluded that there was a statistically significant difference between the predicted probability of injury for workers working on the ground, compared to work activities that are carried out from inside a vehicle. Overall, based on all regression models, when all other variables are held constant, workers on foot experience a higher risk of injury.

The Duration variable was found to have an effect in both regression models. The $p-values$ associated with the Wald chi-square statistic, while not statistically significant in the logistic regression, the difference between a short-term stationary work zone and a mobile work zone is more extreme than the difference between short-term stationary and short duration work zones. This difference is reflected in Figure 2.20, and the Poisson regression models (Figure 2.24 through Figure 2.27).

The most common location of an injury accident was reported as either a freeway or highway. In the Poisson regression models, all other locations predicted a mean estimate of fewer modified or lost days for injury accidents.

Back, or spinal, injuries were the most frequent injuries received by workers injured in California work zones. In the Poisson regression model, compared to most other body regions, spinal injuries required the highest estimated number of lost and modified work days. Only injuries to the neck and abdomen/thorax regions required more lost or modified time. The injury severity score (ISS) caused a statistically significant increase on the mean estimated days of lost time.

From Table 2.9, and Figure 2.6 of the epidemiological evaluation, the highest number of work zone accidents (including both work zone intrusion and within work zone accidents) occurred in areas classified as high or low VMT. Referring to Figure 2.2, this unexpected result is explained. Based on the method used to classify the levels of Vehicle Miles Traveled (VMT) eight of the twelve districts of California were classified as having low VMT. These districts include districts 1, 2, 3, 5, 6, 9, 10, and 12. The medium and high levels of VMT equally split the remaining four districts, with districts 8 and 11 being classified as medium, and 4 and 7 as high. (Figure 2.28 shows the location of the districts and VMT regions.) As there are more regions that were considered to have low VMT, the percentage of serious injuries in those regions is obviously higher. However, the highest number of work zone intrusion accidents occurred in high VMT regions, despite including only two districts. These results, in addition to the statistical significance of the predictor, illustrate the importance in considering VMT when planning for work zone safety.

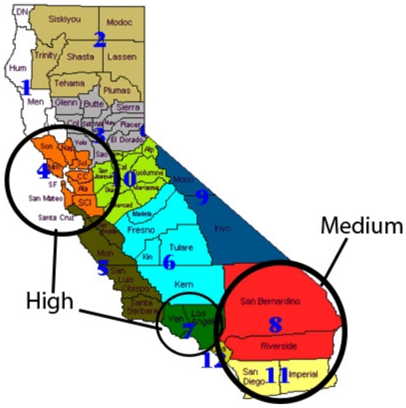


Figure 2.28: Counties, districts and VMT zones of California.

Based on Figure 2.5, there was a statistical trend in the time of day in which a work zone accident occurred. However, while this figure shows the trend of past injury accidents, the results of the regression models help to show the predictive effect of the time of day on the mean estimated number of lost days. According to the Poisson regression models, the estimated lost time due to an injury significantly increased based on the time of day in which the work was being performed. During peak, or rush hours, more traffic is on the roadway, increasing the exposure and risk of the worker. It is not a surprising conclusion that more serious injuries will occur during time periods of heightened exposure.

While roadway conditions cannot be controlled, they do have an effect on injury severity, and thus should be considered when designing the safety plan for a work zone, whenever possible. Overall, based on Type 1 and Type 3 analysis, the Conditions variable was not significant at the $\alpha = 0.05$ level, although at individual levels it did have a significant effect on the lost time estimate.

The Intrusion Angle variable did not have a significant overall effect on the response variable, however, there was a statistically significant effect at a specific variable level (sideswipe, rear end) in the lost time regression model. This variable showed that while rear end intrusions are the most frequent, sideswipe, and head on intrusions also predict a high risk of serious injury.

Most injuries were minor to moderate, with an ISS of ten or less, and according to the graphics, the nature of most reported injuries were soreness, sprain/strain, or bruising. The most likely explanation of the high number of minor injuries is reported activity at the time of the accident. By further division of the Activity Type, it was found that all activities could be categorized as 'driving' or 'on foot'. Since 'driving' was the most reported activity, this is most likely the reason for the hight number of minor injuries. In the statistical analysis, activity type was found to have a significant effect on work zone injury severity. The reason for this is that activities performed from a vehicle have the benefit of positive protection of the vehicle often in the form of a truck mounted attenuator (TMA).

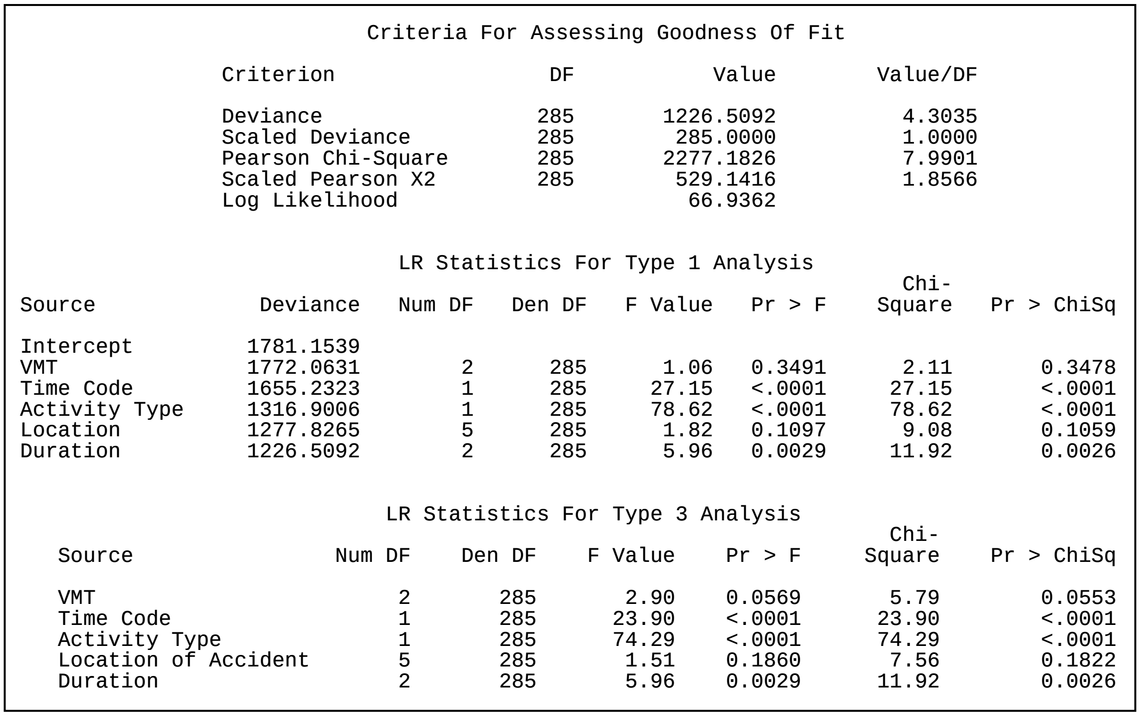
All of the parameters analyzed are useful in understanding how work zone parameters effect injury. This information is essential for evaluation of work zone sites, in preparation for developing a safety plan.

The most effective way to use the information developed here for work zone evaluation is to use a numeric metric, or ‘Risk Index’. A metric will benefit work zone planning, as it presents an objective way to evaluate the risk of injury at a work site. The metric should take into account all work zone parameters found to have a statistical effect on injury severity. These parameters include the VMT, time of day, activity type, location and duration of the work zone. Each parameter is given a value, and using a metric formulation, the effect of all parameters are combined. The work zone with the highest Risk Index represents the work zone that has the highest risk of serious injury. The formulation for the Risk Index follows, where the parameter name would be replaced by a corresponding coefficient:

$$\begin{aligned} \textit{Risk Index} &= \text{(Duration)} + \Big(\text{(No. of Workers)(On Foot)}+ \\ &\quad \text{(No. of Workers)(Driving)}\Big) + \text{(VMT)} + \\ &\quad \Big(\text{(No. of Hours)(Rush Hour)}+ \\ &\quad \text{(No. of Hours)(Non-Peak Hours)}\Big) + \text{(Location)} \end{aligned}$$

In order to come up with a metric containing all five variables, a new regression model was created. Two possible models were created, a logistic model comparing the categorical AIS response variable with the five selected explanatory variables, and a Poisson regression model with the response (or count) variable being ISS. The two models were created using SAS. The logistic model experience quasi-complete separation of the data, which was most likely a result of the limited data points at higher AIS values. However, the Poisson model, typically used for data in which high count or frequency is a rare event, converged. The Goodness of Fit and Type 1 and 3 analysis results are shown in Figure 2.29. The calculated odds ratio values corresponding to each variable level were used as the coefficient values for each variable level.

It was important to keep the variable effects in perspective, therefore, a weight factor was used, specific to the significance of each variable in the Poisson regression model. The F-value, output in the ‘LR Statistics for Type 3 Analysis’, was used, as it is a measure of the significance of the effect by testing the additional contribution of each variable in the model. The F-values were normalized, such that each value represented a percentage of the total weight of the index. This was done by summing all F-values, then dividing each individual F-value by the total sum. The weight factors, and corresponding coefficients are shown in Table 2.19. The Risk Index, defined previously, is



```
                              Criteria For Assessing Goodness Of Fit

                 Criterion                 DF           Value        Value/DF

                 Deviance                  285       1226.5092         4.3035
                 Scaled Deviance           285        285.0000         1.0000
                 Pearson Chi-Square        285       2277.1826         7.9901
                 Scaled Pearson X2         285        529.1416         1.8566
                 Log Likelihood                         66.9362


                                 LR Statistics For Type 1 Analysis
                                                                       Chi-
Source              Deviance    Num DF    Den DF    F Value    Pr > F    Square    Pr > ChiSq

Intercept          1781.1539
VMT                1772.0631         2       285       1.06    0.3491      2.11        0.3478
Time Code          1655.2323         1       285      27.15    <.0001     27.15        <.0001
Activity Type      1316.9006         1       285      78.62    <.0001     78.62        <.0001
Location           1277.8265         5       285       1.82    0.1097      9.08        0.1059
Duration           1226.5092         2       285       5.96    0.0029     11.92        0.0026


                                LR Statistics For Type 3 Analysis
                                                                      Chi-
   Source                  Num DF    Den DF    F Value    Pr > F    Square    Pr > ChiSq

   VMT                          2       285       2.90    0.0569      5.79        0.0553
   Time Code                    1       285      23.90    <.0001     23.90        <.0001
   Activity Type                1       285      74.29    <.0001     74.29        <.0001
   Location of Accident         5       285       1.51    0.1860      7.56        0.1822
   Duration                     2       285       5.96    0.0029     11.92        0.0026
```

Figure 2.29: SAS output for the Poisson regression Risk Index model.

Parameter		Coefficient	Weight
VMT	3 (High)	1.2306	0.0267
	2 (Medium)	0.7312	
	1 (Low)	1.0000	
Time Code	1 (Peak/Rush Hour)	2.7643	0.2202
	0 (Non-peak Hour)	1.0000	
Activity Type	On Foot	3.6194	0.6843
	Driving	1.0000	
Location	Freeway/Highway	1.3024	0.0139
	Shoulder Closure	0.7996	
	City Street	0.7671	
	Freeway Ramp	0.7197	
	Freeway Lane Closure	0.8448	
	Moving Lane Closure	1.0000	
Duration	Mobile	1.4948	0.0549
	Short Duration	0.7990	
	Short-term Stationary	1.0000	

Table 2.19: Coefficient and weight values for the Risk Index.

rewritten as :

$$\begin{aligned} RiskIndex = {} & C_{VMT}W_{VMT} + \Big((\#Hours)C_{Time_0} + (\#Hours)C_{Time_1}\Big)W_{Time} + \\ & \Big((\#Workers)C_{Activity_0} + (\#Workers)C_{Activity_1}\Big)W_{Activity} + C_{Location}W_{Location} + \\ & C_{Duration}W_{Duration} \end{aligned} \tag{2.1}$$

Where C_{VMT} represents the coefficient for the VMT variable, and W_{VMT} represents the weight for the same variable. When evaluating a potential work zone, there will be one coefficient selected corresponding to the appropriate variable level for the VMT, Location, and Duration variables. The Time Code and Activity Type variables are treated differently because one work zone may span both levels of the variable. For example, an eight hour work zone may operate four hours during peak travel time ($C_{Time_1} = 2.7643$) and four hours during non-peak ours ($C_{Time_0} = 1.0000$).

The interpretation of the coefficients follows the interpretation of odds ratios for the Poisson regression. For example, looking again at the coefficients for time of day, for activity during peak/rush hours, $C_{Time_1} = 2.7643$, compared to the coefficient for non-peak activity, $C_{Time_0} = 1.000$. This coefficient system agrees with the interpretation of the regression model: the predicted severity of an injury obtained in work during rush hour is predicted be 2.7643 times the expected injury severity for work being done during non-peak hours.

The developed Risk Index is an objective, and scientifically based method capable of measuring and comparing work zone risk. The index should not be used to determine if the level of risk is acceptable, it should only be used as a comparative tool. Further research should be done, documenting the calculated level of risk and the resulting injuries that occur in the work zone. After sufficient data are collected, the data would be analyzed to determine a threshold risk value based on calculated risk and actual accidents/injuries that take place in the work zone.

2.6 Conclusion

Generally, the injury analysis performed is useful to understand the trends and patterns in work zone injuries. By gaining a better understanding of the injury patterns and work zone parameters that are likely to increase injury risk, governing bodies can be more proactive in work zone safety planning.

The logistic regression analysis of the California work zone injury data determined that the type of activity being performed, the duration of the work zone, and the VMT rating of the area all affected the probability of a worker receiving a non-minor injury. Predicting the mean modified and lost time required after a work zone injury is another way to illustrate injury severity and its affect on the efficiency of the agency. Each modified or lost day corresponds to lost productivity, increased time delay to the traveling public, and ultimately cost to the agency. The statistical analysis found that all factors considered affected the expected modified or lost time due to an injury, although only a few had a statistically significant effect over all, including the VMT of the surrounding area, the location, activities being performed and duration of the work zone, the time of day, and the body region injured.

Combining the results, the development of a Risk Index which included the effects of Duration, Activity Type, VMT, Time of Day, and Location, provides planning agencies with a tool that will aid in work zone safety planning based on the knowledge gained in the injury analysis.

Chapter 3

Cost Benefit Analysis and Risk Assessment

3.1 Cost Benefit Analysis

Cost benefit analysis is a policy or project assessment method that quantifies, in monetary terms, the value of all policy consequences to all members of society, [5]. The net social benefits measure the value of the project or policy, which are found by taking the benefits and subtracting from them the costs. It is important to note that the costs and benefits are considered for society as a whole, not just the specific people or groups involved. For this reason, a cost benefit analysis is commonly called a *social* cost benefit analysis. A basic cost benefit analysis, which may be applied to policies, programs, projects, regulations, demonstrations, and other government interventions, consists of nine basic steps, according to Boardman, et al., [5]:

1. Specify the set of alternative projects.
2. Decide whose benefits and costs count.
3. Catalogue the impacts and select measurement indicators, or units.
4. Predict the impacts quantitatively over the life of the project.
5. Monetize (attach dollar values to) all impacts.
6. Discount benefits and costs to obtain present values.
7. Compute the net present value of each alternative.
8. Perform sensitivity analysis.
9. Make a recommendation based on the net present value and sensitivity analysis.

In this research, an alternative highway work zone set-up, or protection layout was evaluated, namely, use of the Balsi Beam. Therefore, a Balsi Beam protected work zone would serve as the alternate 'project' to be evaluated in the first phase of the cost benefit analysis. The alternative project should be compared to the status quo, which is the traditional work zone set-up (coned-off lane closures). Step 2 touches on the idea that a decision may have different effects on different groups of people. For example, should the analysis be performed from the global, national, state, or local perspective. Because California work zone injury data were used to form estimates for one particular beneficial impact, the entire evaluation should be performed at the state level. Steps 3, 4 and 5 require the collection of impacts of the projects, and placing a monetary value on each cost or benefit. The term 'impact' refers to both inputs, or required resources, and outputs. There are many potential costs and benefits of highly mobile barrier use, including purchase price of the barrier, the equipment necessary to use the barrier, personnel training, time of work zone set-up and work completion, delay time to the traveling public, and injuries averted. The final benefit of highly mobile barriers, injuries averted, will be discussed in more detail in section 3.2, during which a monetary value will be determined for the impact.

The final steps in a cost benefit analysis, as listed, will not be performed in this research. However, it is important to understand the procedure. It is necessary to discount the benefits and costs to obtain present values (step 6) because of society's preference to consume now, rather than later. After the net present value of each cost and benefit is calculated, the net present value of each alternative is calculated by computing the difference between the present value of the benefits and the present value of the costs. While the analyst will recommend the alternative with the largest possible net present value, a sensitivity analysis is important to evaluate any uncertainties in the predicted impacts and/or assigned monetary valuations. Upon completion of the sensitivity analysis, the analyst can make a stronger recommendation.

It is important to note that the result of a cost benefit analysis is only a recommendation, and not a decision. The calculated net present values are merely expected values. The sensitivity analysis may suggest that the recommended alternative may not be the best choice in all situations.

3.2 Injury Cost Model

There are many costs and benefits associated with use of highly mobile barriers, many of which are beyond the scope of this research. However, as mentioned previously, California work zone injury data were used to estimate the benefits of injuries or fatalities averted.

Development of an injury cost model is an important step in the cost benefit analysis of highly mobile barriers. One has to consider both direct economic costs as well as the total economic costs. These costs cover direct losses and economic costs of motor vehicle crashes as well as the economic value society places on the human life and pain and suffering.

The method used here to determine the cost of an injury or fatality averted is to use accident costs. Accident costs are used in economic analyses for choosing among alternate improvements to existing road, street, and highway systems. Or, when dealing with highway safety, accident costs may be used for determining allocation of highway safety resources among programs, evaluating proposed safety regulations, or to convince policy makers that safety programs are beneficial [29].

Three measures of accident costs are commonly used to account for the costs of accidents in different ways,[29]. The first, and the method used in this research, is referred to as the *Comprehensive Cost*, which measures motor vehicle accident costs that include the effects of injuries or fatality on a person's entire life. This measure includes all cost components and places a dollar values on each component. There are eleven components that constitute the comprehensive cost. These components are: property damage, lost earnings, lost household production, medical costs, emergency services, travel delay, vocational rehabilitation, workplace costs, administrative, legal, and pain and lost quality of life. A second measure, *Years Lost Plus Direct Costs* includes the same costs as the comprehensive cost method, however, it replaces lost earnings, lost household production, and pain and lost quality of life with the non-monetary measure of lost years. The remaining components, termed 'direct costs', are also included. Finally, the *Human Capital Cost* measure included all comprehensive cost components with the exception of pain and lost quality of life.

In 1993, the U.S. Department of Transportation adopted a guidance entitled *Treatment of the Value of Preventing Fatalities and Injuries in Preparing Economic Analysis*, in which a procedure was established for determining and using accident costs to estimate the value of a statistical life (VSL), [28]. The document stated that the benefit of preventing a fatality is measured by the VSL, which is defined as the value of improvements in safety that result in a reduction by one in the expected number of fatalities. The VSL, put forth by the U.S. Department of Transportation, is to be used in all departmental economic analyses when the reduction of fatalities or injuries is a benefit. While this estimate is accepted, it is noted that analysts using the VSL must recognize the subjective qualities of the estimate.

The society's valuation of safer transportation is the basis of the VSL, and includes individual travelers' own willingness to pay to reduce the risk of accidental death and injury they face in using the transportation system. Willingness to pay is based on the observed willingness to pay modest amounts for a small reduction in risk. For example, if 10 million passengers on an already safe mode of transportation were willing to pay \$0.20 extra in their fare to reduce the risk of accidental death per trip by 0.0000001, over the 10 million trips, \$2 million would be collected, and one less life would be lost. The willingness to pay would be \$2 million per life, although no one would have actually expressed willingness to pay that amount to save his/her life, [28].

Based on further research, the U.S. DOT published a revised document, in which the VSL was updated based on published research and the procedures of other government agencies, [31]. The new VSL value of $5.8 million was set forth in 2008 as an appropriate reflection of research results.

If fatality reduction is a benefit in a proposal, expected reduction in non-fatal injury is most likely another benefit, as injuries are far more common than fatalities. Determining a willingness to pay value for injury averted is difficult due to the potential injury severity range. In the Departmental guidance, [28], a method to determine the 'fatality equivalent' was presented, based on the research by Miller et al., [17], who, rather than determining a willingness to pay estimate, defined a set of coefficients that can be used to convert VSL into injury estimates. Table 3.1 lists the coefficients used to calculate the equivalent VSL for injury categories defined by the AIS.

MAIS Level	Severity	Fraction of VSL
MAIS 1	Minor	0.0020
MAIS 2	Moderate	0.0155
MAIS 3	Serious	0.0575
MAIS 4	Severe	0.1875
MAIS 5	Critical	0.7625
MAIS 6	Fatal	1.0000

Table 3.1: Coefficients used to calculate the 'fatality equivalent', or fraction of VSL for non-fatal injuries. (MAIS: Maximum Abbreviated Injury Score, VSL: Value of a Statistical Life)

Using the table, and the established VSL value, an injury cost model can be developed and added to the cost benefit analysis. The injury cost model is only one of many social costs and benefit analyzed in a complete cost benefit model.

3.2.1 Injury Cost Estimates

Using the California highway work zone injury data and the guidance set forth by the U.S. Department of Transportation, [31], an injury cost model was developed. Accident/injury costs were calculated for work zone intrusion accidents where a worker injury was reported. In all, there were 299 work zone intrusion accidents evaluated over the ten year period of interest. Figure 3.1 shows the reported maintenance activity, work zone duration, and injury severity (rated by AIS) of the most severe injury for these reported accidents. (Maintenance activity codes are defined in Table 2.11.)

Using the coefficient equivalents defined in Table 3.1, and the injury severity data represented in Figure 3.1, a total cost of injury over the 10 year period was calculated to be $3.167 million for minor injuries, $1.798 million for moderate injuries, $0.334 million for serious injuries, and $29 million for fatalities. The total cost is found to be $34.293 million, which can be estimated to a yearly average of $3.43 million. (These results are shown in the third column (Total Cost) of Table 3.3.)

Using work zone maintenance and duration information, [26], and knowledge of barrier specifications and uses, Table 3.2 was constructed showing various work zone activities and their ap-

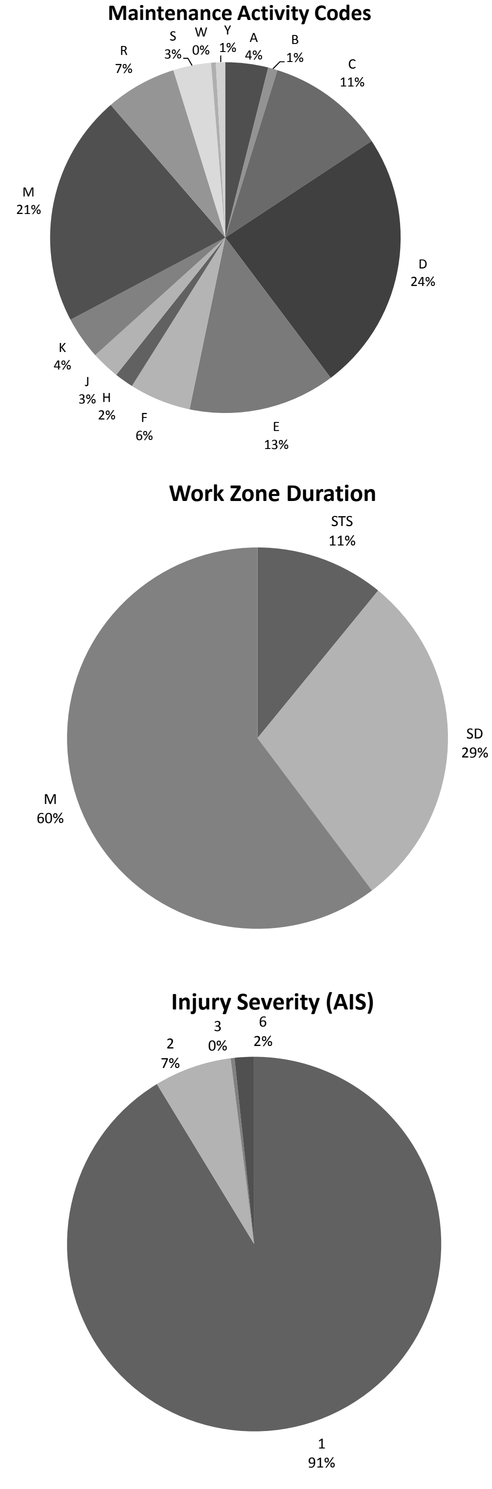


Figure 3.1: Breakdown of maintenance activity, work zone duration and injury severity (AIS) reported during work zone intrusion accidents in a 10 year period in California.(STS: Short-term Stationary, SD: Short Duration, M: Mobile)

plicability for highly mobile barrier protection. (There are many other maintenance activities that may be protected by highly mobile barriers, however, the list presented in Table 3.2, only addresses those maintenance activities present in the data.) Determination of highly mobile barrier protection was based on the best possible work zone situations, considering maintenance activity spatial requirements, duration, and equipment needs.

Maintenance Activities	Duration	BB Eligible
Bridge Maintenance	STS	X
Guardrail Repair	STS	X
Culvert/ Drain Work	SD	X
Lighting Work	SD	X
Sign Work	SD	X
Signal Work	SD	X
Concrete Slab Replacement	STS	X
Asphalt Milling	M	
Level-up Activities	M	
Joint Repair/ Crack Sealing	M	X
Sealcoat/ Asphalt Overlay	M	
Pothole Patching	SD	X
Raised Pavement Marker Work	M	X
Short-line Striping	SD	X
Pavement Striping	M	
Litter Pickup	M	X
On-road Equipment Repairs	SD	X
Landscape Work	STS	X
Snow/ Ice Control	M	
Storm Maintenance	M	

Table 3.2: Summary of maintenance activities eligible for highly mobile barrier protection. (BB: Balsi Beam, STS: Short-term Stationary, SD: Short Duration, M: Mobile)

When considering Balsi Beam deployment, 83, approximately 28% of all work zone intrusion accidents, occurred in work zones that were eligible for Balsi Beam protection, (or 7.5% of all work zone accidents reported). Figure 3.2 shows the percent of maintenance activities, duration and injury severity of work zones appropriate for Balsi Beam deployment. When evaluating the corresponding accident costs, Table 3.3 shows the difference in costs between all work zone intrusion accidents (Total Costs) and work zone intrusion accidents occurring in work zones suitable for highly mobile barrier protection (Averted Costs).

These costs can be used as benefits in the cost benefit analysis in terms of fatalities and injuries averted if a particular barrier is used. For example, one year of Balsi Beam protection at eligible work zone sites is expected to save 0.3 lives, and avoid 1 moderate injury and 7 minor injuries. These avoided injuries amount to a monetary savings of $1.91 million. Caution must be taken when dealing with future costs and benefits, and the appropriate discount must be considered [5]. For

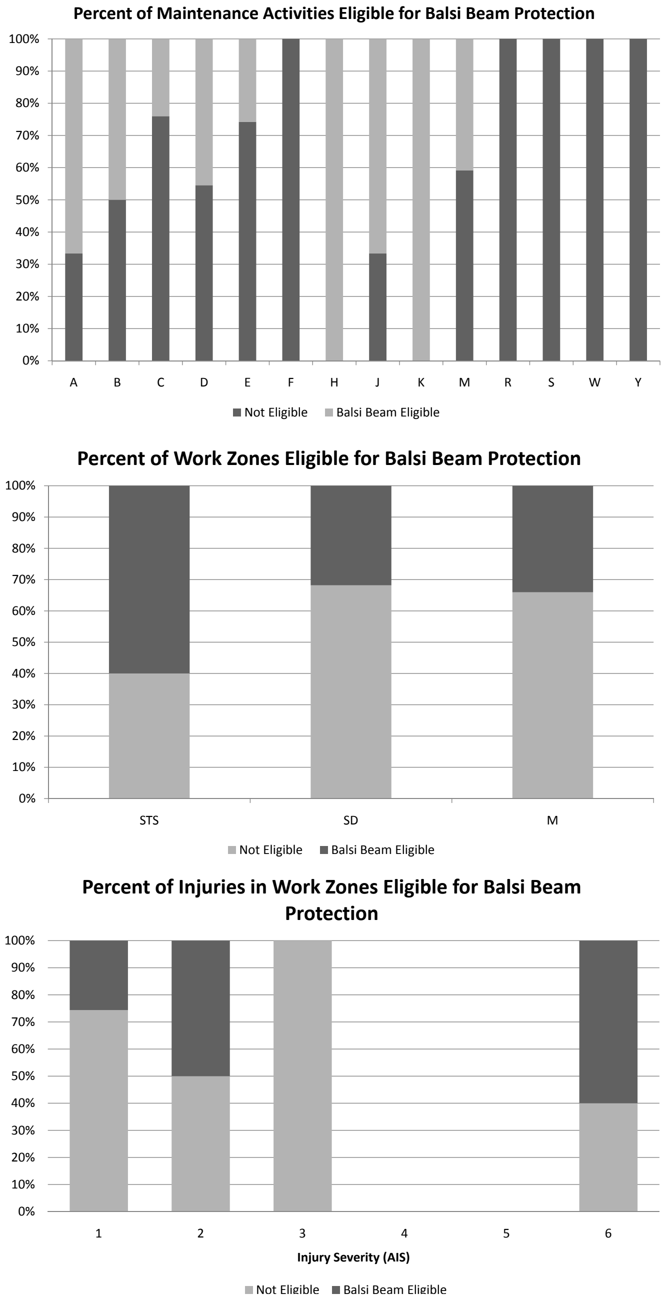


Figure 3.2: Percent of works zones where intrusion accidents were reported eligible for Balsi Beam protection, by maintenance activity, duration, and injury severity.

Injury Severity (MAIS)	Injury Cost (Millions)	Total Costs (Millions)	Averted Costs (Millions)
1	0.0116	3.167	0.812
2	0.0899	1.798	0.899
3	0.3335	0.334	0
4	1.0875	0	0
5	4.4225	0	0
6	5.8000	29.0	17.4
Total		34.298	19.111
Expected Yearly Average		3.430	1.911

Table 3.3: Injury cost model comparing all work zone injury costs (Total) to the expeced averted costs in work zones eligible for Balsi Beam deployment (Averted) over the 10 year period of interest.

this reason, the net benefits of one year of highly mobile barrier protection are examined here.

As previously mentioned, additional impacts, or effects, must be considered to perform a thorough cost benefit analysis. Additional impacts, including barrier deployment time and congestion costs are further examined in the next section.

3.3 Operational Cost Estimates

In addition to the costs and benefits associated with averted injuries and fatalities, other impacts to consider include material and equipment costs, personnel training, time required to set-up and take-down the positive protection, and congestion costs. The costs associated with material and equipment, and personnel training, are outside the scope of this research. However, time of exposure and the effects on congestion may potentially have an effect on the risk of serious injury to the worker. These two elements are further discussed.

3.3.1 Exposure Time

The time necessary to deploy positive protection is important, as it may be the deciding factor in the efficiency and use of a highly mobile barrier. A typical maintenance work zone lane closure, consisting of signage and cones, takes 15–20 minutes to set up. While this time depends on many factors, such as work zone length, traffic volume, and speed limit, the procedure exposes the workers to risk of injury for the entire duration of the work zone maintenance task, in addition to the time required to set up the work zone. Table 3.4 shows the estimated time required for work zone positive protection (Balsi Beam) deployment according to product information and demonstrations. In contrast to traditional work zone delineation, use of positive protection limits the exposure, or risk of injury of the worker to only the time required to deploy the barrier.

The exposure during barrier deployment has not been quantified by means of cost necessary for

Barrier Type	Length of Protected Work Zone	Estimated Deployment Time
Balsi Beam	9 m (30 feet)	10 minutes
Typical Coned Lane Closure	–	15–20 minutes

Table 3.4: Approximate times of deployment for the Balsi Beam, compared with a typical lane closure.

the cost benefit analysis. However, review of Table 3.4 shows that the Balsi Beam requires less time to deploy, thus reducing the amount of exposure workers experience during barrier deployment.

3.3.2 Congestion and Delay

The effect on congestion and traffic delay has the potential to add large costs and benefits to a cost benefit analysis. The effect of a work zone on traffic flow will vary greatly depending on the time of day, traffic composition, and work zone location. However, assuming all are held constant, the additional time and space needed to set up the work zone can have an effect on costs. These costs are addressed using a Road User Cost (RUC) calculation. The RUC is defined as the estimated daily cost to the traveling public resulting from road work being performed. The cost primarily considers lost time caused by any number of conditions including

- Reduced roadway capacity that slows traffic speed and increases travel time,
- Delays in the opening of a new and/or improved facility that prevents users from gaining travel, and
- Detours that add to travel time.

RUC calculation procedures were defined by the Division of Research and Innovation (DRI) at Caltrans and the State of New Jersey Department of Transportation [10, 24], based on NCHRP Report 133: *Procedures for Estimating Highway User Costs, Air Pollution, and Noise Effects*, [11]. The calculations consider cost components associated with unrestricted flow, (free flow), queue, (forced flow), and detour, (circuity). (The NJ Department of Transportation also incorporates crash costs in their calculations.)

Following a template developed by Calrans, the total RUC is found by adding together the calculated RUC associated with the three listed condtions.

$$
\begin{aligned}
RUC_{Total} &= \textit{Sum of all RUCs} \\
&= RUC_{WZ} + RUC_{Delay} + RUC_{Detour}
\end{aligned}
$$

where,

$$
\begin{aligned}
RUC_{WZ} &= \textit{Work Zone reduced speed delay costs} \\
RUC_{Delay} &= \textit{Queue delay costs (Stop and Go)} + \\
& \textit{Queue delay vehicle operation cost (VOC)} \\
RUC_{Detour} &= \textit{Detour delay (due to added length/time)} + \\
& \textit{Detour VOC (due to added length/time)}
\end{aligned}
$$

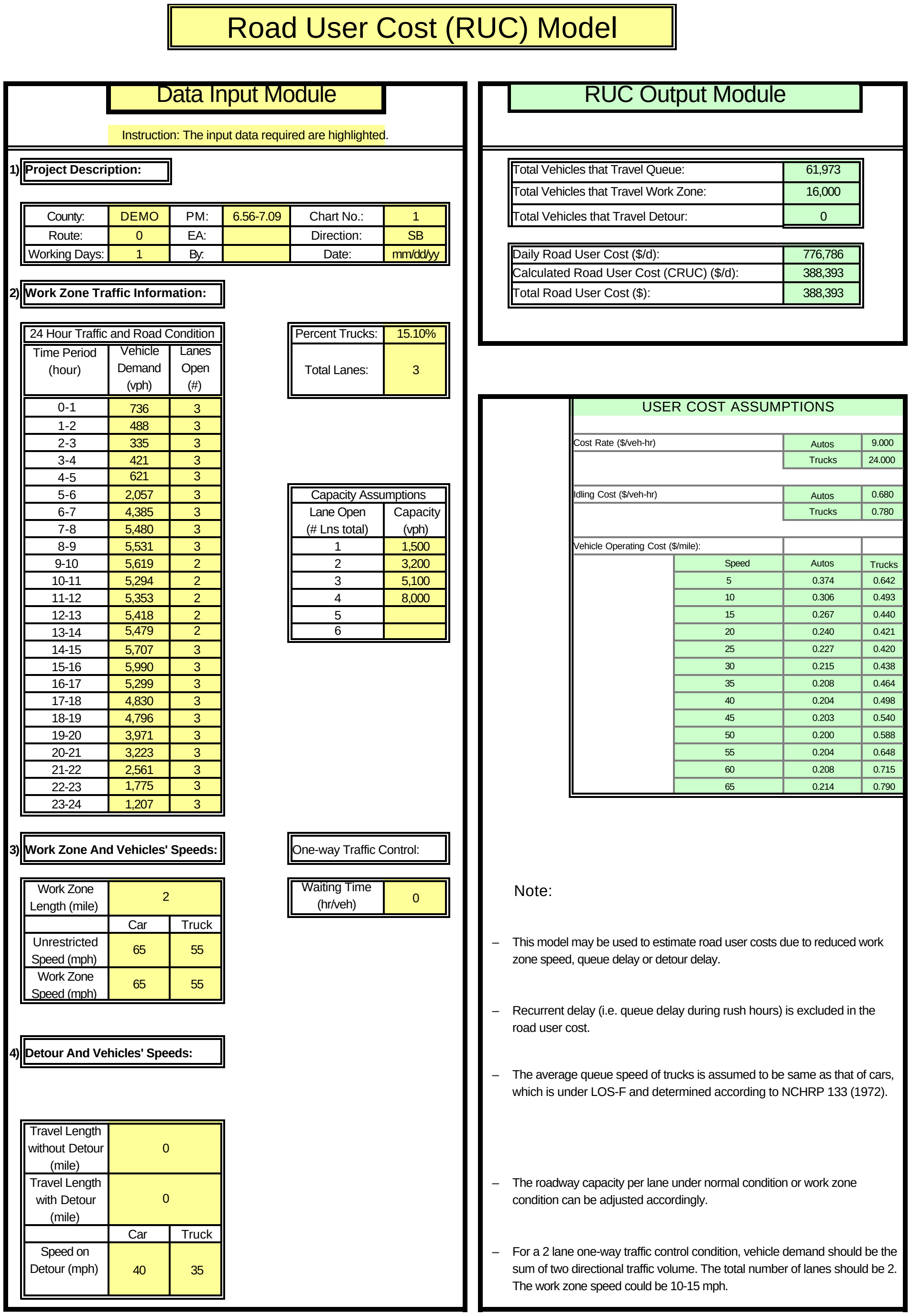
Caltrans (DRI) developed a 'Short Form Calculation Tool', using Microsoft Excel, which includes an Input Module and an Output Module. The Input Module contains specified fields where the user may change cost and capacity estimations for the specific roadway and work site. The required input fields, as shown in Figure 3.3, are:

1. Project description (county, route number, post mile, direction, etc.)
2. Work zone traffic information (24-hour traffic and road conditions, traffic composition, total lanes)
3. Work zone and vehicle speed information (work zone length, unrestricted and work zone speed of vehicles)
4. Detour and vehicle speed information (travel length with and without detour, speed on detour)

The second input field, 'Work zone traffic information', was used to address both the time and spatial needs of the highly mobile barrier. The additional lane needs to set up the work zone are accounted for by adjusting the number of free, or open travel lanes.

Also shown in Figure 3.3, are the outputs calculated by the RUC Module:

- Total vehicles that travel queue
- Total vehicles that travel work zone
- Total vehicles that travel detour
- Daily Road User Cost (RUC) (\$/day)
- Calculated Road User Cost (CRUC) (\$/day)



Road User Cost (RUC) Model

Data Input Module

Instruction: The input data required are highlighted.

1) Project Description:

County:	DEMO	PM:	6.56-7.09	Chart No.:	1
Route:	0	EA:		Direction:	SB
Working Days:	1	By:		Date:	mm/dd/yy

2) Work Zone Traffic Information:

24 Hour Traffic and Road Condition

Time Period (hour)	Vehicle Demand (vph)	Lanes Open (#)
0-1	736	3
1-2	488	3
2-3	335	3
3-4	421	3
4-5	621	3
5-6	2,057	3
6-7	4,385	3
7-8	5,480	3
8-9	5,531	3
9-10	5,619	2
10-11	5,294	2
11-12	5,353	2
12-13	5,418	2
13-14	5,479	2
14-15	5,707	3
15-16	5,990	3
16-17	5,299	3
17-18	4,830	3
18-19	4,796	3
19-20	3,971	3
20-21	3,223	3
21-22	2,561	3
22-23	1,775	3
23-24	1,207	3

Percent Trucks:	15.10%
Total Lanes:	3

Capacity Assumptions

Lane Open (# Lns total)	Capacity (vph)
1	1,500
2	3,200
3	5,100
4	8,000
5	
6	

3) Work Zone And Vehicles' Speeds:

Work Zone Length (mile)	2	
	Car	Truck
Unrestricted Speed (mph)	65	55
Work Zone Speed (mph)	65	55

One-way Traffic Control:

Waiting Time (hr/veh)	0

4) Detour And Vehicles' Speeds:

Travel Length without Detour (mile)	0	
Travel Length with Detour (mile)	0	
	Car	Truck
Speed on Detour (mph)	40	35

RUC Output Module

Total Vehicles that Travel Queue:	61,973
Total Vehicles that Travel Work Zone:	16,000
Total Vehicles that Travel Detour:	0

Daily Road User Cost ($/d):	776,786
Calculated Road User Cost (CRUC) ($/d):	388,393
Total Road User Cost ($):	388,393

USER COST ASSUMPTIONS

Cost Rate ($/veh-hr)	Autos	9.000
	Trucks	24.000
Idling Cost ($/veh-hr)	Autos	0.680
	Trucks	0.780

Vehicle Operating Cost ($/mile):

Speed	Autos	Trucks
5	0.374	0.642
10	0.306	0.493
15	0.267	0.440
20	0.240	0.421
25	0.227	0.420
30	0.215	0.438
35	0.208	0.464
40	0.204	0.498
45	0.203	0.540
50	0.200	0.588
55	0.204	0.648
60	0.208	0.715
65	0.214	0.790

Note:

- This model may be used to estimate road user costs due to reduced work zone speed, queue delay or detour delay.
- Recurrent delay (i.e. queue delay during rush hours) is excluded in the road user cost.
- The average queue speed of trucks is assumed to be same as that of cars, which is under LOS-F and determined according to NCHRP 133 (1972).
- The roadway capacity per lane under normal condition or work zone condition can be adjusted accordingly.
- For a 2 lane one-way traffic control condition, vehicle demand should be the sum of two directional traffic volume. The total number of lanes should be 2. The work zone speed could be 10-15 mph.

Figure 3.3: Sample of the RUC Short Form Calculation Tool created by DRI.

- Total Road User Cost (RUC_{Total})

The RUC tool enables the effect of different protection methods to be more fully evaluated. Using the RUC, the effect on traffic delay can be calculated and quantified. The RUC is another tool used by Departments of Transportation to determine the effectiveness of various alternatives in work zone planning, including detours, temporary roadway or shoulder construction, off-peak hour day work, and night work.

3.3.3 Sample RUC Calculations

To demonstrate the use of the RUC as a tool for work zone protection methods, two sample work zones were evaluated. Assuming that both protection methods (Balsi Beam deployment versus traditional lane closure) provide equal protection in the two ideal situations, spatial needs and deployment time requirements were addressed to calculate an estimated CRUC for two work zones. Table 3.5 lists the spatial and time requirements for each protection method in the two example work zones.

Time Period	Number of Open Lanes			
(hour)	WZA:BB	WZA:Cones	WZB:BB	WZB:Cones
8–9	2	2	2.83	2.67
9–10	1.83	1.67	2	2
10–11	1	1	2	2
11–12	1	1	2	2
12–13	1	1	2	2
13–14	1	1	2	2
14–15	2	1.67	3	2.67
15–16	2	2	3	3

Table 3.5: Portion of the ‘24 Hour Traffic & Road Conditions’ table under the Work Zone Traffic Information field in Figure 3.3. (WZA: Work Zone A, WZB: Work Zone B, BB: Balsi Beam, Cones: Traditional Coned Lane Closure)

Work Zone A (WZA) occurred on a two mile stretch in the southbound direction of a four-lane roadway. If a traditional lane closure were utilized, one travel lane would be available, and one closed for a four hour period from 10:00 to 14:00. Spatial needs for barrier deployment or lane closure are considered, as well as the time for deployment, by adjusting the number of open lanes. The Balsi Beam does not require additional space, however, an additional 10 minutes are necessary for deployment. In comparison, the estimate of 20 minutes was used to account for the time needed to deploy a full lane closure, as shown in Table 3.5. To determine the number of open lanes the deployment time was combined with the spatial needs to produce a fraction. For example, the Balsi Beam requires about 10 minutes to fully deploy. Therefore, from 9–10, 1.83 lanes will be available (2 open lanes for 50 minutes, 1 open lane for the remaining 10 minutes). Using the 20 minute estimate for full (traditional) lane closure, the number of open lanes becomes 1.67 for the hours preceding and following planned maintenance.

Work Zone B (WZB) is modeled after a three mile work zone on the northbound side of a six-lane highway. The traffic composition of WZB consists of 5.00% trucks (compared to 15.10% trucks at WZA). Both work zones reported the same free flow and work zone speed limits, however, due to the larger number of lanes available, WZB experienced a higher vehicle demand. Both Work Zone A and B were analyses performed for work zone planning. The vehicle demand estimates, and traffic composition data were based on data from the PeMS database, [1].

Work Zone A

	Balsi Beam	Cones
Total Vehicles that Travel Queue	24,116	26,122
Total Vehicles that Travel Work Zone	7,500	9,000
Total Vehicle that Travel Detour	0	0
Daily RUC ($/Day)	193,539	263,374
CRUC ($/Day)	96,770	131,687

Work Zone B

	Balsi Beam	Cones
Total Vehicles that Travel Queue	67,662	68,252
Total Vehicles that Travel Work Zone	19,200	22,400
Total Vehicle that Travel Detour	0	0
Daily RUC ($/Day)	883,984	1,014,179
CRUC ($/Day)	441,992	507,090

Table 3.6: RUC estimates for two sample work zones, using the RUC Tool developed by Caltrans [10].

Work Zone A

Barrier Type	CRUC ($/Day)	% Difference
Balsi Beam	96,770	–
Cones	131,687	26.5

Work Zone B

Barrier Type	CRUC ($/Day)	% Difference
Balse Beam	441,992	–
Cones	507,090	12.8

Table 3.7: Percent difference in CRUC for different work zone protection methods.

Using the RUC Tool, shown in Figure 3.3, estimated vehicle travel totals and daily RUCs were calculated. The results are shown in Table 3.6. Table 3.7 summarizes the CRUC and the percent difference (increase) in the CRUC comparing Balsi Beam usage to a traditional lane closure using cones. In these two demonstrations of RUC, the traffic volume can be seen to have a large effect on the RUC. Higher vehicle demand leads to a higher number of vehicles traveling the queue and work zone, which increases user cost. The results shown in Table 3.6 and Table 3.7 show how deployment and spatial requirements affect the RUC estimate.

3.4 Combined Injury and Operational Cost Benefit Analysis

The RUC estimates, which represent two areas of the operational cost benefit analysis (deployment time and congestion effects) can be combined with the injury cost benefit analysis results to present a more thorough evaluation of the two different work zone protection methods.

Injury Severity (MAIS)	Total Cost (Millions)	Balsi Beam Averted Costs (Millions)
1	3.167	0.812
2	1.798	0.899
3	0.334	0
4	0	0
5	0	0
6	29.0	17.4
Total	34.298	19.111
Expected Yearly Average	3.430	1.911

Table 3.8: Injury cost model showing expected averted costs for work zones eligible for Balsi Beam protection compared to the total cost of injury without positive protection.

Recall the results of the injury cost model, which calculated the expected averted costs for work zones eligible for positive protection, based on the California injury data (reprinted in Table 3.8). If the 'Total Cost' column represents the expected injury cost in a traditional lane closure, then the 'Averted Cost' column reports the cost savings of highly mobile barrier use. Rewriting the table, as expected cost savings, Table 3.9 represents the data presented in Table 3.8 in a different manner.

Injury Cost Component ($)

Injury Severity (MAIS)	Traditional Lane Closure	Balsi Beam Protection
1	0	812,000
2	0	899,000
3	0	0
4	0	0
5	0	0
6	0	17,400,000
10 Year Total	0	19,111,000
Yearly Average	0	1,911,000
Operational Cost Component ($/Day)		
Work Zone A	131,687	96,770
Work Zone B	507,060	441,992

Table 3.9: Estimated savings based on injury data and RUC cost calculations.

The second portion of Table 3.9 shows some operational costs for highly mobile barrier use, based on deployment time and congestion effects. Subtracting the estimated operational costs from the expected benefits of averted injuries would yield a better estimate of a cost benefit analysis result. (It is important to remember that there are additional elements not evaluated here, that are necessary to consider for a complete cost benefit analysis.) Obviously, barrier used depends greatly on the planned maintenance activity. However, the results shown here represent a sample analysis and introduce potential cost patterns.

3.5 Risk Assessment Model

A risk assessment is a means of providing quantitative and qualitative measures of the potential severity and probability of injury or damage in order to guide a decision, [7]. In other words, a risk assessment provides a scientific basis for decision making. As a way to aid in decision making in relation to work zone safety planning, a risk assessment was initiated, focusing on Balsi Beam deployment as a means to reduce the risk on highway short-term and temporary work zones.

The typical steps in risk assessment are summarized below:

1. Identify all potential risks and hazards.
2. Determine the probability of occurrence by estimating the likelihood of injury or adverse effects from the risk and the expected frequency of exposure.
3. Identify, evaluate, and implement solutions that will mitigate or reduce risks, using the cost benefit analysis as an aid in solution evaluation.
4. Review and document the risk assessment results on a regular basis and update when necessary.

The initial steps of risk assessment were developed in this research. Identification of risk was established and presented previously in this report, where the trends in work zone accidents producing worker injuries were evaluated. The likelihood of injury, or probability of occurrence was completed using the California work zone injury data to produce the Risk Index, Eqn (2.1). The Risk Index is a metric useful in measuring the risk of injury in highway maintenance work zones. A solutions to mitigate risk, in the form of the Balsi Beam was presented. Social benefit costs were derived for the barriers in the injury cost models, and were presented for further use in the cost benefit analysis. The final steps in risk assessment that remain to be completed include selection and implementation of a risk mitigation device, and an iterative review of the risks following implementation of the highly mobile barriers in use.

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