Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
SD2023-03		

4. Title and Subtitle	5. Report Date August 2026
Develop Methods to Reduce Crashes and Increase Driver Compliance in Work Zones	6. Performing Organization Code
7. Author(s) Priyanka Alluri, Hellen Shita, Enock Mwambeleko, and Albert Gan	8. Performing Organization Report No.
9. Performing Organization Name and Address Florida International University 10555 West Flagler Street, EC 3628 Miami, FL 33174	10. Work Unit No. 11. Contract or Grant No.
12. Sponsoring Agency Name and Address South Dakota Department of Transportation Office of Research, Room 157 700 East Broadway Avenue Pierre, SD 57501-2586	13. Type of Report and Period Covered Final Report March 2024 – August 2026 14. Sponsoring Agency Code

15. Supplementary Notes

This PDF has attachments; see attachment panel to download.

16. Abstract

Work zones are vital for any infrastructure development and maintenance; however, their presence poses risks to motorists, workers, and other road users. This research analyzed work zone data, crash data, and roadway characteristics data to determine factors influencing work zone crash occurrence, injury severity, and driver compliance on South Dakota highways. Data used in the analyses were obtained from the South Dakota Department of Transportation (SDDOT) for the 5-year study period of 2018 to 2022.

Research objectives included a literature review of work zone safety measures in South Dakota and nationwide, a review of state-of-the-art work zone traffic control devices, as well as existing smart work zone (SWZ) technologies and applications. Analyses included crash frequency and crash severity analysis for both rural and urban South Dakota state highways. Findings varied among the variables that increased or decreased the likelihood to work zone crash occurrence on the roadway functional classifications studied. For both limited access and non-limited access facilities (arterials and collectors), variables associated with an increase in the likelihood of severe injury crashes included: lack of safety equipment, driving under the influence (DUI), illness, and disregarding work zone signs.

A speed data analysis was also performed on seven completed projects to evaluate driver compliance. Findings indicated variations among the different projects, showing both significant speed increases and decreases between consecutive locations.

Recommended implementation strategies to reduce work zone crashes, improve driver compliance, and enhance worker safety were presented. SDDOT policies and standards for work zones were also reviewed, and specific revisions were recommended to improve work zone safety for workers and road users.

17. Keywords	18. Distribution Statement
Work Zone Safety, Traffic Control Devices, Smart Work Zone applications	No restrictions. This document is available to the public from the sponsoring agency.

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	151	

Develop Methods to Reduce Crashes and Increase Driver Compliance in Work Zones

Final Report

Report No. SD2023-03

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August 2026

Published by:

South Dakota Department of Transportation
Office of Research
700 East Broadway Avenue
Pierre, South Dakota 57501-2586

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Acknowledgements

This work was performed under the direction of the SD2023-03 Technical Panel:

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Bruce Hunt .... Sioux Falls Area
Christina Bennett .... Operations Support
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List of Abbreviations and Acronyms

A	KABCO Scale: Incapacitating Injury
AADT	Annual Average Daily Traffic
ADT	Average Daily Traffic
AFAD	Automated Flagger Assistance Device
AIC	Akaike Information Criterion
AIS	Abbreviated Injury Score
ATM	Advanced Traffic Marking
B	KABCO Scale: Non-Incapacitating Injury
BIC	Bayesian Information Criterion
C	KABCO Scale: Possible Injury
CB	Citizens Band
CMS	Changeable Message Sign
DMS	Dynamic Message Sign
DOT	Department of Transportation
DSFS	Dynamic Speed Feedback Sign
DUI	Driving Under the Influence
EOQ	End-of-Queue
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
FIU	Florida International University
GIS	Geographic Information System
GORL	Generalized Ordered Response Logit
HAR	Highway Advisory Radio
HSM	Highway Safety Manual
HVE	High Visibility Enforcement
ID	Identification
ITS	Intelligent Transportation System
K	KABCO Scale: Fatal Injury
KML	Keyhole Markup Language
MAC	Major Collectors
MAE	Mean Absolute Error
MCR	Misperceived Closure Rate
MIA	Minor Arterials
MIRE	Model Inventory of Roadway Elements
MM	Mile Marker
MMUCC	Model Minimum Uniform Crash Criteria
MoDOT	Missouri Department of Transportation
Mph	Miles per hour
MSE	Mean Squared Error
MUTCD	Manual on Uniform Traffic Control Devices
NB	Negative Binomial
NHTSA	National Highway Traffic Safety Administration
NTIS	National Technical Information Service
O	KABCO Scale: Property Damage Only
OR	Odds Ratio

PA	Principal Arterials
PCMS	Portable Changeable Message Sign
PCN	Project Control Number
PDF	Portable Document Format
PDO	Property Damage Only
PPRS	Portable Plastic Rumble Strip
QWS	Queue Warning System
RID	Roadway Identification
RMSE	Root Mean Squared Error
RPM	Raised Pavement Marker
SDARS	South Dakota Accident Records System
SDDOT	South Dakota Department of Transportation
SFT	Speed Feedback Trailer
SMD	Speed Monitoring Display
SPE	Speed Photo Enforcement
SWZ	Smart Work Zone
SWZDI	Smart Work Zone Deployment Initiative
TCD	Traffic Control Device
TMA	Truck-mounted Attenuator
TPRS	Temporary Portable Rumble Strips
TRIS	Transportation Research Information Services
TSM&O	Transportation Systems Management and Operations
TTC	Temporary Traffic Control
TxDOT	Texas Department of Transportation
U.S.	United States
VSL	Variable Speed Limit
Vpd	Vehicles per day
WZ	Work Zone
ZINB	Zero-Inflated Negative Binomial
ZIP	Zero-Inflated Poisson

Executive Summary

Work zones are vital for any infrastructure development within a society. However, work zones presence poses risks to motorists, workers, and other road users. With 7,794 miles of highway, the South Dakota Department of Transportation (SDDOT) is diligently working to enhance infrastructure development and foster improved connectivity between cities. As a result, future construction activities, combined with ongoing work, are expected to increase the number of work zones along South Dakota's highway system.

Between 2018 and 2022, South Dakota experienced a total of 1,060 work zone crashes on its state highways. While driver non-compliance to traffic control measures has been identified as a key potential factor contributing to these crashes, identifying other contributing factors to crashes and driver non-compliance along work zones in South Dakota is necessary to implement targeted countermeasures.

Previous studies on work zone safety in South Dakota are limited, highlighting a research gap in understanding South Dakota's work zone safety challenges. This project addresses this gap by analyzing crash data and evaluating the effectiveness of traffic control measures used in work zones on South Dakota highways. Research objectives involved a literature review of work zone safety measures in South Dakota and nationwide, a review of state-of-the-art work zone traffic control devices, as well as existing smart work zone (SWZ) technologies and applications, and an analysis of work zone crashes for the years 2018 – 2022 to identify factors influencing the occurrence (frequency) and severity of work zone crashes in South Dakota. Recommended implementation strategies to reduce work zone crashes, improve driver compliance, and enhance worker safety were also presented. In addition, SDDOT polices and standards for work zone traffic controls were examined, and revisions were recommended, if applicable, to promote work zone safety for workers and road users.

1.1 Literature Review Findings

A comprehensive literature review was conducted on both general and specific aspects of work zone safety, including work zone crash frequency, work zone crash injury severity, truck-involved work zone crash severity, driver compliance along work zones, state-of-the-art work zone traffic control devices, and the use and impact of SWZ applications.

1.1.1 Work Zone Crash Frequency

Findings from previous studies indicate that factors associated with work zone crash frequency vary across locations. General factors contributing to work zone crash occurrence included: longer work zone length and duration, higher Average Annual Daily Traffic (AADT), higher Average Daily Traffic (ADT), greater number of lanes, roadway width restrictions, lane closures, and lane shifts.

1.1.2 Work Zone Crash Severity

General factors contributing to increased crash severity included: work zones with longer durations, workers on foot, lighting conditions, time of day, crashes on rural highways, lane closures, lane shifts, driving under the influence (DUI), and higher speed limits. In addition, roadway width restrictions and work zones on major arterials were associated with fatal and serious injury crashes in work zones.

General factors contributing to increased truck-involved work zone crash severity included: lighting conditions, speeding, crashes in the work zone area, presence of workers, greater number of vehicles involved, drivers under age 35 years, two-way undivided roadways, and higher speed limits.

1.1.3 Driver Compliance Along Work Zones

For work zones, driver compliance refers to the extent to which drivers adhere to the designated speed limit, lane changes and detours, and temporary traffic control devices. Several factors have been associated with driver non-compliance along work zones, including driver distraction, information overload, insufficient signage, or lack of enforcement.

Countermeasures used by different agencies to maintain driver compliance in work zones include the use of dynamic message signs (DMSs), temporary rumble strips, speed feedback signs, lateral deflections, lane narrowing, flashing beacons, higher fines, photo enforcement, lights on contractor vehicles, and the use of SWZ technologies. Smart work zone applications utilize computers, communications, sensor technology and Intelligent Transportation Systems (ITS) for dynamic and impact management of work zones. Examples include Queue Warning Systems (QWSs), lane closure notification systems, traveler information systems, and others.

Previous studies have analyzed the impact of various traffic control devices on improving driver speed compliance along work zones, including police presence, radar speed display, and speed feedback signs. Findings revealed that a number of temporary traffic control devices did not significantly impact work zone safety. However, speed monitoring displays (SMDs) and portable changeable message signs (PCMSs) showed speed reductions of up to seven miles per hour (mph), potentially improving safety at work zones.

1.1.4 State-of-the-Art Work Zone Traffic Control Devices

A number of state agencies have deployed various temporary traffic control devices to enhance safety and mobility along work zones. Temporary traffic control devices reviewed in this research, and their impacts noted by previous studies included:

- Portable rumble strips: Reduced speeds and increased driver compliance.
- Speed monitoring displays: Reduced speeds and increased driver compliance.
- Portable changeable message signs (PCMSs): Reduced speeds with both text-based and graphic-based messages and increased driver compliance.
- Radar drones: Reduced mean speeds, increased driver compliance, and decreased number of crashes.
- Temporary ramp metering: Reduced speeds by over 19% in non-congested conditions.
- Automated Flagger Assisted Devices (AFADs): Lowered approach speeds, increased stopping compliance; however, greater violation rates with an increase in work zone length and a decrease in AADT were observed.
- Mobile barriers and barricades: Mobile barriers provided enhanced safety for workers, but still exposed the workers to traffic during placement and removal.
- Citizens Band (CB) Wizard alert system: Effective in reducing speeds for non-passenger cars during daytime hours.
- Truck-mounted attenuators (TMAs): Positive impacts with fewer vehicles entering the critical zone and reduced costs per crash in injury and damage compared to a vehicle hitting a stationary construction vehicle.

1.1.5 Smart Work Zone Technologies and Applications

Smart work zone applications used by transportation agencies nationwide were reviewed and categorized into three categories: portable changeable message signs (PCMSs), queue warning systems (QWSs), and speed monitoring and management systems.

PCMSs have been used in work zones for a number of years and have shown to be effective in reducing speeds and increasing driver compliance. However, previous studies have found that the degree of effectiveness depends on the placement of PCMSs, the message displayed, and the type of message (text-based or graphic-based). QWSs alert drivers approaching a work zone of slowed or stopped traffic ahead. Previous studies have found QWSs to be effective in reducing crashes, especially for nighttime lane closures.

Speed monitoring and management systems are used for the purpose of monitoring/ regulating speeds along work zones. SWZ applications can be utilized to inform/alert drivers of their speeds (to remain at or below set speeds) and improve safety for both workers and motorists. Speed monitoring and management systems may include Automated Speed Photo-Radar Enforcement (SPE), Speed Monitoring Displays (SMDs), or Variable Speed Limits (VSLs). Other strategies and devices used to enhance visibility and safety in work zone deployments include intrusion alarm systems, lane merge systems, fluorescent/ bright signs, and reflectorized/ bright signs and vests.

1.2 Analysis Results

Several analyses were performed to identify factors contributing to both the occurrence and severity of work zone crashes on South Dakota highways. The analyses included: Descriptive Statistics, Crash Frequency Analysis, Crash Severity Analysis, and Speed Data Analysis.

1.2.1 Descriptive Statistics

Crash data for the study period (2018 – 2022) were provided by SDDOT. A final dataset comprising 1,059 work-zone crashes was used in the analysis. Descriptive statistics of the work zone crash data revealed the following:

- The majority of work zone crashes occurred in 2021, with a total of 313 crashes, followed by 200 crashes in 2022.
- The largest proportion of severe injuries was observed in 2018, where about 7% of the 156 crashes resulted in fatalities and severe injuries.
- Most of the work zone crashes occurred in the summer (43.6%), with 8% resulting in severe injuries and fatalities.
- While most of the crashes occurred on weekdays, a larger proportion of those that occurred on the weekend resulted in severe injuries and fatalities (9.9%).
- The majority of the crashes (47.7%) were rear-end type crashes.
- While only 6.8% of crashes involved DUI, nearly 7% of these crashes resulted in fatalities, and 12.5% resulted in incapacitating injuries.
- While only 7.6% of work zone crashes involved speeding, 3.8% and 15% of these crashes resulted fatalities and incapacitating injuries, respectively.
- The majority of crashes involved drivers aged between 35and 64 (40.5%), followed by drivers aged between 20 and 34 (31.1%). Drivers aged 14–19 years accounted for 11.3%, while drivers aged 65 years and older accounted for 17.1% of crashes.

- The majority of crashes occurred in clear weather (77.5%) and during daylight hours (84.4%).
- Nearly half (47.6%) of crashes involved light trucks, followed by passenger cars (46%).
- Although only 5.1% of crashes involved motorcycles, 9.3% of these crashes were fatal, and 27.8% resulted in incapacitation injuries.
- The majority of crashes occurred on rural highways (29%), followed by urban principal arterials (22.8%).
- The majority of work zone crashes occurred on roadways with higher speed limits: 29.4% with 60-70 mph speed limits and 28.7% with 75-80 mph speed limits.
- The majority of crashes occurred on roadways with concrete surfaces (73.5%), at non-junction locations (71.9%), and on straight and level roadway segments (79.2%).
- Over 55% of crashes occurred on divided roadways, with 1.2% fatal and 4.3% resulting in incapacitating injuries.

1.2.2 Crash Frequency Analysis

To identify features associated with the occurrence of work zone crashes, a crash frequency analysis was performed for both rural and urban South Dakota state highways, for the following six functional roadway classifications:

- Rural – Freeway, Expressway, and Interstate
- Rural – Principal Arterial
- Rural – Major Collector and Minor Arterial
- Urban – Freeway, Expressway, and Interstate
- Urban – Principal Arterial
- Urban – Major Collector and Minor Arterial

The analysis also examined work zone crash frequency based on the four regional areas in South Dakota: Rapid City, Pierre, Mitchell, and Aberdeen for the study period (2018 – 2022). Table 1.1 summarizes the results of the crash frequency analysis for the roadway functional classifications analyzed.

Table 1.1 Summary of crash frequency analysis results

Functional Classification	Analysis Results
Rural – Freeway, Expressway, and Interstate	Increase the likelihood of work zone crashes: ▪ Grading work ▪ Intersection work ▪ Higher Average Daily Traffic (ADT) ▪ Larger project contract amounts ▪ Work zones in the Pierre region
Rural – Principal Arterial	Increase the likelihood of work zone crashes: ▪ Higher speed limits ▪ Greater truck ADT ▪ Wider roadways ▪ Larger project contract amounts Decrease the likelihood of work zone crashes: ▪ Work zones involving pavement markings, rumble strips ▪ Shoulder work

Functional Classification	Analysis Results
Rural – Major Collector and Minor Arterial	Increase the likelihood of work zone crashes: ▪ Shoulder work ▪ Higher ADT ▪ Wider roadways ▪ Larger contract amounts ▪ Work zones in the Pierre region Decrease the likelihood of work zone crashes: ▪ Work zones in the Rapid City region
Urban – Freeway, Expressway, and Interstate	Increase the likelihood of work zone crashes: ▪ Increase in ADT Decrease the likelihood of work zone crashes: ▪ Work zones involving concrete surface repair ▪ Work zones involving pavement markings, rumble strips ▪ Greater truck ADT ▪ Work zones in the Rapid City region
Urban – Principal Arterial	Increase the likelihood of work zone crashes: ▪ Higher ADT ▪ Wider roadways ▪ Wider right-of-way widths ▪ Larger contract amounts ▪ Work zones in the Rapid City region
Urban – Major Collector and Minor Arterial	Not analyzed due to limited data.

1.2.3 Crash Severity Analysis

The crash injury severity analysis involved identifying factors that contribute to more severe injuries resulting from a crash, such as fatalities or incapacitating injuries. A total of 961 work zone crashes were used in this analysis, following the removal of crash events with missing variables from the 1,059 crash dataset. A total of 29 variables were analyzed for two roadway groups: limited access facilities, and arterials and collectors. Findings are presented below.

1.2.3.1 Limited Access Facilities

Variables associated with **increased severity** in work zone crashes on limited access facilities included:

- No safety equipment used (for example, seatbelts, helmets, etc.)
- Driving under the influence (DUI) involved
- Angle crashes
- Overcorrection
- Illness
- Motorcycle involved
- Disregard of signs
- Higher ADT

Variables associated with **decreased severity** in work zone crashes on limited access facilities included:

- Vehicle maneuvering (not slowing or stopping)
- Greater truck ADT

1.2.3.2 Arterial and Collectors

Variables associated with **increased severity** in work zone crashes on arterial and collectors included:

- No safety equipment used (for example, seatbelts, helmets, etc.)
- Driving under the influence (DUI) involved
- Illness
- Other vehicle types (for example, Vans, Semi-trailers, etc.)
- Disregard of signs
- Work zone crashes in the Rapid City region

Variables associated with **decreased severity** in work zone crashes on arterial and collectors included:

- Vehicle maneuvering (not slowing or stopping)
- Drivers aged 65 and older

1.2.4 Speed Data Analysis

A speed data analysis was performed to identify significant speed reductions or increases at work zones or downstream locations. To conduct the analysis, SDDOT provided speed data for seven completed projects:

- I-29 Sioux Falls 0293(106)76: May 2022 – July 2024
- I-229 Minnehaha Co (2021): May 2021 – October 2021
- I-229 Minnehaha Co IM 2292(98)9 (2023): April 2023 – November 2024
- I-229 Minnehaha Co IM 2292(105)3 (2024): July 2024 – October 2024
- I-90 Pennington Co (2021): June 2021 – December 2021
- I-90 Pennington Co 0901(195)32: September 2022 – December 2022
- I-90 Various Co IM-NH 0041(181) (2024): July 2024

The data for some of the projects were categorized into upstream and downstream locations, while others included data at locations with respect to the start of the work zone taper. Findings indicated variations among the different projects, showing both significant speed increases and decrease between consecutive locations. Since the exact location where the sensors were placed is unknown, the results should be used with caution.

1.3 Recommendations

Several recommendations were developed based on the information reviewed and analyses performed in this research effort. The research team provides the following recommendations to the SDDOT to reduce work zone crashes, improve driver compliance, and enhance worker safety;

- SDDOT should establish a centralized work zone data repository and a formal data-sharing framework with contractors and law enforcement agencies. Standardized collection and reporting of work zone, traffic, and operational data (such as traffic volume, speed, sensor information, occupancy data for significant projects, and Traffic Control Device activity logs) will allow SDDOT to consistently evaluate safety and mobility impacts, improve crash reporting accuracy, and support data-driven planning and decision-making.

- SDDOT should apply an ADT-based prioritization framework to focus enhanced safety countermeasures on high-volume roadways. Work zones exceeding recommended ADT thresholds should receive elevated safety consideration, including the provision of advance warning signs upstream of the work zone, the dissemination of real-time work zone information through traveler information systems and navigation applications, the use of speed management strategies, and the deployment of queue warning systems. This data-driven approach ensures that limited resources are allocated where traffic exposure and crash risk are greatest.

- SDDOT should coordinate with law enforcement agencies to implement targeted education and enforcement campaigns in and near work zones. Priority focus areas include DUI enforcement, seat belt compliance, and adherence to move-over laws.

- SDDOT should revise its Flagger Manual to incorporate requirements for flagger rest periods and limits on continuous flagging time.

Chapter 2: Problem Description

Work zone areas typically feature conditions including closed lanes, detours, and the presence of workers, construction equipment, work zone signs, barriers, uneven pavements, etc. The presence of these non-normal conditions along roadways presents additional challenges to the drivers, affecting not only the roadway capacity, but more importantly, the safety of both drivers and workers. Statistics also indicate that areas undergoing highway construction and maintenance are more susceptible to motor-vehicle crashes.

Previous studies have examined historical crash data to identify factors contributing to crashes at work zones. However, contributing factors vary with different geographical areas, traffic control devices used, set policies and standards, driving behaviors, and demographic patterns.

This research analyzed crash data in South Dakota to determine work zone types, traffic control measures, and contributing factors to work zone related crashes. The study aimed to identify practical, applicable, and implementable strategies that can be deployed by SDDOT to reduce work zone crashes, increase driver compliance, and improve the safety of workers and road users. In addition, the study reviewed SDDOT's current policies and standards for work zones to identify potential revisions that can improve work zone safety.

Chapter 3: Research Objectives

This project examined and analyzed work zone types and crashes to identify factors contributing to the occurrence and severity of work zone related crashes. The analysis included work zones along all functional classifications, using the roadway functional classification as defined by the South Dakota's Functional Classification map.

3.1 Objective 1: Analyze Past SDDOT Work Zone Types, Crash Data, Policies, and Standards

To accomplish this objective, the research team will work with the SDDOT Project's Technical Panel to obtain the following data, to the extent possible:

- Work zone data (such as, work zone type, work zone location, etc.)
- Maintenance of Traffic (MOT) and Temporary Traffic Control Plan (TTCP) data
- Crash data for the most recent five years
- Incident data for the most recent five years, if available
- Roadway characteristics inventory data
- Traffic volume data (Average Annual Daily Traffic (AADT))
- Any previous initiatives implemented to address work zone crashes
- SDDOT policies and standards pertaining to work zones

Descriptive statistics analysis of the work zone crash data will be conducted to obtain insights on the distribution of work zone crashes in South Dakota in relation to environmental conditions, roadway geometric characteristics, vehicle factors, and driver characteristics.

Current SDDOT policies and standards used for work zone traffic control will also be reviewed. The review will consist of a comprehensive examination of existing SDDOT documentation, policies, and standards established by the SDDOT pertaining to work zone traffic management. This thorough review aims to assess the effectiveness, compliance, and relevance of current policies, providing insights that can inform potential updates and revisions in alignment with best practices and evolving safety standards.

3.2 Objective 2: Determine Work Zone Types with an Overrepresentation of Crashes

To achieve this objective, crash and the work zone data will be analyzed to identify contributing factors. The approach involves two major phases:

- Work Zone Crash Frequency Analysis
- Work Zone Crash Injury Severity Analysis

3.2.1 Crash Frequency Analysis

Crash frequency analysis involves assessing the occurrence and patterns of traffic crashes. By analyzing relevant data, such as work zone type (for example, construction, maintenance, and utility), work zone location (i.e., functional classification), work zone duration, and geometric characteristics, statistical methods will be employed to identify trends and hotspots. The aim is to understand the frequency and distribution of work zone crashes, enabling the development of targeted strategies for improving safety and reducing the likelihood of work zone crashes in South Dakota. To conduct crash frequency analysis, work zone data, in conjunction with crash, roadway characteristics, and traffic data will be used. However, depending on data availability, and discussion with the project's Technical Panel, the research team will identify the work zones to analyze in this project.

The crash frequency analysis will require segmentation of the work zone data and the roadway characteristics data to obtain homogeneous segments of the work zones. Segmentation is necessary to identify specific subgroups with similar features, allowing for a more focused examination of factors influencing crash frequency within those segments. The research team aims to use this approach as it enhances the precision of the analysis, facilitating the identification of targeted safety measures and interventions for each distinct work zone category, ultimately contributing to a more effective and comprehensive road safety strategy.

3.2.2 Crash Injury Severity Analysis

Crash injury severity analysis involves examining factors influencing the severity of injuries in crashes. The goal is to identify key variables contributing to severe injuries, assisting in the development of targeted interventions and safety measures to mitigate the impact of work zone crashes. Statistical models will be developed to identify factors contributing to injury severity in work zone related crashes. The outcome or target variable for this analysis will be in form of the KABCO injury classification: K (fatal crashes), A (incapacitating crashes), B (non-incapacitating crashes), C (possible injury crashes), and O (property damage only (PDO) crashes). Variables to be included in the crash injury severity analysis include those related to crash characteristics, environmental factors, roadway conditions, vehicle characteristics, and driver characteristics and behavior.

3.3 Objective 3: Recommend Implementation Strategies

The research team aims to accomplish this objective by examining the results from objectives 1 and 2. The influencing factors identified in Sections 3.1 and 3.2 will be used to identify and recommend applicable strategies that the SDDOT could use to reduce work zone crashes, improve driver compliance, and improve worker safety along work zones on all roadways as defined by the South Dakota Functional Classification map, depending on data availability and input from the technical panel. Using the crash frequency analysis, the research team will be able to identify the type and geometric characteristics of work zones that have an overrepresentation of crashes. The crash injury severity analysis will shed light on factors contributing to severe injuries in work zone crashes. Such findings will make it possible to identify feasible and practical countermeasures that will help SDDOT in its efforts towards work zone safety. Potential recommendations could include those related to the use of Intelligent Transportation Systems (ITS), Transportation Systems Management and Operations (TSM&O) strategies, or more specifically, the use of Smart Work Zone (SWZ) technologies or applications.

3.4 Objective 4: Recommend Revisions to Current Policies and Standards

This objective will be accomplished by integrating the findings from the first three objectives. The crash analysis results will shed light on the contributing factors to work zone crashes. The review of existing SDDOT policies and standards related to work zone traffic control will help assess the effectiveness, compliance, and relevance of these policies. As such, the research team will be able to identify the relation between the current policies and the patterns identified in crash occurrence, and provide specific revisions to the current SDDOT policies, procedures, and standards.

Chapter 4: Task Descriptions

This chapter presents a description of the tasks conducted as part of this project. The project objectives were achieved through a total of ten tasks, as listed below.

- Task 1 – Conduct Project Kick-off Meeting
- Task 2 – Conduct a Comprehensive Literature Review
- Task 3 – Collect and Process Data
- Task 4 – Develop Research Methodology
- Task 5 – Analyze Data
- Task 6 – Recommend Implementation Strategies
- Task 7 – Review Existing Policies and Standards and Recommend Revisions
- Task 8 – Submit Draft Final Report
- Task 9 – Submit Final Report
- Task 10 – Present to the SDDOT Leadership

Task 2 was conducted to address Objective 1 through a comprehensive review of the literature and existing practices. Tasks 3 through 5 addressed Objective 2 and included data collection, data processing, methodology development, and data analysis. Task 6 addressed Objective 3 by developing implementation strategies based on the study findings. Task 7 addressed Objective 4 through a review of existing policies and standards and the recommendation of revisions. The following subsections discuss the tasks in detail.

4.1 Task 1: Conduct Project Kick-off Meeting

A virtual kick-off meeting was conducted with the project's Technical Panel to review the project scope and work plan. Attendees included the entire Florida Internation University (FIU) research team, the Project Manager, Project Technical Panel, and the SDDOT Transportation Office of Research Coordinator. The project scope and work plan, the tasks, deliverables, project milestones/timeline, anticipated deployment plan, and anticipated benefits were discussed. Data requirements, availability, and limitations, and the necessity to obtain supplemental data to achieve the research goal and objectives were also discussed. Following the kick-off meeting, the presentation slides, meeting notes, and action items were submitted to the Project Technical Panel and the Transportation Office of Research Coordinator.

4.2 Task 2: Conduct a Comprehensive Literature Review

A comprehensive and in-depth literature review of existing studies was conducted, with the focus on the following topics:

- Factors contributing to work zone crashes on all roadways as defined by the South Dakota Functional Classification map, depending on data availability and input from the technical panel.
- Factors influencing driver compliance along work zones
- State-of-the-art work zone traffic control devices
- Benefits and challenges of existing work zone ITS devices
- Impact of work zone traffic control devices on driver compliance
- Impact of work zone traffic control devices on crash reduction

A number of databases were utilized, including the South Dakota Accident Records System (SDARS), Fatality Analysis Reporting System (FARS), Statewide Construction Project Information, Science Direct, Transportation Research Information Services (TRIS), Inspect, National Technical Information Service (NTIS), General Science, Uncover, Wilson Applied Science & Technology, and Dissertation Abstracts Online.

4.3 Task 3: Collect and Process Data

Extensive data collection efforts were employed, consistent with the Highway Safety Manual (HSM) and other standards (such as, Model Inventory of Roadway Elements (MIRE) and Model Minimum Uniform Crash Criteria (MMUCC)), especially for roadway characteristics and crash data. For this task, the following data were required: roadway characteristics data, traffic volume data, past SDDOT work zone data, work zone related crash data, and traffic incident data.

4.3.1 Roadway Characteristics Data

Roadway characteristics data were collected in two phases. First, an inventory of all work zones in South Dakota was prepared, categorizing them into three groups: (1) interstates and other freeways and expressways, (2) principal arterials and major collectors, and (3) minor arterials and local roads. However, data collected depended on availability and input from the technical panel. A second inventory was prepared of critical roadway cross-section elements related to work zones, including the number of lanes, shoulder types and widths, median types, and widths, Annual Average Daily Traffic (AADT), truck traffic volume, posted speed limits, and others, available from SDDOT.

4.3.2 SDDOT Work Zone Data

Once the roadway characteristics data was identified and processed, the data were merged with past SDDOT work zone data. The work zone data included information about critical work zone characteristics such as project identification (ID), roadway ID, begin and end mile of work zone, duration (begin and end date), lane closure information, and type of activity performed. These data were combined with the roadway characteristics data and the functional classification data using ArcGIS to obtain a comprehensive dataset of the work zones for analysis. The dataset was then extracted into an Excel format for further analysis, including segmentation and crash analysis.

4.4 Task 4: Develop Research Methodology

Task 4 focused on the development of research methodology to determine work zone types, traffic control measures, and contributing factors with an overrepresentation of crashes. This task was divided into three subtasks, as listed below.

4.4.1 Subtask 4(a): Identify Factors Contributing to Injury Severity

This subtask involved developing a statistical methodology to identify factors related to work zone crashes by studying their influence on crash injury severity. The contributing factors analyzed included factors related to crash characteristics (such as, crash type, crash severity, first harmful event, time of crash event, weather condition, road surface condition, etc.), work zone characteristics (such as, type of work zone, presence of workers, traffic control facility at the time of crash, etc.), driver characteristics (such as, age, gender, whether driving under influence or impaired, aggressive driving, speeding, etc.), and vehicle characteristics (such as, age, type of vehicle, vehicle maneuver during crash, etc.). Following a descriptive statistical analysis of the data, a logistic regression analysis was conducted to identify contributing factors to work zone related crash injury severity.

4.4.2 Subtask 4(b): Identify Factors Contributing to Crash Occurrence

For this subtask, a statistical model was used to identify factors contributing to the frequency/occurrence of work zone crashes on roadways as defined by the South Dakota Functional Classification map, depending on data availability and input from the technical panel. Past SDDOT work zone data was used, together with roadway characteristics inventory, to identify the geometric characteristics of the work zones.

Segmentation was the first and most critical step in this subtask. The work zones were segmented based on roadway characteristics. Following the segmentation, rules were formulated to assign crashes to the work zone segments using Microsoft Excel. Negative binomial statistical analysis was considered to identify factors contributing to work zone crash frequency.

4.4.3 Subtask 4(c): Investigate Driver Compliance at Work Zones

This subtask focused on using the following data to investigate driver compliance at work zones:

i. Information on the temporary traffic control (TTC) devices at the work zones (for example, signs, posted speed limit, etc.)
ii. Crash data

By using crash data, the cause of crash related to driver compliance with existing TTC devices, including the posted speed limit, could be identified. Based on data availability, the research team used crash data to identify if drivers were speeding, driving too fast for conditions, or failing to abide by set TTC devices in the vicinity of the work zone. The relation between the posted speed limits (and the information displayed on the TTC devices), driver behavior identified from crash data, and other crash data variables were analyzed to investigate driver compliance at work zones.

Deliverable #1: Upon completion of Tasks 1 through 4, a technical memorandum was submitted, summarizing the comprehensive literature review, data collection and availability, the research methodology to determine work zone types, traffic control measures, and contributing factors to overrepresentation of work zone related crashes. The technical memorandum was submitted to the SDDOT, Office of Research.

4.5 Task 5: Analyze Data

Upon approval of the methodology submitted in Deliverable # 1, the research team conducted the analysis. The analyses focused on the following:

- identifying work zone characteristics and geometry design that have an overrepresentation of work zone crashes;
- determining factors that contribute to crash injury severity at work zones; and
- investigating driver compliance to traffic signs and posted speed limits at work zones.

Deliverable #2: Upon completion of Task 5, the research team submitted a technical memorandum summarizing the findings in Task 5 for approval of the project's Technical Panel. The technical memorandum was submitted to the SDDOT, Office of Research.

4.6 Task 6: Recommend Implementation Strategies

Upon submission and approval of Deliverable #2, the research team examined the findings in detail to identify potential strategies that SDDOT could deploy to reduce work zone related crashes and increase driver compliance along work zones across the state. Strategies adopted by other states to combat work zone crashes and improve worker and road user safety were also identified.

4.7 Task 7: Review Existing Policies and Standards and Recommend Revisions

To achieve this task, the research team requested and reviewed all existing SDDOT policies, procedures, guidelines, and standards pertaining to work zones. Findings from the analysis of contributing factors to work zone crashes and driver non-compliance along work zones assisted the research team with developing specific recommendations for revisions to improve safety and driver compliance at work zones. Policies from other states and their impacts on improving work zone safety were also briefly reviewed.

Deliverable #3: Upon completion of Tasks 6 and 7, a technical memorandum summarizing the findings was submitted to the SDDOT, Office of Research, for approval by the project's Technical Panel.

4.8 Task 8: Submit Draft Final Report

Following the submission and approval of Deliverables 1 through 3, the research team prepared and submitted a Draft Final Report to the Department. The Draft Final Report includes a detailed discussion of the literature review, data, research methodology, findings, conclusions, and recommendations. All SDDOT comments received for previous deliverables were also incorporated in the report.

Deliverable #4: Upon Department approval of Deliverables 1, 2, and 3, the research team submitted the Draft Final Report in PDF and Word formats electronically through email to the SDDOT, Office of Research.

4.9 Task 9: Submit Final Report

Upon addressing the comments received from the SDDOT on the Draft Final Report, the research team will prepare and submit the Final Report to the Department.

Deliverable #5: The research team will electronically submit the Final Report in PDF and Word formats to the SDDOT, Office of Research.

4.10 Task 10: Present to the SDDOT Leadership

The Principal Investigator (PI) presented the research findings to the SDDOT Research Review Board at the conclusion of the project. The purpose of the meeting was to present the project's findings, methodologies, and implications to the SDDOT. This executive presentation aims to highlight key achievements, discuss challenges faced during the research, and provide actionable insights to the Department.

Deliverable #6: The Principal Investigator presented the research findings and recommendations to the SDDOT Research Review Board.

Chapter 5: Findings and Conclusions

This chapter provides an overview of the descriptive statistics and findings from the crash frequency, crash severity, and speed analyses performed to identify factors contributing to both the occurrence and severity of work zone crashes in South Dakota from 2018 to 2022. Data collection and processing and analysis methodology are discussed in detail in Appendices B and C, respectively, of this report. In addition, findings from a comprehensive literature review of work zone crashes is provided in Appendix A.

5.1 Descriptive Statistics

Work zone crash data were obtained from SDDOT in both Excel and shapefile formats for the study period (2018 – 2022). The final dataset included 1,059 work zone crashes that occurred along the South Dakota state highway system. The majority of work zone crashes occurred in 2021 (313 crashes), followed by year 2022 (200 crashes). Most crashes occurred on rural highways (29%) and urban principal arterials (22.8%), followed by urban limited access facilities (19.5%). Of the 91 crashes that occurred on rural principal arterials, 13.2% resulted in incapacitating injuries, the highest proportion among all functional classes.

The largest proportion of severe injuries was observed in 2018, where about 7% of the 156 crashes resulted in fatalities and severe injuries. Additionally, most of the work zone crashes occurred in the summer (462 crashes), with 8% resulting in severe injuries and fatalities. While most of the crashes (886) occurred on weekdays, a larger proportion of those that occurred on the weekend resulted in severe injuries and fatalities (9.9%).

5.2 Crash Frequency Analysis

The crash frequency analysis used Poisson and negative binomial count models to determine contributing factors to work zone crash frequency. The crash modeling analysis revealed key differences across functional classes. On rural limited access facilities, work zone crashes had significantly higher chances of occurring during grading, at intersections, in the Pierre region, with higher ADT and higher project budgets. On urban limited access facilities, work zone crashes had lower chances of occurring during concrete repair or pavement marking, and in the Rapid City region, but sharply increased with ADT. Interestingly, higher truck ADT reduced crash risk.

For rural principal arterials, pavement marking and shoulder work were associated with lower odds of work zone crashes, but work zone crashes had higher odds of occurring in the Rapid City region, with increases in truck ADT, roadway width, and project budget, all linked to higher work zone crash counts. For urban principal arterials, significant predictors of crash occurrence included the region and average daily traffic (ADT). Crashes had about 4.6 times higher odds of occurring in the Rapid City region. Additionally, with each unit increase in the natural logarithm of ADT, crashes had about 6 times higher odds of occurring. Wider roads reduced crash likelihood, while larger project budgets increased crash risks. Work zone crashes on rural major collectors and minor arterials had approximately 6.25 times higher chances of occurring on shoulders and increased with ADT, in the Pierre region, and with the project budget.

5.3 Crash Severity Analysis

The analysis of work zone crash injury severity on limited access facilities, and arterials and collectors revealed notable differences in injury severity predictors. Ordinal logistic regression was employed to identify factors influencing severity across both facility types. Regression coefficients and odds ratios (OR) were examined to determine both the magnitude and direction of the predictors' effects. Odds ratios express the likelihood of experiencing a higher injury severity level relative to a baseline category, given a unit change in the predictor variable. Odds ratios greater than 1 indicate an increased likelihood of more severe injuries associated with a predictor, while odds ratios less than 1 suggest a decreased likelihood. An odds ratio equal to 1 implies no effect on injury severity.

Findings from the ordinal logistic regression model for limited access facilities indicate that out of the 29 variables analyzed, nine variables were significant at the 95% confidence level (P-value ≤ 0.05) while one variable was significant at the 90% confidence level (P-value ≤ 0.10). Factors associated with increased crash severity include: lack of safety equipment (OR = 11.578), DUI (OR = 3.505), angle collisions (OR = 13.912), overcorrection (OR = 11.599), illness (OR = 8.171), motorcycles (20.840), disregard to signs (OR = 2.632), Ln (ADT) (OR = 3.808). On the contrary, variables found to have a negative association with crash severity include driver maneuvering (OR = 0.327) and Ln (Truck ADT) (OR = 0.297).

On arterials and collectors, seven variables were significant at the 95% confidence level while two were significant at 90% confidence level. Variables identified to have higher odds of crashes resulting in severe injuries, with respective odds ratios include: lack of safety equipment usage (OR = 9.553), driving under influence of alcohol and drugs (DUI) (OR = 2.777), illness (OR = 18.693), other vehicle types such as buses and vans (21.732), disregard to signs by drivers (OR = 1.978), Rapid City region (OR = 2.748), and right-of-way width (OR = 1.009). The presence or one unit increase in these variables is associated with increased work zone crash injury severity. On the contrary, vehicle maneuvering (OR = 0.186) and drivers aged 65 years and above (OR = 0.365) were found to have a negative association with crash severity. This implies that the presence of these factors leads to less severe work zone crash injuries. Generally, both limited and non- limited access facilities' (arterials and collectors) analyses emphasize the importance of safe driver behavior, vehicle type, roadway design, and environmental conditions in influencing injury severity in work zone crashes, suggesting targeted safety interventions for each road type.

5.4 Speed Data Analysis

Speed data for seven projects were analyzed in this research effort. The analysis indicates significant speed changes between two consecutive locations along the work zones. While some projects' data were categorized into upstream and downstream locations, other locations included data at locations with respect to the start of the work zone taper. The speed data of the following projects were analyzed.

- I-29 Sioux Falls 0293(106)76: May 2022 – July 2024
- I-229 Minnehaha Co (2021): May 2021 – October 2021
- I-229 Minnehaha Co IM 2292(98)9 (2023): April 2023 – November 2024
- I-229 Minnehaha Co IM 2292(105)3 (2024): July 2024 – October 2024
- I-90 Pennington Co (2021): June 2021 – December 2021
- I-90 Pennington Co 0901(195)32: September 2022 – December 2022
- I-90 Various Co IM-NH 0041(181) (2024): July 2024

A Z-test analysis was used to determine significant speed changes between two consecutive locations: downstream versus upstream or locations in relation to the work zone taper. Findings indicated variations among the different projects, showing both significant speed increases and decrease between consecutive locations. Since the exact location where the sensors were placed was unknown, the results should be used with caution.

5.5 Suggested Implementation Strategies

This section presents the suggested implementation strategies mainly based on the analyses conducted in this project. The discussion aims to reduce the occurrence and severity of work zone crashes, enhance driver compliance, and ultimately improve the safety of workers and road users.

The suggested strategies were organized into four main categories: general, engineering, enforcement, and education strategies. This structured approach recognizes that ensuring work zone safety requires multiple, complementary countermeasures.

5.5.1 General Strategies

This subsection presents the general strategies designed to reduce work zone crashes, improve driver compliance, and enhance worker safety. Suggested general strategies include:

i) Data Collection and Data Retention Procedures
ii) Occupancy Data
iii) Near-Miss Reporting Obligations

5.5.1.1 Data Collection and Data Retention Procedures

Ensuring the availability of reliable data is essential to assess the safety implications of work zones and monitor driver compliance with traffic regulations. It is suggested that SDDOT require contractors to consistently collect, retain, and share data for future safety analyses. Key data elements should include, but not limited to:

- Traffic Control Device (TCD) deployment and activity logs, including TCD type, installation date, and activation/deactivation time stamps
- Speed at marked sensor locations
- Vehicle count
- Occupancy

5.5.1.2 Occupancy Data

Occupancy represents the percentage of time a roadway detection zone is occupied by vehicles during a given observation period, serving as a proxy for traffic density and congestion. Occupancy data can be collected using various sensing technologies such as CCTV cameras (video image processing), radar sensors, and inductive loop detectors. These devices determine the proportion of time vehicles are detected within their monitoring zones. The resulting data are valuable for evaluating traffic flow, identifying congestion patterns, and supporting real-time work zone safety and dynamic traffic management applications.

5.5.1.3 Near-Miss Reporting Obligations

Since crashes are relatively rare and often random, they may not fully reflect the underlying risks present in work zones. Near-miss events, however, provide valuable insight into unsafe conditions and driver behavior that occur before a crash. It is suggested that SDDOT implement mandatory near-miss reporting obligations for DOT crews and contractors, ensuring consistent documentation and submission of such events. This data would allow for proactive identification of risks, guiding targeted interventions to reduce crash likelihood and enhance worker safety.

5.5.2 Engineering Strategies

This subsection presents the engineering strategies designed to reduce work zone crashes, improve driver compliance, and enhance worker safety. Suggested engineering strategies include:

i) Use Proper and Consistent Signs in Accordance with Standard Guidelines
ii) Use Temporary Rumble Strips in Work Zones
iii) Apply Speed Management Engineering
iv) Use Smart Work Zone Technology
v) Exercise Extra Caution in Work Zones on High-Volume and Wider Roadways

5.5.2.1 Use Proper and Consistent Signs in Accordance with Standard Guidelines

Clear and consistent traffic control devices are essential for guiding drivers safely through work zones. SDDOT ensures strict compliance with the Manual on Uniform Traffic Control Devices (MUTCD) and related state guidelines for all work zone signage. Proper placement, visibility, and maintenance of signs reduce driver confusion, improve compliance, and ultimately minimize crash risk. Contractors should be trained and regularly audited to verify that signage is used uniformly and consistently across projects.

5.5.2.2 Use Temporary Rumble Strips in Work Zones

Temporary rumble strips (TPRS) are an effective tool for increasing driver awareness and reducing the likelihood of crashes in work zones. Unlike static signs, which may be overlooked by distracted or inattentive drivers, TPRS provide both audible and tactile feedback that immediately captures driver attention and encourages speed reduction. As a result, TPRS can enhance compliance with work zone traffic control measures and improve overall work zone safety.

During periods of high motorcycle traffic, such as the Sturgis Motorcycle Rally, SDDOT may consider the configuration and placement of TPRS to ensure they provide adequate warning while maintaining motorcycle rideability.

It is suggested that SDDOT adopt the use of temporary rumble strips where feasible to increase driver attentiveness and reduce the likelihood of a work zone crash.

Guidance on Temporary Portable Rumble Strips (TPRS)

In work zones, the primary function of Temporary Portable Rumble Strips (TPRS) is to alert distracted or inattentive drivers of upcoming work zone conditions. Unlike signs, which may be overlooked, rumble strips provide a physical and audible cue that immediately captures driver attention. Based on practices from other State DOTs, TPRS are most effective in the following work zone types:

- *One-Lane, Two-Way Operations*: TPRS are encouraged to be used during one-lane, two-way traffic operations controlled by flaggers or Automated Flagger Assistance Devices (AFADs), particularly on high-speed or high-volume corridors. For example, the Wisconsin DOT (WisDOT) requires TPRS for all flagging operations lasting longer than two hours to reduce vehicle speed and increase driver alertness (WisDOT, 2022). Similarly, the Washington State DOT (WSDOT) recommends TPRS for alternating one-lane, two-way traffic control setups to increase driver awareness and as an optional countermeasure for flagging operations on roadways with posted speeds of 45 mph or higher (WSDOT, 2024a).

- *Speed Reductions*: TPRS is encouraged to be used when there is a change in roadway conditions that requires a reduction in the operating speed. In such cases, TPRS should be placed near the "Reduced Speed Ahead" sign (Wilde, 2021).

- *High-Risk Corridors*: TPRS are encouraged to be used on highways prone to *distracted driving*, such as those adjacent to tourist areas or rural highways which are characterized by high speed limit (Wilde, 2021).

TPRS Placement Locations

An array, typically consisting of three strips, should be installed in advance of the corresponding warning sign, depending on the intended purpose (Wilde, 2021):

- **"***Be Prepared to Stop***"** or **"***One Lane Road Ahead***"** signs (for flagging operations).
- **"***Reduced Speed Ahead***"** signs (for speed change warnings).
- **"***Detour 1000 ft***"** signs (for detours).

Motorcycle Considerations

When TPRS are used on roadways with significant motorcycle traffic, SDDOT may consider configurations that minimize impacts on motorcycle stability and rider comfort. According to ATSSA (2013), sets of six parallel strips spaced approximately 10 ft apart have been found to provide adequate warning for motorists without causing undue discomfort to motorcyclists. Strip dimensions of approximately 46 in. in width and 0.5 in. in height have also been identified as effective in providing auditory and tactile feedback while remaining traversable by motorcycles. Appropriate advance warning signs should be provided to alert motorcyclists to the presence of TPRS.

5.5.2.3 Apply Speed Management Engineering

Speeding remains one of the most critical factors contributing to work zone crashes. Engineering measures such as reduced speed limits, narrowing lane widths, or channelization devices should be applied to encourage drivers to slow down. SDDOT is encouraged to integrate speed management into work zone planning and design, supported by periodic evaluations of speed compliance. Effective speed management not only lowers crash severity but also improves overall driver compliance with traffic control measures.

Based on analyses conducted in this research, shoulder work zones were found to be associated with an increased risk of work zone crashes. One effective strategy to mitigate this risk is the use of traffic calming measures, which are design or operational techniques intended to reduce vehicle speeds and enhance driver awareness. Examples of the traffic calming measures that may be applied in shoulder work zones include using temporary barriers and channelizing devices (Hallmark et al., 2021), lowering the posted speed limit (Gates et al., 2024), shifting and closing lanes (FHWA, 2014), and using signs and markings such as advanced warning systems (NCHRP, 2015).

5.5.2.4 Use Smart Work Zone Technology

The application of Smart Work Zone (SWZ) technologies can provide real-time information to drivers, reducing uncertainty and improving safety. Tools such as Dynamic Speed Feedback Signs (DSFSs), Queue Warning Systems (QWSs), Portable Changeable Message Signs (PCMSs), Dynamic Message Signs (DMSs), and Automated Flagger Assistance Devices (AFADs) enhance driver awareness of changing roadway conditions at work zones. SDDOT is encouraged to expand the use of these technologies, particularly in high-volume work zones, to warn drivers of potential hazards, encourage safe speeds, and minimize sudden braking or lane-changing maneuvers.

5.5.2.5 Exercise Extra Caution in Work Zones on High-Volume and Wider Roadways

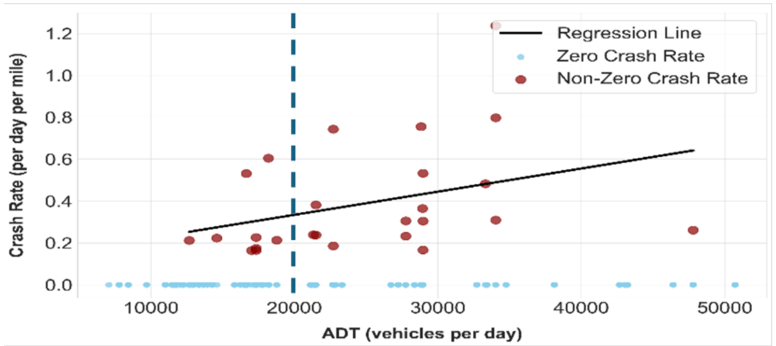
Work zones located on roadways with high Average Daily Traffic (ADT) and wider total roadway width (i.e., a higher number of lanes) were associated with higher work zone crash exposure and severity. SDDOT is encouraged to emphasize the implementation of enhanced safety measures in these locations. By focusing resources on roadways with heavier traffic volumes and a greater number of lanes, the likelihood of severe crashes can be reduced, while also improving driver compliance and protecting workers at work zones.

Both ADT and roadway width were treated as continuous variables in the analysis. Results indicated that an increase in total ADT and roadway width were positively associated with both a higher frequency and greater severity of work zone crashes. Since the variables were continuous in nature, no single threshold value could be inferred directly from the models. For that reason, the descriptive statistics of the work zone crashes by functional classification were used to establish the thresholds.

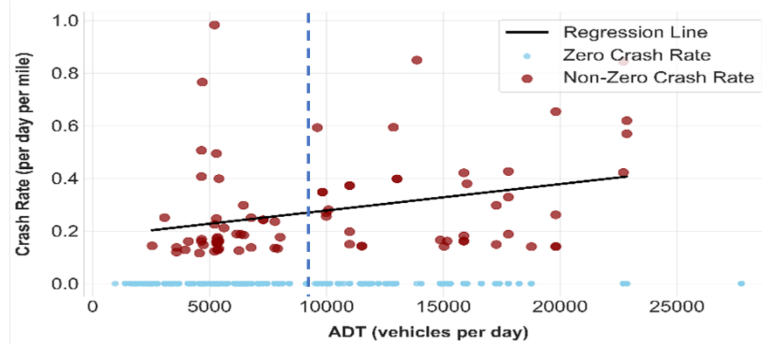
Given the correlation between the ADT and roadway width, i.e., higher volume roads typically have more lanes and thus, greater overall roadway width, the research team selected only ADT to develop the thresholds. Crash counts were normalized by segment length (miles) and work zone duration (days). The exposure was defined as the logarithm of the product of length and duration of the work zone. Crash rate was then computed as crash count divided by exposure. Figure 5.1 presents the ADT-crash rate scatterplots. The regression lines were estimated using only facilities with non-zero crash rates to better represent the relationship between ADT and crash rate among locations where crashes occurred. Overall, the regression lines indicated that crash rates generally increased as ADT increased. The vertical dashed lines represented the selected ADT thresholds for each functional classification based on the observed crash rate distributions.

According to Figure 5.1, on urban limited-access facilities, work zones with ADT > 20,000 vehicles per day (vpd) exhibited higher crash rates than those with lower volumes; therefore, 20,000 vpd was selected as the threshold for enhanced safety measures. For urban principal arterials, the threshold was 14,000 vpd, and for urban major collectors/minor arterials, the threshold was 9,000 vpd. Similarly, the threshold for rural limited-access facilities was 9,000 vpd. The cutoff for rural principal arterials was 2,000 vpd. For rural major collectors/minor arterials, the cutoff was 2,000 vpd.

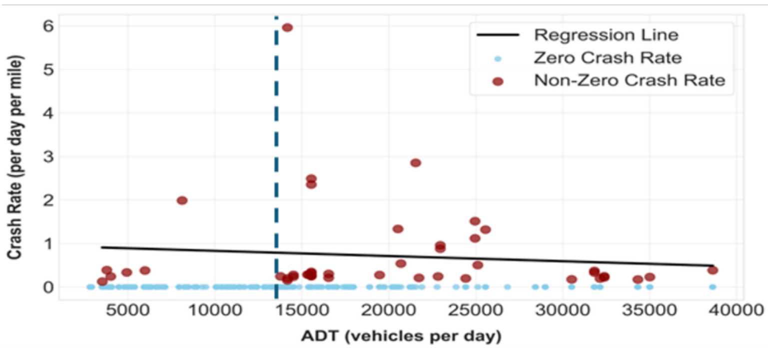
In summary, these engineering strategies, together, provide a foundation for safer work zones by ensuring proper traffic control, incorporating proven countermeasures, managing vehicle speeds, and leveraging smart technologies. These strategies can be supported by enforcement and education strategies that further strengthen overall work zone safety.



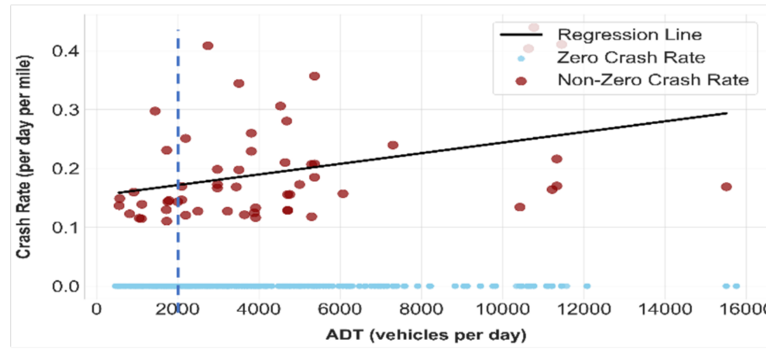
a) Urban Limited Access Facilities



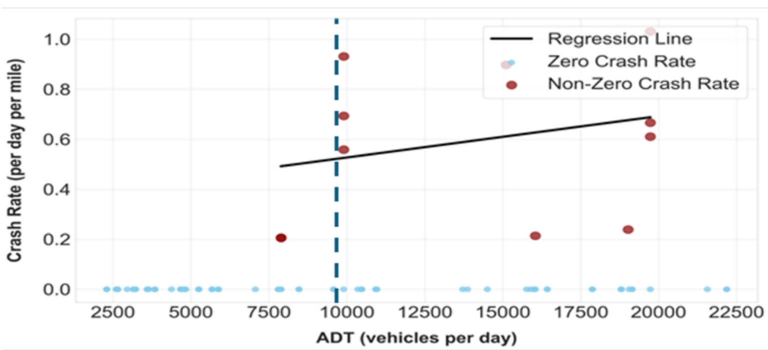
b) Rural Limited Access Facilities



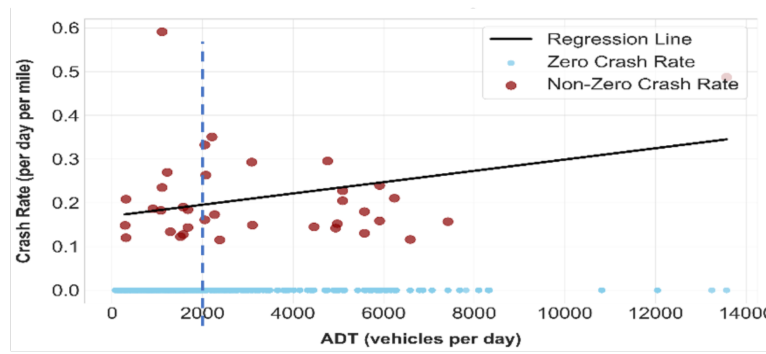
c) Urban Principal Arterials



d) Rural Principal Arterials



e) Urban Major Collectors/Minor Arterials



f) Rural Major Collectors/Minor Arterials

Note: The regression line is estimated using only facilities with non-zero crash rates. The raw data for the scatter plots are available as an attached spreadsheet. Access the Attachments panel to download the data file.

Figure 5.1 ADT-crash rate scatterplots by functional classification

5.5.3 Education Strategies

This subsection presents the education strategies designed to reduce work zone crashes, improve driver compliance, and enhance worker safety. Suggested educational strategies include:

- i) Continue Standardized Training and Certification for Flaggers
- ii) Conduct Public Awareness Campaigns Targeting High-Risk Groups
- iii) Provide Education to Workers on the Importance of Safety Equipment
- iv) Conduct Periodic Evaluation of Outreach Effectiveness
- v) Provide Training and Education Programs to Motorcycle Riders

5.5.3.1 Continue Standardized Training and Certification for Flaggers

Flaggers play a crucial role in managing traffic flow and ensuring worker safety within work zones. SDDOT is encouraged to *continue* enforcing standardized training and certification requirements for all flaggers to maintain consistent practices across projects. Ongoing uniform training ensures flaggers are equipped with the latest safety procedures, enhances signaling consistency, reduces driver confusion, and minimizes the likelihood of crashes resulting from miscommunication or inconsistent flagging practices.

5.5.3.2 Conduct Public Awareness Campaigns Targeting High-Risk Groups

Educating the public, particularly high-risk groups such as young drivers, commercial vehicle operators, motorcycle riders, and frequent roadway users, is essential to improving compliance and reducing work zone crashes. SDDOT is encouraged to implement targeted public awareness campaigns through social media, traditional print media, and community outreach programs. These efforts would increase public understanding of work zone risks and promote safe driving behavior. Examples of public awareness campaigns from other state DOTs include the Texas Department of Transportation (TxDOT) "Stay Alert. When You See This Shirt." campaign, which specifically targets work zone safety by reminding drivers to be attentive and cautious when approaching highway workers wearing high-visibility vests. Similarly, the Minnesota Department of Transportation (MnDOT) "Orange Cones. No Phones." campaign focuses on reducing distracted driving in work zones by encouraging motorists to put their phones away and stay alert whenever orange cones are present.

5.5.3.3 Provide Education to Workers on the Importance of Safety Equipment

Educating construction and maintenance workers on the proper use and importance of safety equipment is essential to improving overall work zone safety. Training programs should emphasize the role of high-visibility personal protective equipment (PPE), such as reflective vests and helmets, in preventing worker injuries. Workers should also be trained on the use of lighting and other visibility-enhancing tools, especially during nighttime or low-visibility conditions. By reinforcing understanding of why these measures are critical not just how to use them SDDOT can foster a stronger safety culture that encourages consistent compliance and reduces the likelihood of work zone crashes and near-miss incidents.

5.5.3.4 Conduct Periodic Evaluation of Outreach Effectiveness

Educational and outreach initiatives are only effective if they produce measurable improvements in safety outcomes. SDDOT is encouraged to periodically evaluate the effectiveness of public campaigns, training programs, and worker safety measures. Evaluations should include feedback from drivers, contractors, and workers, as well as analysis of crash and compliance data. These assessments will help refine future initiatives and maximize their impact on work zone safety.

5.5.3.5 Provide Training and Education Programs to Motorcycle Riders

Although motorcycles represent a small share of registered vehicles, they typically account for a disproportionately high rate of fatalities and serious injuries. For example, in Washington State between 2016 and 2020, motorcycles made up only 3% of registered vehicles but were involved in 15% of all traffic fatalities (Spokane County, 2021). Contributing factors often include excessive speeding, riding under the influence of alcohol or drugs, and unsafe riding behaviors such as improper passing.

The National Highway Traffic Safety Administration (NHTSA) Motorcycle Safety 5-Year Plan provides a framework for improving motorcycle safety nationwide (NHTSA, 2019). Key recommendations included:

- Conducting frequent and accessible rider education and training programs at locations convenient to riders.
- Evaluating crash experiences and identifying trends among motorcycle riders.
- Comparing crash data with training and licensing practices to ensure these efforts directly address the primary causes of crashes.
- Supporting public outreach and enforcement initiatives that promote safe riding behaviors.

South Dakota hosts one of the nation's largest motorcycle events, the Sturgis Motorcycle Rally, which attracts hundreds of thousands of riders and causes significant surges in traffic volumes across the Black Hills each August. The SDDOT has implemented several targeted operational measures during the Rally, including temporary speed-limit reductions on I-90, SD Highway 34, and SD Highway 79, as well as enhanced traveler information and traffic monitoring to improve safety and traffic flow.

Building on the approaches adopted by other states during major motorcycle rallies, SDDOT could further expand rider-focused outreach and public awareness campaigns targeting both motorcyclists and the general road users, with the goal of promoting safe riding behaviors and shared responsibility on the road.

A successful example of such an initiative is Florida's "Ride SMART 2 Daytona" campaign. The Florida Department of Transportation (FDOT), in collaboration with the Motorcycle Safety Coalition, launched the Ride SMART 2 Daytona campaign to promote rider safety during Daytona Beach Bike Week. The campaign emphasizes the importance of protecting all road users with messaging such as "Everyone has something to get home to" (FDOT, 2024).

The Ride SMART 2 Daytona initiative encourages bikers to ride SMART (Ride Smart Florida, n.d.). S.M.A.R.T. is defined as:

S: Say no to drinking and riding
M: Make yourself more visible to motorists
A: Always wear your helmet when you ride
R: Ride in control
T: Train regularly

Overall, consistent communication and outreach efforts are strongly encouraged to enhance motorcycle safety, particularly during periods of elevated exposure such as major rally weeks. Regardless of the event's magnitude, coordinated messaging between transportation agencies, law enforcement, and community partners plays a vital role in reminding both riders and motorists to share the road responsibly. Sustained education, visibility, and engagement before, during, and after such events can significantly reduce risky behaviors and promote a safer travel environment for all roadway users.

Collectively, these education-focused strategies aim to equip both workers and the traveling public with the knowledge and tools needed to navigate work zones safely. Standardized training strengthens the skills of those managing traffic, while public awareness campaigns and safety equipment enhance visibility and compliance. Periodic evaluations ensure these initiatives remain effective and adaptable to evolving challenges. Together, they provide a strong foundation that complements engineering and enforcement efforts to create safer, more efficient work zones.

5.5.4 Enforcement Strategies

This subsection presents the enforcement strategies designed to reduce work zone crashes, improve driver compliance, and enhance worker safety. Suggested enforcement strategies include:

i) Enforce Traffic Laws such as Seat Belt Usage, DUI, and Distracted Driving
ii) Implement Worker Safety Plans
iii) Enforce Move-Over Law at Work Zones
iv) Apply High-visibility Enforcement (HVE) at Work Zone Sites

5.5.4.1 Enforce Traffic Laws such as Seat Belt Usage, DUI, and Distracted Driving

Strong enforcement of existing traffic laws is essential to ensure safe driver behavior in and around work zones. SDDOT is encouraged to partner with law enforcement agencies to emphasize seat belt compliance, prevent impaired driving, and reduce distracted driving. Visible enforcement campaigns and targeted patrols within or near active work zones would deter unsafe behaviors and increase compliance with traffic regulations. Such actions not only protect workers but also reduce the likelihood of severe crashes involving drivers and passengers.

5.5.4.2 Implement Worker Safety Plans

Worker safety is directly linked to the enforcement of clear safety protocols on-site. It is suggested that SDDOT require all contractors to develop and adhere to formal Worker Safety Plans as a condition of project approval. These plans should include enforcement mechanisms such as routine safety inspections, compliance monitoring, and corrective actions when safety rules are violated. By holding contractors accountable, SDDOT can ensure that workers consistently use protective gear, follow proper procedures, and operate within a structured safety framework that minimizes risks.

5.5.4.3 Enforce Move-Over Law at Work Zones

The Move-Over Law requires drivers to change lanes or slow down when approaching emergency, law enforcement, or maintenance vehicles stopped on the shoulder with flashing lights. In the context of work zones, strict enforcement of this law is critical to protecting workers operating near moving traffic. SDDOT is encouraged to partner with state law enforcement to increase awareness and actively enforce compliance with the Move-Over Law in and around work zones.

Together, these enforcement strategies strengthen accountability for both drivers and contractors. By increasing compliance with traffic laws and requiring structured Worker Safety Plans, SDDOT can reduce unsafe behaviors, ensure consistent protection for workers, and reinforce the effectiveness of engineering and education measures. Enforcement thus serves as the critical link that upholds safety standards and sustains consistent long-term improvements in work zone safety.

5.5.4.4 Apply High-visibility Enforcement (HVE) at Work Zone Sites

Intersection work zones are particularly high-risk areas due to the increased potential for conflict points, temporary signal phase changes, lane closures, and driver confusion caused by shifting traffic patterns. These conditions often lead to red-light running, speeding, and abrupt lane changes, increasing the likelihood of crashes. To mitigate these risks, high-visibility enforcement is encouraged, particularly during the early stages of construction and peak traffic periods. The visible presence of law enforcement serves as a deterrent to unsafe driving behaviors by reminding motorists to comply with posted speed limits and temporary signal controls. For example, the Pennsylvania Department of Transportation (PennDOT) has successfully advanced work zone safety through its Work Zone Speed Safety Camera (WZSSC) program, which has proven effective in reducing vehicle speeds and improving driver compliance within work zones (PennDOT, 2025).

Together, these enforcement strategies strengthen accountability for both drivers and contractors. By increasing compliance with traffic laws and requiring structured Worker Safety Plans, SDDOT can reduce unsafe behaviors, ensure consistent protection for workers, and reinforce the effectiveness of engineering and education measures. Enforcement serves as the critical link that upholds safety standards and sustains consistent long-term improvements in work zone safety.

5.5.5 Revisions to the Existing Work Zone Safety Policies, Procedures, and Standards

This subsection presents the suggested revisions to the existing work zone safety policies, procedures, and standards based on the review of the documents provided by SDDOT. The revisions focused on enhancing work zone safety by refining the clarity, consistency, and applicability of the policies, procedures, guidelines, and standards. Suggested revisions involve the following:

i) Construction Manuals
ii) Work Zone Safety and Mobility Plan
iii) Flagger Manual

5.5.5.1 Construction Manuals

Revisions were identified in two of the three Construction Manual chapters provided.

Chapter 15: Work Zone Traffic Control

The *Speed Reduction* section in Chapter 15 includes the following language:

> “Typical work zone speed limits for lane closures are set at 65 mph or 10 mph below the original posted speed limit. When traffic is immediately adjacent to construction work being performed, the speed may be reduced to 45 mph when workers are present. Specific site conditions or work may justify other regulatory or advisory speed limits.”

The research team suggests incorporating language on Variable Speed Limit (VSL) systems, integrated with other Intelligent Transportation Systems (ITS) where feasible. This is because VSL systems adjust speed limits based on real-time traffic and roadway conditions to enhance safety and mobility.

This revision is based on the following excerpt from MUTCD (FHWA, 2023)**:**

Support (Section 6A.01; Paragraph 10): Operational improvements might be realized by using intelligent transportation systems (ITS) in work zones. The use in work zones of ITS technology, such as portable camera systems, highway advisory radio, **variable speed limits**, ramp metering, traveler information, merge guidance, warning systems for vehicles exiting the work space, and queue detection information, is aimed at increasing safety for both workers and road users and helping to ensure a more efficient traffic flow. The use in work zones of ITS technologies has been found to be effective in providing traffic monitoring and management, data collection, and traveler information.

Chapter 16: Route Restrictions

Chapter 16 primarily discusses width restrictions, while height restrictions are not explicitly addressed. The research team proposes expanding Chapter 16 to include vertical clearance restrictions. More specifically, when vertical clearance is restricted, it is suggested to post a Low Clearance Advance (W12-2) sign in advance of the structure and, where clearance varies by lane, post a Low Clearance Overhead (W12-2b) over the affected lane. The numeric value shall match the posted clearance on all related low-clearance signs. Examples of the W12-2 and W12-2b signs are shown in Figure 5.2.

This revision is based on the following excerpt from MUTCD (FHWA, 2023)**:**

Standard (Section 2C.25): The Low Clearance Advance (W12-2) sign shall be used to warn road users of vertical clearances less than 14 feet 6 inches, or vertical clearances less than 12 inches above the statutory maximum vehicle height, whichever is greater.

Standard (Section 2C.25): If used, the Low Clearance Overhead (W12-2b) sign shall be placed over a lane or shoulder to indicate the portion of the structure with low clearance if the posted clearance does not apply to the entire structure.

(a) W12-2 Sign

(b) W12-2b Sign

Figure 5.2 Vertical clearance warning signs

5.5.5.2 Work Zone Safety and Mobility Plan

A Transportation Management Plan (TMP) lays out a set of coordinated transportation management strategies and describes how they will be used to manage the work zone impacts of a road project. According to the *Work Zone Safety and Mobility Plan*, TMP components include: Temporary Traffic Control, Transportation Operations, and Public Information. For significant projects, TMPs that include all three components are used.

The research team suggests evaluating TMPs on an as-needed basis, especially for significant projects. In other words, for construction work zones, in addition to post-project review, TMP evaluations may also be conducted mid-project, on a weekly, bi-weekly, or monthly basis, as appropriate, depending on the anticipated traffic and safety impacts of the work zone.

5.5.5.3 Flagger Manual

The research team suggests adding requirements for rest periods or limits on continuous flagging time, similar to requirements provided in the WSDOT *Temporary Traffic Control Flagging Operations Manual* (WSDOT, 2024b). Suggested requirements include:

- Flaggers receive a rest period of at least 10 minutes, on the employer's time, for each 4-hour work period.
- Rest periods must be scheduled as near as possible to the midpoint of the work period.
- A flagger must not be allowed to work more than three (3) hours without a rest period.

5.5.6 Summary

The goal of the suggested strategies is to reduce the occurrence and severity of work zone crashes, enhance driver compliance, and improve the safety of workers and road users on South Dakota highways. The strategies were organized into four primary categories: general, engineering, enforcement, and education strategies, as follows:

General Strategies

- Improve data collection and data retention procedures
- Establish near-miss reporting obligations

Engineering Strategies

- Use proper and consistent signing in accordance with standard guidelines
- Use proven safety countermeasures (PSCs) adapted to work zones
- Apply speed management engineering
- Use smart work zone technology
- Exercise extra caution in work zones on high-volume and wider roadways

Education Strategies

- Continue standardized training and certification for flaggers
- Conduct public awareness campaigns targeting high-risk groups
- Provide education to workers on the importance of safety equipment
- Conduct periodic evaluation of outreach effectiveness
- Provide training and education programs to motorcycle riders

Enforcement Strategies

- Enforce traffic laws such as seat belt usage, DUI, and distracted driving
- Implement worker safety plans
- Enforce Move-Over Law
- Apply high-visibility enforcement (HVE) at work zone sites

In addition to these strategies, a review of South Dakota's existing policies, procedures, guidelines, and standards related to work zone safety was conducted. The purpose of the review was to assess how current practices align with national best practices, identify strengths, and highlight opportunities for improvement. Overall, the review found that SDDOT's existing requirements align well with established national standards. A few revisions were provided for potential areas for improvement based on practices adopted by other state DOTs or on Federal Highway Administration (FHWA) guidance, such as the MUTCD.

Chapter 6: Recommendations

This chapter discusses recommended implementation strategies to reduce work zone crashes, improve driver compliance, and enhance worker safety in South Dakota work zones.

6.1 Background

Work zones are essential for the construction, maintenance, and improvement of transportation infrastructure. However, despite their necessity, these areas pose significant safety risks to workers, motorists, and other road users. The temporary and dynamic nature of work zones often results in changes to roadway geometry, lane configurations, and traffic control measures, which can increase the likelihood of crashes.

This research analyzed the crash frequency and crash severity of work zones crashes on South Dakota highways to understand the underlying factors contributing to both the occurrence and severity of work zone crashes. Analysis results are summarized in Tables C.30 and C.31 in Appendix C of this report. Speed analyses were also performed to evaluate driver compliance in work zones, including project-specific speed analyses (refer to Appendix C). Recommendations presented are based on the analyses conducted in this research effort.

6.2 Recommended Implementation Strategies

This section presents the recommended implementation strategies mainly based on the analyses conducted in this project. The recommendations aim to reduce the occurrence and severity of work zone crashes, enhance driver compliance, and ultimately improve the safety of workers and road users.

6.2.1 Work Zone Data Collection

SDDOT should collaborate with contractors and law enforcement agencies to establish a centralized Work Zone data repository. Creating a unified and accessible data system will address current data availability challenges and enable consistent evaluation of work zone safety and mobility impacts across the state.

To ensure consistency and comparability across regions, SDDOT should standardize data collection procedures and clearly define required variables. In coordination with law enforcement agencies, crash reporting forms and procedures should also be updated to explicitly indicate whether a crash is work zone related. This improvement will enhance the accuracy of work zone crash identification and strengthen future safety analyses.

In addition, SDDOT should implement a formal data-sharing requirement for all active work zones. Contractors should be required to collect and submit work zone, traffic, and operational data in a standardized format. This approach will allow SDDOT to systematically evaluate work zone performance, safety outcomes, mobility impacts, and driver compliance.

The following data categories should be collected for each work zone project.

6.2.1.1 Work Zone Related Data

- Work zone location (such as GPS coordinates)
- Work zone characteristics (for example, work zone type, segment length)
- Worker presence
- Traffic control device (TCD) deployment and activity logs, including activation and deactivation times (for example, PCMS, temporary signals, dynamic speed displays)

6.2.1.2 Traffic Data

- Traffic volume (per lane, where feasible)
- Speed data (per lane) at upstream, within-work-zone, and downstream locations
- Sensor information, including:
    - Exact location (GPS coordinates)
    - Type of sensor (for example, radar, Bluetooth, loop detector, portable traffic sensor, CCTV)
    - Data collection intervals and duration

For significant projects, as identified in the SDDOT Work Zone Safety and Mobility Plan, contractors should also collect:

- Occupancy data
  Occupancy represents the percentage of time a detection zone is occupied by vehicles during a specified interval and serves as a proxy for traffic density and congestion. Occupancy can be measured using radar sensors, inductive loop detectors, or video image processing systems. This information supports congestion monitoring, mobility assessment, and real-time safety and traffic management applications in work zones.

Establishing a centralized work zone data repository, standardizing data collection procedures, and updating crash reporting practices to clearly identify work zone–related crashes will significantly enhance SDDOT's ability to evaluate both mobility and safety impacts. These improvements will support data-driven decision-making.

6.2.2 Prioritization of Work Zones on High-volume Roadways

SDDOT, in coordination with contractors, should increase the prioritization of safety countermeasures on roadways with higher traffic volumes, where exposure and crash risk are inherently greater. Applying a prioritization framework based on Average Daily Traffic (ADT) will help ensure that safety resources are allocated where they can produce the greatest safety and mobility benefits.

Table 6.1 presents the proposed ADT thresholds by functional classification. In addition to ADT-based prioritization, specific work zone types were found to be associated with higher crash frequency.

- On rural limited access facilities, work zones involving grading activities and intersection-related work should be prioritized.
- On rural major collectors and minor arterials, shoulder work zones should be prioritized.

For work zones meeting or exceeding the recommended ADT thresholds, SDDOT should consider implementing enhanced safety measures, including:

- Provision of advance warning signs upstream of the work zone to improve driver awareness
- Dissemination of real-time work zone information through traveler information systems and navigation applications such as Waze, Google Maps, and Apple Maps to improve driver awareness.
- Increased use of speed management strategies (such as speed feedback signs, reduced speed zones)
- Deployment of queue warning systems

Using ADT-based thresholds establishes a data-driven methodology for prioritizing and allocating safety resources based on traffic exposure and risk.

Table 6.1 Proposed ADT thresholds by functional classification

Functional Classification	ADT Threshold (vehicles per day)
Urban Limited Access Facilities	ADT > 20,000
Urban Principal Arterials	ADT > 14,000
Urban Major Collectors/Minor Arterials	ADT > 9,000
Rural Limited Access Facilities[1]	ADT > 9,000
Rural Principal Arterials	ADT > 2,000
Rural Major Collectors/Minor Arterials[2]	ADT > 2,000

* = Prioritize grading and intersection-related work zones;

** = Prioritize shoulder work zones.

6.2.3 Coordination with Law Enforcement for Education and Enforcement

SDDOT should coordinate with law enforcement agencies to implement targeted education and enforcement efforts focused on traffic laws that have been shown to significantly influence crash frequency and severity in and near work zones. Strategic enforcement, combined with public education, can improve driver compliance and reduce high-risk behaviors.

Priority enforcement and education areas should include:

- Driving Under the Influence (DUI) enforcement near work zone corridors
- Seat belt compliance, given its strong association with injury severity
- Move over law, especially for shoulder work zones

Coordinated enforcement campaigns, especially during high-risk periods such as nighttime operations, lane closures, and peak travel times, can reduce work zone crashes and traffic violations, thereby improving safety in work zones.

6.2.4 Revisions to the Flagger Manual

SDDOT should add requirements for rest periods or limits on continuous flagging time, similar to requirements provided in the WSDOT *Temporary Traffic Control Flagging Operations Manual* (WSDOT, 2024b). Suggested requirements include:

- Flaggers receive a rest period of at least 10 minutes, on the employer's time, for each 4-hour work period.
- Rest periods must be scheduled as near as possible to the midpoint of the work period.
- A flagger must not be allowed to work more than three (3) hours without a rest period.

Chapter 7: Research Benefits

This research provides practical, applicable, and implementable strategies that can be deployed by SDDOT to reduce work zone crashes, increase driver compliance, and improve the safety of workers and road users. Factors associated with work zone frequency, injury severity, and driver compliance were identified, and specific implementation strategies to improve work zone safety were presented. Recommend revisions to the SDDOT work zone policies and standards were also provided.

Previous studies on work zone safety in South Dakota are limited, highlighting a research gap in understanding South Dakota's work zone safety challenges. This project addresses this gap by analyzing crash data and evaluating the effectiveness of traffic control measures used in work zones on South Dakota highways.

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Appendix A: Literature Review

Work zones are vital for any infrastructure development within a society. However, their presence poses risks to motorists, workers, and other road users. According to the Manual on Uniform Traffic Control Devices (MUTCD), work zones are areas along roadways where construction, maintenance, or utility activities take place (Federal Highway Administration [FHWA], 2023). They are usually marked by signs, closed lanes, channelizing devices, barriers, pavement markings, and/or work vehicles (Pesti et al., 2008; Zhao et al., 2019).

Work zones are characterized by four major component areas: the advance warning area, the transition area, the activity area, and the termination area. The advance warning area is where road users are informed about the upcoming work zone area. The Federal Highway Administration (FHWA) provides recommendations for the spacing of the signs placed along the warning area based on the functional classification of the roadway (FHWA, 2023). The transition area is where road users are channelized to a new path. The activity area is the section where the actual construction or maintenance work is being performed, and the termination area is used to return road users to their normal/original path (Dias, 2015). Figure A.1 shows the typical layout of work zone components.

A.1 Work Zone Safety Across the United States

The United States (U.S.) is likely to experience more and longer work zones due to the need for continuous capacity improvement, future highway construction needs, the aging of highway infrastructure, and the increase in highway fund investments (Khattak et al., 2002; Vieira et al., 2023; Chen & Tarko, 2012). Work zones along roadways are necessary as they play a crucial role in maintaining and improving the roadway infrastructure, ultimately enhancing roadway safety and mobility. For instance, the construction of flyovers aims to separate traffic by grade, reducing travel time and the number of conflict points. Additionally, the construction of pedestrian bridges improves safety by separating pedestrians from high-speed traveling vehicles, improving pedestrian safety. Work zones also enable the improvement of existing roadways through maintenance activities, such as repainting, resurfacing, and filling potholes, leading to smoother traffic flow, improved roadway safety, and longer-lasting road surfaces.

Despite the benefits, numerous studies have identified both mobility and safety impacts associated with the presence of work zones (Dias, 2015; Khattak et al., 2002; Qi et al., 2005, 2013). Congestion on roadways, which are already over capacity, inconvenience and costs to delayed motorists, and increased incidents are some of the most significant challenges that arise with the presence of work zones along roadways (Shepard & Cottrell, 1984). Such impacts often lead to reduced roadway capacity, increased delays, longer travel times, and driver frustration, which may contribute to unsafe driving behaviors, such as speeding and abrupt lane changes. Consequently, such behaviors tend to increase both major and minor crash risks, compromising the safety of motorists and road workers. Additionally, work zone equipment, workers, construction barriers, and other items along work zones create more conflicts that can lead to hazardous conditions and crashes (Khattak et al., 2002).

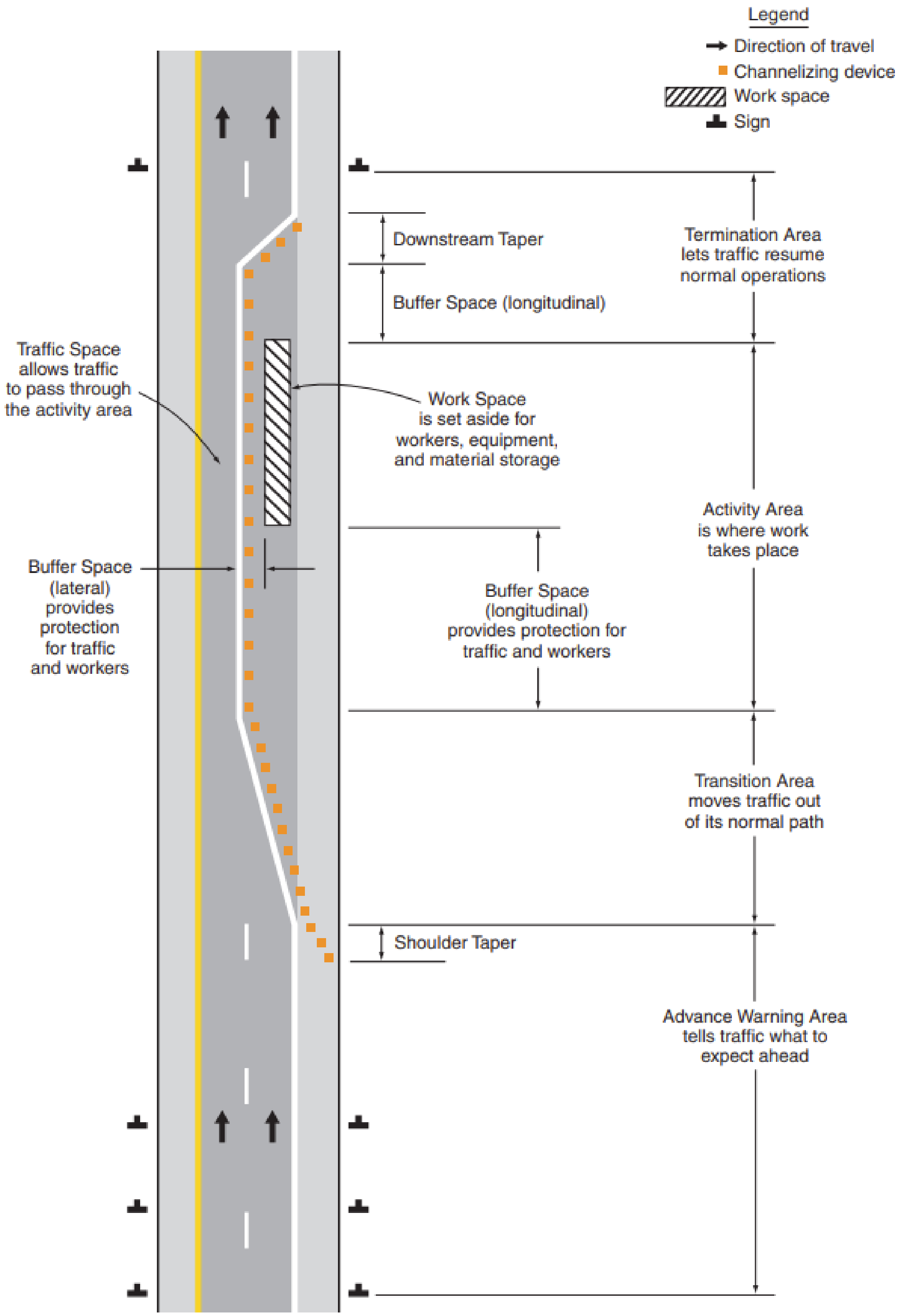
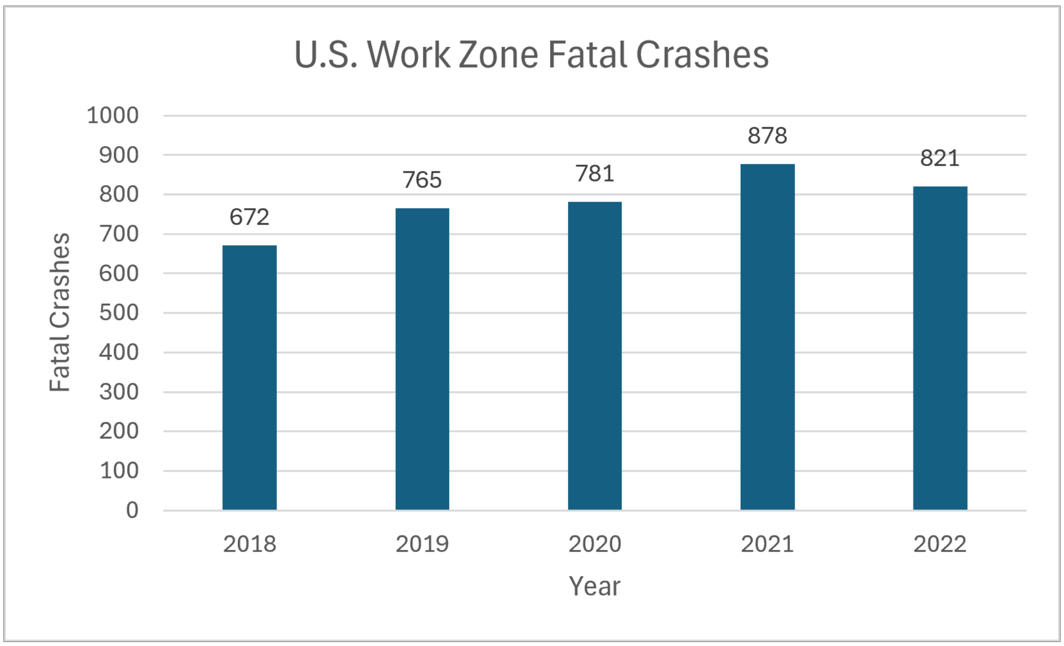


Figure A.1 Layout of a typical work zone
Source: MUTCD (FHWA, 2023)

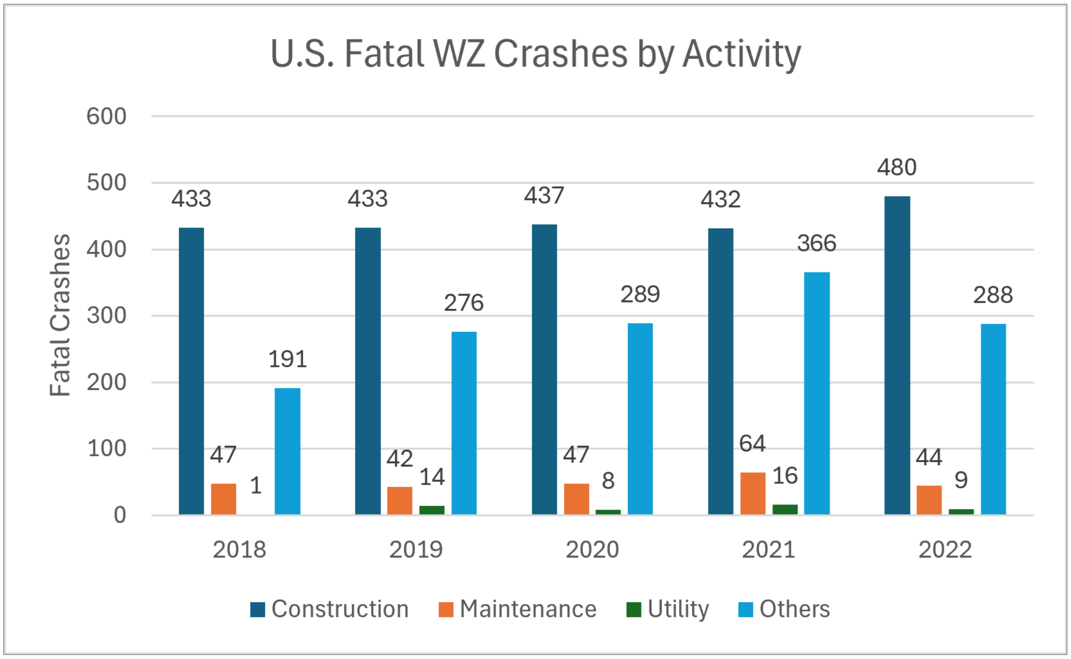
Economic impacts of work zones have been identified in the National Work Zone Safety Information Clearinghouse (National Highway Traffic Safety Administration [NHTSA], 2023). Work zones lead to about 35% of congestion in rural areas and about 10% total delays nationally. This delay translates to about 586.5 million hours of vehicle delay, which is about $8.1 billion in user delay costs. Additionally, work zones have led to about $36 billion in comprehensive societal crash costs, which is associated with the occurrence of crashes along work zones. The Fatality Analysis Reporting System (FARS) database reports that more than 700 fatalities occur every year within the U.S. as a result of work zone crashes (National Highway Traffic Safety Administration [NHTSA], 2023). In addition, approximately 24,000 injury crashes and 52,000 Property Damage Only (PDO) crashes occur in the U.S. annually (Khattak et al., 2002). Figure A.2 illustrates the trend of fatal work zone crashes across the U.S. from 2018 to 2022. As shown in Figure A.2, fatal work zone crashes increased over the five-year period, with a slight decrease observed in 2022.



Year	2018	2019	2020	2021	2022	Total
Frequency	672	765	781	878	821	3,917

Figure A.2 National fatal work zone crashes by year

The FARS database also contains the distribution of national fatal work zone crashes by type of work zone activity, as shown in Figure A.3. A greater proportion of fatal crashes occurred along construction work zones compared to other types of activities, such as maintenance and utility works. The National Work Zone Safety Information Clearinghouse has more information on national work zone fatal crash statistics (National Highway Traffic Safety Administration [NHTSA], 2023). While these statistics only show the trend for fatal work zone crashes across the U.S., previous studies have indicated increased injury severity resulting from work zone crashes (Shaheed & Gkritza, 2014).



Activity - Year	2018	2019	2020	2021	2022	Total
Construction	433	433	437	432	480	2,215
Maintenance	47	42	47	64	44	244
Utility	1	14	8	16	9	48
Others	191	276	289	366	288	1,410
Total	672	765	781	878	821	3,917

Figure A.3 National fatal work zone crash distribution by type of activity

Ensuring traffic flow, road safety, and roadwork progress simultaneously may be challenging, especially on freeways (Yang et al., 2013). One step towards improving safety and mobility along U.S. work zones is identifying contributing factors to crash occurrence, injury severity, and driver compliance. Understanding these factors is useful not only for transportation agencies, but also for contractors and roadwork crews in temporary traffic control planning. Additionally, this knowledge can assist agencies in identifying and potentially implementing new strategies to reduce crashes, increase driver compliance along work zones, and ultimately improve overall roadway safety and mobility.

A.2 Work Zone Safety in South Dakota

With about 7,794 miles of highway within its four regions and 36 construction projects completed between 2022 and 2023, South Dakota Department of Transportation (SDDOT) is diligently working to enhance infrastructure development and foster improved connectivity between cities (SDDOT, 2024a). As a result, future construction activities, combined with ongoing work, are expected to increase the number of work zones along South Dakota's highway system. SDDOT has made various efforts to promote safety awareness among motorists to improve work zone safety. SDDOT has been observing Work Zone Awareness Week with activities to engage the public, such as Go Orange Day and Billboard Contests (SDDOT, 2024b).

While SDDOT consistently surpasses the minimum guidelines outlined in the MUTCD to ensure safety at work zones, a significant number of crashes still occur along its work zones. For instance, between 2018 and 2022, South Dakota experienced a total of 1,060 work zone crashes on its state highways. Driver non-compliance to traffic control measures has been identified as a key potential factor contributing to these crashes. Therefore, identifying the contributing factors to crashes and driver non-compliance along work zones in South Dakota is necessary to implement targeted countermeasures.

In 2014, Reiprich et al. (2014) conducted a study to analyze work zone crashes in South Dakota. The analysis showed that males under the age of 25 were overrepresented, while those over the age of 65 were underrepresented, particularly at night (Reiprich et al., 2014). A 3:2 ratio of males to females involved in work zone crashes was also identified, which was considered to be a reflection of the proportion of drivers on the road (Reiprich et al., 2014). Regarding crashes that were related to misperceived closure rate (MCR) (i.e., crashes where drivers suddenly discover that a rear-end crash with a leading vehicle was inevitable), a larger proportion occurred during daylight conditions. However, the authors stated that one of the study's limitations was the current population in urban areas (by then), as the population in South Dakota urban areas did not exceed 150,000. The authors therefore reported that the findings from the study could not be used to generalize complex urban freeway systems. As the population of South Dakota has grown significantly in the past ten years, with cities such as Sioux Falls currently having a population of over 210,000, a 30% increase from 2013 (City of Sioux Falls, 2024), the need to understand its current work zone safety conditions becomes necessary.

This research project analyzed work zone safety and driver compliance across South Dakota, adding to the existing body of knowledge by extending the crash analysis study to urban freeways. This effort involved analyzing past SDDOT work zone types, crash data, and roadway data to determine factors that overrepresent work zone crashes. Additionally, this research project aimed to recommend implementation strategies and any necessary revisions to current policies and standards for improving overall work zone safety in South Dakota.

A.3 Work Zone Crash Frequency

Several studies have proven that the predominant location for work zone crashes is the work zone activity area, independent of roadway type (Akepati & Dissanayake, 2011; Garber & Zhao, 2002; Katta, 2013). Most of the work zone crashes have been attributed to increased complexity, reduced lane widths, presence of equipment, and driver distraction along the work zone activity area. Rear-end crashes have also been proven to be the most dominant type of collision among work zone crashes (Akepati & Dissanayake, 2011; Garber & Zhao, 2002; Katta, 2013). However, while descriptive statistics simply provide the distribution of the data, statistical frequency analysis is vital in understanding underlying patterns.

Crash frequency analysis involves the identification of roadway, human, and environmental conditions that are statistically associated with work zone crashes (Lee & Abdel-Aty, 2005). Frequency analysis usually involves models, such as Poisson regression or Negative Binomial, that handle count data, i.e., crash count per given segment or point. For instance, when crashes are identified per every homogenous segment of a roadway or an intersection point, the count models analyze related features that are associated with the occurrence of more crashes. Frequency analysis allows for the examination of interactions among detector variables and the estimation of the relative significance of the variables, leading to more reliable conclusions and effective suggestions for countermeasures.

Using data from 60 work zones in New Jersey, Yang et al. (2013) identified that longer work zones and higher traffic volumes per lane were highly associated with the occurrence of both PDO and injury crashes. Findings also revealed that a greater number of lanes and a greater number of dropped lanes were both attributed to an increase in work zone crash occurrence. Alternatively, factors that were associated with lower crash occurrence included nighttime, higher speed limits, and work zones on state roadways (Yang et al., 2013). In a 2002 study using California data, Khattak et al. (2002) identified that the total crash rate during work zone periods was 21.5% higher (0.79 crashes per million vehicle kilometers) compared to pre-work zone periods (0.65 crashes per million vehicle kilometers). The study also revealed a 17.3% injury crash rate and a 23.8% non-injury crash rate for active work zones compared to inactive work zones. Similar to the study in New Jersey by Yang et al. (2013), work zone length, work duration, and Annual Average Daily Traffic (AADT) were associated with higher crash frequency in California (Khattak et al., 2002).

Another work zone crash frequency study was conducted in Kansas for the years 2010-2013 (Dias, 2015). The descriptive statistics indicated that most work zone crashes occurred on level and straight segments, during the day, along the activity area, and involved rear-end crashes. However, descriptive statistics only show crash data distribution and not the association of the variables with the target variable (either severity or frequency). The study indicated that higher AADT was associated with increased total work zone crash frequency. A unit increase in the natural log of AADT was observed to increase total work zone crashes by three (3) and fatal and injury crashes by four (4) (assuming all other variables remained constant). Nighttime work zone operation was associated with a reduction in total crash frequency (Dias, 2015). The model also indicated that work zones on other principal arterials (different from freeways and expressways) experienced 0.3 times fewer fatal and injury crashes compared to those on major arterials. In another similar study conducted in Michigan, single-lane closures, multilane closures, and work zones involving lane shifts were associated with increased crash occurrence (Rista et al., 2017).

Chen and Tarko (2012) analyzed the influence of law enforcement on work zone crash frequency and found that the presence law enforcement was attributed to a 41.5% reduction in work zone crash frequency. The study also identified that the work zone's length and traffic volume were associated with an increase in work zone crash frequency. In other words, longer work zones were associated with increase in work zone crashes, most likely due to increased exposure. However, the rate of increase of crash frequency decreased with increasing volume or AADT. This suggested that longer work zones with higher AADT exhibit lower crash rates than shorter work zones with less traffic. Work zones located in urban areas were also associated with higher work zone crash frequency. This finding can be attributed to the presence of complex traffic maneuvers due to intersections and ramps, heterogeneity in the traffic flow patterns, and restricted geometric design in urban areas compared to rural areas. Other factors that were attributed to increased work zone crash frequency in Indiana included work zones on collector roads, the period between November and December, lane splitting and lane shifting, and construction zones with high work intensity (i.e., projects with a cost of more than $35,000 per mile per day) (Chen & Tarko, 2012).

With rear-end crashes being prevalent among crashes that occur along work zones, Qi et al. (2013) identified the influencing factors behind this trend. Their study indicated that work zones associated with capacity and pavement improvement, work zones controlled by flaggers, and work zones with alternating one-way traffic were major influencers of rear-end crashes. Longer duration of capacity and pavement type of work zones were also attributed to a high association with crash frequency compared to other work zone types. Traffic control devices and work zone type displayed the highest impact on the occurrence of rear-end crashes along work zones in Kansas (Qi et al., 2013).

Factors influencing the occurrence of work zone crashes in different areas across the U.S. are summarized in Table A.1. The summary indicates that longer duration and length of work zones are common factors identified in previous studies that influence work zone crash occurrence. In addition, most studies have observed higher traffic volume or AADT to influence work zone crash occurrence.

Table A.1 Factors contributing to work zone crash frequency

Location	Identified Factors	Model(s) Used	Source
New Jersey	• Longer work zone length • Longer work zone duration • Higher volume per lane • Greater number of lanes • Greater number of dropped lanes	Bayesian Random Effects Negative Binomial	(Yang et al., 2013)
New Jersey	• Longer work zone length • Higher AADT • Greater number of operating lanes • Speed reduction • Longer work zone duration • Work zones operating in nighttime • Width restriction (FI*) • Work zones along major arterials (FI*)	Fixed Effects Negative Binomial	(Ozturk et al., 2013)
California	• Longer work zone length • Longer work zone duration • Higher ADT	Fixed Effects Negative Binomial	(Khattak et al., 2002)
Kansas	• Higher AADT	Negative Binomial	(Dias, 2015)
New York (Rear-end crashes only)	• Capacity improvement work zones • Pavement improvement work zones • Work zones with alternating one-way traffic • Full lane and partial lane blockage • Short-term work zones • Work zones on urban and rural principal arterials • Higher AADT	Truncated Negative Binomial	(Qi et al., 2013)
Indiana	• Longer work zone length • Work zones on full-access control roadways • Work zones on collector roadways • Work zones with high work intensity (construction cost > $35,000/day/mile) • Work zones in late Fall (Nov-Dec) • Work zones involving lane splitting and lane shifting • Work zones in urban areas	Random Effects Negative Binomial	(Chen & Tarko, 2012)
Michigan	• Single lane closures • Multilane closures • Lane shifts	Random Parameter Negative Binomial	(Rista et al., 2017)

Note: FI* indicates fatal and injury crashes; ADT = Average Daily Traffic; AADT = Annual Average Daily Traffic.

Other factors identified in previous studies could be a result of differences in geographical locations, funding, scope, duration of the research projects, data availability, and other factors. Therefore, it is necessary to use all available recent work zone and crash data in South Dakota to better understand the factors influencing work zone crash occurrence. Identifying these factors will be useful to safety engineers, maintenance personnel, and all responsible agencies to determine targeted countermeasures to eliminate work zone crashes.

A.4 Work Zone Crash Severity

To reduce the number and severity of work zone crashes, transportation agencies are exploring a variety of safety initiatives. Work zone awareness campaigns, safe system approaches, and other programs have been introduced to reduce both the frequency and severity of crashes (SDDOT, 2024b). Changes in travel way patterns, the presence of workers, and reduced speed limits along work zones all contribute to the potential occurrence and severity of work zone crashes (Khattak et al., 2002).

Several researchers have studied injury severity in work zone crashes, and many different factors have been found to influence the severity. Crash injury severity is defined by the highest level of injury incurred by any person involved in a crash. Most states use the KABCO scale, which defines injury severity based on five severity categories (Burch et al., 2014). With the KABCO scale, 'K' represents a fatal injury, 'A' represents an incapacitating injury, 'B' represents a non-incapacitating injury, 'C' represents possible injury, and 'O' represents no injury or PDO. Another scale used in identifying the level of injury in a crash is the Abbreviated Injury Score (AIS), which is based on an injury's threat to life and associated with the victim's probability of survival (Burch et al., 2014).

Most previous studies used the KABCO scale to examine injury severity resulting from work zone crashes. While some studies used all five severity levels when analyzing the data, others combined the levels into three categories: fatal, injury, and no injury. Nevertheless, all the studies sought to understand environmental, roadway, human, and vehicle factors influencing the increase in crash injury severity. Ghasemzadeh and Ahmed (2019) found that weather and lighting conditions were among the most significant factors determining the severity of work zone crashes. Results from the study indicated that drivers involved in work zone crashes at dusk and dawn were highly likely to be involved in severe crashes. The authors attributed this trend to driver sleepiness, inattention, and lack of alertness at dusk and dawn, and when combined with complex traffic maneuvers along work zones, crashes tended to result in severe injuries (Ghasemzadeh & Ahmed, 2019).

Work zone configuration has also been found to influence the severity of work zone crashes. In a study by Osman et al. (2018), five different work zone configurations were analyzed, including lane closure, lane shift, crossover, shoulder or median work, and intermittent or mobile configurations. The study used Minnesota work zone data and found that partial control of access, rural roadways, crashes occurring during evening and weekend times, and crashes occurring along curved segments were associated with increased injury severity. Work zones involving lane closure and lane shift were associated with injuries, but not severe injuries, compared to shoulder or median work zones.

In California, Wong et al. (2011) identified that work zone crashes occurring during non-peak hours or those that involve workers on foot (i.e., not using vehicles) had a higher likelihood of resulting in severe injuries. The higher injury severity likelihood in non-peak hours could be attributed to free flow conditions with higher speeds leading to greater kinetic impacts, causing severe injuries. The study also identified that crashes occurring in freeway work zones or work zones with longer durations were more likely to result in severe injuries, compared to work zone crashes on other roadway types or short-term work zones (Wong et al., 2011).

In Tennessee, it was identified that locations with more travel lanes tend to experience severe crashes in daylight compared to dark conditions. However, driving under the influence of alcohol and drugs was found to influence the occurrence of severe injuries in dark-lighted and dark-unlighted conditions compared to daylight conditions (Wei et al., 2017). Using a binary logistic regression model, Katta (2013) conducted a study to identify contributing factors in work zone crash injury severity in Ohio. The study found that the number of vehicles involved, the occurrence of rear-end and head-on collisions, and dark lighting conditions contributed to more severe work zone crashes. Additionally, the study also found that the transition area along work zones, careless driving and DUI, speed limits above 65 mph, female at-fault drivers, and missing or obscured traffic control devices were also attributed to the occurrence of more severe work zone crashes Katta (2013).

Sze & Song (2019) analyzed work zone crash severity in New Zealand and found that crashes involving motorcyclists and pedestrians or workers in work zones were associated with severe injuries. This trend may be explained by a lack of physical separation between vehicles and vulnerable road users (i.e., motorcyclists, bicyclists, and pedestrians). On the other hand, work zone crashes that occurred in the evening, at nighttime, or involved more than one vehicle were found to have a lower likelihood of resulting in injuries. A study on work zone crashes in Egypt by Zhang & Hassan (2019a) found that younger drivers (< 35 years), older drivers (> 50 years), and male drivers influence injury severity during nighttime crashes, compared to middle-aged drivers and female drivers. The authors attributed these findings to the inexperience of young drivers and longer reaction times of older drivers. The increased severity with male drivers was attributed to a greater tendency of male drivers to take risks, such as speeding and driving aggressively. Other factors identified by the study included the number of lanes closed, the presence of curved segments, rural areas, and the involvement of heavy vehicles in work zone crashes. Table A.2 summarizes the reviewed studies related to work zone crash injury severity.

Table A.2 Factors contributing to work zone crash severity

Location	Increasing Severity	Decreasing Severity	Model	Source
California	• Crashes in non-peak hours • Workers on foot • Crashes on freeways/highways • Work zones with longer durations		Logistic Regression	(Wong et al., 2011)
Washington	• Crashes in rural principal arterials • Dusk and dawn conditions • Roadways with higher speed limits • Driving under the influence of alcohol and drugs (DUI) • Crashes involving female at-fault drivers • Curve segments without lighting	• Crashes Occurring in Peak Hours • Sideswipe Crashes • Multi-Vehicle Crashes • Crashes Occurring in the Intersection-Influence Area • Work Zones Equipped with Amber/Flashing Red Lights • Rainy Weather	Ordered Probit Model	(Ghasemzadeh & Ahmed, 2019)

Table A.2 Factors contributing to work zone crash severity (continued)

Location	Increasing Severity	Decreasing Severity	Model	Source
Tennessee	During Daylight • Increase in the number of lanes (daytime) • Head-on crashes In Dark-Lighted Conditions • Driving under the influence (Dark-Not-Lighted conditions) In Dark-Unlighted Conditions • Driving under the influence (Dark-Not-Lighted conditions)			(Wei et al., 2017)
Minnesota	• Lane closure and lane shifts • Partial control of access • Crashes on rural roadways • Crashes in the evening times and during weekends • Curved road segments		Mixed Generalized Ordered Response Probit Model	(Osman et al., 2018)
Ohio	• Greater number of vehicles involved • Crashes in dark conditions • Rear-end and head-on crashes • Crashes in transition and activity area • DUI and careless driving • Speed limits above 65 mph • Involvement of female at-fault drivers • Traffic signals and traffic flashers • Missing and obscured traffic control devices		Binary Logistic Regression Model	(Katta, 2013)
New Zealand	• Involvement of vulnerable road users	• Crashes occurring on weekdays • Evening and night times • Involved more than one vehicle	Multinomial Logistic Regression	(Sze & Song, 2019)
Egypt (Nighttime Work Zone Crashes)	• Younger and older drivers • Male drivers • Rainy conditions • More number of lanes closed • Exceeding speed limits • Crashes occurring along curved segments • Involvement of heavy vehicles • Work zone crashes in rural areas		Mixed Multinomial Logit Model	Zhang & Hassan, (2019a)

A.5 Truck-Involved Work Zone Crash Severity

Narrow lanes along work zones have been a concern for larger vehicles, specifically trucks (Khattak & Targa, 2004). Using North Carolina truck-involved work zone crash data, Khattak and Targa (2004) identified factors contributing to severe injuries and fatalities. The study found that truck-involved multivehicle crashes significantly influenced the severity of the crashes, especially when they occurred on two-way undivided or unprotected median roadways. In addition, it was observed that the level of injury severity increased when there was a closed roadway that required a detour on the opposite side and when the roadway was characterized by higher speed limits.

In 2016, another study was conducted in Minnesota to determine the influence of large trucks on injury severity of work zone crashes (Osman et al., 2016). Results from a generalized ordered response logit (GORL) model revealed that daytime, lower AADT, and higher speed limits had the greatest influence on increasing injury severity of truck-involved work zone crashes. Alternatively, crashes occurring along roadways with lower speed limits (< 35 mph), curbed shoulders, on a wet roadway surface, and during peak or congested hours were associated with lower injury severity.

Madarshahian et al. (2023) examined the influence of higher speed limits in truck-involved work zone crashes. The study utilized two mixed-effect random parameter logistic models for interstates with speed limits greater than 60 mph and non-interstates with speed limits less than 60 mph. Findings indicated that dark conditions, female at-fault drivers, and speeding were found to influence injury severity in both interstate and non-interstate locations. However, U.S. primary roadways (among the non-interstates), younger drivers below 35 years, activity areas in the work zone, and the presence of workers were found to influence injury severity only on non-interstate roadways. Crashes involving more than three vehicles and rear-end crashes were found to influence injury severity only on interstates (Madarshahian et al., 2023). Table A.3 summarizes the reviewed studies related to work zone crash injury severity involving trucks.

Table A.3 Factors contributing to truck-involved work zone crash severity

Location	Increasing Factors	Decreasing Factors	Model	Source
South Carolina	• Dark conditions • Female at-fault drivers • Over-speeding • Crashes in the activity area along the work zone • Drivers under age 35 years • Presence of workers along the work zone • Greater number of vehicles involved • Rear-end crashes	• Crashes occurring on weekdays • Sideswipe crashes • Collisions with fixed objects	Mixed Random Parameter Logit Models	(Madarshahian et al., 2023)
North Carolina	• Two-way undivided roadways • Two-way unprotected median roadways • Detour on the opposite side • Crashes occurring adjacent to the work area • Higher posted speed limits		Ordered Probit	(Khattak & Targa, 2004)
Minnesota	• Daytime • Non-access-controlled roadways • Higher speed limits • Crashes occurring on principal arterials • Lower AADT • One-unit trucks • Single vehicle crashes	• Lower speed limits • Curbed roadways • Wet surface conditions • Crashes occurring in peak hours One or more lane closure	Generalized Ordered Logit Model	(Osman et al., 2016)

Note: AADT = Annual Average Daily Traffic.

A.6 Overall Factors Affecting Work Zone Crash Injury Severity

Table A.4 summarizes the overall factors affecting injury severity along work zones identified in previous studies. The factors are categorized as roadway, environmental, temporal, human, vehicle, road user, and work zone characteristics. Roadway factors include those related to roadway geometry and traffic patterns associated with the location of the crash, such as AADT, roadway alignment and grade, speed limit, and roadway functional classification. Environmental factors include area characteristics, such as urban and rural, weather conditions, lighting conditions, surface conditions, the presence of workers, and others. Temporal factors are associated with time, such as day of the week and time of the day. Human factors are characteristics associated with the driver, such as age, gender, speeding, and distraction. Work zone characteristics are related to the properties/nature of the work zone itself, such as the type of activity being performed or the specific location within the work zone.

Table A.4 Overall factors affecting work zone crash severity

Category	Factor Type	Source
Roadway Factors	• Work zone location • Horizontal curved segments • Higher speed limits • Crashes on freeways/highways • Crashes on rural principal arterials • Roadways with more lanes	(Wong et al., 2011) (Li & Bai, 2007) (Li & Bai, 2009) (Sze & Song, 2019) (Ghasemzadeh & Ahmed, 2019) (Zhang & Hassan, 2019a)
Environmental Factors	• Non-peak hours • Lack of daylight • Adverse weather conditions • Involvement of vulnerable road users	(Wong et al., 2011) (Ghasemzadeh & Ahmed, 2019)
Vehicle Factors	• Heavy vehicles • Passenger Cars • Higher vehicle age	(Zhang & Hassan, 2019b) (Weng & Meng, 2011)
Temporal Factors	• Work zones with longer duration • Crashes occurring at night	(Wong et al., 2011) (Zhang & Hassan, 2019a)
Human Factors	• Speeding • Distracted driving • Following too close for conditions • Driver age (26-65 years) • Driving under the influence of alcohol and drugs • Crashes involving female at-fault drivers	(Zhang & Hassan, 2019b) (Zhang & Hassan, 2019b) (Wong et al., 2011) (Dias, 2015) (Ghasemzadeh & Ahmed, 2019)
Work Zone Characteristics	• Work zones with lane closures and lane shifts • Activity area • Termination area • Type of work zone activity	(Osman et al., 2018) (Mokhtarimousavi et al., 2021)

A.7 Driver Compliance Along Work Zones

Driver compliance refers to the ability and extent to which drivers follow the rules and regulations set by the responsible agencies or personnel. Along work zones, driver compliance includes the extent to which drivers adhere to the designated speed limit, lane changes and detours, temporary traffic control devices, etc. Several factors have been associated with driver non-compliance along work zones, including driver distraction, information overload, insufficient signage, or lack of enforcement.

Ensuring driver compliance within work zones is crucial to improving the safety and operational performance of the transportation network. The significance of work zones lies not only in their contribution to infrastructure development but also in the critical need to safeguard the well-being of both motorists and workers. Non-compliance with established traffic control measures poses a substantial threat to safety, leading to an increase in crash frequency and injuries (Debnath et al., 2014). As highways encounter growing traffic demands and increasing construction activities, fostering a culture of unwavering driver compliance to work zone regulations is vital in mitigating risks, reducing crashes, and enhancing overall safety and efficiency on roadway networks. Understanding the factors influencing driver behavior related to traffic control measures is necessary to identify effective strategies to improve driver compliance.

A.7.1 Speed Compliance Along Work Zones

Speeding or driving above the set work zone speed limit has been proven to be among the key factors influencing both the frequency and severity of work zone crashes. However, speeding in work zones has remained a challenge (Ravani & Wang, 2018), and as a result, several agencies are working to effectively reduce speeding in work zones. To understand how work zone speed limits are determined, Savolainen et al. (2022) conducted a nationwide survey in the U.S. to identify different strategies used in determining work zone speed limits. The survey identified several factors that guide states in determining work zone speed limits, including:

- permanent speed limit,
- facility type,
- presence of workers along work zones,
- protection facility,
- work zone duration,
- work zone length, and
- type of work zone activity.

These factors collectively inform a tailored approach to setting work zone speed limits, balancing the need for safety with traffic flow considerations. By understanding these determinants, agencies better address speeding issues and enhance safety protocols, ultimately reducing crash rates and mitigating severity in work zones. Setting lower speed limits for work zones in high-speed facilities, such as freeways, must also consider the effects of reduced speeds, as higher speed differentials could compromise safety and lead to rear-end crashes. The presence of workers along the work zones and the duration of their presence necessitate lower speed limits to ensure the workers' safety.

The type of protection, or separation between traffic flow and the work area, also influences the set speed limit. For instance, positive protection barriers could allow for relatively higher work zone speed limits. In some cases, the work zone speed limit is dynamic, i.e., changes hourly or daily depending on traffic conditions and worker presence (Savolainen et al., 2022). While shorter work zones do not necessarily lead to lower set speed limits, work zones expected to last longer could influence the use of lower speed limits. Such factors are crucial in considering the amount of speed reduction required to maintain both safety and mobility along work zones.

A.7.2 Impact of Countermeasures

Countermeasures used by different agencies to maintain driver compliance along work zones include the use of dynamic message signs (DMSs), temporary rumble strips, speed feedback signs, lateral deflections, lane narrowing, flashing beacons, higher fines, photo enforcement, lights on contractor vehicles, and the use of Smart Work Zone (SWZ) technologies (Savolainen et al., 2022). Smart work zone applications utilize computers, communications, sensor technology and Intelligent Transportation Systems (ITS) for dynamic and impact management of work zones. Examples include Queue Warning Systems (QWSs), lane closure notification systems, traveler information systems, and others. Previous studies have analyzed the impact of various traffic control devices on improving driver speed compliance along work zones, including using police presence along work zones, radar speed display, speed feedback signs, and others.

In California, Ravani and Wang (2018) conducted a study to identify the influence of the presence of police vehicles along work zones, together with radars. Using different scenarios, the results indicated that using radar speed display and passive police vehicles had the best outcome in regulating driver speed along work zones, especially in urban areas. Findings also revealed that using multiple police vehicles along the work zone resulted in drivers maintaining lower speeds throughout the work zone. Such countermeasures have been deployed to increase the conspicuity of the work zone and discourage speeding among the drivers (Ravani & Wang, 2018).

Whitmire et al. (2011) modeled simulation scenarios to investigate the effect of in-vehicle visual and audio modalities to examine driver speed compliance along work zones. The in-vehicle visual warnings were placed on the right side of the dashboard's upper surface, displaying messages such as "Work Zone Ahead", "Begin Work Zone", and "Slow Down", written in Black text with an orange background. The audio warnings were presented using mounted speakers below the visual display. Results from the study revealed that drivers responded much faster to the audio alerts than to the visual alerts. The authors also suggested the use of both audio and visual warnings for only a few seconds, followed by only visual warnings until compliance is attained (Whitmire et al., 2011).

In Texas, Brewer et al. (2006) conducted field studies to determine effective measures that encourage drivers to comply with work zone speed limits. The measures studied include the use of a speed display trailer, a DMS with radar, and a speed limit sign with an orange border. Speed feedback devices displaying the driver's speed were observed to have the greatest potential in improving compliance along work zones. The study also observed that without active enforcement, drivers tended to travel at their desired speeds, regardless of the work zone speed limit (Brewer et al., 2006). After surveying state Departments of Transportation (DOTs) across the U.S., Iowa DOT conducted a field study to evaluate the performance of speed feedback trailers (SFTs) in the presence of law enforcement. Findings revealed that the visible presence of law enforcement reduced work zone speeds by about 5 to 7 mph (Savolainen et al., 2022). Also observed was that for effective speed reduction by drivers, the SFT should be located near the work area, i.e., near the end of the taper rather than at the start of the taper.

In Indianapolis, Indiana, Wasson et al. (2011) conducted a study to examine the change in space mean speeds of vehicles in the presence of law enforcement. Findings indicated that the vehicles' space mean speeds reduced by 5 mph in the presence of enforcement. However, space mean speeds increased after the enforcement detail ended. In addition, it was also observed that even with law enforcement presence, 75% of the vehicles still exceeded the posted speed limit, with the exception of work zones with a 45-mph posted speed limit, where only 25% of the vehicles exceeded the posted speed limit (Wasson et al., 2011).

In a study by Pesti and McCoy (2001), speed monitoring displays (SMDs) were deployed at three different sites for five weeks in Lincoln, Nebraska, to understand the long-term and residual effect of SMDs on vehicle speeds. The SMDs were found to significantly lower the 85th percentile vehicle speed by 2-7 mph and the mean speed by 3-4 mph, as well as increase speed uniformity during the 5-week duration. Higher speed reductions and greater compliance were observed with passenger cars than other vehicles. After the SMDs were removed, significant increases in speed were observed. However, the speeds did not return to pre-deployment levels, indicating a lasting/residual effect of SMDs on speed reduction (Pesti & McCoy, 2001).

Saito and Bowie (2003) conducted a similar study to examine the influence of SMDs and law enforcement in reducing the mean speed of vehicles along work zones in Utah. Based on field tests, the authors concluded that the average speed was reduced by seven mph with the use of SMDs, compared to an average speed reduction of three mph when standard work zone practices were used. In addition, the mean speed was reduced by nine mph in the presence of law enforcement (Saito & Bowie, 2003). Findings also revealed that law enforcement only impacted the work zone areas, However, the effects from the SMDs continued further downstream, and thus, SMDs could offer a better option, given their economic feasibility over law enforcement. Table A.5 summarizes the studies reviewed related to work zone driver compliance.

Using modeled driving simulation scenarios, Strawderman et al. (2013) studied the influence of work zone sign design and placement on driver compliance. . The study concluded that sign placement was more significant in influencing driver speed compliance, with more compliance achieved when signs were placed at a greater distance before the start of the work zone. Additionally, it was observed that static work zone signs led to greater compliance, followed by the use of DMSs with complete messages on one display frame. DMSs displaying more information had the lowest speed compliance rates among drivers (Strawderman et al., 2013).

Rahman et al. (2017) studied the effect of DMS design using driving simulation and 44 participants. Contrary to findings by Strawderman et al. (2013), Rahman et al. (2017) found that DMS content and placement did not significantly influence speed reduction and driver compliance. However, findings revealed that a longer refresh rate (i.e., time lapse between the appearance and disappearance of a message) on the DMS, about three seconds, led to better driver compliance, giving drivers enough time to read and interpret the message. It was also observed that mentioning the presence of workers on the DMS heightens driver awareness and that the use of DMSs was most effective at nighttime compared to daytime (Rahman et al., 2017).

In Australia, a Tobit model was used to identify factors contributing to driver non-compliance along work zones. The results showed that light/passenger vehicles and their followers, vehicles as platoon leaders, vehicles with a larger gap from the leader vehicle, and vehicles not in a platoon were more likely to exceed speed limit by greater margins (Debnath et al., 2014). The design and placement of work zone warning signs have also been found to affect the level of compliance among drivers. Work zone signs are designed with the goal of warning drivers of the presence of work zone conditions ahead, with minimal distraction and high effectiveness. The placement of these signs should ensure maximum visibility and provide sufficient reaction time to drivers to make adjustments.

Table A.5 Summary of studies on work zone driver compliance

Location	Assessed Countermeasures	Findings	Source
California	• Radar speed display with police decal and lighting	• Speed reduction by 2.9 – 7.0 mph.	(Ravani & Wang, 2018)
	• Passive use of a police vehicle with radar speed display	• Speed reduction by 5.2 – 8.8 mph.	
	• Passive use of a police vehicle without radar speed display	• Speed reduction by 0.8 – 6.0 mph.	
	• Active police speed enforcement near work zones	• Speed reduction by 1.9 – 8.7 mph.	
Texas	• Speed display trailer • Portable changeable message sign with radar • Orange border speed limit sign	• Speed display had the highest influence on driver's work zone speed compliance. • Orange borders on speed limit signs have minimal impacts on driver compliance.	(Brewer et al., 2006)
Indiana	• Law enforcement	• Space mean speed reduced by five mph. • Space mean speeds increased 30 minutes after enforcement ended.	(Wasson et al., 2011)
Nebraska	• Speed monitoring displays (SMDs)	• Mean speed reduction of 3-4 mph. • Speed reduction of 2-7 mph. • The 85th percentile speeds were observed to be lower in two out of three sites (3-4 mph reduction). • The uniformity of speeds increased. • Speed limit compliance increased over the 5-week period. • More compliance was observed in passenger cars. • Statistically Significant speed reductions were observed even after SMDs were removed.	(Pesti & McCoy, 2001)
Utah	• No treatment • Speed monitoring display • Law enforcement	• Speeds reduced by three mph with no treatment. • Speeds reduced by seven mph with SMDs. • Speeds reduced by nine mph with law enforcement. • Effects of police were localized, but SMD effects continued further downstream.	(Saito & Bowie, 2003)
Texas	• Rumble strips • Speed displays	• Less Impact observed for rumble strips. • For rumble strips, more effect pronounced among trucks (7.2 mph reduction in mean speed). • More compliance observed with speed displays than rumble strips. • About ten mph reduced with speed displays.	(Fontaine & Carlson, 2001)

Note: SMD = Speed monitoring display.

Table A.5 Summary of studies on work zone driver compliance (continued)

Location	Assessed Countermeasures	Findings	Source
Mississippi	• Driving Simulation • Dynamic Message Signs	• Greater placement distances were associated with higher speed reduction and compliance • Greater speed reduction with static signs or DMS signs with a complete statement on one frame • Longer refresh rate (i.e., time lapse between the appearance and disappearance of a message) on the DMS led to more compliance • Mentioning the presence of workers on DMS increases awareness • DMS was more effective at night compared to daytime	(Strawderman et al. 2013) (Rahman et al., 2017)
Southern University U.S.	• Driving Simulation • Traditional signage • In-vehicle visual warning • In-vehicle audio warning	• The audio warning led to higher compliance than the visual and traditional signage.	(Whitmire et al., 2011)
Australia	• Speed limit compliance in work zones	• Traffic compositions and speeds surrounding traffic significantly influence travel speeds • Light vehicles and their followers and leaders of platoons speed more than others	(Debnath et al., 2014).

Note: SMD = Speed monitoring display.

A.8 State-of-the-Art Work Zone Traffic Control Devices

A number of agencies have deployed various temporary traffic control devices to enhance safety and mobility along work zones. These devices are used to temporarily manage and control traffic at work zones. Examples of temporary traffic control devices include:

- Portable rumble strips
- Radar drones
- Temporary ramp metering
- Mobile barriers and barricades
- Automated Flagger Assisted Devices
- Citizens Band (CB) Wizard alert system
- Truck-mounted attenuators

The following subsections discuss these traffic control devices, their benefits, challenges, and impact on traffic compliance and crash reduction ability to improve mobility and safety for motorists and workers in work zones. To evaluate their effectiveness in reducing crashes, numerous studies have examined how these strategies influence speed reduction and increase driver compliance, given that speeding is one of the leading causes of work zone crashes and a factor that influences work zone crash injury severity (Brown et al., 2022; Shahin et al., 2023). In addition, Nnaji et al., (2020) conducted a systematic review from 147 journal articles between 1995 and 2018 and identified that approximately 70% of the articles focused on speed reduction systems. Table A.6 summarizes the findings on traffic and speed control devices from previous studies.

A.8.1 Portable Rumble Strips

Adhesive rumble strips have the ability to generate in-vehicle sound and vibration, alerting drivers in a work zone environment (Wang et al., 2011). Different types of rumble strips have been investigated to examine their influence on speed reduction and compliance among drivers in work zones. These include advanced traffic marking (ATM) rumble strips (i.e., molded plastic rectangular bump placed on the pavement with adhesive pad), rumblers (i.e., temporary rumble strips), steel rumble strips, and portable plastic rumble strips (PPRSs). A national survey conducted by Wang et al., (2011). indicated that ten states mentioned that rumble strips were ineffective in reducing speeds along work zones. Fontaine and Carlson (2001) also reported that rumble strips were not as effective compared to SMDs. However, their study identified a pronounced speed reduction effect among trucks (7.2 mph reduction) compared to passenger cars (2 mph reduction).

In Kansas, the deployment of rumble strips is required for maintenance work zones requiring a lane closure along a two-lane highway. A study conducted by Meyer (2000) to identify the impact of orange removable rumble strips indicated that with a higher visibility, orange rumble strips had the potential to significantly reduce a vehicles' speed, by about 2.2 mph for passenger cars and 2.3 mph for trucks (Meyer, 2000). In Missouri, Sun et al. (2011) identified a net improvement in safety with the deployment of temporary rumble strips (placed at an angle of 29 degrees so that each wheel would hit the strips independently), observing a 3.7 mph reduction in speeds and a 2.9% increase in speed compliance. Zech et al. (2005) studied the effects of reusable rumble strips, as well as the use of rumble strips with police presence in New York. Using a dataset of more than 500,000 vehicles observed, the authors found that the rumble strips reduced speeds by 2.4 mph and 2.0 mph among passenger cars and trucks, respectively. When the rumble strips were used in conjunction with the presence of enforcement, a 3-6 mph speed reduction was observed among all vehicles (Zech et al., 2005).

A.8.2 Radar Drones

Radar drones simulate law enforcement presence through the emission of radar signals. In other words, these are devices designed to simulate the presence of police officers using a radar gun, without actual presence of police officer. The drones function with the intention of encouraging drivers with radar detection in their vehicles to slow down and comply to the speed limit (Wang et. al., 2011). For that reason, vehicles equipped with radar detection tend to decelerate after they detect the radar transmission. In Texas, using radar drones resulted in a 1-2 mph reduction in mean speeds and a 2.1% increase in speed limit compliance (Fontaine et al., 2000). In addition, survey responses in Texas indicated that while workers appreciated the easy setup of radar drones, they were not sure of their effectiveness over extended periods of time (Fontaine et al., 2000).

In South Carolina, drone radars were investigated to understand their impact on reducing speeds along work zones to improve safety (Eckenrode et al., 2007). The study found that the effectiveness of radar drones was widely dependent on the number of radar detectors within the traffic stream (i.e., vehicles with the radar), with about a 3.5 mph speed reduction when the radar drone was activated (Eckenrode et al., 2007). In 1992, a study conducted in South Dakota observed a 21.1% decrease in statewide crashes following the placement of drones in 500 of the 602 state vehicles (Fors 1999). The identified impacts/benefits of radar drones, together with their lower cost of implementation, have made them an optimal choice (Eckenrode et al., 2007).

A.8.3 Temporary Ramp Metering

Ramp meters have been identified as effective measures in regulating traffic flow and improving traffic operations along freeways and parallel arterials (Haj-Salem & Papageorgiou, 1995; Sun et al., 2013). Sun et al. (2013) evaluated the use of ramp meters along work zones in Missouri through field deployment. Findings from the study suggested that ramp meters at work zones are more effective when deployed at locations with potential congestion and that temporary ramp meters should be turned on only during high congestion periods. However, temporary ramp metering was not recommended for flows below roadway capacity as more delays were observed (Sun et al., 2013). The analysis further found that temporary ramp meters with three-section signal heads led to greater compliance than two-section signal heads. This finding may be due to drivers being more familiar with three-section signal heads.

A.8.4 Mobile Barriers and Barricades

Mobile barriers are among the most common devices used in temporary traffic control along work zones. Mobile barriers act as a separation between moving traffic and workers/activity area. In a survey conducted in Queensland, Debnath et al. (2015) found that most of the survey respondents (including fully and semi-exposed workers) claimed that mobile barriers are optimal for long-term work zones due to their elaborate installation and removal process. In addition, the survey respondents argued that while the barriers offer enhanced safety, traffic controllers (those responsible in setting up the traffic control devices) were still exposed to moving traffic, and that more safety measures should always be deployed with mobile barriers.

A.8.5 Automated Flagger Assisted Devices

Automatic flagger assistance devices (AFADs) have been used by several states to control traffic along work zones. The AFAD system is a portable traffic control system designed to replace flaggers located near moving traffic along a work zone. Among the benefits of the AFAD system is the enhanced safety of replacing flaggers exposed to moving traffic while maintaining traffic control for vehicles approaching the work zone (Cottrell, 2006). Missouri DOT (MoDOT) examined the effectiveness of the AFAD system using both simulator and field studies (Brown et al., 2018). The MoDOT AFAD system involved a STOP/SLOW paddle, a red/yellow light, and a changeable message sign (CMS) installed onto a truck-mounted attenuator. Findings from the study indicated that the average vehicle approach speed when using the AFAD was 23.2 mph and 27.4 mph when using a flagger. While the full stop location and the compliance rate were observed to be farther and higher for the AFAD system (61.07 ft and 98.44%, respectively), it was also observed to be closer and lower using a flagger (49.68 ft and 98.04%, respectively). As a result, the AFAD system was found to perform better than the traditional flagger method in temporary traffic control (Brown et al., 2018).

Using field deployment observations and interviews about the AFAD system in Minnesota, it was determined that the AFAD works better when used along two-lane roads and that for worst-case scenarios, two people are required to operate the system. Additionally, it was identified that the setup and takedown required more effort compared to the traditional flagging, but still within reasonable range (Terhaar, 2014). In Texas, the AFAD system was also tested along two-lane roadways to determine its effectiveness. It was determined that, with the use of the AFAD system, the violation rate decreased with an increase in AADT. This was explained by the possibility of low volume roads to be more used by locals, who know the low likelihood of encountering oncoming vehicles and thus choose to disregard

AFAD instructions. However, different trends were observed in relation to work zone length, i.e., the longer the work zone, the more violations to the AFAD system were observed (Finley et al., 2011).

A.8.6 CB Wizard Alert System

The CB Wizard alert system is a citizens band (CB) short-range radio voice communication system that is used to give alerts to people in vehicles, homes, offices and other locations where wireless telephone service is unavailable. In Missouri, the CB alert system was tested by placing a trailer-mounted CB wizard alert system about six miles upstream of a work zone with a lane closure along I-70 (Sanford Bernhardt et al., 2001). When the right lane was closed, the wizard transmitted the following message "This is the Missouri Department of Transportation. The right lane of Eastbound I-70 is closed ahead. Watch for slow or stopped traffic." It was identified that the CB alert system was more effective during the day compared to nighttime, and the non-passenger vehicles were observed to be more compliant than other vehicle types. However, during nighttime, it was observed that the CB alert used with orange rumble strips had a similar effect on both passenger and non-passenger vehicles (Sanford Bernhardt et al., 2001).

A.8.7 Truck-Mounted Attenuators

Truck-mounted attenuators (TMAs) are energy-absorbing devices attached to heavy shadow vehicles to act as mobile barriers. TMAs are designed to protect workers by absorbing the impact of vehicles entering work zones due to distraction or impairment (White et al., 2021). Schrock et al. (2014) reported that the TMA system was able to prevent about 77 crashes along New York work zones. These crashes were a result of vehicles hitting the trucks, and thus, preventing vehicles from entering the work zone. In addition, TMAs were also found to have a positive cost-benefit ratio, with about $23,000 savings per crash in injury and damages, compared to if a vehicle hit a stationary object directly in a work zone (Humphreys & Sullivan, 1991). While these devices have been deployed with the main objective of deflecting energy from colliding vehicles, thus improving worker safety, the effectiveness of TMAs has been identified by determining the recognition distance and the percentage of vehicles entering the critical zone along work zones. Findings from the study revealed that advance warning signs placed about 400 meters before the TMAs led to a 27% reduction of non-compliant vehicles (i.e., vehicles entering the critical zone) (Smith et al., 2006).

Table A.6 Work zone traffic and speed control devices

Device	Location	Assessed Device(s)	Findings	Source
Portable Rumble Strips	New Jersey	• Portable plastic rumble strips (PPRS)	• Compliance was observed to improve (reduction in number of speeding vehicles along work zones) by about 11%.	(Yang et al., 2015)
	Kansas	• Orange removable rumble strips	• 2.2 mph reduction for passenger cars and 2.3 mph reduction in trucks. • Very easy to install and remove.	(Meyer, 2000)
	Kansas	• Portable plastic rumble strips (PPRS) at flagger-controlled work zone	• Drivers became more cautious when approaching the PPRS. • About 6.0 to 13.8 mph speed reduction among all vehicles.	(Wang et al., 2011)
	Missouri	• Temporary rumble strips	• Average Speed decrease of 3.7 mph. • Increase in speed compliance by 2.9%.	(Sun et al., 2011)
	Western New York	• Reusable rumble strips (3M)	• About 2.4 and 2.0 mph speed reduction among passenger cars and trucks, respectively. • Reusable, easy to install and remove. • Reusable. • About 3.0 to 6.0 mph speed reduction if used with police presence.	(Zech et al., 2005)
Speed Monitoring Displays	Nebraska	• Speed monitoring displays (SMDs)	• 3 to 4 mph mean speed reduction. • 2 to 7 mph 85th percentile speed reduction. • 20% to 40% increase in driver compliance.	(Pesti & McCoy, 2001)
	Nevada	• Speed trailers	• 8-9 mph speed reduction along freeways and principal arterials.	(Teng et al., 2009)
	Utah	• No treatment (MUTCD signs and barriers) • SMDs • Police Enforcement	• With no treatment, a 3-mph speed reduction was observed. • With the SMD, a 7-mph speed reduction was observed. • With police treatment, a 9-mph speed reduction was identified.	(Saito et al., 2003)
	Texas	• Speed display trailer • Changeable message sign with radar • Orange-border speed limit sign	• Speed display had the highest influence on driver's work zone speed compliance. • Orange borders on speed limit signs have minimal impacts on driver compliance.	(Brewer et al., 2005)

Note: AFAD =Automated Flagger Assistance Device; TMA = Truck Mounted Attenuator; AADT =Annual Average Daily Traffic; SMD = Speed Monitoring Display; PCMS = Portable Changeable Message Sign; CB Wizard = Citizens Band Wizard.

Table A.6 Work zone traffic and speed control devices (continued)

Device	Location	Assessed Device(s)	Findings	Source
Portable Changeable Message Signs	Kansas	• PCMS placed at 750 ft • PCMS placed at 575 ft • PCMS placed at 400 ft	• PCMS placed at 575 feet had the highest impact in reducing speed difference between trucks and passenger vehicles, hence reducing truck-related crash risk	(Bai et al., 2015)
	Kansas	• Text-Based PCMS • Graphic-Based PCMS	• About 13% speed reduction with the text-based PCMS • About 17% speed reduction with the graphic-based PCMS	(Bai et al., 2011)
	South Carolina	• Radar Equipped PCMS	• 3-10 mph speed reduction along work zone	(Sorrell et al., 2007)
	Virginia	• Radar equipped PCMS	• About 3-10 mph speed reduction. • Observed 85th percentile speed reduction. • Increase in driver compliance by 50%. • Messages with individual confrontation had the highest impact in speed reduction, compared to regular advisory (for example, 'YOU ARE SPEEDING SLOW DOWN" performed better than "EXCESSIVE SPEED SLOW DOWN").	(Garber & Patel, 1994).
	United Arab Emirates	• PCMS along work zones • Survey on PCMS Perception	• No significant speed differences before and after PCMS installation • Majority of drivers and workers perceive PCMS as an effective tool for work zone safety.	(Ahmed et al., 2015)
Radar Drones	Texas	• Radar drones	• Speed reduction about 1.6 mph before the taper area. • Speed reduction about 0.5 mph within the activity area. • About 1-2 mph mean speed reduction and 2.1% increase in the number of compliant drivers.	(Fontaine et al., 2000)
	South Carolina	• Radar drones	• About 3.5 mph mean speed reduction along work zones. • Dependent on the number of vehicles equipped with radar detectors.	(Eckenrode et al., 2007)
	Georgia	• Radar drone with safe warning system (SWS) for radar-equipped vehicles	• No significant speed changes were observed • For vehicles equipped with radar, speed reductions were observed.	(Oliveira et al., 1996)
	South Dakota	• Radar drones placed in 500 out of 602 state vehicles	• 21.1% decrease in statewide crashes	(Fors 1999)

Table A.6 Work zone traffic and speed control devices (continued)

Device	Location	Assessed Device(s)	Findings	Source
Temporary Ramp Metering	Missouri	• Temporary ramp metering along work zones	• In non-congested conditions, the temporary Ramp Meter speeds are reduced by about 19.5%.	(Sun et al., 2013)
Automated Flagger Assistance Devices	Missouri	• Normal flagger • Automated flagger assistance devices	• Approach speed = 23. 2 mph for AFAD and 27.4 mph for flagger. • Full stop location from work zone = 61.07 ft for AFAD and 49.68 mph for flagger. • Stopping Compliance = 98.45% for AFAD and 98.06% for flagger. • Approaching speed for 1st following vehicle = 20.63 mph for AFAD and 23.09 mph for flagger.	(Brown et al., 2018)
	Minnesota	• Automated flagger assistance devices	• AFAD s work well on two-lane roadways. • In worst case scenarios, two people are required to operate one AFAD set. • More effort for setup and take down compared to traditional flagging.	(Terhaar, 2014)
	Texas	• Automated flagger assistance devices	• Violation rates increase with decrease in AADT. • Violation rates increase with increase in work zone length.	(Finley et al., 2011)
CB Wizard Alert System	Missouri	• CB Wizard alert system • White lane drop arrows • Orange rumble strips	• Lane drop arrows and CB Wizard were found effective in speed reduction for approaching vehicles. • The effect of CB radio was prevalent among non-passenger vehicles. • An increase in the number of vehicles below the speed limit with the CB alert system. • About 46.2% reduction in mean speed of passenger vehicles during nighttime.	(Sanford Bernhardt et al., 2001)

Note: AFAD =Automated Flagger Assistance Device; TMA = Truck Mounted Attenuator; AADT =Annual Average Daily Traffic; SMD = Speed Monitoring Display; PCMS = Portable Changeable Message Sign; CB Wizard = Citizens Band Wizard.

Table A.6 Work zone traffic and speed control devices (continued)

Device	Location	Assessed Device(s)	Findings	Source
Truck-Mounted Attenuators	Virginia	• Automated truck mounted attenuator	• The Automated TMA was found effective in improving the safety of the TMA drivers.	(White et al., 2021).
	Texas	• Benefit cost-ratio of TMAs	• About $23,000 saved per crash in injury and damage compared to when a vehicle hits a stationary construction vehicle along a work zone.	(Humphreys & Sullivan, 1991)
	New York	• Truck mounted attenuator	• About 77 crashes were prevented from entering the work area where striking the TMA was the primary cause of the crashes.	(Schrock et al., 2014)
	New Zealand	• Truck mounted attenuator	• Placing advance warning signs about 400 meters before the TMA was the optimum practice (27.7% fewer vehicles entering the critical zone) leading to increased compliance. • Retroreflective tape on the edges of the message board improved the average recognition distance of the TMA by at least 38 meters at night.	(Smith et al., 2006)

Note: AFAD =Automated Flagger Assistance Device; TMA = Truck Mounted Attenuator; AADT =Annual Average Daily Traffic; SMD = Speed Monitoring Display; PCMS = Portable Changeable Message Sign; CB Wizard = Citizens Band Wizard.

A.9 Smart Work Zone Technologies and Applications

Apart from the traditional methods used in temporary traffic control, recent advancements have increasingly integrated technology into the systems to improve safety and mobility along work zones. This increase in technology integration has led to the development of SWZ technologies and applications (Nnaji et al., 2020). Smart work zone applications utilize computers, communications, sensor technology, and Intelligent Transportation Systems (ITS) for dynamic management of work zones for traffic impacts, such as queue and speed management (Pant, 2017).

SWZ applications typically include:

- A sensor network to identify real-time traffic conditions,
- A data processing algorithm to analyze the data collected by the sensor,
- Output devices to relay the information analyzed on changeable message signs (CMSs) located at set locations along the highways (Pant, 2017), and
- A communication network to link the other components (Li et al., 2012).

The following sections discuss different SWZ applications, how they have been used, and their impacts on improving work zone safety and mobility. The applications discussed can be categorized into:

- Portable Changeable Message Signs
- Queue Warning Systems
- Speed Monitoring and Management Systems

A.9.1 Portable Changeable Message Signs (PCMSs)

Portable changeable message signs (PCMSs) have been used along work zones for many years in the U.S. Different types of PCMSs use different software, electronics, and external interfaces to communicate accurate, timely, and pertinent information to travelers along roadways (Walton et al., 2001). Messages displayed on PCMSs include "WORK ZONE/AHEAD/SLOW DOWN", or "FLAGGER AHEAD/PREPARE/TO STOP" or "SLOW DOWN". Walton et al. (2001) evaluated drivers' understanding of sequential PCMSs along work zones. They suggested maintaining a maximum of four units of information on a single PCMS, as more units resulted in lower comprehension rates among drivers.

Garber and Patel (1994) conducted field studies in Virginia to examine the effectiveness of using PCMSs with radar unit in reducing speeds compared to standard MUTCD signage. The MUTCD signage compared in this study were the standard speed limit reduction signs, R2-5a, R2-5b, and W13-1, which are advisory signs informing drivers of reduced speed conditions requiring them to slow down. The R2-5a was a warning sign informing drivers of "REDUCED SPEED AHEAD" while the R2-5b was also a warning sign specifying the reduced speed, such as "REDUCED SPEED 30." Findings indicated that PCMSs connected with radar technology were effective in reducing mean speeds by about 10 mph and increasing the proportion of compliant drivers by about 50%. The study also identified the level of effectiveness of the following messages, listed in order from the most effective: 1) YOU ARE SPEEDING SLOW DOWN, 2) HIGH SPEED SLOW DOWN, 3) REDUCE SPEED IN WORK ZONE, and 4) EXCESSIVE SPEED SLOW DOWN (Garber & Patel, 1994).

In South Carolina, field studies conducted before and after the deployment of radar-equipped PCMSs found an overall speed reduction of about 3-10 mph among vehicles in the work zones. Radar-equipped PCMSs have the ability to detect motorist's speed and inform the driver to slow down when speeding (Sorrell et al., 2007). Findings from the study further indicated that when the PCMS message portrays penalty information, such as "YOU ARE SPEEDING" followed by "MINIMUM FINE $200", more speed reductions were observed, compared to standard messages, such as "YOU ARE SPEEDING" followed by "SLOW DOWN". To reduce the risk for truck-related crashes along work zones. Bai et al. (2015) concluded that PCMSs have the most impact when placed about 575 feet away from the W20-1 sign (i.e., Road Work Ahead sign). The 575 feet distance was recommended because it resulted in smaller speed differences between trucks and passenger cars, potentially mitigating truck-related crashes due to speed differences, hence improving safety.

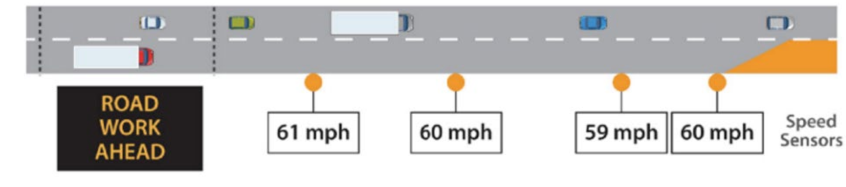
Text-based PCMSs have been identified to have limitations, especially for road users who do not speak the used language. Bai et al. (2011) conducted a study to identify the effectiveness of graphic-based PCMSs. Findings indicated that while a text-based PCMS led to a 13% mean speed reduction, a graphic-based PCMS led to a 17% mean speed reduction. Additionally, the same study's survey identified that drivers felt the graphic PCMS increased their attention compared to the text-based CMS (Bai et al., 2011). In the United Arab Emirates, PCMSs were investigated to identify their impact on reducing vehicle speeds along work zones (Ahmed et al., 2015). While survey results showed that motorists and workers perceived PCMSs as effective, field results indicated no significant differences in speeds before and after the PCMS installation.

In North Carolina, a study was conducted to understand the impact of PCMS on crash rates, by using data recorded from trailer sensors to trigger messages on the PCMS. They identified that lower number of crashes occurred when the PCMS system was used compared to when it was not (April to November 2003). Only 22 crashes occurred within that time. Due to a short study period, the study findings were not conclusive, and they recommended future studies to include longer durations, for both conditions (i.e. with and without the PCMS system) (Edara et al., 2013).

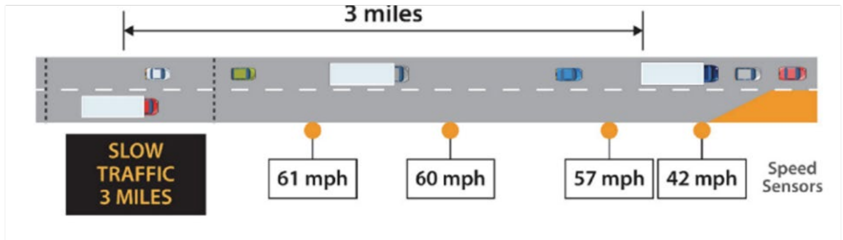
A.9.2 Queue Warning Systems (QWSs)

The Queue Warning System (QWS) involves the use of technologies that detect queues as they approach the vicinity of a work zone and inform upstream drivers through ITS equipment such as DMSs. The queue systems inform upstream drivers of the queue conditions along downstream work zones to give motorists ample time to slow or stop to prevent rear-end collisions. An End-of-Queue (EOQ) Warning System is composed of portable work zone ITS equipment constituting easily deployable radar speed sensors linked to one or more of the portable DMSs.

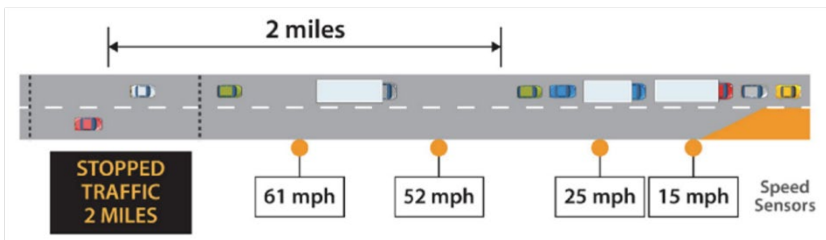
Ullman et al. (2016) studied the safety effects associated with the deployment of QWSs along Texas work zones. The EOQ system was deployed upstream of nighttime lane closures. The EOQ warning system deployed alerted drivers entering a work zone through static warning signs, law enforcement, and portable rumble strips, all positioned to get the attention of the motorists. The DMS was set to display the message “Road Work Ahead” if there were no slowed or stopped traffic downstream of the work zone. When slowed or stopped traffic was present downstream, the DMS displayed “Slow Traffic 3 Miles” or “Stopped Traffic 3 miles”, indicating the presence of slowed or stopped traffic, respectively, after 3 miles from DMS’s location, hence, alerting drivers to adjust their speeds (Ullman et al., 2016). Figure A.4 shows the EOQ system deployed in Texas. Combined with portable rumble strips, the QWS was observed to have a Crash Modification Factor of 0.559 for nighttime lane closures, equal to a 44% reduction in work zone crashes. Additionally, as a result of the QWS, less severe injuries were observed for non-speeding and non-rear-end crashes.



Without traffic detected.



With slowed traffic 3 miles downstream.



With slowed traffic 2 miles downstream.

Figure A.4 End-of-queue (EOQ) warning system in Texas
Source: (Ullman et al., 2016)

A.9.3 Speed Monitoring and Management Systems

SWZ applications falling under this category operate for the sole purpose of monitoring/ regulating speeds along work zones. Vehicles colliding at higher speeds can result in more severe injuries for both workers and motorists. Speed monitoring SWZ applications can be utilized to inform/alert drivers of their speeds (to remain at or below set speeds) and improve overall safety in work zones. Speed monitoring and management systems may include:

- Automated Speed Photo-Radar Enforcement (SPE)
- Speed Monitoring Displays
- Variable Speed Limits

A.9.3.1 Automated Speed Photo-Radar Enforcement (SPE)

The Automated Speed Photo-Radar Enforcement (SPE) includes the use of fixed or mobile cameras to capture images of speeding vehicles. Multiple studies have been conducted to analyze the impacts of Speed Photo Enforcement (SPE) in both highway safety and mobility. A study was conducted at Illinois work zones, where two SPE vans were placed along the road (Benekohal et al., 2008). One radar SPE was placed upstream at a particular location while the other was placed 1.5 miles downstream of the work zone. Speeds were measured at both locations with the SPE. Results indicated that the use of SPE led to a speed reduction of 3.2 to 7.3 mph while the percentage of vehicles exceeding the speed limit reduced from 40% to 8%. Speeds were observed to decrease from 17% to 4%. Moreover, it was observed that the speed reduction was more significant in the upstream location compared to the downstream location. The conclusion of the study was on the ability of SPE to reduce speeds and increase speed limit compliance at work zones. Benekohal et al. (2009) and Medina et al. (2009) also identified reduced speeds along work zones due to the deployment of automated SPE.

A.9.3.2 Speed Monitoring Displays (SMDs)

Speed Monitoring Displays (SMDs) are a technology deployed along roadways or work zones to inform drivers of their running speed, in conjunction with the set speed limit, to encourage drivers to slow down if they are speeding (Pesti & McCoy, 2001). Several studies have identified that most vehicle speeds are reduced with the use of SMDs, at both work zone and non-work zone conditions (Bloch, 1998). In Nebraska, SMDs were deployed along a 2.7-mile segment for a 5-week duration along a freeway work zone on I-80 (Pesti & McCoy, 2001). An 85th percentile speed reduction of about 2-7 mph was observed, indicating a 20% - 40% increase in compliance among motorists. In the same study, the long-term effectiveness of SMDs was identified, as speed reductions were observed even a week after the SMDs were removed (Pesti & McCoy, 2001). Moreover, SMDs have been deployed and analyzed in several other states, including Nevada, Utah, and Texas (see Table A.6). In most of these studies, SMDs have been found to increase driver compliance along the work zones.

A.9.3.3 Variable Speed Limits (VSLs)

Variable speed limits use detectors to collect data on the current traffic flow or weather conditions and then dynamically update the speed limits to reflect the conditions (Fudala & Fontaine, 2010). VSLs used along work zones have a major aim of improving speed harmonization (reducing speed variance) among vehicles, which has the potential to reduce crashes and improve work zone safety (Lyu et al., 2017). VSLs have been identified to reduce system travel time through increased uniformity in traffic speeds. Apart from their mobility impacts, VSLs have also been reported to have significant impact in crash reduction along freeways, reducing about 10% to 30% of crashes (Fudala & Fontaine, 2010). Fudala and Fontaine (2010) by using microsimulation were able to identify VSL impacts on safety surrogate measures, as they observed reduction in lane changes and number of stops, which could potentially reduce work zone crashes.

A.9.4 Other SWZ/ITS Applications

The National Work Zone Safety Information Clearinghouse has a collection of more material related to the use, impact, and effectiveness of smart work zone devices (American Road & Transportation Builders Association [ARTBA], n.d.). These devices include:

- Real time traveler information systems
- Dynamic lane merge
- Incident management
- Speed safety cameras
- Entering/exiting vehicle notifications
- Lane Closure Notification Systems
- Traveler Information Systems
- Connected Vehicles (CV) and Automated Vehicles (AV) operations in work zones

While most studies have identified the mobility impact of these devices, few studies have evaluated their safety impacts, specifically on crash reduction.

A.10 Other Devices

Other devices, tools, and strategies have also been deployed to control traffic and speed along work zones. These strategies or tools are mostly used to enhance the visibility of already existing deployments, aiming to improve effectiveness or alert drivers of work zone conditions. Such devices and tools include:

- Intrusion alarm systems
- Lane merge system
- Fluorescent/bright signs
- Reflectorized/bright suits and vests

In 1999, Iowa, Kansas, Missouri, and Nebraska created what is called the Midwest States Smart Work Zone Deployment Initiative (SWZDI), with Wisconsin joining in 2001 (Edara et al., 2013). Through this initiative, multiple research studies have been conducted to identify ways of improving both safety and mobility along work zones (Edara et al., 2013; Liu et al., 2021; Sun et al., 2014). In 2013, the SWZDI studied the perception of effectiveness and the usage of the work zone intelligent transportation systems (Wang et al., 2011). Findings from a nationwide survey in the U.S., conducted by Wang et al. (2011), showed that PCMSs, TMAs, and SMDs are the most frequently used traffic safety devices in short-term work zones, with PCMSs and TMAs rated with 100% effectiveness among the interviewed states (26 and 23 states, respectively). Other devices used by several states included portable rumble strips, CB Wizard alert system, Highway Advisory Radio (HAR), radar drones, and intrusion alarms.

A.11 Summary

The review of existing literature indicates that factors associated with work zone crash frequency vary across locations. However, work zone length, duration, and daily traffic volume have been identified as common factors associated with the occurrence of work zone crashes. Different factors were also observed to associated with work zone crash severity, including roadway, environment, driver, and vehicle characteristics. Previous studies have also found that a number of temporary traffic control devices did not significantly impact work zone safety. However, SMDs and PCMSs showed speed reductions of up to seven mph, potentially improving safety at work zones.

Previous studies on work zone safety in South Dakota are limited, highlighting a research gap in understanding South Dakota's work zone safety challenges. This project addresses this gap by analyzing crash data and evaluating the effectiveness of traffic control measures used in work zones on South Dakota highways.

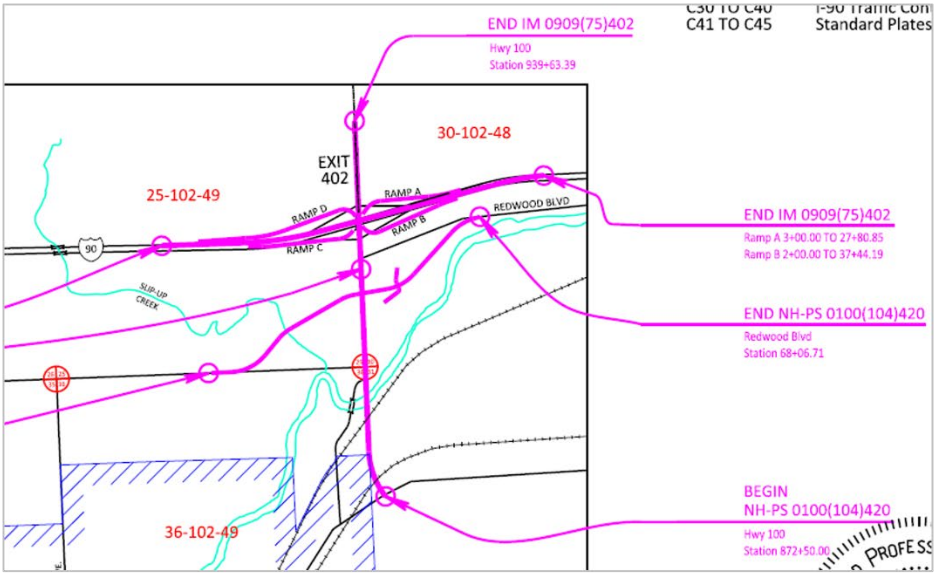
Appendix B: Data Collection and Processing

Several datasets were required to identify factors influencing the occurrence (i.e., frequency) and severity of work zone crashes. Work zone data, crash data, and roadway characteristics data were collected from SDDOT for a 5-year analysis period from 2018 to 2022. This appendix discusses the data collection and processing required to perform the analyses.

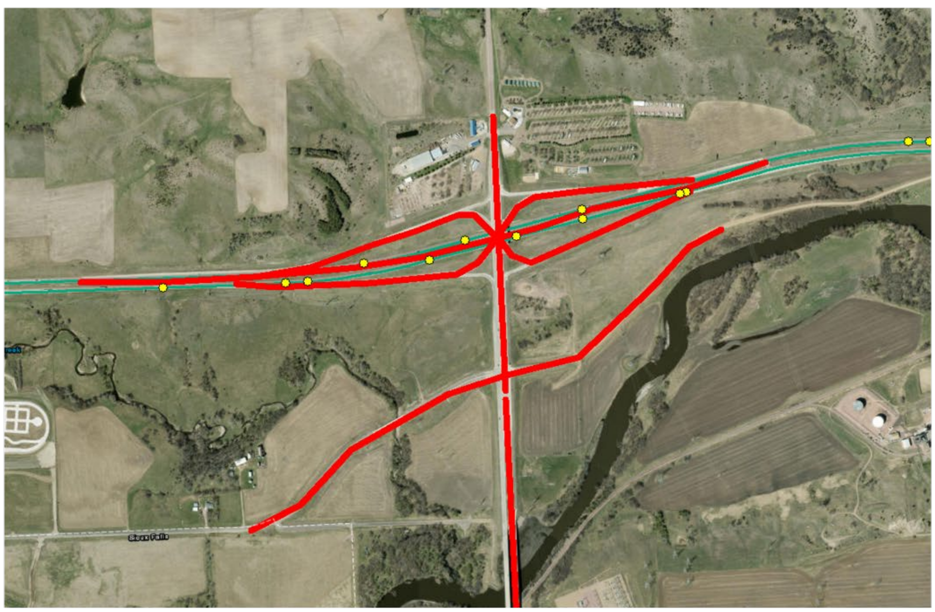
B.1 Work Zone Data

Work zone data were provided by SDDOT in the form of PDF files. A total of 1,335 PDF files were obtained, each containing between four and 50 pages of project-related information. These files were organized into five folders based on the office that announced the project: the central office and the four regional offices: Rapid City, Pierre, Mitchell, and Aberdeen. Although South Dakota is officially divided into four regions, the central office files include projects that span across all regions. Of the total files, 858 were from the central office, 157 from Rapid City, 84 from Pierre, 94 from Mitchell, and 142 from the Aberdeen region.

Each PDF file represented a particular work zone and included information such as the location of the work zone (specific roadway(s)) and the begin and end mileposts. From each PDF file, the locations of the work zones were identified manually using the roadway locations and then transferred to Google Earth to create Keyhole Markup Language (KML) files. The KML files were then transferred to ArcGIS and converted into shapefiles. Figure A.5(a) shows a sample of the PDF version of a work zone data obtained from SDDOT. Figure A.5(b) shows the extracted PDF data inserted in Google Earth. The Google Earth file was then imported into ArcGIS as a KML file, and then converted into a Geographic Information System (GIS) shapefile.



(a) Work zone data in PDF format



(b) Work zone data in Google Earth extracted from the PDF document

Figure A.5 Extraction of work zone data

This process was repeated for all 1,335 work zone plans obtained until each plan was plotted in ArcGIS as a shapefile. Figure A.6 presents a map showing the distribution of all work zone plans along the South Dakota state highway network (2018 – 2022). After the work zones were plotted as shapefiles, the roadway system shapefile was converted into a route. This means that all roadway segments with the same roadway ID name were combined to form a single long route by using the common roadway ID name and their begin and end mileposts (beg_mileage and end_mileage) columns in the dataset. This created continuous routes for all state highway system roadways.

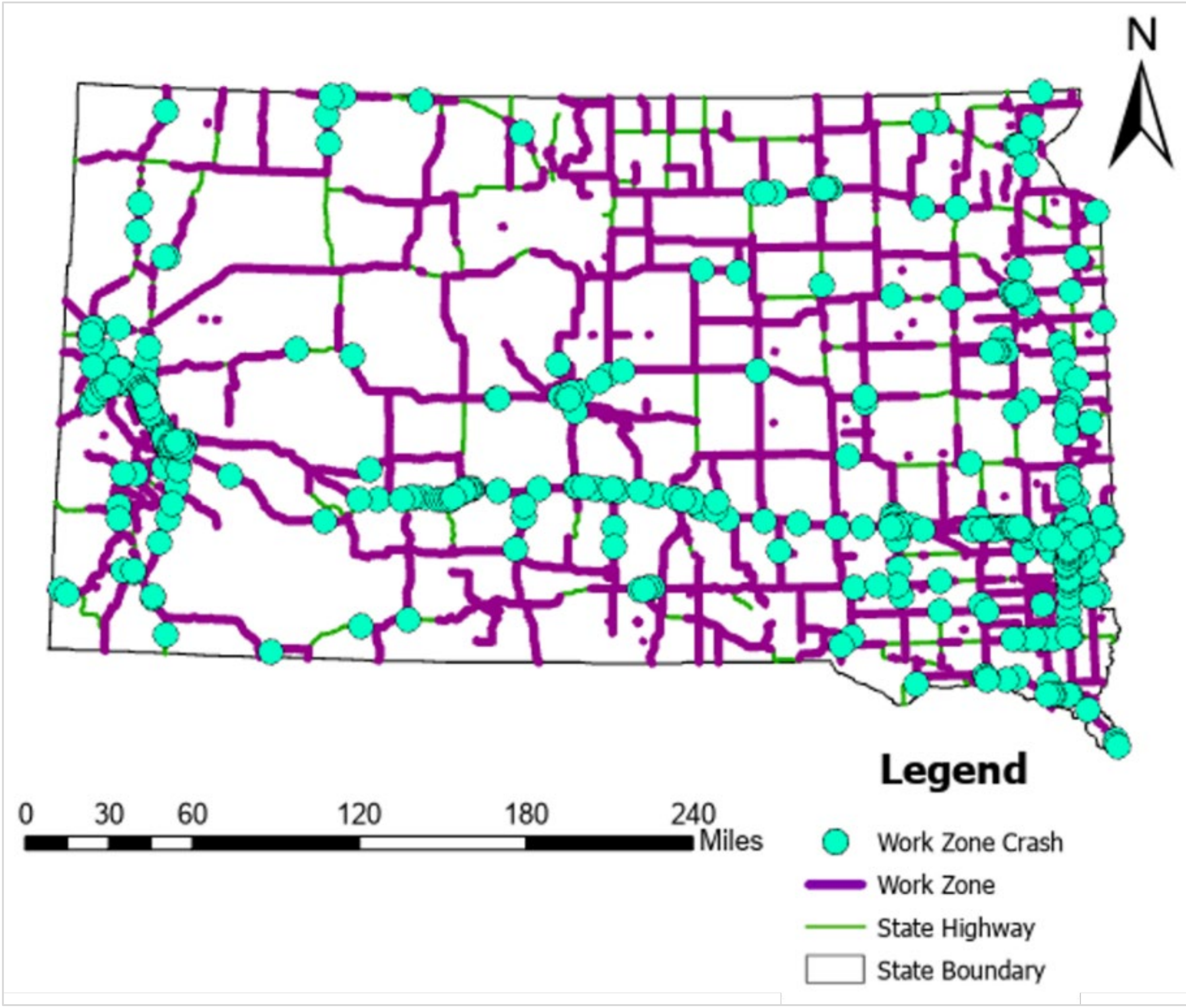


Figure A.6 Distribution of state highway work zones and crashes (2018 – 2022)

Each work zone segment has a unique identifier, while segments from the same work zone plan share a common base name derived from the PDF, as shown in Figure A.7. To accurately represent different directions of travel, separate segments were created for each direction.

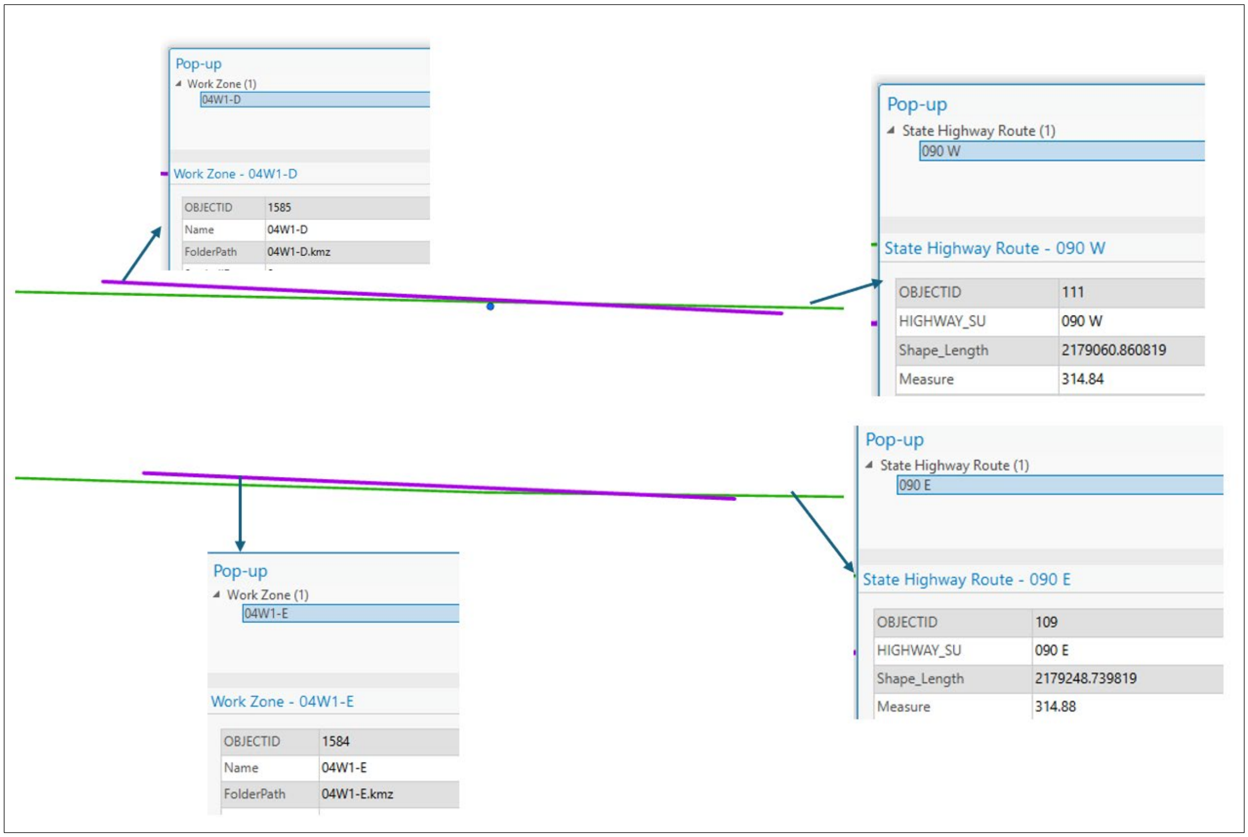
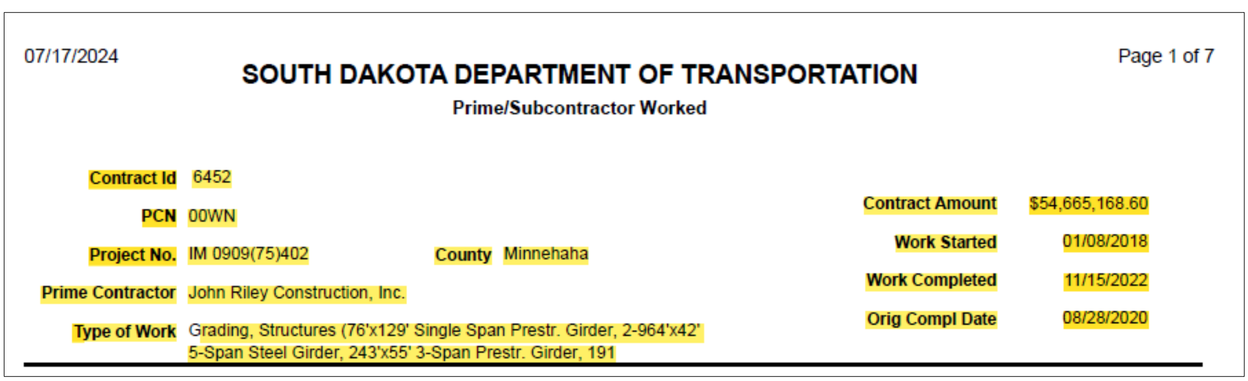


Figure A.7 Unique identifiers for each work zone segment

Similar to the work zone plans, the PDF files of contractor work dates were also obtained from SDDOT. These files contained the begin and end dates for the work zones, as well as information related to the work zone plans, sharing the Project Control Number (PCN) numbers as unique identifiers. The files were also obtained in five main folders, one for the central office plans and one folder from each of the four regional offices (Rapid City, Aberdeen, Mitchell, and Pierre). Figure A.8 shows a sample of a contractor's work dates file (corresponding with Figure A.5), indicating the work zone ID and contract number, project number, the contractors, type of work zone activity, the contract amount, and work zone start and end dates corresponding to the sample work zone plan.


07/17/2024

SOUTH DAKOTA DEPARTMENT OF TRANSPORTATION

Prime/Subcontractor Worked

Page 1 of 7

Contract Id 6452

PCN 00WN

Project No. IM 0909(75)402 **County** Minnehaha

Prime Contractor John Riley Construction, Inc.

Type of Work Grading, Structures (76'x129' Single Span Prestr. Girder, 2-964'x42' 5-Span Steel Girder, 243'x55' 3-Span Prestr. Girder, 191

Contract Amount $54,665,168.60

Work Started 01/08/2018

Work Completed 11/15/2022

Orig Compl Date 08/28/2020

Figure A.8 Contractor work zone data sample

Using R, the information in the contractor work dates files was extracted and compiled into a single Excel file containing all relevant variables. The variables included:

- Contract ID
- Project Number
- Prime Contractor
- Type of Work Performed
- County
- Contract Amount
- Work Start Date
- Work Completion Date
- Original Completion Date

Two primary Excel files were created. The first file, the *Work Zone File*, contained the unique identifier, roadway ID, beginning milepost, and ending milepost. The second file, the *Work Zone Information File*, contained details such as the project's PCN, contractor information, type of work zone activity, county, project cost, and start and end dates. Using R programming, these two files were merged based on their shared unique identifiers linked to each project's PCN number. The result was a comprehensive dataset containing all relevant work zone information. When the files were merged, a total of 1,730 work zone segments were identified.

B.2 Crash Data

South Dakota crash data for the years 2018 to 2022 were obtained from SDDOT in Excel and shapefile formats. Only crashes that occurred along the South Dakota state highway system were provided. A total of 1,060 work zone crashes that occurred from 2018 to 2022 were extracted and reviewed. However, one crash had a missing category under the injury severity variable and was removed, resulting in a final dataset of 1,059 crashes. Figure A.9 shows the distribution of work zone crashes used in the analysis.

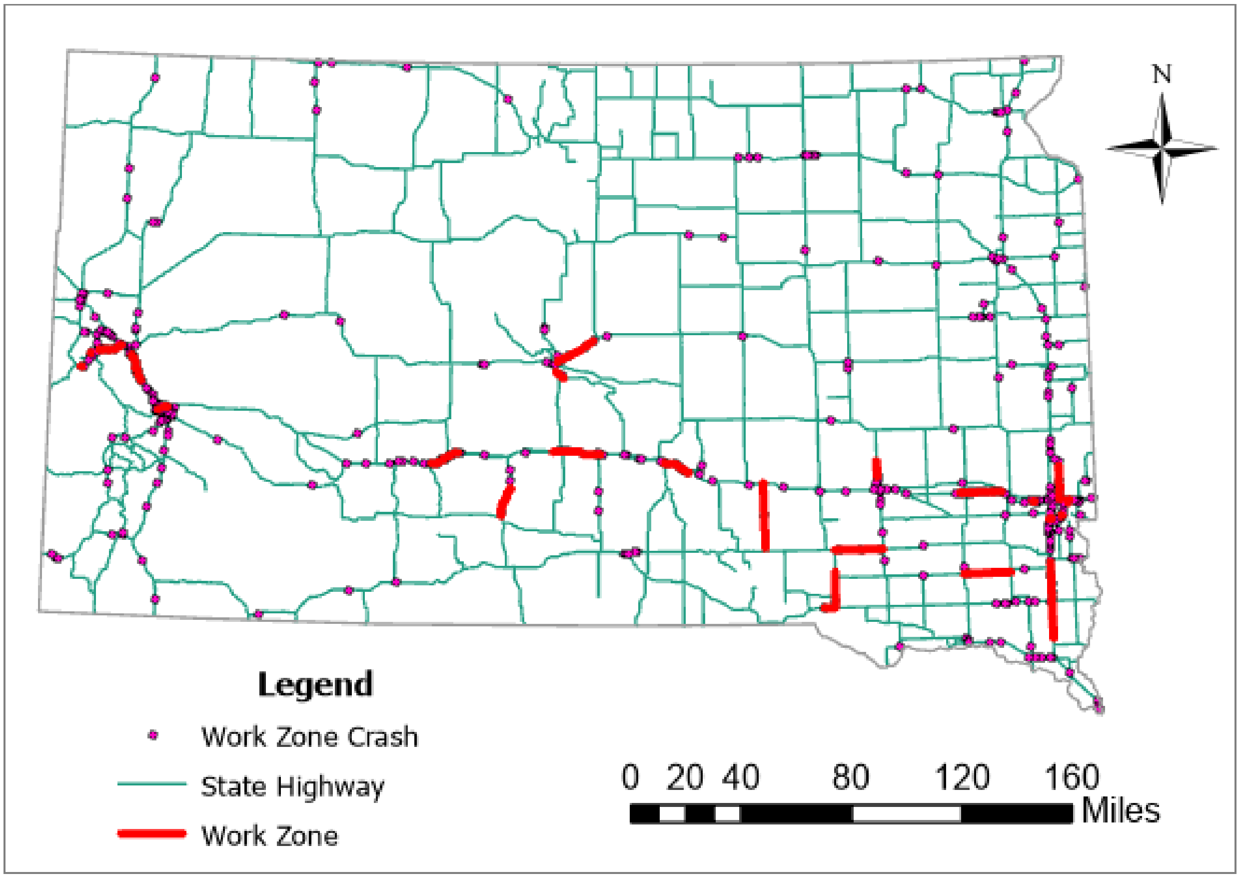


Figure A.9 Distribution of work zones and work zone crashes in South Dakota

Variables describing crash data can be categorized into two main groups: categorical variables and continuous variables. Categorical variables represent data in distinct categories. In other words, these variables have a limited number of possible values. For instance, *weather* can only be identified in its distinct categories, such as clear, cloudy, rainy, or snow. Similarly, *lighting conditions* can only be identified in limited forms, including daylight, dark and lighted, dark and not lighted, etc. On the other hand, continuous variables can take an infinite range of values within a particular range. For instance, the Average Daily Traffic (ADT) value, the peak hour percentage, truck ADT, shoulder and median widths, right-of-way widths, driver age, posted speed limit, and others. For this study, age and speed limit variables were converted into categorical values by creating reasonable range values for easy interpretation. The following subsections discuss the categorical and continuous variables used in the analysis.

B.2.1 Categorical Variables

The categorical variables used in the analysis were obtained from the crash data Excel file provided by SDDOT for the 1,059 crash records included in the final dataset. The variables were categorized into the following groups: temporal factors, crash characteristics, roadway characteristics, driver characteristics, environmental factors, and vehicle characteristics.

B.2.1.1 Temporal Factors

Temporal factors describe the relationship between the work zone crashes and the time of crash occurrence. Crash year (2018 – 2022), day of the week (weekday or weekend), and season were the temporal factors identified in the dataset. The seasons were defined as Fall (September – November), Spring (April – May), Summer (June – August), and Winter (December – March).

B.2.1.2 Crash Characteristics

Crash characteristics describe the event, including actions leading up to the crash, during the crash, or after the crash. These typically include variables that capture the vehicle's maneuver before the crash, whether the crash involved a pedestrian or bicycle, the most harmful event identified, and the type of collision. Crash data for each categorical variable were analyzed using the following sub-categories:

- Pedestrian/Bicycle involvement (Yes or No)
- Vehicle Maneuver (Maneuvering, Slowing/Stopping, Straight ahead, or Unknown)
- Most Harmful Event (Fixed Object, Vehicle in transport, or Other)
- Type of Collision (Angle, Head-on, Front to rear, Rear to rear, Sideswipe (opposite side), Sideswipe (same side), or Single vehicle)

B.2.1.3 Roadway Characteristics

Roadway characteristics involve all features that describe the roadway segment where the crash occurred. Such variables include the posted speed limit, nature of the roadway surface, type of junction, highway type, roadway alignment, travel direction, and the roadway functional classification. Crash data for each categorical variable were analyzed using the following sub-categories:

- Speed Limit (≤ 35 mph, 40-55 mph, 60-70 mph, 75-80 mph, or Unknown)
- Road Surface (Asphalt, Concrete, Dirt, Gravel, or Other)
- Type of Junction (Crossover, Four-way intersection, Driveway, Interchange, Intersection, Non-junction, Railway crossing, or Unknown)
- Highway Type (Ramp, State Road)
- Divided/ Undivided Roadway (Divided, Undivided, or Unknown)
- Alignment (Curve at hill crest, Curve and level, Curve on grade, Straight and hill crest, Straight and level, or Straight on grade)
- Travel Direction (Eastbound, Westbound, Northbound, or Southbound)
- Functional Classification (Rual (Freeway, Expressway, Interstate), Rural (Major Collector, Major Arterial), Rural Principal Arterial, Urban (Freeway, Expressway, Interstate), Urban (Collector, Major Arterial), or Urban Principal Arterial)
- Roughness (Good or Fair/poor)

B.2.1.4 Driver Characteristics

Driver Characteristics refer to human-related factors observed at the time of the crash. These include the use of safety equipment, speeding behavior, driving under the influence (DUI), overcorrection, fatigue, distraction, illness, driver age, and the driver's actions contributing to the crash. Crash data for each categorical variable were analyzed using the following sub-categories:

- Safety Equipment Used (Used, None used, or Unknown)
- Speeding (Yes or No)
- Driving Under the Influence (Yes or No)
- Overcorrection (Yes or No)
- Fatigue (Yes or No)
- Distraction (Yes or No)
- Illness (Yes or No)
- Driver's Age (12-19 years, 20-34 years, 35-64 years, or ≥ 65 years of age)
- Driver Contribution (Disregarded traffic signs, Distraction/DUI/Illness, Driving Too fast/ Exceeding speed limit, Failure to yield/ keep proper lane, Followed too closely, Improper maneuver, None, Other, or Unknown)

B.2.1.5 Environmental Factors

Environmental factors related to the work zone crashes included weather and lighting conditions. Crash data for each categorical variable were analyzed using the following sub-categories:

- Lighting Conditions (Dark – lighted, Dark – unlighted, Dark – unknown, Dawn, Daylight, or Dusk)
- Weather Conditions (Clear, Cloudy, Severe weather, or Unknown)

B.2.1.6 Vehicle Characteristics

Vehicle characteristics identified in the crash data only included the type of the vehicle. The sub-categories analyzed for this variable included:

- Vehicle type (Light truck, motorcycle, Passenger car, Semi-trailer, Other, or Unknown)

B.2.2 Continuous Variables

Continuous variables include features related to the crash that can have an infinite number of values within a particular range. These include variables such as the ADT, truck ADT, peak-hour percentage, bus and motorcycle percentages, and shoulder, median, and right-of-way widths. In this research, the variables were obtained from the roadway GIS shapefile and merged with the crash data using the Spatial Join tool in ArcGIS.

The Spatial Join tool in ArcGIS functions by associating data from two different layers based on their spatial relationship. In this case, the crash data layer (2018 – 2022) was the target layer/feature to be joined with the roadway data layer. For every crash point, the tool identified the corresponding/nearest segment and transferred the segment data attributes to that particular crash point. Layers available for the roadway data included:

- State highway system layer (contains roadway ID and begin and end mileposts)
- Speed limit layer
- Average Daily Traffic (ADT) layer
- Roadway system layer (contains all other roadway information, such as direction, functional classification, year built, shoulder and right-of-way widths, etc.)

The Spatial Join process was repeated for each of these layer features (i.e., speed limit, ADT, and roadway system). A buffer distance of 40 feet was used for all spatial join processes. This means that every crash was joined with roadway data from intersected segments or segments within 40 feet. The result of the spatial join process is a combined dataset, containing all values originally in the crash data file and the joined roadway data. Using the "VLOOKUP" tool in Excel and the unique crash identifier, all of the data were merged into one file, with crashes as rows, and all obtained variables as columns.

B.3 Roadway Characteristics Data

South Dakota roadway data were obtained in a shapefile format, with the state highway shapefile containing multiple layers of information related to the highway system. These layers included details such as speed limits, functional classification, ADT, truck ADT, roadway width, and right-of-way width. Each of these variables was recorded along with its corresponding beginning and ending mileposts, reflecting the variation in roadway characteristics along different segments of the highway network. The data were extracted from GIS and exported as separate Excel files for each variable. For each dataset, the file contained the roadway ID, begin post, end post, and corresponding value of the variable. For instance, in the speed limit file, the data contained four columns: the roadway ID, the beginning post, the ending post, and the speed limit. These different files, each with corresponding values, were then used for segmentation purposes, where work zone segments were created whenever any of the roadway variables changed. Table B.1 lists the six roadway functional classifications analyzed in this study.

Table B.1 Roadway functional classification

Area Type	Functional Classification
Rural	Freeway, Expressway, and Interstate
	Principal Arterial
	Major Collector and Minor Arterial
Urban	Freeway, Expressway, and Interstate
	Principal Arterial
	Major Collector and Minor Arterial

B.4 Summary

Work zone data, crash data, and roadway characteristics data were obtained from SDDOT. The work zone data was manually extracted from the PDF files, and the information was imported into Google Earth to create KML files. The KML files were then imported into ArcGIS to create shapefiles. The shapefiles were joined with the work zone information obtained from the contractors' work data files, which contained the duration and type of work zone activities. Crash data for the years 2018 through 2022 were obtained in both Excel and GIS shapefiles. Roadway characteristics data were obtained from the GIS shapefiles, and the roadway attributes were merged with the crash data using the Spatial Join tool in ArcGIS.

Appendix C: Analysis Methodology and Discussion

C.1 Descriptive Statistics

Work zone crash data were obtained from SDDOT in both Excel and shapefile formats for the study period (2018 – 2022). The final dataset included 1,059 work zone crashes that occurred along the South Dakota state highway system. Figure C.1 illustrates the spatial distribution of the work zone crashes used in the analysis.

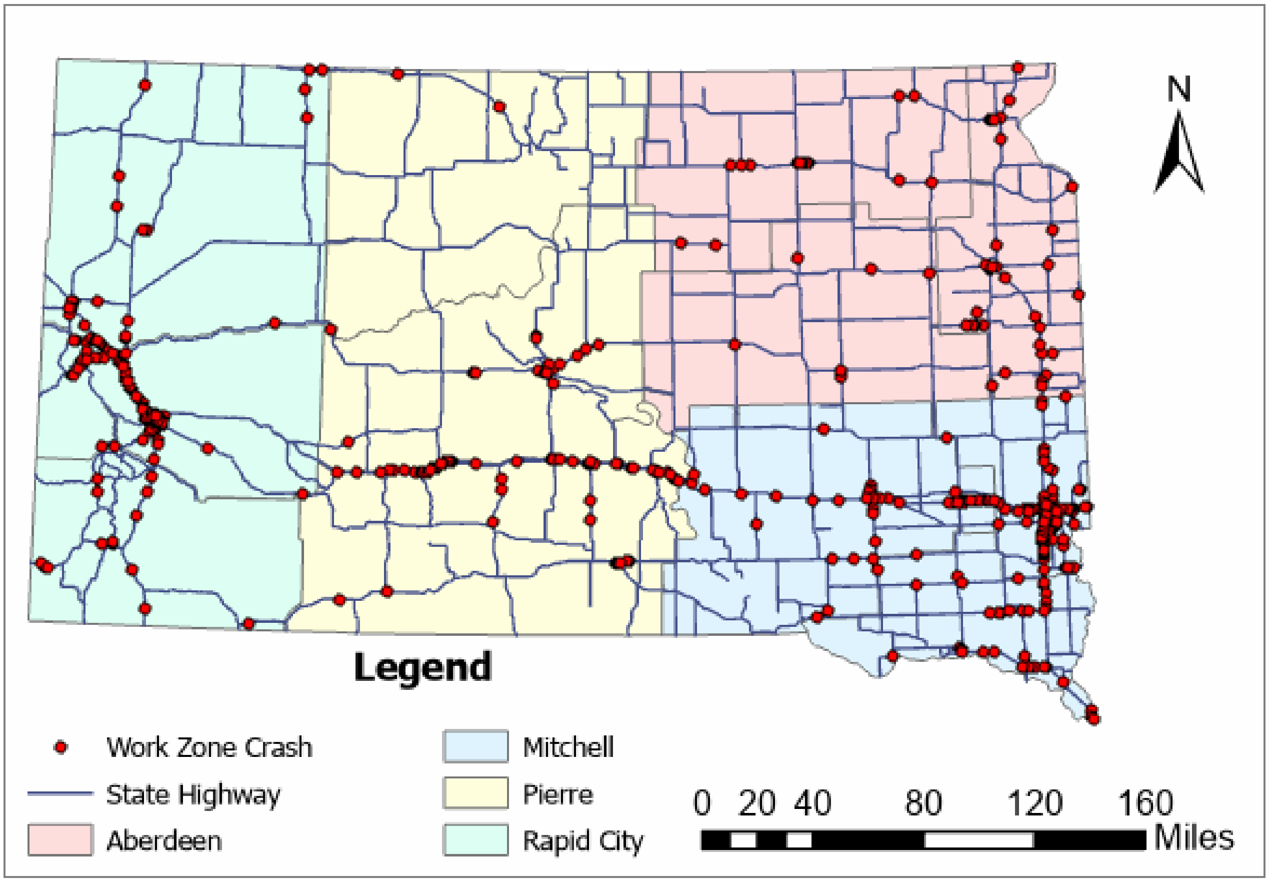
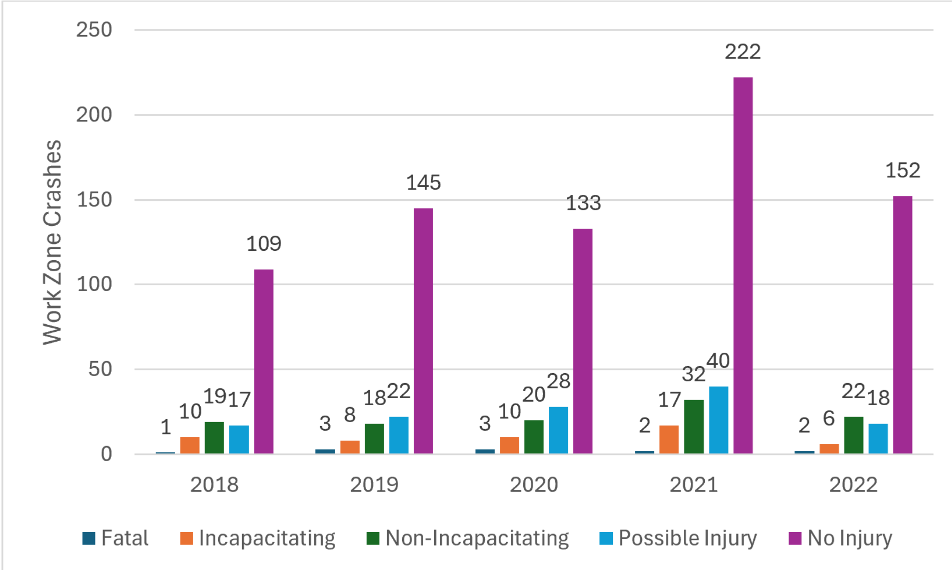


Figure C.1 Work zone crashes along South Dakota state highway network

Figure C.2 shows the distribution of the 1,059 work zone crashes in relation to the crash year and injury severity. The highest number of work zone crashes occurred in 2021, with 222 PDO crashes, 89 injury crashes, and two fatal crashes. As expected, PDO crashes were the most predominant crash type in each year of the study period.



Crash Severity Year	2018	2019	2020	2021	2022	Total
Fatal	1	3	3	2	2	11
Incapacitating	10	8	10	17	6	51
Non-Incapacitating	19	18	20	32	22	111
Possible Injury	17	22	28	40	18	125
No Injury	109	145	133	222	152	761
Total	156	196	194	313	200	1059

Figure C.2 Work zone crashes by year and crash severity

C.1.1 Categorical Variables

The categorical variables used in the analysis were obtained from the crash data Excel file provided by SDDOT for the 1,059 crash records included in the final dataset. The variables were categorized into the following groups: temporal factors, crash characteristics, roadway, driver, environmental, and vehicle factors.

C.1.1.1 Temporal Factors

Temporal factors included the crash year, season, and day of the week the crash occurred. The seasons were defined as follows: Fall (September–November), Spring (March–May), Summer (June–August), and Winter (December–February). As indicated in Table C.1, the majority of work zone crashes occurred in 2021, with a total of 313 crashes, followed by 200 crashes in 2022. The largest proportion of severe injuries was observed in 2018, where about 7% of the 156 crashes resulted in fatalities and severe injuries. Additionally, most of the work zone crashes occurred in the summer (462 crashes), with 8% resulting in severe injuries and fatalities. While most of the crashes (886) occurred on weekdays, a larger proportion of those that occurred on the weekend resulted in severe injuries and fatalities (9.9%).

Table C.1 Distribution of work zone crashes by temporal factors

Variable	Category	K	%	A	%	B	%	C	%	O	%	Total	%
Crash Year	2018	1	0.6%	10	6.4%	19	12.2%	17	10.9%	109	69.9%	156	14.7%
	2019	3	1.5%	8	4.1%	18	9.2%	22	11.2%	145	74.0%	196	18.5%
	2020	3	1.5%	10	5.2%	20	10.3%	28	14.4%	133	68.6%	194	18.3%
	2021	2	0.6%	17	5.4%	32	10.2%	40	12.8%	222	70.9%	313	29.6%
	2022	2	1.0%	6	3.0%	22	11.0%	18	9.0%	152	76.0%	200	18.9%
Season	Fall	2	0.6%	10	2.8%	32	9.1%	41	11.7%	266	75.8%	351	33.1%
	Spring	1	0.6%	10	5.8%	15	8.8%	21	12.3%	124	72.5%	171	16.1%
	Summer	7	1.5%	30	6.5%	57	12.3%	51	11.0%	317	68.6%	462	43.6%
	Winter	1	1.3%	1	1.3%	7	9.3%	12	16.0%	54	72.0%	75	7.1%
Weekday	Weekday	9	1.0%	36	4.1%	88	9.9%	107	12.1%	646	72.9%	886	83.7%
	Weekend	2	1.2%	15	8.7%	23	13.3%	18	10.4%	115	66.5%	173	16.3%

Note: K = Fatal; A = Incapacitating injury; B = Non-incapacitating injury; C = Possible injury; O = No injury/PDO.

C.1.1.2 Crash Characteristics

Crash characteristics describe the event, including actions leading up to the crash, during the crash, or after the crash. These typically include variables that capture the vehicle's maneuver before the crash, whether the crash involved a pedestrian or bicycle, the most harmful event identified, and the type of collision. Table C.2 summarizes the descriptive statistics for the crash characteristics obtained from the work zone crash data.

Table C.2 Distribution of work zone crashes by crash characteristics

Variable	Category	K	%	A	%	B	%	C	%	O	%	Total	%
Ped/ Bike	No	10	0.9	48	4.6	109	10.4	125	11.9	761	72.3	1053	99.4
	Yes	1	16.7	3	50.0	2	33.3	0	0.0	0	0.0	6	0.6
Vehicle Maneuver	Maneuvering	0	0.0	7	4.1	11	6.4	7	4.1	146	85.4	171	16.1
	Slow/Stopping	1	0.3	12	3.1	39	9.9	69	17.6	272	69.2	393	37.1
	Straight ahead	10	2.0	32	6.5	61	12.4	49	9.9	341	69.2	493	46.6
	Unknown	0	0.0	0	0.0	0	0.0	0	0.0	2	100	2	0.2
Most Harmful Event	Fixed Object	3	2.2	7	5.1	10	7.2	8	5.8	110	79.7	138	13.0
	Vehicle in transport	4	0.5	23	3.0	75	9.7	106	13.7	567	73.2	775	73.2
	Other	4	2.7	21	14.4	26	17.8	11	7.5	84	57.5	146	13.8
Type of Collision	Angle	1	0.7	4	2.6	20	13.1	23	15.0	105	68.6	153	14.4
	Head-on	0	0.0	0	0.0	1	33.3	0	0.0	2	66.7	3	0.3
	Single vehicle	6	2.1	28	9.9	38	13.4	18	6.3	194	68.3	284	26.8
	Front to rear	2	0.4	17	3.4	48	9.5	81	16.0	357	70.7	505	47.7
	Rear-to-rear	0	0.0	0	0.0	0	0.0	0	0.0	1	100	1	0.1
	Sideswipe (Opposite)	2	18.2	1	9.1	1	9.1	0	0.0	7	63.6	11	1.0
	Sideswipe (Same)	0	0.0	1	1.0	3	2.9	3	2.9	95	93.1	102	9.6

Note: K = Fatal; A = Incapacitating injury; B = Non-incapacitating injury; C = Possible injury; O = No injury/PDO.

Only six (6) work zone crashes involved pedestrians/bicyclists, of which one (16.7%) resulted in a fatality, and three (50%) crashes resulted in incapacitating injuries. Regarding the vehicle maneuver, out of the

1,059 crashes, about 16% occurred while the driver was maneuvering, 37.1% occurred while the driver was slowing or stopping in a work zone, and 46.6% occurred when the driver was driving straight ahead. Of those that occurred while the driver was driving straight, about 2% resulted in fatalities, while 6.5% resulted in incapacitating injuries. Of the total crashes, 13% involved motorists hitting fixed objects, 73.2% involved motor vehicles in transport, and 13.8% involved other harmful events, such as encountering animals and other equipment.

In relation to the type of collision, the majority of the crashes were rear-end crashes (47.7%) followed by single-vehicle crashes, which had the largest proportion of incapacitating injuries compared to other types of collision.

B.1.1.3 Roadway Characteristics

Roadway characteristics involve all features that describe the roadway segment where the crash occurred. Variables analyzed included: the posted speed limit, nature of the roadway surface, type of junction, highway type, roadway alignment, travel direction, and the roadway functional classification. Table C.3 summarizes the statistics of the roadway characteristics analyzed.

The statistics indicate that most crashes occurred on roadways with higher speed limits, above 60 mph, and included more crashes that resulted in fatalities and severe injuries. Additionally, most work zone crashes occurred on concrete surfaces (73.5%), at non-junction locations (71.9%), on divided highways (55.1%), and on straight and level roadway segments. About 14.3% of crashes that occurred on combined curve and grade segments resulted in fatalities. Most crashes occurred on rural highways (29%) and urban principal arterials (22.8%), followed by urban limited access facilities (19.5%). Of the 91 crashes that occurred on rural principal arterials, 13.2% resulted in incapacitating injuries, the highest proportion among all functional classes.

B.1.1.4 Driver Characteristics

Driver characteristics refer to human-related factors observed at the time of the crash. These include the use of safety equipment, speeding behavior, DUI, overcorrection, fatigue, distraction, illness, driver age, and the driver’s actions contributing to the crash. Table C.4 presents the distribution of South Dakota work zone crashes for the driver-related variables analyzed.

Statistics indicate that of the 1,059 crashes, the majority involved drivers who were using a safety restraint system, with 977 crashes (92.3%) recorded under this condition. Of the 56 crashes that involved no use of restraint system, 37.5% resulted in incapacitating injuries and 10.7% resulted in fatalities, compared to 3% and 0.5% of those that used restraint system respectively. Crashes involving risky driving behaviors, such as speeding, DUI, driver overcorrection, and fatigue were associated with a higher proportion of fatalities and severe injuries compared to crashes that did not involve these behaviors.

Table C.3 Distribution of work zone crashes by roadway characteristics

Variable	Category	K		A		B		C		O		Total	
		Count	%	Count	%	Count	%	Count	%	Count	%	Count	%
Speed Limit (mph)	≤ 35	1	0.5%	2	1.0%	23	11.0%	29	13.8%	155	73.8%	210	19.8%
	40-55	3	1.7%	8	4.5%	26	14.7%	37	20.9%	103	58.2%	177	16.7%
	60-70	1	0.3%	25	8.0%	28	9.0%	33	10.6%	224	72.0%	311	29.4%
	75-80	5	1.6%	13	4.3%	32	10.5%	22	7.2%	232	76.3%	304	28.7%
	Unknown	1	1.8%	3	5.3%	2	3.5%	4	7.0%	47	82.5%	57	5.4%
Road Surface	Asphalt (blacktop)	4	1.5%	22	8.3%	25	9.4%	30	11.3%	184	69.4%	265	25.0%
	Concrete	7	0.9%	27	3.5%	83	10.7%	93	12.0%	568	73.0%	778	73.5%
	Dirt	-	-	-	0.0%	-	-	-	-	4	100.0%	4	0.4%
	Gravel	-	-	2	18.2%	2	18.2%	2	18.2%	5	45.5%	11	1.0%
	Other	-	-	-	-	1	100.0%	-	-	-	-	1	0.1%
Type of Junction	Crossover related	-	-	-	-	-	-	-	-	1	100.0%	1	0.1%
	Four-way intersection	-	-	2	2.2%	14	15.6%	13	14.4%	61	67.8%	90	8.5%
	Driveway related	-	-	-	-	-	-	-	-	-	-	-	-
	Interchange area	-	-	3	2.8%	5	4.6%	11	10.1%	90	82.6%	109	10.3%
	Intersection related	-	-	-	-	4	10.5%	5	13.2%	29	76.3%	38	3.6%
	Non-junction	10	1.3%	43	5.7%	79	10.4%	87	11.4%	542	71.2%	761	71.9%
	Railway crossing	-	0.0%	-	-	-	-	1	100.0%	-	-	1	0.1%
	Unknown	1	3.0%	1	3.0%	6	18.2%	5	15.2%	20	60.6%	33	3.1%
Highway Class	Ramp	-	0.0%	-	-	2	13.3%	2	13.3%	11	73.3%	15	1.4%
	State Road	11	1.1%	51	4.9%	109	10.4%	123	11.8%	750	71.8%	1044	98.6%
Divided/Undivided	Divided roadway	7	1.2%	25	4.3%	46	7.9%	59	10.1%	447	76.5%	584	55.1%
	Undivided roadway	4	1.0%	23	5.6%	60	14.6%	61	14.8%	263	64.0%	411	38.8%
	Unknown	-	0.0%	3	4.7%	5	7.8%	5	7.8%	51	79.7%	64	6.0%
Alignment	Curve and hill crest	-	0.0%	1	20.0%	1	20.0%	-	-	3	60.0%	5	0.5%
	Curve and level	1	2.2%	4	8.9%	7	15.6%	1	2.2%	32	71.1%	45	4.2%
	Curve on grade	3	14.3%	1	4.8%	2	9.5%	2	9.5%	13	61.9%	21	2.0%
	Straight and hill crest	-	0.0%	5	15.6%	1	3.1%	2	6.3%	24	75.0%	32	3.0%
	Straight and level	6	0.7%	36	4.3%	88	10.5%	101	12.0%	608	72.5%	839	79.2%
	Straight on grade	1	0.9%	4	3.4%	12	10.3%	19	16.2%	81	69.2%	117	11.0%

Table C.3 Distribution of work zone crashes by roadway characteristics (continued)

Variable	Category	K		A		B		C		O		Total	
		Count	%	Count	%	Count	%	Count	%	Count	%	Count	%
Travel Direction	Eastbound	8	2.0%	17	4.2%	44	10.9%	47	11.7%	287	71.2%	403	38.1%
	Northbound	1	0.5%	7	3.6%	19	9.8%	21	10.9%	145	75.1%	193	18.2%
	Other	-	-	1	33.3%	-	0.0%	-	-	2	66.7%	3	0.3%
	Southbound	-	-	9	5.4%	14	8.4%	25	15.1%	118	71.1%	166	15.7%
	Westbound	2	0.7%	17	5.8%	34	11.6%	32	10.9%	209	71.1%	294	27.8%
Functional Classification	Rural - FW, EXP, INT	5	1.6%	15	4.9%	32	10.4%	25	8.1%	230	74.9%	307	29.0%
	Rural MC & MA	-	0.0%	6	7.4%	11	13.6%	8	9.9%	56	69.1%	81	7.6%
	Rural Principal Arterial	2	2.2%	12	13.2%	15	16.5%	7	7.7%	55	60.4%	91	8.6%
	Unknown	1	1.8%	3	5.3%	2	3.5%	4	7.0%	47	82.5%	57	5.4%
	Urban- FW, EXP, INT	1	0.5%	10	4.8%	12	5.8%	27	13.0%	157	75.8%	207	19.5%
	Urban MA & Collector	-	0.0%	1	1.3%	10	13.3%	9	12.0%	55	73.3%	75	7.1%
	Urban Principal Arterial	2	0.8%	4	1.7%	29	12.0%	45	18.7%	161	66.8%	241	22.8%
Roughness	Good	10	1.1%	45	5.0%	97	10.8%	106	11.8%	644	71.4%	902	85.2%
	Fair/Poor	1	0.6%	6	3.8%	14	6.9%	19	12.1%	117	74.5%	157	14.8%

Note: FW = Freeway; EXP = Expressway; INT = Interstate; MC =Major Collector; MA = Minor Arterial; K = Fatal; A = Incapacitating injury; B = Non-incapacitating injury; C = Possible injury; O = No injury/PDO.

Table C.4 Distribution of work zone crashes by driver factors

Variable	Category	K		A		B		C		O		Total	
		Count	%	Count	%	Count	%	Count	%	Count	%	Count	%
Safety Equipment	None used	6	10.7%	21	37.5%	11	19.6%	4	7.1%	14	25.0%	56	5.3%
	Safety Equipment Used	5	0.5%	29	3.0%	97	9.9%	119	12.2%	727	74.4%	977	92.3%
	Unknown	-	0.0%	1	3.8%	3	11.5%	2	7.7%	20	76.9%	26	2.5%
Speeding	No	8	0.8%	39	4.0%	103	10.5%	116	11.8%	713	72.8%	979	92.4%
	Yes	3	3.8%	12	15.0%	8	10.0%	9	11.3%	48	60.0%	80	7.6%
Driving Under the Influence	No	6	0.6%	42	4.3%	96	9.7%	117	11.9%	726	73.6%	987	93.2%
	Yes	5	6.9%	9	12.5%	15	20.8%	8	11.1%	35	48.6%	72	6.8%
Overcorrection	No	11	1.1%	49	4.7%	107	10.2%	124	11.9%	755	72.2%	1046	98.8%
	Yes	-	0.0%	2	15.4%	4	30.8%	1	7.7%	6	46.2%	13	1.2%
Fatigue	No	11	1.1%	47	4.5%	108	10.4%	124	11.9%	748	72.1%	1038	98.0%
	Yes	-	0.0%	4	19.0%	3	14.3%	1	4.8%	13	61.9%	21	2.0%
Distraction	No	10	1.0%	49	5.0%	97	10.0%	111	11.4%	707	72.6%	974	92.0%
	Yes	1	1.2%	2	2.4%	14	16.5%	14	16.5%	54	63.5%	85	8.0%
Illness	No	10	1.0%	51	4.9%	105	10.0%	123	11.7%	759	72.4%	1048	99.0%
	Yes	1	9.1%	-	0.0%	6	54.5%	2	18.2%	2	18.2%	11	1.0%
Driver's age (Years)	12-19	1	0.8%	4	3.3%	13	10.8%	17	14.2%	85	70.8%	120	11.3%
	20-34	3	0.9%	13	4.0%	32	9.7%	50	15.2%	231	70.2%	329	31.1%
	35-64	7	1.6%	23	5.4%	45	10.5%	43	10.0%	311	72.5%	429	40.5%
	≥ 65	-	0.0%	11	6.1%	21	11.6%	15	8.3%	134	74.0%	181	17.1%
Driver Contribution	Disregarded traffic signs	-	0.0%	5	8.8%	9	15.8%	9	15.8%	34	59.6%	57	5.4%
	Distraction/DUI/Illness	2	1.6%	8	6.3%	24	18.8%	18	14.1%	76	59.4%	128	12.1%
	Driving Too fast/ Exceeding speed limit	3	4.2%	9	12.7%	6	8.5%	9	12.7%	44	62.0%	71	6.7%
	Failure to yield/ keep proper lane	3	1.3%	14	6.0%	28	12.0%	26	11.2%	162	69.5%	233	22.0%
	Followed too closely	1	0.4%	4	1.5%	18	6.8%	45	16.9%	198	74.4%	266	25.1%
	Improper maneuver	-	0.0%	1	1.4%	1	1.4%	2	2.7%	70	94.6%	74	7.0%
	None	2	0.9%	9	4.1%	22	9.9%	14	6.3%	175	78.8%	222	21.0%
	Other	-	0.0%	1	20.0%	2	40.0%	1	20.0%	1	20.0%	5	0.5%
	Unknown	-	0.0%	-	0.0%	1	33.3%	1	33.3%	1	33.3%	3	0.3%

Note: K = Fatal; A = Incapacitating injury; B = Non-incapacitating injury; C = Possible injury; O = No injury/PDO; DUI = Driving Under the Influence.

C.1.1.5 Environmental Characteristics

Environmental factors related to the work zone crashes included weather and lighting conditions. Table C.5 summarizes the work zone crash statistics in relation to the environmental characteristics.

Table C.5 Distribution of work zone crashes by environmental factors

Variable	Category	K		A		B		C		O		Total	
		Frq.	%	Frq.	%	Frq.	%	Frq.	%	Frq.	%	Frq.	%
Lighting	Dark - lighted	-	0.0	4	7.7	2	3.8	8	15.4	38	73.1	52	4.9
	Dark - unlighted	1	1.2	9	10.8	8	9.6	4	4.8	61	73.5	83	7.8
	Dark - unknown	-	0.0	-	0.0	-	0.0	-	0.0	1	100	1	0.1
	Dawn	-	0.0	1	9.1	-	0.0	2	18.2	8	72.7	11	1.0
	Daylight	9	1.0	37	4.1	100	11.2	109	12.2	639	71.5	894	84.4
	Dusk	1	5.6	-	0.0	1	5.6	2	11.1	14	77.8	18	1.7
Weather	Clear	10	1.2	42	5.1	89	10.8	91	11.1	589	71.7	821	77.5
	Cloudy	1	0.6	8	4.4	18	10.0	28	15.6	125	69.4	180	17.0
	Severe Weather	-	0.0	1	1.8	4	7.0	6	10.5	46	80.7	57	5.4
	Unknown	-	0.0	-	0.0	-	0.0	-	0.0	1	100	1	0.1

Note: Frq. = Frequency/Count; K = Fatal; A = Incapacitating injury; B = Non-incapacitating injury; C = Possible injury; O = No injury/PDO.

As indicated in Table C.5, most crashes occurred during daylight hours (894 crashes, accounting for 84.4%), with nine crashes resulting in fatalities. Crashes that occurred in dark – unlighted conditions had the highest proportion of severe injuries (approximately 10%), followed by those that occurred during dark – lighted conditions, with 7.7% resulting in severe injuries. In relation to weather conditions, most crashes occurred in clear weather (77.5%), followed by cloudy weather conditions (17%).

C.1.1.6 Vehicle Characteristics

Vehicle characteristics identified in the crash data only included the type of vehicle. As shown in Table C.6, the majority of work zone crashes involved light trucks (504 crashes), followed by passenger vehicles (487 crashes). However, a significantly higher proportion of motorcycle-involved crashes resulted in fatalities (9.3%) and incapacitating injuries (27.8%), compared to only 0.4% and 5% for light truck crashes, respectively.

Table C.6 Distribution of work zone crashes by vehicle type

Vehicle Type	K		A		B		C		O		Total	
	Frq	%	Frq	%	Frq	%	Frq	%	Frq	%	Frq	%
Light truck	2	0.4	25	5.0	44	8.7	57	11.3	376	74.6	504	47.6
Motorcycle	5	9.3	15	27.8	20	37.0	8	14.8	6	11.1	54	5.1
Other	1	7.7	2	15.4	3	23.1	2	15.4	5	38.5	13	1.2
Passenger car	3	0.6	9	1.8	44	9.0	58	11.9	373	76.6	487	46.0
Semi-trailer	-	-	-	-	-	-	1	25.0	3	75.0	4	0.4
Unknown	-	0.0	-	0.0	-	0.0	-	0.0	1	100	1	0.1

Note: Frq. = Frequency/Count; Note: K = Fatal; A = Incapacitating injury; B = Non-incapacitating injury; C = Possible injury; O = No injury/PDO.

C.1.2 Continuous Variables

Continuous variables include features related to the crash that can have an infinite number of values within a particular range. These include variables such as the Average Daily Traffic (ADT), truck ADT, peak hour percentage, bus and motorcycle percentage, and shoulder, surface, median, and right-of-way widths. The data were merged with the crash data using the Spatial Join tool in ArcGIS.

The Spatial Join tool in ArcGIS functions by associating data from two different layers based on their spatial relationship. In this case, the crash data layer (2018 – 2022) was the target layer/feature to be joined with the roadway data layer. For every crash point, the tool identified the corresponding/nearest segment and transferred the segment data attributes to that particular crash point. Layers available for the roadway data included:

- State highway system layer (contains roadway ID and begin and end mileposts)
- Speed limit layer
- ADT layer
- Roadway system layer (contains all other roadway information, such as direction, functional classification, year built, shoulder and right-of-way widths, etc.)

The Spatial Join process was repeated for each layer feature (i.e., speed limit, ADT, and roadway system). The result of the spatial join process was a combined dataset, containing all values originally in the crash data file and the joined roadway data.

C.2 Crash Frequency Analysis

Crash frequency analysis identifies features associated with the occurrence of work zone crashes along the roadway. The analysis involves creating homogeneous work zone segments and determining the number of crashes that occurred along each work zone segment. Models such as Poisson and Negative Binomial, along with their corresponding zero-inflated models, can then be applied to the count data to identify roadway and work zone features associated with increased work zone crashes.

C.2.1 Data

Several datasets were required to identify factors influencing the occurrence (frequency) of work zone crashes. Work zone data, crash data, and roadway characteristics data were collected from SDDOT for a

5-year analysis period (2018 – 2022). The data collection, cleaning, and preparation processes are described in detail in Appendix B of this report.

A total of 1,059 work zone crashes were used in the analysis. Work zone data and contractor work dates data were merged, creating a total of 1,730 were zone segments. The roadway characteristics data were extracted from GIS and exported as separate Excel files for each variable. These different files were then used for segmentation purposes, where work zone segments were created whenever any of the roadway variables changed.

C.2.2 Segmentation

To perform the crash frequency analysis, crashes must be assigned to the respective work zones based on the location, date, and time of crash occurrence. Data processing for the segmentation process involved generating homogeneous roadway sections and assigning crashes to homogeneous segments. This process is necessary for conducting a systematic analysis of roadway safety. The comprehensive work zone data obtained was then used in conjunction with the roadway characteristics data during the segmentation process. In the segmentation process, a new work zone segment was created whenever there was a change in any of the following variables:

- Work zone segment (from the work zone comprehensive file)
- Speed limit
- Functional classification
- ADT
- Truck ADT
- Roadway width (surface + shoulder widths)
- Right-of-way width

Homogeneous segments were obtained based on roadway identification (RID) and the begin and end mileposts. The final dataset contained the following columns for each row, representing a homogeneous work zone segment.

- Roadway ID
- Segment name
- Project number
- Prime contractor
- Type of work zone activity
- County
- Contract amount
- Begin date and end date
- Begin milepost and end milepost
- Speed limit
- Functional class
- ADT
- Truck ADT
- Roadway width
- Right-of-way width
- Region

Before the segmentation process, the work zone file contained a total of 1,730 rows, each representing a work zone segment and corresponding information, including beginning and ending dates, beginning and ending mileposts, contract amounts, type of work zone, and other details. Segmentation was then performed with other roadway features, including functional classification, speed limit, ADT, truck ADT, roadway and right-of-way widths. A new segment was created each time one of these variables changed for every work zone segment. The segmentation process resulted in a total of 11,350 segments. The data was then cleaned and merged so that no two rows matched in every variable. In other words, the work zone segments were combined if they had all similar variable rows, and the end post of the previous segment was similar to the begin post of the following segment. A total of 7,125 segments resulted after this process. The data was cleaned to remove any rows with empty cells, resulting in a total of 6,559 work zone segments.

Using the crash roadway ID, its milepost, and crash date, crashes were assigned to their respective work zone segments depending on their roadway ID, milepost, and date of occurrence. This final dataset was then cleaned to remove rows with empty cells and dates that do not match the study period (2018 – 2022). Work zone segments that started and ended before 2018 were removed from the dataset. Segments that started before 2018 but ended after 2018 were revised to have a start date of January 1, 2018. Work zones with end dates after 2022 were revised to have a completion date of December 31, 2022. This was done to match the crash dataset study period (January 01, 2018 to December 31, 2022). The final dataset, after this process, contained 6,552 work zone segments, as summarized in Table C.7.

Table C.7 Work zone segments by roadway functional classification

Area Type	Functional Class	No. of Segments	Total Lane Miles (Directional)	Crashes
Rural	Freeway, expressway, and interstate	997	2,161	131
	Principal arterial	2,021	2,742	64
	Major collector and minor arterial	2,491	4,422	44
Urban	Freeway, expressway, and interstate	425	223	45
	Principal arterial	498	120	140
	Major collector and minor arterial	120	30	34

The descriptive statistics in Table C.8 further reveal key differences in roadway and project characteristics across the six functional classes. Speed limits are highest on rural limited access facilities, with a mean of 75 mph, compared to urban principal arterials and major collectors and minor arterials principal arterials and major collectors and minor arterials, which average 40 mph and 44 mph, respectively. ADT is higher on urban limited access facilities (mean = 19,867 veh/day) and decreases progressively in rural areas, with rural major collectors and minor arterials recording the lowest (mean = 1,245 veh/day). Truck ADT follows a similar pattern, with the highest values in urban limited access facilities (1,450 veh/day) and the lowest in rural major collectors and minor arterials (102).

In terms of roadway width, urban principal arterials tend to have the widest roads (mean = 55 feet), while rural major collectors and minor arterials have the narrowest (mean = 36 feet). Right-of-way (ROW) widths are observed to be higher in freeway categories, with urban limited access facilities averaging 172 feet and rural limited access facilities averaging 162 feet. Lastly, contract amounts vary significantly, with urban major collectors and minor arterials projects having the highest average ($107,832), followed by urban principal arterials projects ($53,324), whereas rural limited access facilities have the lowest average ($15,782).

Table C.9 summarizes the descriptive statistics for the categorical variables, showing the directional miles and number of crashes. The total work zone lengths and associated crash counts across regions and activity types illustrate variability by location and type of work. Regionally, the Mitchell area had the highest total work zone length (2,956.6 miles) and the highest number of crashes (166), followed by Rapid City (1,752.2 miles, 178 crashes). In contrast, the Aberdeen region recorded the lowest crash count (58) while covering over 2,278.1 miles. By work zone activity, the longest total lengths were observed for asphalt surface treatment (4,464.5 miles, 68 crashes) and milling (1,403.6 miles, 52 crashes), with crash counts distributed across both urban and rural areas. Grading activities were observed, involving approximately 180 miles and 147 crashes. Other activities such as maintenance & repair, pavement markings, and signs/signals showed moderate lengths with relatively low crash counts.

Table C.8 Descriptive statistics for continuous variables

Variable	Category	Crash Count	Mean	Std. Dev.	Min.	25th P.	50th P.	75th P.	Max.
Speed (mph)	Urban limited access facilities	425	66	8	45	65	65	75	80
	Urban PA	498	40	10	25	35	35	45	65
	Urban MAC & MIA	120	44	10	25	35	45	50	65
	Rural limited access facilities	997	75	8	45	70	80	80	80
	Rural PA	2021	55	13	25	45	65	65	65
	Rural MAC & MIA	2491	55	13	20	45	65	65	65
ADT (veh/day)	Urban limited access facilities	425	19,867	2	7,070	13,669	18,218	27,761	50,731
	Urban PA	498	11,914	2	2,823	7,949	13,746	17,494	38,626
	Urban MAC & MIA	120	7,068	2	2,303	3,847	5,882	14,656	22,184
	Rural limited access facilities	997	6,575	2	970	4,689	6,400	11,542	27,761
	Rural PA	2,021	2,935	2	474	1,870	3,180	4,642	15,765
	Rural MAC & MIA	2,491	1,245	3	72	680	1,314	2,474	13,570
Truck ADT (veh/day)	Urban limited access facilities	425	1,450	2	101	1,123	1,430	1,736	4,883
	Urban PA	498	471	2	64	305	478	810	1,483
	Urban MAC & MIA	120	220	2	48	128	207	422	838
	Rural limited access facilities	997	892	2	95	767	1,028	1,347	3,216
	Rural PA	2,021	288	2	55	194	304	444	1,176
	Rural MAC & MIA	2,491	102	3	2	54	124	206	977

Note: MAC=Major Collectors; MIA = Minor Arterials; PA = Principal Arterials.

Table C.8 Descriptive statistics for continuous variables (continued)

Variable	Category	Crash Count	Mean	Std. Dev.	Min.	25th P.	50th P.	75th P.	Max.
Roadway width (ft)	Urban limited access facilities	425	43	8	28	38	40	48	68
	Urban PA	498	55	14	18	44	59	64	92
	Urban MAC & MIA	120	45	12	16	36	40	56	75
	Rural limited access facilities	997	39	7	24	38	38	38	102
	Rural PA	2,021	43	9	23	36	40	48	112
	Rural MAC & MIA	2,491	36	9	9	30	32	40	95
Right-of-Way Width (ft)	Urban limited access facilities	425	172	67	100	150	50	150	360
	Urban PA	498	124	52	57	80	100	150	300
	Urban MAC & MIA	120	120	46	40	80	100	150	290
	Rural limited access facilities	997	162	57	50	150	150	190	470
	Rural PA	2,021	152	50	50	100	150	200	600
	Rural MAC & MIA	2,491	147	47	33	100	150	180	600
Contract Amount ($USD)	Urban limited access facilities	425	22,641	5	1,097	7,332	19,930	66,171	1,329,083
	Urban PA	498	53,324	5	1,339	14,765	44,356	162,755	6,582,993
	Urban MAC & MIA	120	107,832	5	2,441	36,316	120,572	336,045	6,582,993
	Rural limited access facilities	997	15,782	9	90	3,294	16,318	80,822	5,956,538
	Rural PA	2,021	35,440	8	22	8,103	40,135	162,755	6,582,993
	Rural MAC & MIA	2,491	26,923	9	11	6,003	26,903	133,252	13,256,519

Note: MAC=Major Collectors; MIA = Minor Arterials; PA = Principal Arterials.

Table C.9 Descriptive statistics for categorical variables: directional miles (crashes)

-	-	Directional Miles (Crashes)						-
Variable	Category	Urban Limited Access Facilities	Urban Principal Arterials	Urban MAC & MIA	Rural Limited Access Facilities	Rural Principal Arterials	Rural MAC & MIA	Total
Region	Aberdeen	–	47.2 (32)	4.4 (0)	494.3 (5)	477.5 (7)	1254.7 (14)	2278.1 (58)
	Mitchell	61.4 (33)	24.2 (17)	10.9 (1)	763.4 (79)	824.5 (16)	1272.2 (20)	2956.6 (166)
	Pierre	–	9.9 (1)	2.8 (0)	422.4 (32)	835.9 (14)	1439.1 (9)	2710.1 (56)
	Rapid City	161.6 (12)	38.2 (90)	12.2 (33)	480.4 (15)	603.7 (27)	456.1 (1)	1752.2 (178)
Work Zone Activity	Asphalt treatment	14.4 (14)	23.4 (0)	11.2 (0)	705.0 (30)	1106.5 (14)	2604.0 (10)	4464.5 (68)
	Concrete surface repair	15.9 (4)	5.7 (15)	4.1 (0)	285.7 (36)	245.5 (10)	8.1 (0)	565.0 (65)
	Grading	1.5 (0)	11.7 (74)	5.4 (33)	31.0 (21)	68.0 (8)	62.7 (11)	180.4 (147)
	Intersection	0.1 (0)	15.0 (2)	0.2 (0)	9.3 (4)	61.7 (3)	48.5 (0)	134.8 (9)
	Maintenance & Repair	91.2 (4)	23.3 (29)	2.7 (0)	263.8 (3)	150.5 (1)	152.8 (1)	684.4 (38)
	Milling	4.7 (3)	5.2 (0)	3.2 (0)	138.1 (19)	584.9 (19)	667.5 (11)	1403.6 (52)
	Pavement marking/ rumble strips	38.7 (7)	27.1 (3)	3.1 (1)	300.1 (11)	181.0 (1)	264.7 (1)	814.7 (24)
	Shoulder	9.2 (2)	1.1 (1)	–	105.3 (1)	135.6 (7)	28.9 (8)	280.0 (19)
	Signs/Signals	46.0 (9)	2.9 (16)	0.7 (0)	276.9 (4)	81.8 (0)	222.9 (0)	631.1 (29)
	Structure	1.3 (2)	4.1 (0)	–	45.2 (2)	126.0 (1)	362.0 (2)	538.6 (7)

Note: ( ) indicates number of crashes; MAC=Major Collectors; MIA = Minor Arterials; PA = Principal Arterials.

C.2.3 Frequency Analysis Models

This section presents the models used to analyze the frequency of work zone crashes. Four different count models were employed, including the Poisson, Negative Binomial, Zero-inflated Poisson (ZIP), and Zero-inflated Negative Binomial (ZINB) models. Performance metrics, including log likelihood, the Akaike Information Criterion (AIC), the Bayesian Information Criterion (BIC), and the Pearson chi-square statistics, were used to determine the best-performing model for each functional class dataset.

Count models are widely used to understand the influence of roadway characteristics or work zone features on crash frequency. Traditional regression models are unsuitable for count data, as they assume continuous outcome variables, which is not the case with count data (since count values cannot be negative) (Strawderman et al., 1999). Models such as the Poisson, Negative Binomial, and Zero-inflated models can effectively handle the characteristics of count data and have been widely used in multiple safety studies (Abdel-Aty & Radwan, 1999; Abdulhafedh, 2016; Chimba et al., 2014; Jiang et al., 2011). For this analysis, the number of crashes was normalized by segment length (in miles) and duration (in days). In other words, the exposure variable was the logarithm of the product of length and duration of the work zone. The following section discusses the four count models used in this study.

C.2.3.1 Poisson and Negative Binomial Models

The Poisson model assumes that the mean and the variance of the dependent variable (crash count, in this study) are equal, a term known as equidispersion. It assumes that the parameter λ_i or the expected crash frequency for each case is given by Equation (1), which guarantees a non-negative value for all values of λ_i (Michener & Tighe, 1992) and hence the probability of a work zone crash occurring at segment *i* is given by (Mouatassim & Ezzahid, 2012):

$$P(v) = \frac{e^{-\lambda_i} \lambda_i^{y_i}}{y_i!} \qquad \text{Eq. (1)}$$

$$\lambda_i = exp(X_i\beta) \qquad \text{Eq. (2)}$$

where, y_i is the response variable (crash count), X_i is the vector of the explanatory variables, and β is the coefficient (Son et al., 2011). However, the variance of crash counts is usually higher than its mean, making the Poisson model usually unsuitable for crash count analysis (Son et al., 2011). The Negative Binomial model is more flexible, as it relaxes the equidispersion of the data by adding a random term to the Poisson model (Poch & Mannering, 1996). The model assumes that the count variable follows a negative binomial distribution, and its probability mass function (PMF) can be written as:

$$P(Y_i = y_i) = \frac{\Gamma(y_i+\alpha^{-1})}{\Gamma(y_i+1)\Gamma(\alpha^{-1})}\left(\frac{\alpha^{-1}}{\alpha^{-1-}+\mu_1}\right)^{\alpha^{-1}}\left(\frac{\mu_i}{\alpha^{-1}+\mu_i}\right)^{y_i} \qquad \text{Eq. (3)}$$

where, y_i is the observed crash count and μ_i is the mean of the distribution such that $\mu_i = \lambda_i = exp(X_i\beta + U_i)$ where U_i is the added random parameter, Γ is the gamma function, and α is the overdispersion parameter. However, excess zeros in crash count data contribute to the overdispersion parameter. Zero-inflated models, such as the Zero-inflated Poisson, Zero-inflated Negative Binomial, and Zero-Hurdle Models, can handle the overdispersion due to excess zeros (Son et al., 2011).

C.2.3.2 Zero-inflated Models

The Zero-inflated Poisson (ZIP) model is used when the data has excess zeros and assumes a combination of two processes. One process models the zero inflation, including a proportion (1-p) and another models the non-zero counts using the zero-truncated Poisson model (Mouatassim & Ezzahid, 2012). The ZIP model can, therefore, be written as:

$$P(Y_i = y_i|x_i, z_i) = \begin{cases} \theta_i(z_i) + (1 - \theta i(zi))Pois(\lambda_i; 0|xi) & if\ y_i = 0 \\ 1 - (\theta i(zi))Pois(\lambda_i;\ y_i|xi) & if\ y_i > 0 \end{cases} \quad \text{Eq. (4)}$$

where, z_i is a vector of covariates defining the two probabilities when y = 0 and when y >0. On the other hand, the Zero-inflated Negative Binomial (ZINB) model is applied to data that exhibit both overdispersion and excess zeros (Raihan et al., 2019). Given the random nature of freeway work zone crashes, the ZINB model can account for work zone segments with no crashes, which is impossible to explain by the negative binomial model. The probability mass function of the ZINB is given by:

$$P(Y_i = y_i|x_i, z_i) = \begin{cases} \theta_i(z_i) + (1 - \theta i(zi))g(\lambda_i; 0|xi) & if\ y_i = 0 \\ 1 - (\theta i(zi))g(\lambda_i;\ y_i|xi) & if\ y_i > 0 \end{cases} \quad \text{Eq. (5)}$$

where, g(λ_i) is the negative binomial distribution presented in Equation (2) (Raihan et al., 2019).

The first part illustrates the probability that no crashes will occur in segment *i*, while the bottom part presents the likelihood that a segment will experience at least one crash. The four models were applied to the data, and performance metrics were reported to identify the best-performing model in predicting crash occurrence along freeway work zones. The four models were developed using a total of eight (8) variables: Ln (ADT), Ln (Truck ADT), type of work zone activity, Ln (Contract amount), speed, roadway width, right-of-way width, and region. The Akaike Information Criterion (AIC), the Bayesian Information Criterion (BIC), log likelihood, mean squared error (MSE), mean absolute error (MAE), and root mean squared error (RMSE) statistics were calculated for each model.

C.2.3.3 Model Performance Metrics

The data was classified into six categories based on functional class and location type, specifically considering urban and rural designations for limited access facilities, principal arterials, and a combined group of major collectors and minor arterials. This resulted in the creation of the following six distinct datasets:

- Urban limited access facilities
- Rural limited access facilities
- Urban principal arterials
- Rural principal arterials
- Urban major collectors and minor arterials
- Rural major collectors and minor arterials

However, the urban major collectors and minor arterials category had very few segments (120 segments in 30 miles) and was therefore exempt from further analysis. Six model performance metrics were estimated to determine the best prediction model for each dataset. Akaike Information Criterion (AIC), the Bayesian Information Criterion (BIC), loglikelihood, mean squared error (MSE), mean absolute error (MAE), and root mean squared error (RMSE) statistics were estimated for all four models for each dataset.

The loglikelihood measures how well a statistical model fits the observed data. In count models, such as the Poisson and negative binomial models, the log likelihood calculates the probability of observing the actual data given the model parameters. The loglikelihood values at the convergence of each model were compared, and the model exhibiting the highest log likelihood is regarded as the optimal model (Naderan

& Shahi, 2010). The AIC and the BIC balance the goodness of fit and the complexity of the model. The AIC is calculated as AIC = – 2(ln *L* - *p*) while the BIC is calculated as BIC = -2(ln *L* –(ln *n*)* *p*) where *n* is the number of observations, *L* is the likelihood of the model, and *p* is the number of parameters of the model (Naderan & Shahi, 2010; Osuji et al., 2016; Son et al., 2011). Lower AIC and BIC values indicate a better model (Osuji et al., 2016; Son et al., 2011).

Other metrics used to assess the model's performance include the mean squared error (MSE), mean absolute error (MAE), and root mean squared error (RMSE) statistics. These metrics help identify the difference between actual and predicted values. The MSE is calculated as the average of the squared differences between predicted and actual values. The MAE is the average of the absolute differences between actual and predicted values. RMSE is simply the square root of the MSE value. Collectively, these metrics provide a comprehensive view of model accuracy and error dispersion (Chai & Draxler, 2014). Equations (6) through (8) illustrate the calculation of these error metrics.

$$MSE = \frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \qquad \text{Eq. (6)}$$

$$MAE = \frac{1}{n} \sum_{i=1}^{n} |y_i - \hat{y}_i| \qquad \text{Eq. (7)}$$

$$RMSE = \sqrt{\frac{1}{\Pi} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2} \qquad \text{Eq. (8)}$$

All three error values were computed for each of the four models in the five datasets. Models that showed higher log likelihood, lower AIC and BIC values, and the lowest error values were considered the best-performing models and were therefore selected for count/frequency analysis. The following section presents the results from the model performance and frequency analysis for each dataset.

C.2.4 Frequency Analysis Results

Frequency analysis involved the use of count models to identify variables that are associated with the occurrence of more work zone crashes. The dataset, comprising a total of 6,552 rows, was divided into six categories, similar to the functional classes (see Table C.7). The urban major collector and minor arterial classes were not analyzed due to limited data availability (120 segments and 30 miles). Four models were used for frequency analysis, including the Poisson, Negative Binomial, Zero-inflated Poisson (ZIP), and Zero-inflated Negative Binomial (ZINB). Positive coefficient values from the model results indicate that an increase in the corresponding variable is associated with a higher likelihood of work zone crash occurrence, while negative coefficients suggest a decreased likelihood of such crashes. The odds ratios are calculated as exponents of the coefficient values and provide a more interpretable measure of this relationship by quantifying how the odds of a crash change with a unit increase in the variable. Odds ratios greater than 1 indicate increased odds, while values less than 1 indicate reduced odds of crash occurrence.

C.2.4.1 Rural Limited Access Facilities

The rural limited access facilities dataset comprises freeways, interstates, and expressways located in rural areas, as identified in the South Dakota Roadway Characteristic Inventory. Before conducting frequency analysis for this dataset, the correlation matrix was plotted. The matrix indicates that the natural log of

ADT was correlated to the natural log of truck ADT with a coefficient of 0.78. For that reason, the Ln (Truck ADT) variable was removed from further analysis. Figure C.3 shows the correlation matrix for the rural freeway dataset.

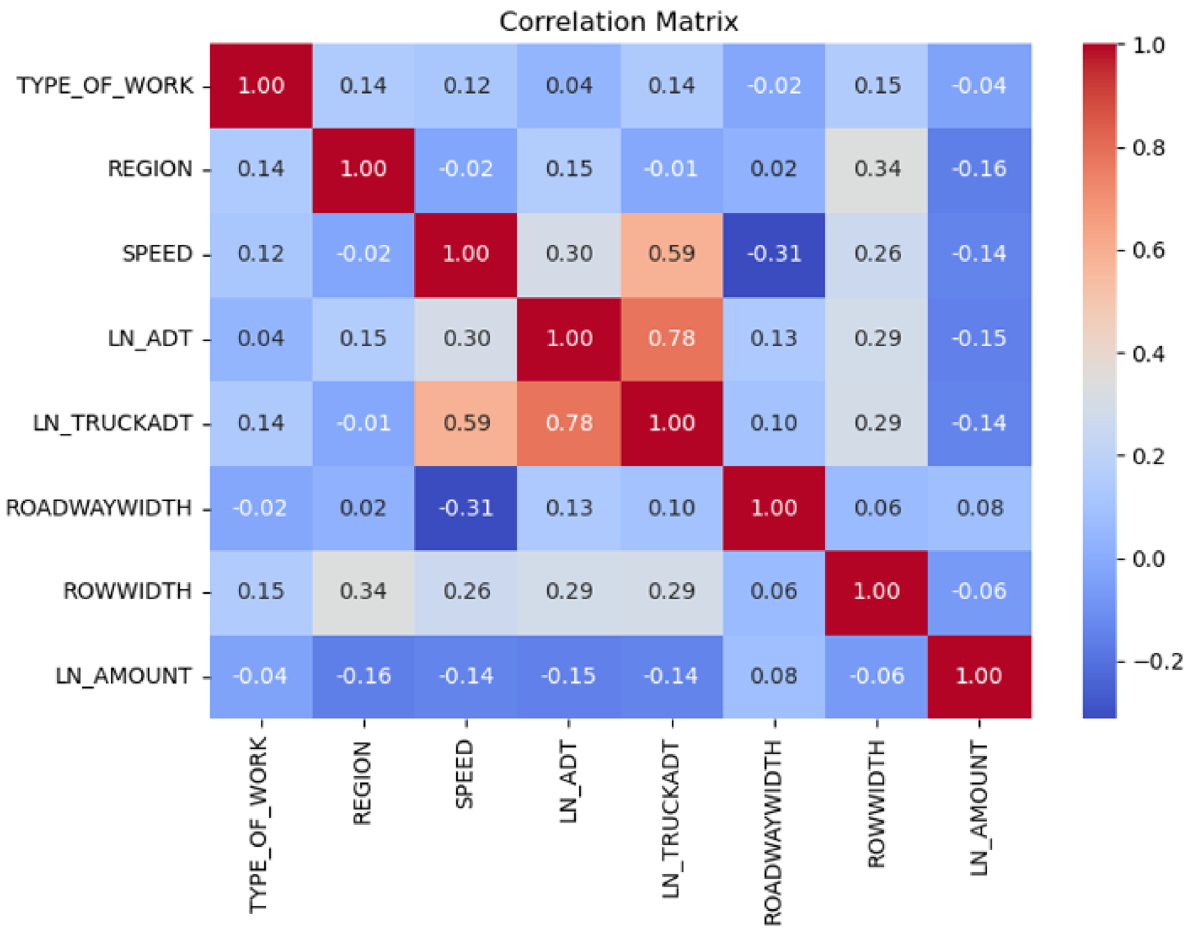


Figure C.3 Correlation matrix for rural limited access facilities

The four models were then run, and the corresponding performance metrics were calculated and summarized in Table C.10. Findings show that the Negative Binomial model outperformed other models, with lower AIC and BIC values, and a higher log likelihood, indicating the best balance between goodness of fit and model complexity. While its prediction error metrics (MSE = 0.213, RMSE = 0.461) are slightly higher than the Poisson model, the NB model is more appropriate for count data that exhibit overdispersion, where the variance exceeds the mean (0.32 > 0.13). This makes it theoretically and statistically the most reliable model for this context.

Table C.10 Model comparison results for rural limited access facilities

Model	AIC	BIC	LogLik	MSE	MAE	RMSE
Poisson	552.204	-6429.292	-258.102	**0.207**	0.154	**0.455**
Negative Binomial (NB)	**541.636**	**-6519.471**	**-252.818**	0.213	**0.153**	0.461
Zero-inflated Poisson	588.176	681.366	-275.088	0.218	0.159	0.467
Zero-inflated NB	544.085	642.180	-252.042	0.210	**0.153**	0.459

Note: AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; MSE = Mean Squared Error; MAE = Mean Absolute Error; RMSE = Root Mean Squared Error; Mean: 0.13; Variance: 0.32; **Bold** values indicate the best performance for each metric.

Table C.11 summarizes the results of the NB model for the rural limited access facilities functional class dataset. The findings indicate that crashes have approximately three times higher odds of occurring during grading activities and 20 times higher odds of occurrence when the work zone is located at an intersection, compared to work zones involving asphalt surface treatment. This highlights the elevated crash risk associated with work zones located at intersections in rural limited access facilities. This elevated risk may be associated with increased vehicle interactions at intersections compared to other roadway locations.

Table C.11 Negative binomial model results for rural limited access facilities

Variable	Category	Coefficient	Odds Ratio	Std Error	P value	CI Lower	CI Upper
Intercept		-23.121	-	2.873	<0.001	-28.752	-17.489
Type of Work	Asphalt surface treatment*	-	-	-	-	--	
	Concrete surface repair	0.221	-	0.339	0.515	-0.444	0.886
	Grading	**1.017**	**2.765**	**0.482**	**0.035**	**0.072**	**1.962**
	Intersection	**3.004**	**20.162**	**0.773**	**<0.001**	**1.488**	**4.519**
	Maintenance& Repair	-1.043	-	0.646	0.107	-2.309	0.224
	Milling	0.289	-	0.389	0.457	-0.472	1.051
	Pav. marking/r. strips	-0.405	-	0.468	0.387	-1.323	0.512
	Shoulder	0.258	-	1.086	0.812	-1.871	2.387
	Signs/Signals	-0.460	-	0.662	0.487	-1.757	0.837
	Structure	0.692	-	0.786	0.379	-0.849	2.233
Region	Aberdeen*	-	-	-	-	-	-
	Mitchell	0.640	-	0.630	0.310	-0.594	1.874
	Pierre	**1.144**	**3.138**	**0.596**	**0.055**	**-0.025**	**2.312**
	Rapid City	0.575	-	0.653	0.378	-0.704	1.854
Speed		-0.016	-	0.025	0.505	-0.064	0.032
Ln (ADT)		**1.493**	**4.450**	**0.300**	**<0.001**	**0.904**	**2.082**
Roadway Width		-0.026	-	0.021	0.203	-0.067	0.014
ROW Width		-0.004	-	0.003	0.227	-0.009	0.002
Ln (Contract Amount)		**0.470**	**1.600**	**0.077**	**<0.001**	**0.319**	**0.621**

Note: * indicates base category; **Bold** values indicate significance at 95% confidence level; CI = Confidence Interval; ADT = Average Daily Traffic.

The findings also indicate that work zone crashes have about 3 times higher likelihood of occurring in the Pierre region compared to the Aberdeen region along rural limited access facilities. Additionally, a unit increase in the natural logarithm of ADT is associated with about 4.45 times likelihood of a crash occurring, indicating that higher traffic volumes significantly increase the risk of crashes in rural limited access facilities work zones. Projects with higher funding amounts are also observed to have a higher likelihood (1.6 times higher odds) of work zone crash occurrence. This may be attributed to the fact that larger budgets often correspond to more extensive and longer-duration projects, which in turn may elevate exposure and risk within the work zone.

C.2.4.2 Urban Limited Access Facilities

Similar to rural limited access facilities, the urban limited access facilities dataset includes freeways, interstates, and expressways found in urban areas, as identified in the South Dakota Roadway Characteristics Inventory. The correlation matrix on Figure C.4 indicates that no two variables were correlated with a coefficient above 0.7. All variables were therefore retained in the model for analysis. The model performance analysis suggests that, despite the NB model having relatively larger errors compared to the Poisson model, it has lower AIC and BIC values, and higher log likelihood values, implying a superior balance between goodness of fit and model simplicity. The NB model was therefore used to determine the influence of the predictor variables on the crash count outcome. The ZINB model failed to converge during estimation, indicating instability or overparameterization, and was therefore removed from comparison. Table C.12 summarizes count models' performance metrics for the urban limited access facilities dataset.

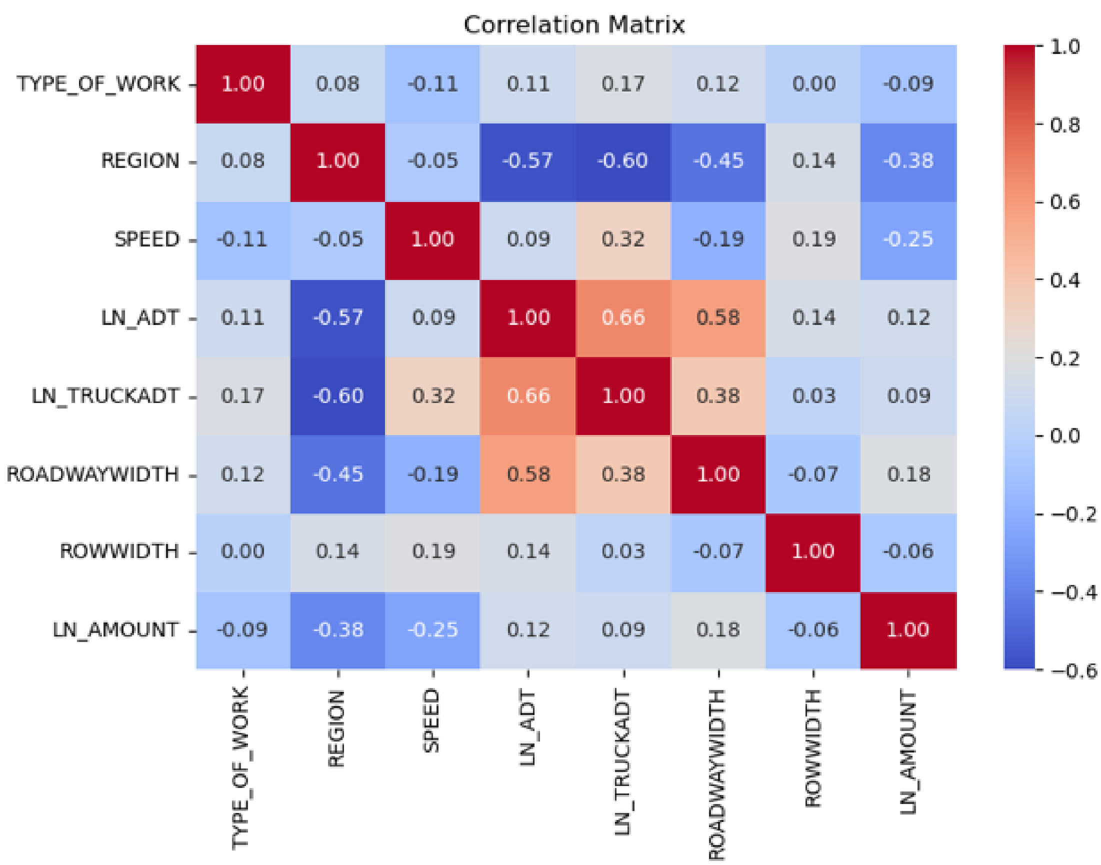


Figure C.4 Correlation matrix for urban limited access facilities

Table C.12 Model comparison results for urban limited access facilities

Class	Model	AIC	BIC	Log Lik	MSE	MAE	RMSE
Urban limited access facilities	Poisson	236.806	-2327.310	-101.403	**0.158**	**0.143**	**0.397**
	Negative Binomial	**228.964**	**-2361.812**	**-97.482**	0.182	0.145	0.427
	Zero-inflated Poisson	233.073	306.011	-98.537	0.186	0.148	0.432

Note: AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; MSE = Mean Squared Error; MAE = Mean Absolute Error; RMSE = Root Mean Squared Error; Mean: 0.11; Variance: 0.26; **Bold** values indicate the best performance for each metric.

Table C.13 summarizes the results of the negative binomial analysis for urban limited-access facilities. Findings indicate that, compared with asphalt surface treatment, the odds of crashes are approximately 80% (OR = 0.203) and 70% (OR = 0.297) lower when a work zone involves concrete surface repair and pavement marking/rumble strips, respectively, along urban limited-access facilities. In addition, findings show that work zone crashes along urban limited access facilities are 84% (OR = 0.158) less likely to occur within the Rapid City region compared to the Mitchell region.

The Aberdeen and Pierre regions did not have any urban limited-access facilities within the dataset. Among the continuous variables, the NB model results show that work zone crashes have 10 times more odds of occurring with a unit increase in the natural log of ADT in urban limited-access facilities. At the same time, they have 76% lower odds of occurring with a unit increase in the natural log of Truck ADT. This can be attributed to the fact that higher overall traffic volumes increase the exposure of vehicles and, consequently, the probability of collisions along urban limited access facilities. However, higher truck volumes may be associated with more controlled traffic management strategies, which could reduce the potential risk of work zone crashes.

Table C.13 Negative binomial results for urban limited access facilities

Variable	Category	Coefficient	Odds Ratio	Std Error	P value	CI Lower	CI Upper
Intercept	-	-17.909	<0.001	9.903	0.071	-37.318	1.501
Type of Work	Asphalt surface treatment*	-	-	-	-	-	-
	Concrete surface repair	**-1.595**	**0.203**	**0.774**	**0.039**	**-3.113**	**-0.078**
	Grading	-20.216	<0.001	17,128.9	0.999	-33,592.3	33,551.8
	Intersection	-17.962	<0.001	20,911.8	0.999	-41,004.4	40,968.4
	Maintenance& Repair	-0.900	0.406	0.811	0.267	-2.491	0.690
	Milling	-0.868	0.420	0.918	0.344	-2.667	0.931
	Pav. marking/r. strips[1]	**-1.215**	**0.297**	**0.667**	**0.069**	**-2.521**	**0.092**
	Shoulder	0.359	1.432	1.132	0.751	-1.860	2.578
	Signs/Signals	0.359	1.431	1.014	0.724	-1.629	2.346
	Structure	0.004	1.004	1.161	0.997	-2.271	2.279
Region	Mitchell *	-	-	-	-	-	-
	Rapid City[1]	**-1.848**	**0.158**	**1.010**	**0.067**	**-3.827**	**0.131**
Speed		0.028	1.028	0.036	0.435	-0.042	0.098
Ln (ADT)		**2.322**	**10.195**	**1.059**	**0.028**	**0.247**	**4.397**
Ln (Truck ADT)		**-1.445**	**0.236**	**0.708**	**0.041**	**-2.831**	**-0.058**

Variable	Category	Coefficient	Odds Ratio	Std Error	P value	CI Lower	CI Upper
Roadway Width		-0.059	0.943	0.043	0.164	-0.143	0.024
ROW Width		-0.007	0.993	0.004	0.102	-0.016	0.001
Ln (Contract Amount)		0.225	1.253	0.171	0.189	-0.111	0.561

Note: *indicates base category; **Bold** indicates significance at 95% confidence level; [1] indicates significance at 90% confidence level; CI = Confidence Interval; ADT = Average Daily Traffic; ROW = Right-of-way.

C.2.4.3 Rural Principal Arterials

The correlation matrix in Figure C.5 indicates that no two variables were correlated with a coefficient above 0.7. All variables were therefore retained in the model for analysis.

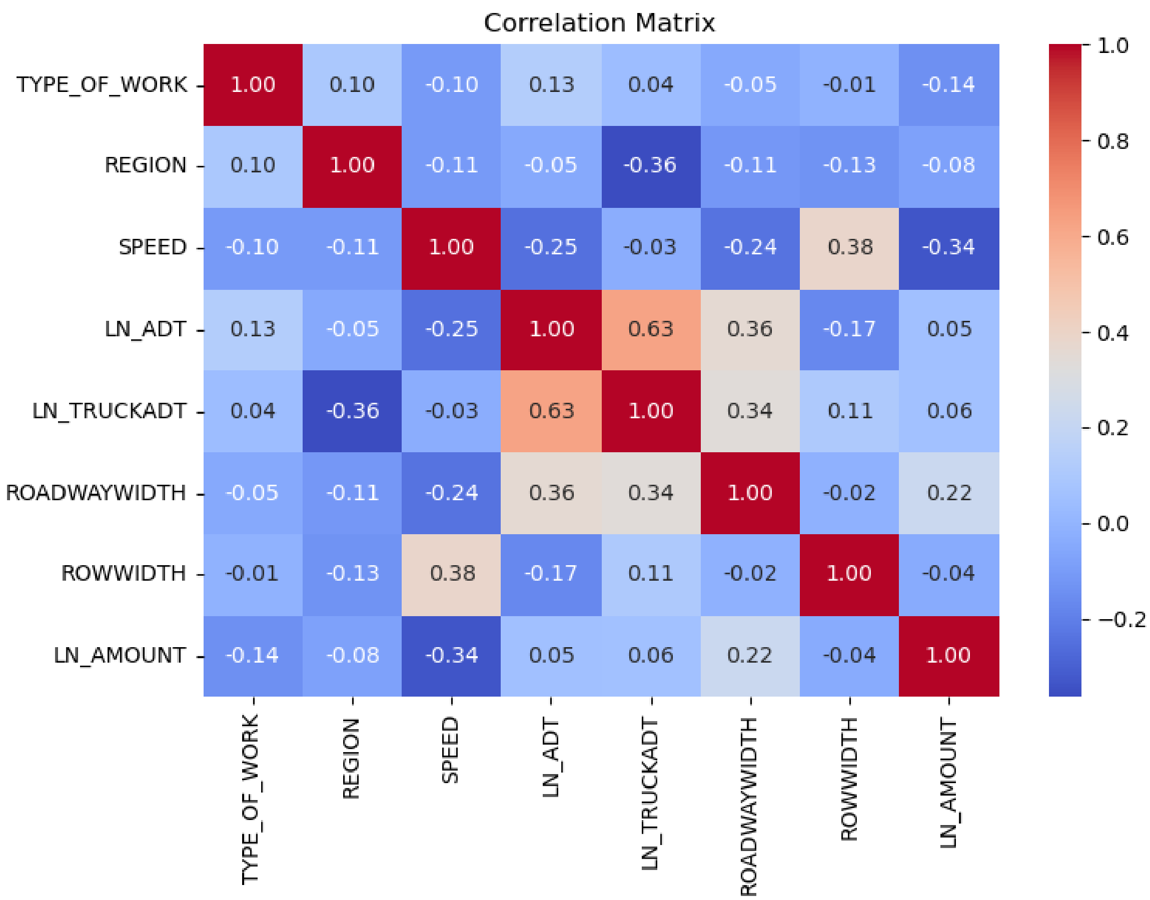


Figure C.5 Correlation matrix for rural principal arterials

The model comparison results summarized in Table C.14 indicate that the Poisson model performed better than the other models, with lower AIC and BIC values, higher log likelihood, and lower error metrics. Similar to the urban limited access facilities, the ZINB model did not converge, indicating instability or overparameterization, and was therefore omitted from comparison. The small difference between the mean (0.03) and variance (0.04) of the crash counts for this dataset supports the use of the Poisson model, as it assumes equidispersion (a condition where the mean and variance of the data are approximately equal). Additionally, the Vuong test yielded a very small P-value, indicating that the Poisson model performed significantly better than the Zero-inflated Poisson model for this dataset.

Table C.14 Model comparison results for rural principal arterials

Class	Model	AIC	BIC	LogLik	MSE	MAE	RMSE
Rural PA	**Poisson**	**425.549**	**-14966.808**	**-193.774**	**0.032**	**0.050**	**0.179**
	Negative Binomial	428.933	-15009.888	-195.466	0.032	0.050	0.180
	Zero-inflated Poisson	442.245	554.472	-201.122	0.033	0.051	0.183

Note: AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; MSE = Mean Squared Error; MAE = Mean Absolute Error; RMSE = Root Mean Squared Error;
Mean: 0.03; Variance: 0.04; Vuong Test (ZIP vs Poisson): z = -9.052, p = <0.001; **Bold** values indicate the best performance for each metric.

Table C.15 summarizes results from the Poisson model for the rural principal arterials. The results indicate that work zone crashes have approximately 86% lower odds (OR = 0.142) of occurring when the work zone involves pavement markings or rumble strips, and about 60% lower odds (OR = 0.399) when the work zone is located on the shoulder, compared to work zones involving asphalt surface treatment.

Table C.15 Poisson model results for rural principal arterials

Variable	Category	Coefficient	Odds Ratio	Std Error	P value	CI Lower	CI Upper
Intercept	-	-17.174	<0.001	2.567	<0.001	-22.206	-12.142
Type of Work	Asphalt surface treatment*	-	-	-	-	-	-
	Concrete surface repair	0.158	-	0.451	0.726	-0.725	1.041
	Grading	0.267	-	0.485	0.582	-0.683	1.216
	Intersection	0.324	-	0.842	0.701	-1.327	1.975
	Maintenance& Repair	-0.952	-	1.042	0.361	-2.994	1.092
	Milling	-0.582	-	0.379	0.124	-1.325	0.160
	Pav. marking/r. strips	***-1.944***	***0.143***	***1.062***	***0.067***	***-4.025***	***0.138***
	Shoulder	***-0.918***	***0.399***	***0.487***	***0.059***	***-1.872***	***0.036***
	Signs/Signals	-20.046	-	15,782.383	0.999	-30,952.948	30,912.856
	Structure	-0.985	-	1.064	0.354	-3.070	1.100
Region	Aberdeen*	-	-	-	-	-	-
	Mitchell	0.312	-	0.596	0.600	-0.855	1.480
	Pierre	0.255	-	0.601	0.672	-0.924	1.434
	Rapid City	**1.543**	**4.677**	**0.574**	**0.007**	**0.418**	**2.667**
Speed		-0.010	-	0.015	0.501	-0.040	0.020
Ln (ADT)		0.095	-	0.321	0.767	-0.533	0.724
Ln (Truck ADT)		**0.705**	**2.024**	**0.327**	**0.031**	**0.064**	**1.346**
Roadway Width		**0.040**	**1.041**	**0.014**	**0.005**	**0.012**	**0.068**
ROW Width		0.000	-	0.004	0.968	-0.007	0.007
Ln (Contract Amount)		**0.235**	**1.264**	**0.092**	**0.011**	**0.055**	**0.415**

Note: * indicates base category; **Bold** indicates significance at 95% confidence level; ***Bold*** indicates significance at 90% confidence level; CI = Confidence Interval; ADT = Average Daily Traffic.

Findings also indicate that work zone crashes along rural principal arterials have approximately

4.7 times higher chances of occurring in Rapid City compared to the Aberdeen region. Regarding the continuous variables, the findings indicate that work zone crashes have approximately twice the chances of occurring with a unit increase in the natural logarithm of the truck ADT, and about a 4.1% increase in chances (OR = 1.041) with a one-foot increase in roadway width. Similar to urban and rural limited access facilities, work zone crashes on rural principal arterials have approximately 26% higher chances (OR = 1.264) of occurring with a unit increase in the natural logarithm of the project budget. This may be attributed to the fact that larger budgets often correspond to more extensive and longer-duration projects, which in turn may elevate exposure and risk within the work zones.

C.2.4.4 Urban Principal Arterials

The correlation matrix in Figure C.6 indicates that no two variables were correlated with a coefficient above 0.7. All variables were therefore retained in the model for further analysis. Table C.16 summarizes results from the count models' performance metrics.

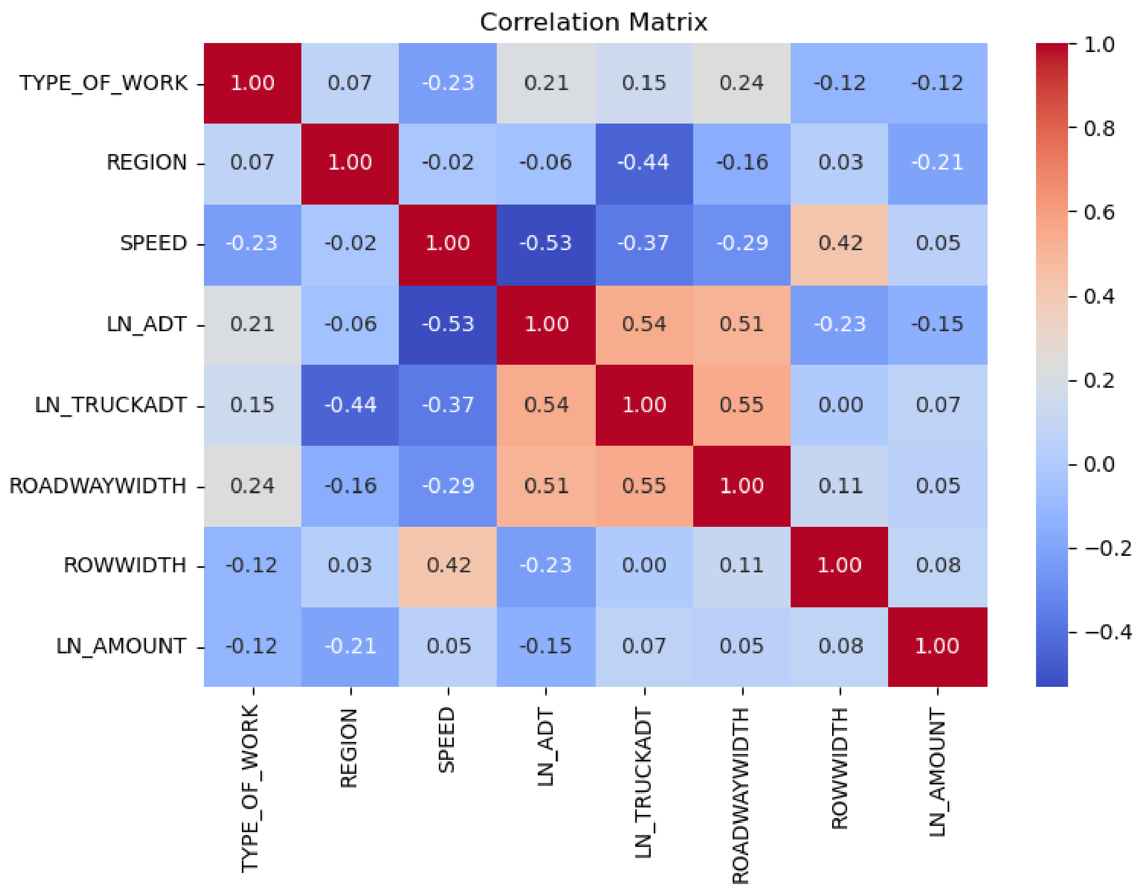


Figure C.6 Correlation matrix for urban principal arterials

Based on the comparison of model performance metrics in Table C.16, the Negative Binomial model is the best choice overall. It has the lowest AIC (335.835) and lowest BIC (-2840.955), indicating a significantly better statistical fit than the other models. Additionally, it achieves the highest log likelihood (-148.917), further supporting its superior ability to capture the data structure. While its predictive error, measured in terms of MSE (2.834) and RMSE (1.683), is slightly higher than that of the Poisson model, the difference in error is modest and outweighed by the significantly better model fit. The Poisson model, despite having a lower MSE and RMSE, exhibits significantly higher AIC and BIC values, suggesting that it does not provide a better explanation of the data. The Zero-inflated models perform worse both in terms of fitness and prediction errors. Therefore, considering both statistical goodness-of-fit and reasonable predictive performance, the Negative Binomial model was the most appropriate choice for modeling crash counts in this dataset.

Table C.16 Model comparison results for urban principal arterials

Model	AIC	BIC	LogLik	MSE	MAE	RMSE
Poisson	408.062	-2716.621	-185.031	**2.037**	**0.282**	**1.427**
Negative Binomial	**335.835**	**-2840.955**	**-148.917**	2.834	**0.283**	1.683
Zero-inflated Poisson	430.107	514.319	-195.054	2.321	0.313	1.524
Zero-inflated NB	340.704	429.127	-149.352	3.331	0.282	1.825

Note: AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; MSE = Mean Squared Error; MAE = Mean Absolute Error; RMSE = Root Mean Squared Error;
Mean: 0.28; Variance: 4.09;
Vuong Test (ZIP vs Poisson): z = -3.038, p = 0.002 (Standard model is better);
Vuong Test (ZINB vs NB): z = -0.457, p = 0.648 (No difference); **Bold** values indicate the best performance for each metric.

The Vuong test was also performed for this dataset to identify the superiority of the inflated models compared to the corresponding standard models. The test comparing the ZIP and Poisson models yielded a significant result (z = -3.038, p = 0.002), indicating that the Poisson model fits the data better than the Zero-inflated Poisson model. For the ZINB vs. NB comparison, the non-significant result (z = -0.457, p = 0.648) suggests no meaningful improvement from using the ZINB model. The NB model was therefore used to identify the influence of the predictor variables on crash count. Table C.17 summarizes the results from the NB model for the urban principal arterial dataset.

None of the work zone types were found to be significant at a 90% confidence level within the urban principal arterial dataset. Similar to rural principal arterials, model results indicate that work zone crashes along urban principal arterials have approximately 4.6 times higher odds of occurring in the Rapid City region compared to the Aberdeen region. This implies that the Rapid City region has higher chances of experiencing work zone crashes along its principal arterials, irrespective of the area's nature (i.e., urban or rural). Findings also indicate that the influence of ADT on work zone crashes along urban principal arterials is significant, as crashes have approximately six times higher odds of occurring with a unit increase in the natural logarithm of ADT.

Roadway width was associated with a negative coefficient and an odds ratio of 0.961, indicating that each one-foot increase in roadway width is associated with a 3.9% decrease in the likelihood of work zone crashes. In contrast, the right-of-way width showed the opposite effect, with an odds ratio of 1.007, indicating a slight increase in the odds of crashes occurring as the right of way width increases. Similar to the other functional classes, the natural logarithm of the contract amount was observed to have a positive coefficient, indicating a 48% increase in the odds of work zone crashes with a unit increase in the natural logarithm of the project contract amount. Higher budget amounts may reflect larger and longer projects, which could increase exposure and collision likelihood in work zones.

Table C.17 Negative binomial results for urban principal arterials

Variable	Category	Coefficient	Odds Ratio	Std Error	P value	CI Lower	CI Upper
Intercept	-	-47.114	-	14,218.171	0.997	-27,914.217	27,819.988
Type of Work	Asphalt surface treatment*	-	-	-	-	-	-
	Concrete surface repair	22.279	-	14,218.170	0.999	-27,844.822	27,889.380
	Grading	22.870	-	14,218.170	0.999	-27,844.231	27,889.970
	Intersection	18.928	-	14,218.170	0.999	-27,848.173	27,886.028
	Maintenance& Repair	21.116	-	14,218.170	0.999	-27,845.985	27,888.216
	Milling	-0.811	-	36,248.023	1.000	-71,045.630	71,044.009
	Pav. marking/r. strips	19.933	-	14,218.170	0.999	-27,847.168	27,887.033
	Shoulder	21.524	-	14,218.170	0.999	-27,845.577	27,888.624
	Signs/Signals	22.105	-	14,218.170	0.999	-27,844.995	27,889.206
	Structure	-0.133	-	31,470.722	1.000	-61,681.614	61,681.349
Region	Aberdeen*	-	-	-	-	-	-
	Mitchell	-0.551	-	0.748	0.461	-2.016	0.915
	Pierre	0.913	-	1.355	0.501	-1.743	3.568
	Rapid City	**1.531**	**4.623**	**0.567**	**0.007**	**0.419**	**2.643**
Speed		-0.008	--	0.023	0.737	-0.054	0.038
Ln (ADT)		**1.773**	**5.888**	**0.480**	**<0.001**	**0.833**	**2.713**
Ln (Truck ADT)		0.053	-	0.392	0.893	-0.715	0.821
Roadway Width		**-0.040**	**0.961**	**0.014**	**0.005**	**-0.068**	**-0.012**
ROW Width		***0.007***	***1.007***	***0.004***	***0.071***	***-0.001***	***0.014***
Ln (Contract Amount)		**0.391**	**1.478**	**0.144**	**0.007**	**0.108**	**0.673**

Note: * indicates base category; **Bold** indicates significance at 95% confidence level; ***Bold*** indicates significance at 90% confidence level; CI = Confidence Interval; ADT = Average Daily Traffic.

C.2.4.5 Rural Major Collectors & Minor Arterials

The Pearson correlation matrix in Figure C.7 shows a correlation coefficient of 0.71 between the natural logarithm of ADT and natural logarithm of Truck ADT. The Truck ADT variable was therefore removed from further analysis.

Table C.18 shows the model performance comparison metrics for the rural collectors and minor arterials dataset. The Poisson model was selected as the best-performing model for this dataset. It showed the lowest AIC (321.218), the lowest RMSE (0.133), and the highest log-likelihood (-142.609), indicating the best overall fit among the three. Its error metrics (MSE and MAE) are also equal to or better than the others.

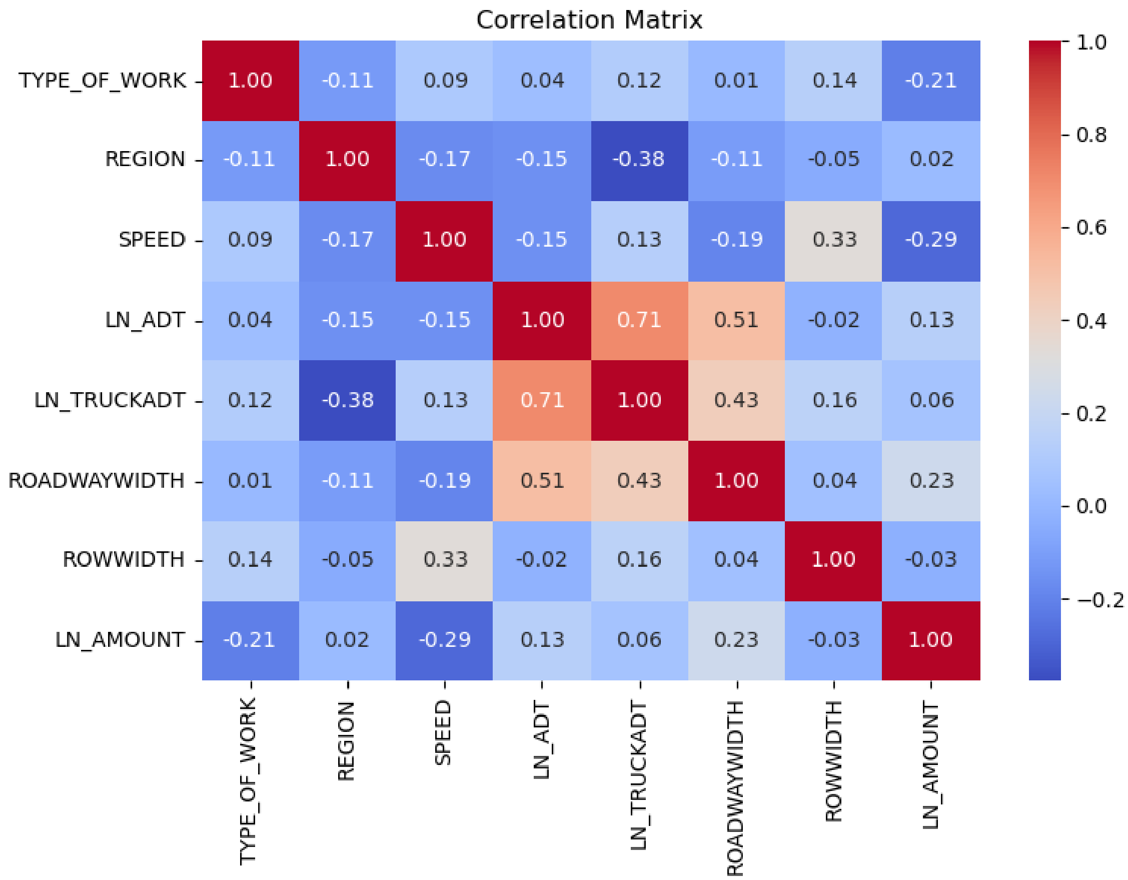


Figure C.7 Correlation matrix for rural collectors and arterials

Table C.18 Model comparison results for rural major collectors and minor arterials

Facility	Model	AIC	BIC	LogLik	MSE	MAE	RMSE
Rural Major Collectors and Minor Arterials	**Poisson**	**321.218**	-19132.318	**-142.609**	**0.018**	**0.027**	**0.133**
	Negative Binomial	323.942	**-19160.816**	-143.971	**0.018**	**0.027**	0.135
	Zero-inflated Poisson	351.281	461.870	-156.641	0.018	0.028	0.134

Mean = 0.02, Variance = 0.03; **Bold** values indicate the best performance for each metric.

Despite the Negative Binomial model having a slightly lower BIC, the Poisson model outperforms in most other criteria. The minimal difference between the mean and variance (0.02 and 0.03) in the data likely makes equidispersion a reasonable assumption. The Zero-inflated Poisson (ZIP) model performed worse than other models and was therefore not preferred. Table C.19 summarizes the findings from the Poisson model for the rural major collectors and minor arterials dataset.

Findings from Table C.19 indicate that, on rural major collectors and minor arterials, work zone crashes have approximately 6.25 times higher odds of occurring when the work zone is located along the shoulder, compared to work zones involving asphalt concrete treatment on the roadway. Additionally, while crashes have about 3.65 times higher odds of occurring in the Pierre region compared to the Aberdeen region, they have approximately 87% lower odds (OR = 0.128) of occurring in the Rapid City region relative to the Aberdeen region. Similar to the previous models, the natural logarithm of ADT, roadway width, and the natural logarithm of the contract amount are positively associated with higher odds of work zone crashes along rural major collectors and minor arterials.

Table C.19 Poisson model results for rural major collectors and minor arterials

Variable	Category	Coefficient	Odds Ratio	Std. Error	P value	CI Lower	CI Upper
Intercept	-	-23.047	<0.001	2.932	<0.001	-28.794	-17.300
Type of Work	Asphalt surface treatment*	-	-	-	-	-	-
	Concrete surface repair	-21.111	-	30352.340	0.999	- 59510.605	59468.383
	Grading	0.145	-	0.563	0.797	-0.958	1.248
	Intersection	-19.611	-	41511.964	1.000	- 81381.565	81342.343
	Maintenance& Repair	-0.287	-	1.070	0.788	-2.384	1.809
	Milling	0.269	-	0.465	0.562	-0.641	1.180
	Pav. marking/r. strips	-0.950	-	1.085	0.381	-3.076	1.176
	Shoulder	**1.833**	**6.251**	**0.535**	**0.001**	**0.785**	**2.881**
	Signs/Signals	-20.116	-	27335.681	0.999	- 53597.066	53556.834
	Structure	-0.120	-	0.805	0.882	-1.699	1.458
Region	Aberdeen*		-	-	-	-	-
	Mitchell	-0.578	-	0.396	0.145	-1.355	0.199
	Pierre	**1.294**	**3.647**	**0.604**	**0.032**	**0.111**	**2.477**
	Rapid City	***-2.059***	***0.128***	***1.114***	***0.065***	***-4.243***	***0.125***
Speed		0.000	-	0.019	0.990	-0.037	0.037
Ln (ADT)		**1.371**	**3.939**	**0.280**	**<0.001**	**0.822**	**1.920**
Roadway Width		***0.037***	***1.038***	***0.022***	***0.086***	***-0.005***	***0.079***
ROW Width		0.000	-	0.005	0.941	-0.009	0.010
Ln (Contract Amount)		**0.222**	**1.248**	**0.110**	**0.043**	**0.007**	**0.437**

Note: * = base category; **Bold** indicates significance at 95% confidence level; ***Bold*** indicates significance at 90% confidence level.

C.2.5 Summary

Crash frequency analysis used Poisson and Negative Binomial count models to determine contributing factors to work zone crash frequency. The crash modeling analysis revealed key differences across functional classes. On rural limited access facilities, work zone crashes had significantly higher chances of occurring during grading, at intersections, in the Pierre region, with higher ADT and higher project budgets. On urban limited access facilities, work zone crashes had lower chances of occurring during concrete repair or pavement marking, and in the Rapid City region, but sharply increased with ADT. Interestingly, higher truck ADT reduced crash risk. For rural principal arterials, pavement marking and shoulder work were associated with lower odds of work zone crashes, but work zone crashes had higher odds of occurring in the Rapid City region, with increases in truck ADT, roadway width, and project budget, all linked to higher work zone crash counts. For urban principal arterials, significant predictors of crash occurrence included the region and average daily traffic (ADT). Crashes had about 4.6 times higher odds of occurring in the Rapid City region. Additionally, with each unit increase in the natural logarithm of ADT, crashes had about 6 times higher odds of occurring. Wider roads reduced crash likelihood, while larger project budgets increased crash risks. Work zone crashes on rural major collectors and minor arterials had approximately 6.25 times higher chances of occurring on shoulders and increased with ADT, in the Pierre region, and with the project budget.

C.3 Crash Severity Analysis

Crash injury severity analysis involves identifying factors contributing to more severe injuries resulting from a crash, such as fatalities or incapacitating injuries. This analysis helps identify human, vehicle, temporal, roadway, or crash characteristics contributing to crash injury severity. Crash severity analysis is useful to engineers, policymakers, and transportation agencies in implementing strategies to reduce the severity of crashes, including those that occur along work zones (Li et al., 2012).

The injury severity of crashes in this dataset was categorized into five levels: fatal (K), incapacitating (A), non-incapacitating (B), possible injury (C), and no injury (O). To perform injury severity analysis, classification models including binary, ordinal, and multinomial logistic regression were used and compared to identify the best-performing model (Chen et al., 2020a, 2020b; Dissanayake & Roy, 2014; Duddu et al., 2019).

The result of the crash severity analysis is a model equation with variable coefficients, P-values, and standard errors for each variable category. The magnitude and direction of the coefficients indicate the strength and type of relationship each variable category has with injury severity. Significant variables will be identified by the observed P-values, depending on the level of confidence required. The following sections discuss the models used for analyzing crash injury severity.

C.3.1 Analysis Models

C.3.1.1 Binary Logistic Regression

Binary logistic regression is a statistical method used to model a relationship between one or more independent variables (predictors) and a binary dependent variable (outcome). The outcome variable has only two possible outcomes, often coded as 0 and 1 (Dissanayake & Lu, 2002; Sultan Ali et al., 2024), such as success vs. failure, severe vs. minor injury, etc. Unlike linear regression, where the outcome is continuous, binary logistic regression estimates the probability that the dependent variable equals 1, given the values of the independent variables (Dissanayake & Lu, 2002). The probabilities must fall between 0 and 1; therefore, logistic regression utilizes the logit function to map the linear combination of predictors to a probability.

The general form of the logistic regression equation is given by Equation (9) (Dissanayake & Lu, 2002).

$$logit(P) = 1 + \ln\left(\frac{P}{1-P}\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 \dots \dots . \beta_n X_n \qquad \text{Eq. (9)}$$

The probability of a crash in outcome severity is given by Equation (10) (Amarasingha & Chandrasiri, 2025).

$$\Pr(Y = 1|X) = logit^{-1} = \frac{e^{\beta_i X_i}}{1 + e^{\beta_i X_i}} \qquad \text{Eq. (10)}$$

where, *P* is the probability of the outcome being 1 (the outcome event), $\left(\frac{P}{1-P}\right)$ is the odds of the outcome happening and its natural log, and is the logit of the probability, β_0 is the intercept, and β_i are the coefficients of the variables X_i.

The target variable has to be categorized into two classes to perform a binary logistic regression. In this study, two classes for the target variable (injury severity) can be obtained by grouping the categories into classes, such as injury vs. non-injury (KABC vs. O), or severe injury vs. minor injury (KA vs. BCO), depending on the data distribution.

C.3.1.2 Multinomial Logistic Regression

Unlike binary logistic regression, multinomial logistic regression can have several outcomes (n), and the results usually contain (n-1) models describing the different levels of the outcome variable. For instance, if the crash severity is grouped into three categories (K, ABC, O) the results will contain coefficients for the (K) class model and the (ABC) class model, while (O) is treated as the base outcome variable.

If the dependent variable is Y, which has i^{th} degrees, and the independent variables are considered as X_{i1}, $X_{i2}, \cdots, X_{ij}$ and j is the number of predictors, the multinomial logistic regression model for the crash k having severity level i can be expressed as shown in Equation (11) (Eboli et al., 2020).

$$\text{Logit}\left(P_k\left(Y_{ij} \leq 1 \mid X_j\right)\right) = \text{Ln}\left(\frac{P_k\left(Y_{ij} \leq 1 | X_j\right)}{1-P_k\left(Y_{ij} \leq i | X_j\right)}\right) = \alpha_i + \beta_{11}X_{i1} + \beta_{i2}X_{i2} + \cdots + \beta_{ij}X_{ij} \qquad \text{Eq. (11)}$$

where, α_i and β_{ij} represent the constant for the crash severity level i and the regression coefficient, respectively; $P_k(Y_{1j} \leq i \mid X_J)$ is the cumulative probability Y_{1J} under the conditional form of $i \mid X_J$ and $\sum_{i=1}^{1} \quad P_k(Y_{1J} \leq i \mid X_1) = 1$.

Thus, the multinomial logistic probability model can be expressed by Equation (12) (Shiran et al., 2021).

$$P_k\left(Y_{ij} \leq 1 \mid X_j\right) = \frac{\exp\left(\alpha_i + \sum_{i=1}^{1} \beta_{ij}X_{ij}\right)}{1+\exp\left(\alpha_i + \sum_{i=1}^{1} \beta_{ij}X_{ij}\right)} \; i = 1,2, \dots, 5; j = 1,2, \dots, J \qquad \text{Eq. (12)}$$

C.3.1.3 Ordinal Logistic Regression

Ordinal logistic regression is an extension of the binary logistic regression model designed to handle multiple categories. It is well-suited for analyzing scenarios where the injury level of the outcome variable is ordinal (Mwambeleko, 2022; Kinero et al., 2024). The logit form of the proportional odds model is expressed by Equation (13).

$$\text{logit}\left[\pi_j(x)\right] = \ln\left(\frac{\pi_j(x)}{1-\pi_j(x)}\right) = \alpha_j + \left(-\beta_1 X_1 - \beta_2 X_2 - \cdots - \beta_p X_p\right) \qquad \text{Eq. (13)}$$

where, $\pi_j(x) = P(Y \leq j \mid x_1, x_2, \dots, x_P)$, which gives the probability of being equal to or below the j level for any given set of predictors, j is a discrete index $\{1,2, \dots, j-1\}$, α_j is the cutoff point, and $\beta_1, \beta_2, \dots, \beta_P$ are the logit coefficients.

To calculate the probability of being equal to or below the j^{th} level, Equation (13) can be rewritten as shown in Equation (14).

$$\text{logit}\left[P\left(Y \leq j \mid x_1, x_2, \dots, x_p\right)\right] = \left(\frac{P\left(Y \leq \beta x_1, x_2 \dots, x_p\right)}{P\left(Y > x_1, x_2 \dots, x_p\right)}\right) = \alpha_I + \left(-\beta_1 X_1 - \beta_2 X_2 - \cdots - \beta_p X_p\right) \qquad \text{Eq. (14)}$$

The results of the ordinal logistic regression provide a model equation with coefficients that indicate the direction and magnitude of each variable category's impact on crash injury severity. The model coefficients suggest whether a particular variable category increases or decreases the likelihood of a more severe injury crash.

C.3.2 Data Analysis Results

The crash data comprised a total of 1,059 crashes. However, these included several unknown values in some of the variables. After carefully removing all unknown values, a total of 961 crashes remained. These were used for further analysis, as shown in the following sections.

C.3.2.1 Limited Access Facilities

For the purpose of work zone crash injury severity, the data was divided into two subsets: limited access facilities (freeways, interstates, and expressways) and arterials and collectors. This categorization was done to specifically examine whether the influence of predictor variables on injury severity differs significantly between these two functional roadway classes. Figure C.8 shows the correlation matrix for the predictor variables. As a correlation threshold of 0.7 was used, no variable was removed from further analysis due to correlation. However, during analysis, the code identified extreme collinearity between the motorcycle variable and the second level of the most harmful event, leading to high error values. The motorcycle variable was therefore not included in the analysis.

Model performance metrics were evaluated for the limited access facilities dataset. The outcome variable, crash severity, was grouped into different categories depending on the nature of the model. The ordinal logistic regression with the KA_BC_O categorization showed the highest prediction performance compared to the other models, as observed in Table C.20.

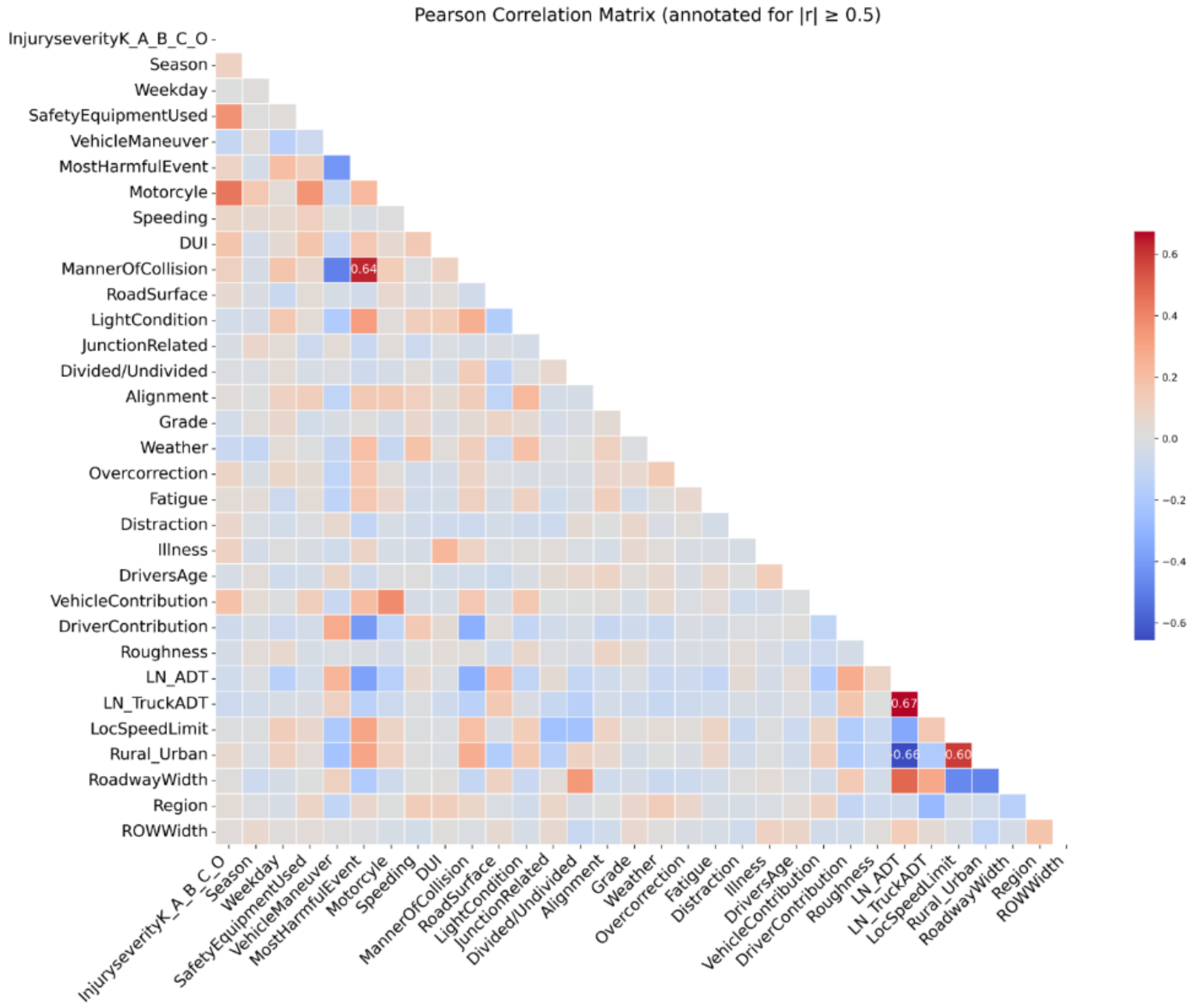


Figure C.8 Correlation matrix of work zone crashes on limited access facilities

Table C.20 Correlation matrix of work zone crashes on limited access facilities

Model	Severity categorization	Accuracy	Log Likelihood	AIC	BIC
Multinomial logistic	KA_BC_O	0.727	-188.701	589.402	1012.232
Ordinal Logistic regression	**KA_BC_O**	**0.765**	**-214.615**	**519.231**	**698.395**
	K_A_B_C_O	0.760	-268.783	645.566	860.835
	KA_B_C_O	0.753	-252.204	608.407	815.572

Note: AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; MSE = Mean Squared Error; MAE = Mean Absolute Error; RMSE = Root Mean Squared Error; K = Fatal injury; A = incapacitating injury; B = non-incapacitating injury; C = possible injury; O = no injury or property damage only; **Bold** values indicate the best performance for each metric.

Table C.21 summarizes the findings from the ordinal logistic regression model. Findings indicate that out of the 29 variables analyzed, nine variables were significant at the 95% confidence level (P-value ≤ 0.05) while one variable were significant at the 90% confidence level (P-value ≤ 0.10). Among those significant at a 95% confidence level are the non-use of safety equipment, vehicle maneuver, DUI, manner of collision, overcorrection, vehicle type, driver contribution (disregard to signs), and natural logarithms of ADT and Truck ADT. Only driver illness was found significant at 90% confidence level.

Findings indicate that when safety equipment, such as a seatbelt or helmet, is not used, work zone crashes have about 11 times higher chances of resulting in higher injury severity compared to when it is used. Work zone crashes on limited access facilities have about 67% lower chances (OR = 0.327) of resulting in severe injuries when the driver is maneuvering compared to when they are driving straight along the work zone.

Other variables that were observed to increase the likelihood of severe injuries include driving under the influence (OR = 3.505) and overcorrection (OR=11.599). Compared to sideswipe crashes, angle crashes have about 13 times higher chances of resulting in severe injuries. Regarding the type of vehicle involved, when a work zone crash involves a motorcycle, the results indicate that work zone crashes have about 20 times higher odds of resulting in severe injuries compared to when a crash does not involve a motorcycle.

Table C.21 Ordinal logistic regression results for limited access facilities

Variable	Category	Coefficient	Odds Ratio	Std. Error	P value
Season (Fall)	Spring	0.475	-	0.460	0.302
	Summer	0.416	-	0.332	0.210
	Winter	0.281	-	0.842	0.739
Day of week (Weekday)	Weekend	0.434	-	0.398	0.275
Safety Equipment Used (Yes)	**None used**	**2.449**	**11.578**	**0.634**	**0.000**
Vehicle Maneuver (Straight ahead)	Slowing/Stopped in Lane	0.073	-	0.381	0.848
	Maneuvering	**-1.117**	**0.327**	**0.550**	**0.042**
Speeding (No)	Yes	0.363	-	0.496	0.463
DUI (No)	**Yes**	**1.254**	**3.505**	**0.538**	**0.020**
Manner of Collision (Sideswipe)	Rear-end	0.992	-	0.723	0.170
	No collision between 2 MV	0.527	-	0.746	0.480
	Angle	**2.633**	**13.912**	**0.847**	**0.002**
Road surface (Asphalt (blacktop))	Concrete	0.047	-	0.434	0.914
Light Condition (Daylight)	Dark - lighted roadway	0.990	-	0.929	0.287
	Dark - roadway not lighted	-0.153	-	0.626	0.807
	Dusk/Dawn	0.011	-	1.027	0.992
Junction Related (No)	Yes	-0.423	-	0.463	0.361
Traffic way (Divided)	Undivided	-1.113	-	1.687	0.510
Roadway alignment (Straight)	Curve	-1.199	-	0.805	0.136
Roadway Grade (Level)	Grade	-0.483	-	0.369	0.190

Note: **Bold** indicates significant at 95% CI (P-value ≤ 0.05) and 90% CI (P-value ≤ 0.1); ADT = Average Daily Traffic.

Table C.21 Ordinal Logistic Regression Results for Limited Access Facilities (continued)

Variable	Category	Coefficient	Odds Ratio	Std. Error	P value
Weather condition (Clear)	Cloudy	-0.167	-	0.455	0.713
	Severe	-0.619	-	0.655	0.345
Overcorrection (No)	**Yes**	**2.451**	**11.599**	**0.842**	**0.004**
Fatigue (No)	Yes	0.152	-	1.222	0.901
Distraction (No)	Yes	0.752	-	0.619	0.224
Illness (No)	**Yes**	**2.101**	**8.171**	**1.100**	**0.056**
Drivers age (35-64)	20-34	-0.377	-	0.337	0.264
	12-19	-0.473	-	0.584	0.419
	>=65	0.056	-	0.393	0.886
Vehicle Type (Passenger vehicle)	Light trucks	0.476	-	0.295	0.107
	Motorcycle	**3.037**	**20.840**	**0.625**	**0.000**
	Trucks	-0.418	-	0.887	0.638
Driver Contribution (None)	**Disregard to signs**	**0.968**	**2.632**	**0.347**	**0.005**
Roughness (>=4) Good	Fair/poor (<4.0)	-1.127	-	1.224	0.357
Regions (Aberdeen)	Mitchell	0.778	-	1.385	0.574
	Pierre	1.562	-	1.349	0.247
	Rapid City	0.187	-	1.405	0.894
Area (Urban)	Rural	0.607	-	0.529	0.252
LN_ADT		**1.337**	**3.808**	**0.535**	**0.012**
LN_TruckADT		**-1.214**	**0.297**	**0.546**	**0.026**
LocSpeedLimit		-0.027	-	0.036	0.451
Roadway Width		-0.034	-	0.031	0.274
ROW Width		-0.001	-	0.003	0.786
Thresholds	0|1	4.560	-	3.677	0.215
	1|2	6.703	815.166	3.689	0.069

Note: **Bold** indicates significant at 95% CI (P-value ≤ 0.05) and 90% CI (P-value ≤ 0.1); ADT = Average Daily Traffic.

Disregarding signs shows a positive coefficient and an odds ratio of about 2.6, implying that crashes related to drivers disregarding work zone signs have 2.6 times higher odds of resulting in severe injuries compared to those that do not involve any risky behavior. This highlights the importance of enhancing compliance in highway work zones. Findings indicate that an increase in ADT is associated with increased crash injury severity, with an odds ratio of 3.808. On the contrary, the natural logarithm of the truck ADT is observed with a negative coefficient and an odds ratio of 0.297, indicating that the higher the truck ADT, the lower the odds of crashes resulting in severe injuries along work zones. This could be attributed to the fact that higher truck volumes often lead to lower overall travel speeds due to their slower acceleration and reduced maneuverability, which may reduce the severity of crash impacts. Additionally, the presence of more trucks may prompt greater caution and attentiveness among drivers in work zones.

C.3.2.2 Arterials and Collectors

Arterials and collectors in this project refer to principal arterials, major and minor collectors, and local roads. Similar to the other models, a correlation matrix was first developed before the analysis was conducted. Figure C.9 shows that the nature of the area (urban/rural) was highly correlated with the natural logarithm of ADT and the location speed limit (correlation coefficient above 0.7). For this reason, the rural-urban variable was removed from further analysis. For this dataset, only the ordinal models were performed and compared. The findings indicated that the KA_BC_O categorization achieved the best performance compared to the other models, as shown in Table C.22. Ordinal logistic regression was then performed on the data, with the outcome variable categorized as KA_BC_O. The findings are summarized in Table C.23.

Table C.22 Model performance summary for arterials and collectors

Ordinal Logistic	Severity Categorization	Accuracy	Log Likelihood	AIC	BIC	McFaddenR^2
Model 1	**KA_BC_O**	**0.637**	**-197.770**	**489.541**	**667.236**	**0.231**
Model 2	K_A_B_C_O	0.625	-252.945	613.891	818.384	0.239
Model 3	KA_B_C_O	0.656	-255.715	607.431	789.055	0.204

Note: AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; K = Fatal injury; A = incapacitating injury; B = non-incapacitating injury; C = possible injury; O = no injury or property damage only.; **Bold** values indicate the best performance for each metric.

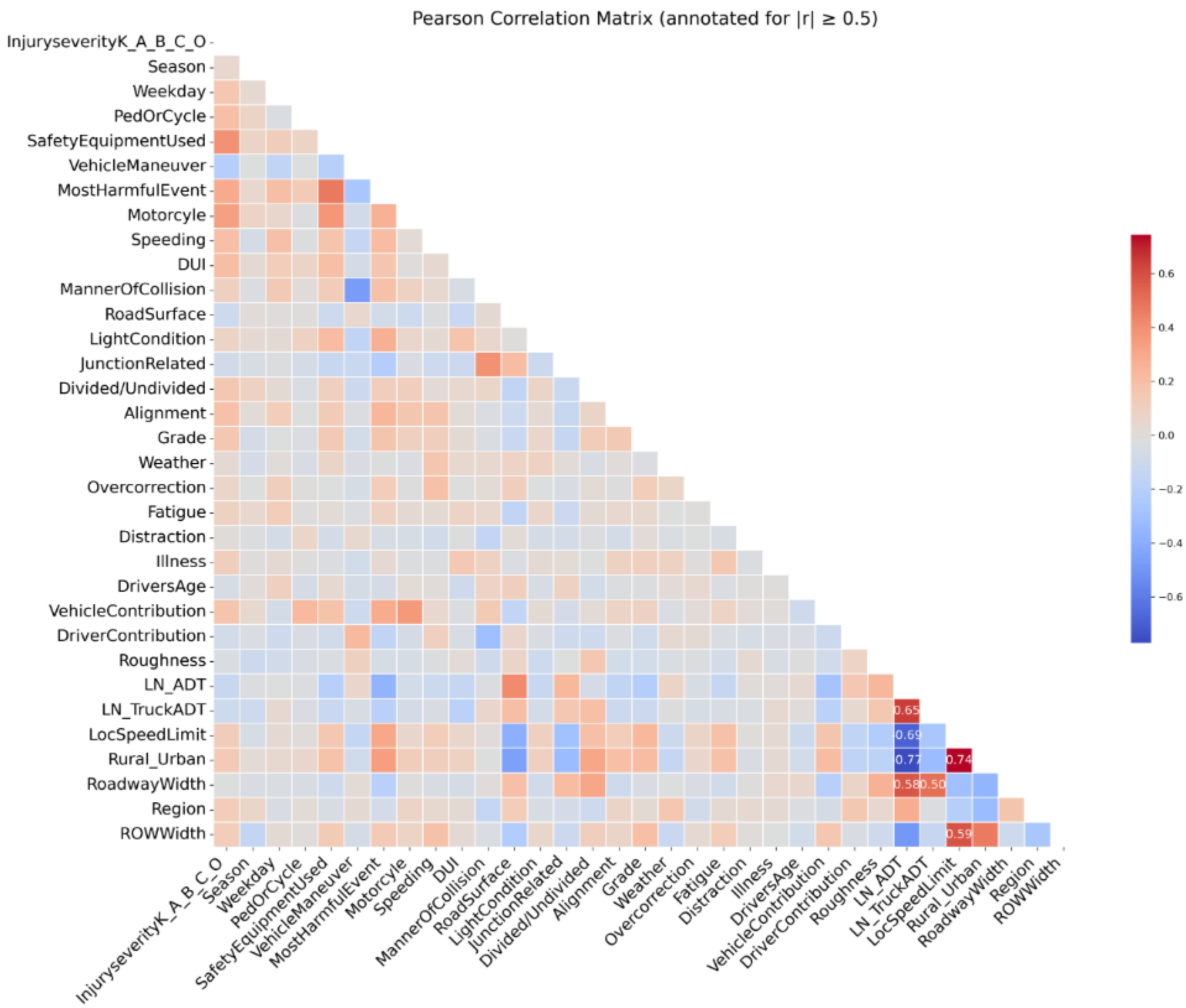


Figure C.9 Correlation matrix of work zone crashes on arterials and collectors

Table C.23 Ordinal logistic regression results for arterials and collectors

Variable	Category	Value	Odds Ratio	Std. Error	P value
Season (Fall)	Spring	-0.031	-	0.450	0.945
	Summer	0.202	-	0.349	0.564
	Winter	0.377	-	0.570	0.509
Day of week (Weekday)	Weekend	0.386	-	0.435	0.374
Safety equipment used (Yes)	**No**	**2.257**	**9.553**	**0.725**	**0.002**
Vehicle Maneuver (Straight ahead)	Slowing/Stopped	-0.669	-	0.534	0.210
	Maneuvering	**-1.681**	**0.186**	**0.660**	**0.011**
Speeding (No)	Yes	0.636	-	0.620	0.305
DUI (No)	**Yes**	**1.021**	**2.777**	**0.499**	**0.041**
Manner of Collision (Sideswipe)	Rear-end	0.852	-	0.841	0.311
	No collision btw 2 MV	-0.659	-	0.977	0.500
	Angle	-0.266	-	0.882	0.763
Road surface (Asphalt blacktop)	Concrete	-0.302	-	0.398	0.449
	Other	0.131	--	0.846	0.877
Light Condition (Daylight)	Dark - lighted	-0.702	-	0.660	0.287
	Dark - not lighted	-0.882	-	0.754	0.242
	Dusk/Dawn	0.333	-	0.712	0.640
Junction Related (No)	Yes	0.191	-	0.390	0.624
Traffic way (Divided)	Undivided	0.754	-	0.480	0.116
Roadway alignment (Straight)	Curve	0.773	-	0.824	0.348
Roadway Grade (Level)	Grade	0.638	-	0.441	0.148
Weather (Clear)	Cloudy	0.318	-	0.332	0.337
	Severe	0.313	-	0.957	0.743
Overcorrection (No)	Yes	1.583	-	2.224	0.476
Fatigue (No)	Yes	0.506	-	0.812	0.534
Distraction (No)	Yes	-0.457	-	0.535	0.393
Illness (No)	**Yes**	**2.928**	**18.693**	**1.274**	**0.022**
Drivers age (35-64)	20-34	0.465	-	0.342	0.174
	15- 19	0.545	-	0.409	0.183
	≥65	**-1.007**	**0.365**	**0.501**	**0.044**
Type of vehicle (Passenger car)	Light trucks	-0.153	-	0.314	0.626
	Motorcycle	1.043	-	1.360	0.443
	Trucks	-0.210	-	1.083	0.847
	Other	**3.079**	**21.732**	**1.606**	**0.055**
Driver Contribution (None)	**Disregard to signs**	**0.682**	**1.978**	**0.380**	**0.073**
Regions (Aberdeen)	Mitchell	0.288	-	0.566	0.611
	Pierre	0.457	-	0.723	0.528
	Rapid City	**1.011**	**2.748**	**0.504**	**0.045**
Roughness (≥4) Good	Fair/Poor (<4)	-0.160	-	0.379	0.673

Note: **Bold** indicates significant at 95% CI (P-value ≤ 0.05) and 90% CI (P-value ≤ 0.1); ADT = Average Daily Traffic.

Table C.23 Ordinal Logistic Regression Results for Arterials and Collectors (continued)

Variable	Category	Value	Odds Ratio	Std. Error	P value
Ln (ADT)		-0.043	-	0.369	0.907
Ln (Truck ADT)		0.152	-	0.312	0.626
Speed Limit		-0.019	-	0.019	0.319
Roadway Width		-0.004	-	0.012	0.714
ROW Width		**0.009**	**1.009**	**0.004**	**0.027**
Thresholds	0|1	3.088	-	3.230	0.339
	1|2	6.025	-	3.250	0.064

Note: **Bold** indicates significant at 95% CI (P-value ≤ 0.05) and 90% CI (P-value ≤ 0.1); ADT = Average Daily Traffic.

Findings indicate that seven variables were significant at the 95% confidence level, while two variables were significant at the 90% confidence level. Safety equipment non-usage, vehicle maneuver, driving under the influence of alcohol or drugs (DUI), illness, driver age, region, and right-of-way width were found significant at 95% CI, while the type of vehicle and driver disregard to signs were found significant at 90% CI.

The lack of safety equipment usage was observed with a coefficient of 2.257 and an odds ratio of 9.553. The high odds ratio indicates that when a vehicle occupant is not wearing a seatbelt or helmet, they have approximately 9.5 times higher odds of incurring severe injuries compared to when they are wearing one. On the contrary, vehicle maneuvering is associated with 81.4% lower odds of severe injuries (OR = 0.186) when crashes occur along arterials and collectors. This can be attributed to the relatively lower speeds and more controlled driving conditions on arterials, collectors, and local roads, which may enable drivers to maneuver safely and avoid severe injuries in the event of a crash.

As expected, DUI is associated with an increased likelihood of severe injuries in the case of work zone crashes along arterials and collectors. With a coefficient of 1.021, crashes involving DUI have about 2.78 times higher chances of resulting in more severe injuries compared to those that do not involve DUI. Illness is positively associated with increased crash severity along work zones on arterials and collectors. Work zone crashes involving drivers with illness have over 18 times higher odds of resulting in severe injuries compared to crashes that do not involve an ill driver. This may be attributed to physical impairments, reduced alertness, and a reduced ability for fast decision-making, factors usually associated with illness. When a work zone crash occurs under these circumstances, such limitations can reduce the driver's ability to effectively respond to the hazardous conditions within a work zone, escalating the severity of injuries sustained.

Findings further indicate that crashes involving older drivers above 65 years have lower odds of resulting in severe injuries compared to those that involve relatively younger drivers. Specifically, crashes involving seniors have 63.5% lower odds of severe injuries compared to those involving middle-aged drivers. Crashes occurring on arterials and collector work zones within the Rapid City region have 2.748 times higher odds of resulting in severe injuries compared to those that occur in the Aberdeen region. Lastly, a unit increase in the right-of-way width is observed to increase the likelihood of crash severity by approximately 0.9% (OR = 1.009). For work zones on arterials and collectors, this pattern may be attributed to the possibility of speeding in wider road environments, which can encourage risky driving behaviors such as sudden lane changes, thereby increasing the likelihood of severe injuries when crashes occur in work zones.

C.3.3 Summary

The analysis of work zone crash injury severity on limited access facilities, and arterials and collectors revealed notable differences in injury severity predictors. Ordinal logistic regression was employed to identify factors influencing severity across both facility types. Regression coefficients and odds ratios were examined to determine both the magnitude and direction of the predictors' effects. Odds ratios express the likelihood of experiencing a higher injury severity level relative to a baseline category, given a unit change in the predictor variable. Odds ratios greater than 1 indicate an increased likelihood of more severe injuries associated with a predictor, while odds ratios less than 1 suggest a decreased likelihood. An odds ratio equal to 1 implies no effect on injury severity.

Findings from the ordinal logistic regression model for limited access facilities indicate that out of the 29 variables analyzed, nine variables were significant at the 95% confidence level (P-value ≤ 0.05) while one variable was significant at the 90% confidence level (P-value ≤ 0.10). Factors associated with increased crash severity include: lack of safety equipment (OR = 11.578), DUI (OR = 3.505), angle collisions (OR = 13.912), overcorrection (OR = 11.599), illness (OR = 8.171), motorcycles (20.840), disregard to signs (OR = 2.632), Ln (ADT) (OR = 3.808). On the contrary, variables found to have a negative association with crash severity include driver maneuvering (OR = 0.327) and Ln (Truck ADT) (OR = 0.297).

On arterials and collectors, seven variables were significant at the 95% confidence level while two were significant at 90% confidence level. Variables identified to have higher odds of crashes resulting in severe injuries, with respective odds ratios include: lack of safety equipment usage (OR = 9.553), driving under influence of alcohol and drugs (DUI) (OR = 2.777), illness (OR = 18.693), other vehicle types such as buses and vans (21.732), disregard to signs by drivers (OR = 1.978), Rapid City region (OR = 2.748), and right-of-way width (OR = 1.009). The presence or one unit increase in these variables is associated with increased work zone crash injury severity. On the contrary, vehicle maneuvering (OR = 0.186) and drivers aged 65 years and above (OR = 0.365) were found to have a negative association with crash severity. This implies that the presence of these factors leads to less severe work zone crash injuries. Generally, both limited and non- limited access facilities' (arterials and collectors) analyses emphasize the importance of safe driver behavior, vehicle type, roadway design, and environmental conditions in influencing injury severity in work zone crashes, suggesting targeted safety interventions for each road type.

C.4 Speed Data Analysis

Speed data collected along work zones is valuable for assessing driver compliance with speed limits. The SDDOT office provided speed data for seven projects. The data was acquired from private contractors, Ver-Mac, and was provided in Excel files. Each dataset was delivered in Excel format and included 15-minute interval records of variables such as speed, occupancy, and vehicle count for the entire project duration. The speed data were provided for the following projects, along with their respective durations.

- I-29 Sioux Falls 0293(106)76: May 2022 – July 2024
- I-229 Minnehaha Co (2021): May 2021 – October 2021
- I-229 Minnehaha Co IM 2292(98)9 (2023): April 2023 – November 2024
- I-229 Minnehaha Co IM 2292(105)3 (2024): July 2024 – October 2024
- I-90 Pennington Co (2021): June 2021 – December 2021
- I-90 Pennington Co 0901(195)32: September 2022 – December 2022
- I-90 Various Co IM-NH 0041(181) (2024): July 2024

Each project dataset had different data descriptions depending on the location of the sensors. Using the variable names, the research team was able to identify speed, occupancy, and vehicle count along the work zone and the downstream conditions. The Z-test (z-statistical test) was used to determine the significance of speed variation between two locations. A one-tailed z-test was used, as the study aimed to identify the presence of significant speed reductions/increases at work zones or downstream locations. Identifying these speed patterns help assess driver compliance with work zone signage. Specifically, significant speed reductions approaching a work zone suggest higher levels of compliance, while the absence of such reductions may indicate low compliance with temporary traffic control measures. The following section discusses how the z-test values are computed and what the corresponding results imply.

C.4.1 Z-Test

For all projects, the data included speed, occupancy, and traffic volume values at 15-minute time intervals for the entire project duration. From the column headers in the data, the research team identified upstream and downstream values for each location. Since the exact location where the sensors were placed is unknown, the results should be used with caution.

The z-statistic was used to determine significant speed changes from upstream and downstream locations, or at a specific distance before the start of the work zone taper. The z-statistic can be calculated as presented by Equation (15).

$$Z = \frac{\mu_2 - \mu_1}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}} \qquad \text{Eq. (15)}$$

where,

Z = critical value of the normal distribution at 95% CI,
μ_1 = traffic mean speed at the upstream location,
S_1 = standard deviation of traffic speed at the upstream location,
n_1 = number of sensor speed readings at the upstream location,
μ_2 = traffic mean speed at the downstream location,
S_2 = standard deviation of traffic speed at the downstream location, and
n_2 = number of sensor speed readings at the downstream location.

The null hypothesis, H_0, is that the difference in the means of traffic speeds at the upstream and downstream locations is zero (i.e., H_0: $\mu_2 = \mu_1$).

The alternative hypothesis, H_a, is that either the upstream or downstream location has a higher speed compared to the other at a 95% confidence level (i.e., H_a: $\mu_2 < \mu_1$).

To reject the null hypothesis (i.e., there is a significant reduction or increase in speed), the z- statistic should be less than Z_α at 95% CI. Z_α represents the critical value in the normal distribution (according to the Central Limit Theorem) at a 95% confidence interval (-1.645). Any z-statistic value less than -1.645 or greater than 1.645 indicates a statistically significant reduction or increase in speed, respectively. The proportion of significant speed changes will reflect the extent to which motorists comply with speed reduction signs at work zones.

C.4.2 Peak Hour Analysis

For every project, the z-statistic values were computed based on the peak hour durations. Specifically, the speed data for all months, in 15-minute intervals, was aggregated into peak hours which were assumed as follows:

- AM peak hour: 7:00 AM to 10:00 AM
- PM peak hour: 3:00 PM to 6:00 PM
- Off-peak hours: All other times

C.4.3 Project-specific Results

The following sections discuss the speed data analysis results for each specific project. As mentioned earlier, the z-test was used to determine whether there were significant speed changes between the work zone location and the downstream location during both peak and off-peak hours. For other projects with multiple sensor locations, the z-test was used to determine significant speed changes between two consecutive sensor locations where the data was collected. Due to limited data availability, vehicle count and occupancy data were not analyzed. Only speed was analyzed using the z-test.

C.4.3.1 I-29 Sioux Falls 0293(106)76

This project was located along the 41st Street and I-29 interstate route in Minnehaha County. The project ran along 41st Street, between Marion Road and Shirley Avenue, covering a distance of approximately 1 mile. The project involved different activities, including grading, structures, curb and gutter, storm sewer, sidewalk improvement, pavement marking, signals, lighting, and permanent signing. The project started in May 2022 and ended in July 2024. Figure C.10 presents the project plan.

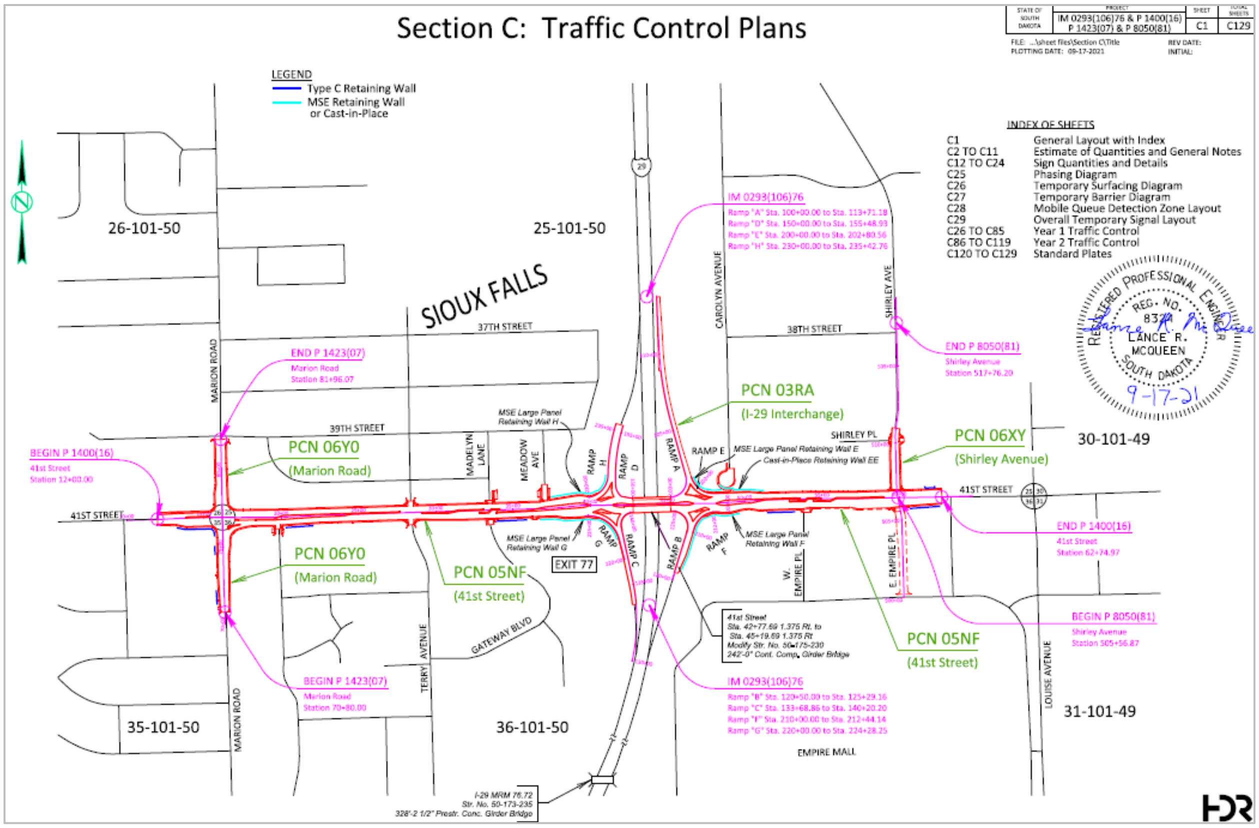


Figure C.10 I-29 Sioux Falls 0293(106)76 project plan

From the sensor data, a total of nine distinct locations and their corresponding downstream locations were identified, where data were collected monthly from May 2022 to July 2024. All monthly files were combined into a single, comprehensive Excel file. Using the Python programming language, the data was then aggregated by peak hours and off-peak hours. The z- test was then performed to identify if there are significant speed changes between work zone locations and their corresponding downstream locations. Table C.24 summarizes the z-statistic test results for the different sensor locations.

Results summarized in Table C.24 show that for AM and PM peak hours, there was a significant increase in speed at the downstream location for seven out of the nine locations. The two remaining locations at Zone 3 did not exhibit any significant speed changes during either the AM or PM peak hours. However, during off-peak hours, three out of the nine locations showed no significant changes in speed. During off-peak hours, an increase in average speed was observed. However, this change was not significant at the 95% confidence level changes in speed.

Table C.24 Speed data analysis results for I-29 Sioux Falls project

Period	Zone/Sensor	Z Statistic	P value	Conclusion (95%)
AM Peak	Zone 01 - NB I-29 Sensor 01	10.647	<0.001	Significant increase downstream
	Zone 02 - NB I-29 Sensor 01	21.977	<0.001	Significant increase downstream
	Zone 02 - NB I-29 Sensor 02	18.723	<0.001	Significant increase downstream
	Zone 03 - NB I-29 Sensor 01	-63.188	1.000	No significant change
	Zone 03 - NB I-29 Sensor 02	-150.619	1.000	No significant change
	Zone 04 - SB I-29 Sensor 01	11.849	<0.001	Significant increase downstream
	Zone 04 - SB I-29 Sensor 02	19.055	<0.001	Significant increase downstream
	Zone 05 - SB I-29 Sensor 01	56.814	<0.001	Significant increase downstream
	Zone 05 - SB I-29 Sensor 02	70.235	<0.001	Significant increase downstream
PM Peak	Zone 01 - NB I-29 Sensor 01	24.912	<0.001	Significant increase downstream
	Zone 02 - NB I-29 Sensor 01	18.741	<0.001	Significant increase downstream
	Zone 02 - NB I-29 Sensor 02	23.491	<0.001	Significant increase downstream
	Zone 03 - NB I-29 Sensor 01	-56.565	1.000	No significant change
	Zone 03 - NB I-29 Sensor 02	-189.170	1.000	No significant change
	Zone 04 - SB I-29 Sensor 01	34.256	<0.001	Significant increase downstream
	Zone 04 - SB I-29 Sensor 02	22.604	<0.001	Significant increase downstream
	Zone 05 - SB I-29 Sensor 01	47.642	<0.001	Significant increase downstream
	Zone 05 - SB I-29 Sensor 02	55.846	<0.001	Significant increase downstream
Off-peak	Zone 01 - NB I-29 Sensor 01	3.258	<0.001	Significant increase downstream
	Zone 02 - NB I-29 Sensor 01	10.064	<0.001	Significant increase downstream
	Zone 02 - NB I-29 Sensor 02	41.445	<0.001	Significant increase downstream
	Zone 03 - NB I-29 Sensor 01	-23.266	1.000	No significant change
	Zone 03 - NB I-29 Sensor 02	-200.977	1.000	No significant change
	Zone 04 - SB I-29 Sensor 01	-33.354	1.000	No significant change
	Zone 04 - SB I-29 Sensor 02	3.426	<0.001	Significant increase downstream
	Zone 05 - SB I-29 Sensor 01	97.585	<0.001	Significant increase downstream
	Zone 05 - SB I-29 Sensor 02	131.781	<0.001	Significant increase downstream

C.4.3.2 I-90 IM 0902(112)59 Project

The I-90 IM 0902(112)59 Project was located in Pennington County, as shown in Figure C.11. The project lasted for seven months, from June 2021 to December 2021. The project was located along the I-90 route at Exit 59, extending from MM 59.02 to MM 59.38, with a total length of approximately 0.36 miles (0.58 km). Some of the work zone activities in this project included grading, curb and gutter installation, storm sewer construction, asphalt concrete surfacing, pavement markings, lighting, signal installation, and pavement marking works.

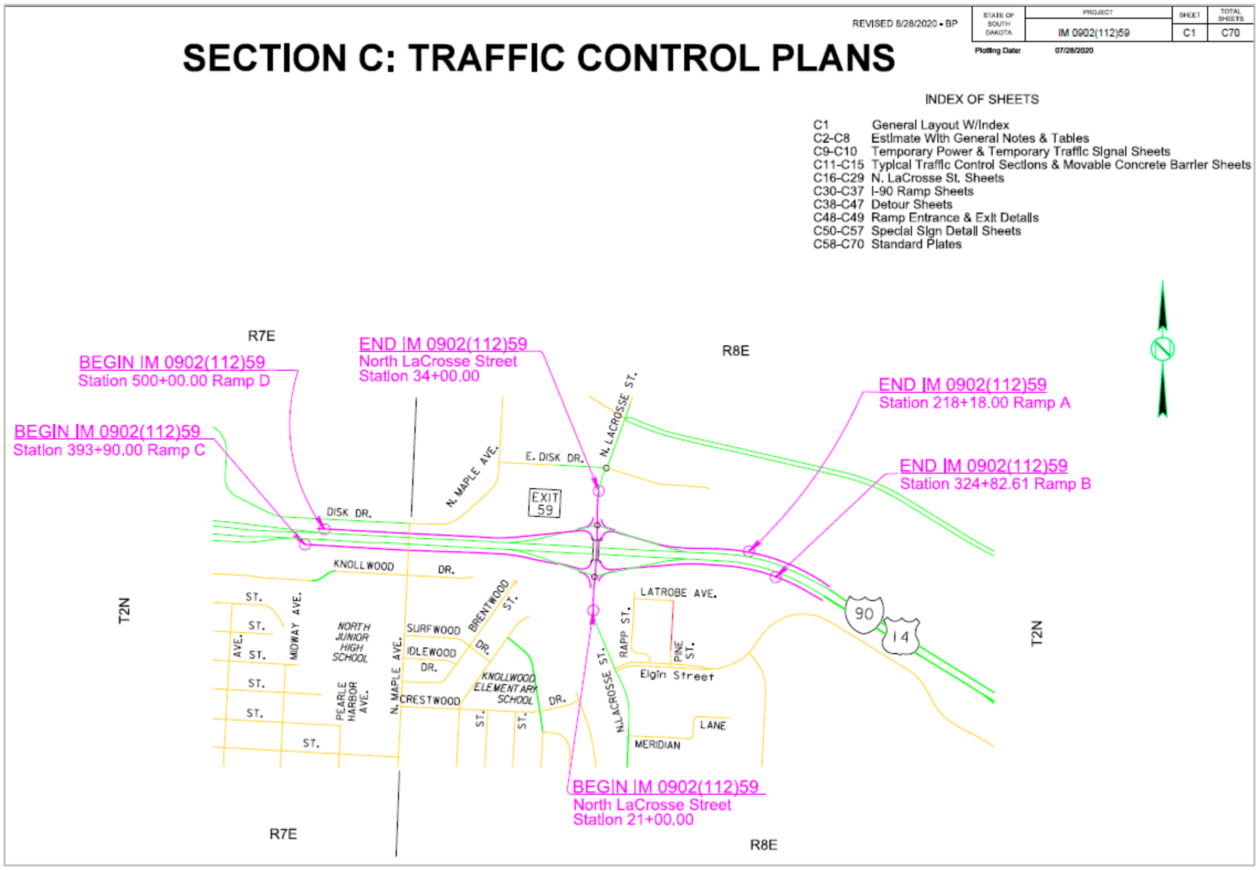


Figure C.11 I-90 IM 0902(112)59 Pennington County project plan

For this project, Doppler sensors were located at specific distances before and at the work zone location (beginning of the work zone taper). The analysis was conducted to identify significant speed increases or decreases between two consecutive locations, in each direction. For instance, in the EB location, sensors were located 2.0 miles, 1.0 miles, and at the taper. For this direction, the analysis was conducted to identify significant speed changes between the 2.0- and 1.0-mile locations before the taper, and between the 1.0-mile and the taper. Table C.25 summarizes the z- statistic test results for the different sensor locations with respect to the taper location.

Results in Table C.25 indicate that along the EB direction, there was a significant increase in speed for all conditions at all hours. In other words, there was a significant speed increase from 2.0 miles before taper to 1.0 miles before taper. There was also a speed increase from 1.0 miles before the taper to the taper location. However, in the WB direction, significant speed reductions were observed from 0.3 miles before the taper to the taper location during all hours. This implies that drivers reduced their speed as they approached the beginning of the work zone in the WB direction, but drivers on the EB direction increased their speed as they approached the work zone. Additional data, such as origin-destination traffic patterns, are needed to understand the contrasting pattern in driver behavior better.

Table C.25 Speed data analysis results for I-90 IM 0902(112)59 project

Dir.	Time	Test	Mean Upstream	Mean Downstream	Z statistic	P value	Conclusion (95%)
Eastbound	AM peak	2.0 mi to 1.0 mi	62.58	63.65	10.745	<0.001	Significant Increase
		1.0 mi to the taper	63.83	64.72	12.891	<0.002	Significant Increase
	PM peak	2.0 mi to 1.0 mi	62.60	62.97	3.778	<0.003	Significant Increase
		1.0 mi to the taper	63.20	64.16	12.42	<0.004	Significant Increase
	Off-peak	2.0 mi to 1.0 mi	63.12	64.02	19.783	<0.005	Significant Increase
		1.0 mi to the taper	64.19	64.70	11.604	<0.006	Significant Increase
Westbound	AM peak	1.3 mi to 0.3 mi	56.94	65.08	59.531	<0.007	Significant Increase
		0.3 mi to the taper	65.05	60.25	-53.551	<0.008	Significant Decrease
	PM peak	1.3 mi to 0.3 mi	57.58	64.41	39.953	<0.009	Significant Increase
		0.3 mi to the taper	64.44	59.65	-55.809	<0.010	Significant Decrease
	Off-peak	1.3 mi to 0.3 mi	57.68	64.81	99.181	<0.011	Significant Increase
		0.3 mi to the taper	64.84	60.20	-94.62	<0.012	Significant Decrease

Note: Dir. = Direction.

C.4.3.3 I-90 IM-NH 0041(181)

This project was located along the I-90, State Highway SD 34, and US Highway 14 in Lawrence, Meade, Pennington, and Jackson Counties. The project segment along I-90 started at MM 9.34 and ended at MM 15.00, extending about 5.66 miles. The segment along SD 34 extended from MM 35.82 to MM 38.83, extending about 3.01 miles, as shown on Figure C.12. The data for this project was available only for July 2024. Speed sensor data for this project was collected only for the I-90 segment. No data was available from the other project sections.

Table C.26 summarizes the z-statistic test results for the different sensor locations. Sensors in this project were located at particular distances from the taper: 0.75 miles, 0.6 miles, 0.2 miles, and at 0.0 miles (i.e., at the taper). Results in Table C.26 indicate that there were no significant speed changes during the AM peak hours for both WB and SB directions. During the PM peak hours, a significant speed increase was observed along the WB direction, from 0.75 miles to 0.6 miles to the taper. Along the EB direction, significant speed reductions were observed from 0.75 to 0.6 miles to the taper. However, a significant speed increase was observed from the 0.2- mile to the taper location. This implies there was a tendency for drivers to lower their speeds further from the work zone and increase their speeds closer to the work zone during PM peak hours. During off-peak hours, no significant speed changes were observed in both directions.

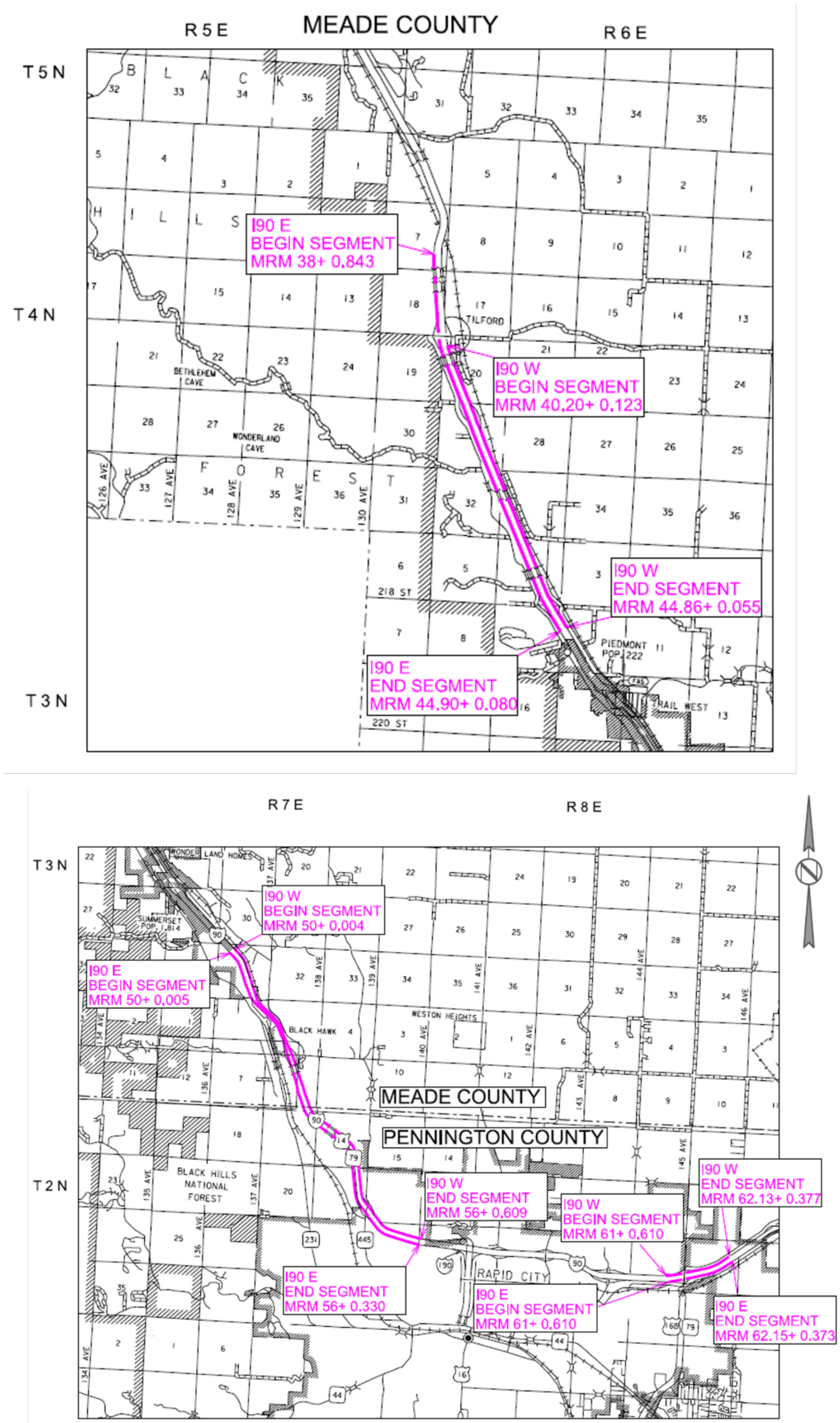


Figure C.12 I-90 IM-NH 0041(181) project plan

Table C.26 Speed data analysis results for I-90 IM-NH 0041(181) project

Time Period	Dir.	From (mi)	To (mi)	Mean From	Mean To	Z Statistic	P value	Conclusion (95%)
AM Peak	WB	0.75	0.6	56.87	57.17	0.117	0.907	No Significant Change
		0.6	0.2	57.17	58.06	0.311	0.756	No Significant Change
		0.2	0	58.06	56.37	-0.581	0.561	No Significant Change
	EB	0.75	0.6	66.3	66.94	0.348	0.728	No Significant Change
		0.6	0.2	66.94	65.28	-0.988	0.323	No Significant Change
		0.2	0	65.28	63.99	-0.806	0.42	No Significant Change
PM Peak	WB	0.75	0.6	35.28	45.06	2.778	0.005	Significant Increase
		0.6	0.2	45.06	38.11	-1.448	0.148	No Significant Change
		0.2	0	38.11	44.34	1.3	0.194	No Significant Change
	EB	0.75	0.6	62.29	55.57	-2.422	0.015	Significant Decrease
		0.6	0.2	55.57	53.18	-0.642	0.521	No Significant Change
		0.2	0	53.18	61.42	2.917	0.004	Significant Increase
Off peak	WB	0.75	0.6	53.51	55.5	0.952	0.341	No Significant Change
		0.6	0.2	55.5	51.11	-1.816	0.069	No Significant Change
		0.2	0	51.11	52.2	0.477	0.633	No Significant Change
	EB	0.75	0.6	60.01	58.42	-0.823	0.411	No Significant Change
		0.6	0.2	58.42	57.39	-0.457	0.648	No Significant Change
		0.2	0	57.39	57.63	0.109	0.913	No Significant Change

Note: EB = Eastbound; WB = Westbound.

C.4.3.4 IM 2292 (108)0 Project

The IM 2292 (108)0 Project took place along the I-229 state route and lasted for six months, from May 2021 to October 2021. The project was present in both NB and SB directions of the I-229, from MM 0.93 to MM 2.08 (Exit 1 to Exit 2), extending a distance of about 1.15 miles. The project involved several activities, including NRC pavement repair, partial-depth patching, planning of PCC pavement, asphalt concrete resurfacing, and installation of durable pavement markings. Figure C.13 presents the work zone plan corresponding to the IM 2292 (108)0 Project.

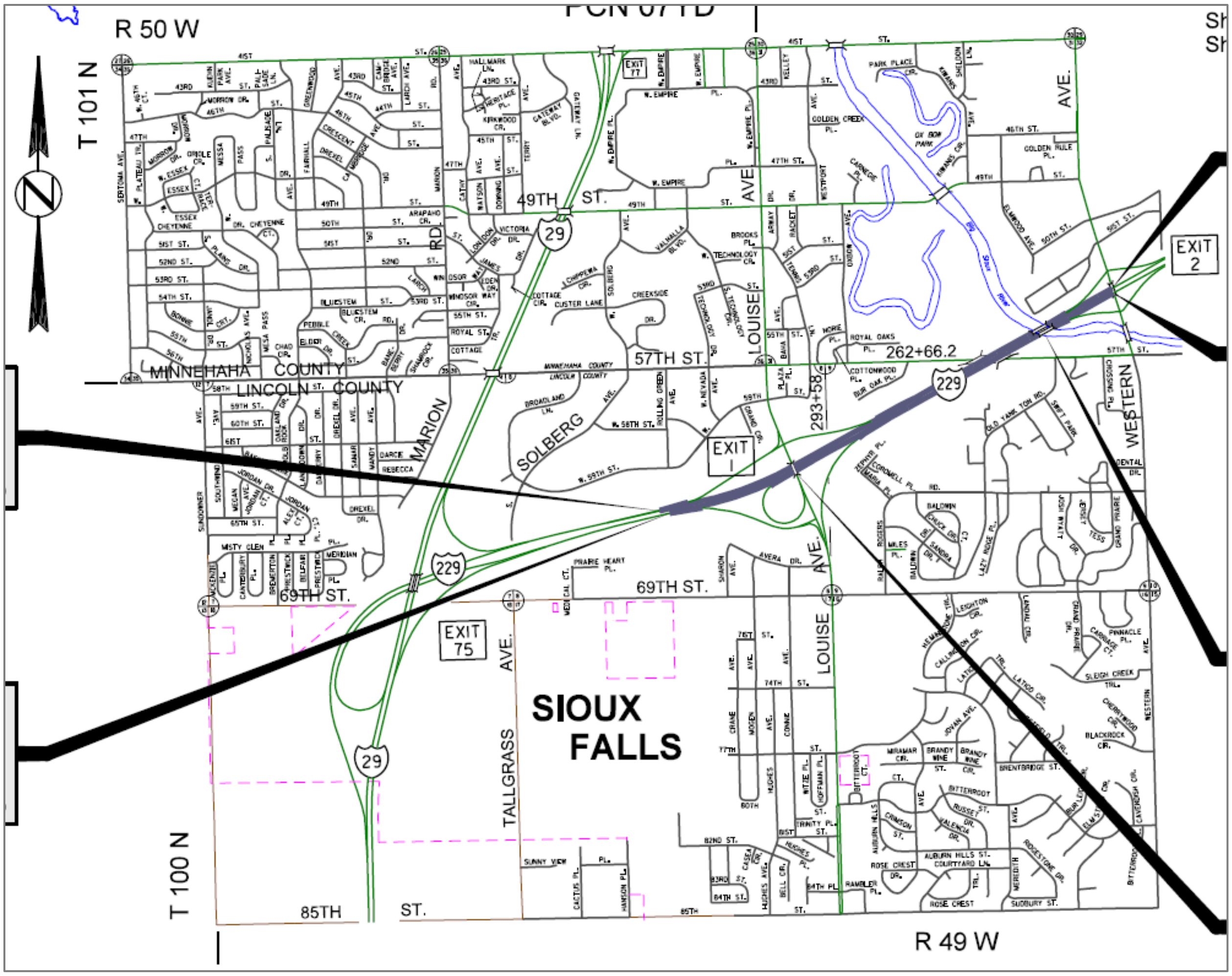


Figure C.13 IM 2292 (108)0 project plan

Speed, vehicle count, and occupancy data were collected from Doppler radars located along the project. Using the z-test statistic, significant speed changes were determined between two consecutive Doppler radars. Table C.27 summarizes the z-statistic test results for the different sensor locations.

Table C.27 Speed data analysis results for IM 2292 (108)0 project

Dir.	Period	From	To	Mean (From)	Mean (To)	Z statistic	P value	Conclusion (95%)
NB I- 229	AM Peak	Doppler 1	Doppler 2	62.027	61.787	-0.895	0.185	No significant change
	PM Peak	Doppler 1	Doppler 2	60.888	61.987	3.511	<0.001	Significant increase
	Off-Peak	Doppler 1	Doppler 2	64.196	62.352	-27.194	<0.001	Significant decrease
SB I-229	AM Peak	Doppler 1	Doppler 2	60.329	59.795	-1.832	0.033	Significant decrease
	PM Peak	Doppler 1	Doppler 2	58.013	57.248	-1.997	0.023	Significant decrease
	Off-Peak	Doppler 1	Doppler 2	62.919	60.947	-26.307	<0.001	Significant decrease
	AM Peak	Doppler 2	Doppler 3	59.795	68.889	39.342	<0.001	Significant increase
	PM Peak	Doppler 2	Doppler 3	57.248	69.134	40.606	<0.001	Significant increase
	Off-Peak	Doppler 2	Doppler 3	60.947	68.201	118.855	<0.001	Significant increase

Note: Dir. = Direction.

Findings show that there were no significant speed changes during the AM peak hours for the NB direction. However, while a significant speed increase was observed from Sensor 1 to Sensor 2 during peak hours, a significant speed reduction was observed during off-peak hours. Three Doppler sensors were placed along the SB direction. The z-statistic values were calculated to determine speed changes from Sensor 1 to Sensor 2 and from Sensor 2 to Sensor 3. Varying effects were observed during the different peak hours. Significant speed reductions were observed from Sensor 1 to Sensor 2, while significant speed increase was observed from Sensor 2 to Sensor 3 for all periods.

C.4.3.5 I-229 IM 2292(98)9 Project

This project was located along Benson Road and Interstate 229 in Minnehaha County, as shown in Figure C.14. The project lasted for about 20 months, from April 2023 to November 2024. The project included structural work, grading, PCC pavement, curb and gutter, storm sewer, roadway lighting, signals, pavement marking and permanent signing. The data for this project dataset included sensor data at locations along the work zones.

Findings summarized in Table C.28 show that during the AM peak hour, two out of the four locations experienced a significant speed increase, while the other two experienced a speed decrease. However, during the PM peak hour, only Zone 1 showed a significant increase in speed at the downstream location, while all other locations experienced a significant speed reduction. Similar to the AM peak hour, only Zone 1 and Zone 4 experienced a significant increase in speed at the downstream location. Zones 2 and 3 experienced a significant reduction in speed from the work zone location to the downstream location.

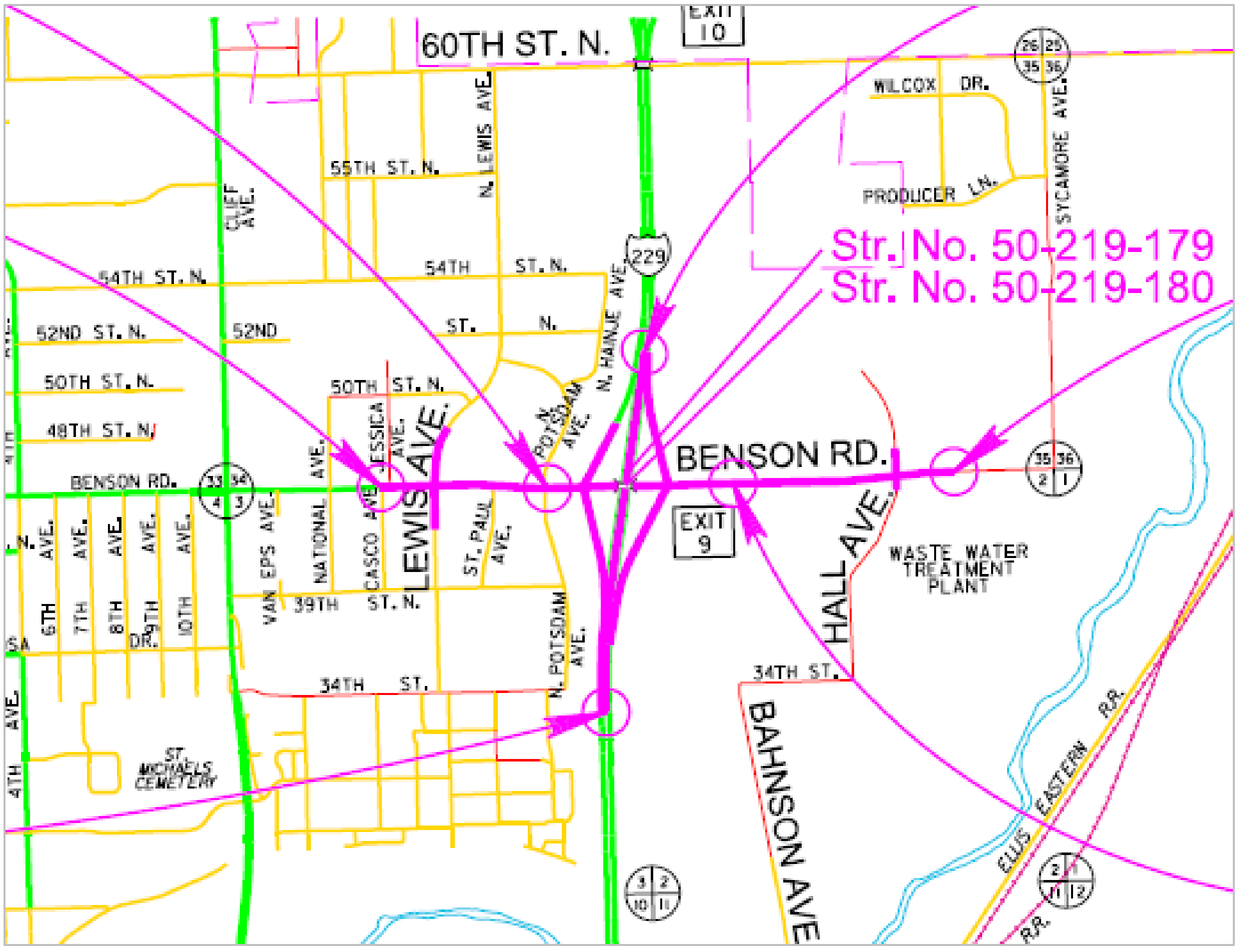


Figure C.14 IM 2292 (98)9 project plan at Benson Road

Table C.28 Speed data analysis results for I-229 IM 2292(98)9 project

Period	Zone/Sensor	Mean Upstream	Mean Downstream	Z Statistic	P value	Conclusion (95%)
AM Peak	Zone 01 - NB I-229 Sensor 01	65.247	66.189	21.495	<0.001	Significant increase downstream
	Zone 02 - NB I-229 Sensor 01	66.413	63.586	-76.662	<0.001	Significant decrease downstream
	Zone 03 - NB I-229 Sensor 01	63.162	61.973	-12.519	<0.001	Significant decrease downstream
	Zone 04 -SB I-229 Sensor 01	61.405	62.181	13.364	<0.001	Significant increase downstream
PM Peak	Zone 01 - NB I-229 Sensor 01	64.818	66.207	34.851	<0.001	Significant increase downstream
	Zone 02 - NB I-229 Sensor 01	66.201	64.396	-58.782	<0.001	Significant decrease downstream
	Zone 03 - NB I-229 Sensor 01	62.025	60.547	-10.407	<0.001	Significant decrease downstream
	Zone 04 -SB I-229 Sensor 01	61.705	61.574	-2.389	0.008	Significant decrease downstream

Period	Zone/Sensor	Mean Upstream	Mean Downstream	Z Statistic	P value	Conclusion (95%)
Off-Peak	Zone 01 - NB I-229 Sensor 01	64.861	65.796	35.043	<0.001	Significant increase downstream
	Zone 02 - NB I-229 Sensor 01	65.641	63.340	-121.155	<0.001	Significant decrease downstream
	Zone 03 - NB I-229 Sensor 01	62.245	62.180	-2.452	0.007	Significant decrease downstream
	Zone 04 -SB I-229 Sensor 01	61.184	62.128	37.310	<0.001	Significant increase downstream

Note: NB = Northbound; SB = Southbound.

C.4.3.6 Project IM 2292(105)3

This project was located along the I-229 route from MM 3.49 to MM 4.95, extending a total distance of 1.46 miles. The work was performed along both the NB and SB directions, as shown in Figure C.15. The project lasted four months, from July to October 2024. Similar to some of the other projects, sensors were placed at the upstream and downstream locations. The z-statistic test was used to identify significant speed changes (increases or decreases) between the two locations. Table C.29 summarizes the findings from the analysis.

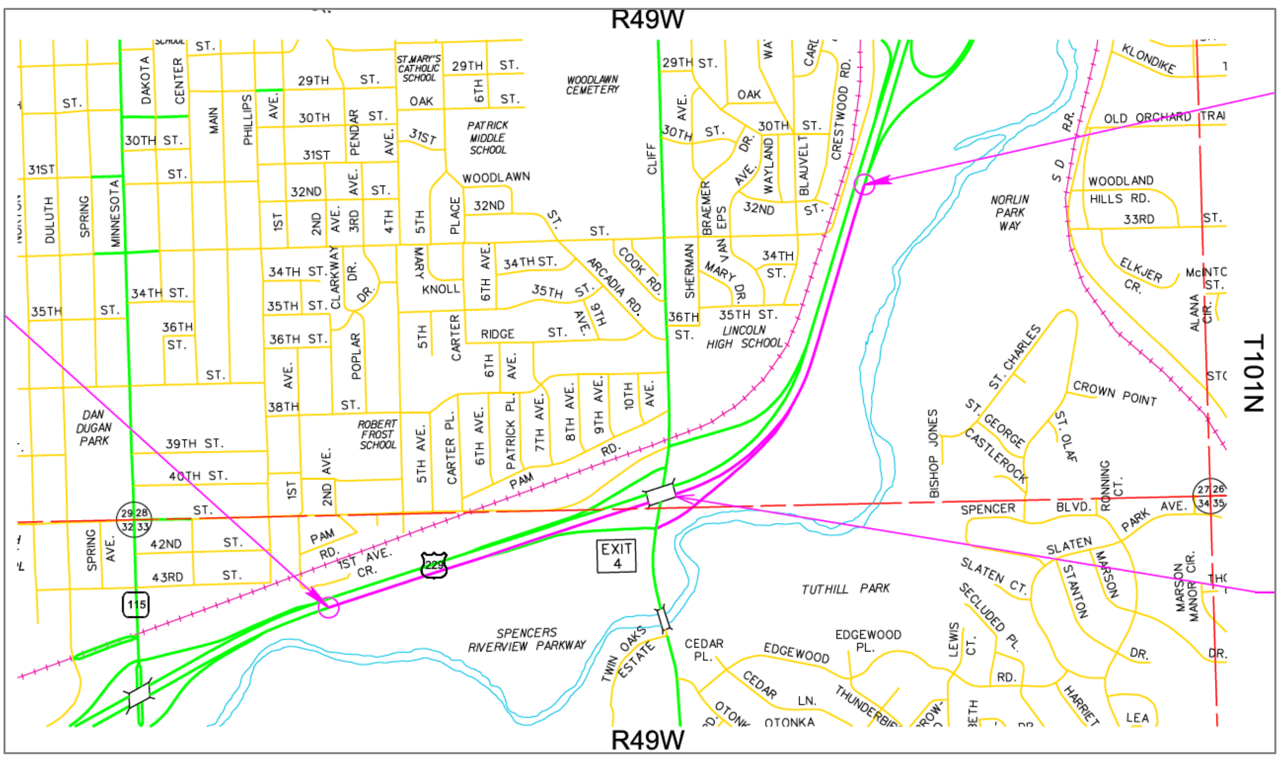


Figure C.15 IM 2292(105)3 project plan

Findings from the z-statistic test, summarized in Table C.29, indicate significant speed increases at the downstream locations. The speed increase implies that motorists slow down at the upstream locations (work zones) and then increased their speeds as they left the work zone locations. Only one location out of the six sensor locations was observed to have a significant speed reduction at the downstream location: the NB segment at MM 1.8, Sensor 7.

Table C.29 Speed data analysis results for Project IM 2292(105)3

Period	Zone/Sensor	Mean Upstream	Mean Downstream	Z Statistic	P value	Conclusion (95%)
AM Peak	SB I-229 MM 0.0 Sensor 8 (MW)	57.14	63.28	13.298	<0.001	Significant increase downstream
	NB I-229 MM 2.0 Sensor 5 (MW)	62.06	63.96	18.376	<0.001	Significant increase downstream
	SB I-229 MM 1.5 Sensor 6 (MW)	47.08	68.19	17.535	<0.001	Significant increase downstream
	SB I-229 MM 2.0 Sensor 13 (MW)	57.02	62.93	17.274	<0.001	Significant increase downstream
	NB I-229 MM 1.8 Sensor 7 (MW)	60.30	61.09	3.383	<0.001	Significant increase downstream
	SB I-229 MM 3.0 Sensor 3 (MW)	53.76	64.07	14.429	<0.001	Significant increase downstream
PM Peak	SB I-229 MM 0.0 Sensor 8 (MW)	58.68	61.30	5.083	<0.001	Significant increase downstream
	NB I-229 MM 2.0 Sensor 5 (MW)	61.76	63.05	7.735	<0.001	Significant increase downstream
	SB I-229 MM 1.5 Sensor 6 (MW)	44.51	67.72	20.172	<0.001	Significant increase downstream
	SB I-229 MM 2.0 Sensor 13 (MW)	52.41	61.87	19.585	<0.001	Significant increase downstream
	NB I-229 MM 1.8 Sensor 7 (MW)	57.29	60.65	8.261	<0.001	Significant increase downstream
	SB I-229 MM 3.0 Sensor 3 (MW)	53.73	64.25	14.765	<0.001	Significant increase downstream
Off- Peak	SB I-229 MM 0.0 Sensor 8 (MW)	56.72	61.92	27.351	<0.001	Significant increase downstream
	NB I-229 MM 2.0 Sensor 5 (MW)	61.78	62.30	11.772	<0.001	Significant increase downstream
	SB I-229 MM 1.5 Sensor 6 (MW)	46.38	67.61	45.062	<0.001	Significant increase downstream
	SB I-229 MM 2.0 Sensor 13 (MW)	59.98	61.89	29.380	<0.001	Significant increase downstream
	NB I-229 MM 1.8 Sensor 7 (MW)	59.79	59.26	-5.778	<0.001	Significant decrease downstream
	SB I-229 MM 3.0 Sensor 3 (MW)	53.33	62.70	35.464	<0.001	Significant increase downstream

Note: SB = Southbound; NB = Northbound; MM = Mile Marker.

C.4.3.7 I-90 Pennington Co 0901(195)32

This project was located along I-90, approximately 204.88 ft north and 474.14 ft west of the southwest corner of Township 5 North. It extended from MM 35.06 to MM 40.20, covering a total distance of about 5.14 miles. The scope of work included grading, structural improvements, lighting installation, permanent signage, pavement markings, concrete surfacing, e-screening, and building construction along the corridor. However, due to insufficient data, the z-statistic analysis could not be performed for this project.

C.5 Summary of Analysis Findings

C.5.1 Crash Frequency Analysis

Table C.30 summarizes findings from the crash frequency analysis. The arrows represent the direction of influence of the predictor variable on crash frequency. Upward-facing arrows indicate that the presence or increase of that variable leads to an increase in work zone crash frequency. For rural limited access facilities, grading, works done at intersections, work zones in the Pierre region, increase in ADT, and increase in the project contract amount are associated with an increase in work zone crashes. For urban limited access facilities, only ADT is associated with an increase in work zone crash frequency. In contrast, work zones involving concrete surface repair, pavement markings and rumble strips, work zones in the Rapid City region, and truck ADT are negatively associated with work zone crash occurrence. Specifically, the presence or increase in these factors lead to fewer work zone crashes on urban limited access facilities.

On rural principal arterials in South Dakota, factors such as higher speed limits, greater truck average daily traffic (ADT), wider roadways, and larger project contract amounts are associated with increased work zone crash frequency. In contrast, work zones involving pavement markings, rumble strips, and shoulder-related activities are linked to fewer crashes. Within urban principal arterials, work zones in the Rapid City region, higher ADT, wider roadways, wider right-of-way widths, and large project contract amounts are linked to more work zone crashes. Finally, findings indicate that on rural major collectors and minor arterials, factors such as shoulder work, location in the Pierre region, higher ADT, greater roadway width, and larger contract amounts are positively associated with an increase in work zone crashes. In contrast, the Rapid City region is more likely to experience fewer work zone crashes along its major collectors and minor arterial corridors.

Works related to grading and intersections are indicated by an upward-facing arrow, suggesting that their presence leads to an increase in work zone crashes. Work zones involving pavement markers are observed to be negatively associated with crash frequency in urban limited-access facilities and rural principal arterials. While shoulder-related work zones tend to reduce crash frequency on rural principal arterials, they are associated with an increase in crashes on major collectors and minor arterials. The Pierre region is likely to experience an increase in work zone crashes along its rural limited-access facilities, major collectors, and minor arterials. The Rapid City region is likely to observe more work zone crashes along its urban principal arterials, and fewer crashes along its urban limited access facilities and rural major collectors and minor arterials. The truck ADT is observed to have an increasing effect on rural principal arterials but a decreasing effect on urban limited access facilities.

Table C.30 Analysis results summary on the likelihood of work zone crash occurrence

Activity / Region	Variable	Rural Limited Access Facilities	Urban Limited Access Facilities	Rural Principal Arterials	Urban Principal Arterials	Rural Major Collectors and Minor Arterials
Work Zone Activity	Asphalt surface treatment*	-	-	-	-	-
	Concrete surface repair	-	Decrease	-	-	-
	Grading	Increase	-	-	-	-
	Intersection	Increase	-	-	-	-
	Maintenance& Repair	-	-	-	-	-
	Milling	-	-	-	-	-
	Pav. marking/r. strips	-	Decrease	Decrease	-	-
	Shoulder	-	-	Decrease	-	Increase
	Signs/Signals	-	-	-	-	-
	Structure	-	-	-	-	-
Region	Aberdeen*	-	-	-	-	-
	Mitchell	-	-	-	-	-
	Pierre	Increase	-	-		Increase
	Rapid City	-	Decrease	-	Increase	Decrease
Speed		-	-	Increase	-	-
Ln (ADT)		Increase	Increase	-	Increase	Increase
Ln (Truck ADT)		-	Decrease	Increase	-	-
Roadway Width		-	-	Increase	Increase	Increase
Right-of-Way Width		-	-		Increase	-
Ln (Contract Amount)		Increase	-	Increase	Increase	Increase

Note: * = Variable base category; Increase = increased likelihood of a work zone crash; Decrease = decreased likelihood of a work zone crash.

C.5.2 Crash Injury Severity Analysis

Table C.31 summarizes the results from the crash severity analysis. The up arrow indicates variables associated with increased severity in work zone crashes, while the down arrow represents variables associated with reduced crash injury severity. For both limited access and non- limited access facilities (arterials and collectors), the following variables were observed to increase the likelihood for crashes resulting in severe injuries.

- Lack of safety equipment
- DUI
- Illness
- Disregarding signs

In contrast, vehicle maneuvering was found to be negatively associated with crash severity for both types of facilities. On limited access facilities, angle collisions, motorcycles, and the natural logarithm of ADT were found to increase the likelihood of severe injuries while vehicle maneuvering and the natural logarithm of truck ADT were found to have a negative association with crash severity. On arterials and collectors, factors such as vehicle type (for example, tractor-trailers and vans), location in the Rapid City region, and wider right-of-way were positively associated with increased crash severity. In contrast, drivers aged 65 years and above were associated with lower crash severity levels, indicating a negative relationship.

Table C.31 Analysis results summary on the likelihood of a severe work zone crash

Variable (Base category)	Category	Limited Access Facilities	Arterials and Collectors
Season (Fall)	Spring	-	-
	Summer	-	-
	Winter	-	-
Day of week (Weekday)	Weekend	-	-
Safety Equipment Used (Yes)	None used	Increase	Increase
Vehicle Maneuver (Straight ahead)	Slowing/Stopped in Lane		
	Maneuvering	Decrease	Decrease
Motorcycle involved (No)	Yes	-	-
Speeding (No)	Yes	-	-
DUI (No)	Yes	Increase	Increase
Manner of Collision (Sideswipe)	Rear-end	-	-
	No collision between 2 MV	-	-
	Angle	Increase	-
Road surface (Asphalt (blacktop))	Concrete	-	-
	Other	-	-
Light Condition (Daylight)	Dark - lighted roadway	-	-
	Dark - roadway not lighted	-	-
	Dusk/Dawn	-	-
Junction Related (No)	Yes	-	-
Traffic way (Divided)	Undivided	-	-
Roadway alignment (Straight)	Curve	-	-
Roadway Grade (Level)	Grade	-	-
Weather condition (Clear)	Cloudy	-	-
	Severe	-	-
Overcorrection (No)	Yes	Increase	-
Fatigue (No)	Yes	-	-
Distraction (No)	Yes	-	-
Illness (No)	Yes	Increase	Increase
Drivers age (35-64)	20-34	-	-
	15-19	-	-
	≥ 65	-	Decrease
Vehicle Contribution (Passenger vehicles)	Light trucks	-	-
	Motorcycles	Increase	-
	Trucks	-	-
	Others (vans, tractor-trailers, etc.)	-	Increase
Driver Contribution (None)	Disregard of signs	Increase	Increase
Roughness (≥ 4) Good	Roughness (< 4.0) Fair/poor	-	-
Region (Aberdeen)	Mitchell	-	-
	Pierre	-	-
	Rapid City	-	Increase
Nature of area (urban)	Rural	-	-
Ln (ADT)		Increase	-

Variable (Base category)	Category	Limited Access Facilities	Arterials and Collectors
Ln (Truck ADT)		Decrease	-
Location Speed Limit		-	-
Roadway Width		-	-
Right-of-Way Width		-	Increase

Note: * = Variable base category; Increase = increased likelihood of a severe work zone crash; Decrease = decreased likelihood of a severe work zone crash.

C.5.3 Speed Data Analysis

Speed data for seven projects were analyzed in this research effort. The analysis indicates significant speed changes between two consecutive locations along the work zones. While some projects' data were categorized into upstream and downstream locations, other locations included data at locations with respect to the start of the work zone taper. The speed data of the following projects were analyzed.

- I-29 Sioux Falls 0293(106)76: May 2022 – July 2024
- I-229 Minnehaha Co (2021): May 2021 – October 2021
- I-229 Minnehaha Co IM 2292(98)9 (2023): April 2023 – November 2024
- I-229 Minnehaha Co IM 2292(105)3 (2024): July 2024 – October 2024
- I-90 Pennington Co (2021): June 2021 – December 2021
- I-90 Pennington Co 0901(195)32: September 2022 – December 2022
- I-90 Various Co IM-NH 0041(181) (2024): July 2024

A Z-test analysis was used to determine significant speed changes between two consecutive locations: downstream versus upstream or locations in relation to the work zone taper. Findings indicated variations among the different projects, showing both significant speed increases and decrease between consecutive locations. Since the exact location where the sensors were placed is unknown, the results should be used with caution.