Investigation of Commercial Motor Vehicle (CMV)-Related Crashes in Ohio Work Zones

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16. Abstract

This research project was conducted to identify causation trends and factors that contribute to commercial motor vehicle (CMV)-involved work zone crashes in Ohio. In addition, the research project examined how workspace access points contribute to the CMV crash risk in work zones. In Phase 1, the research team reviewed previous research findings, conducted a preliminary crash analysis, and identified potential projects and novel data sources. In Phase 2, the research team reviewed the characteristics, narratives, and diagrams of fatal, serious injury suspected, and minor injury suspected CMV-involved work zone crashes to determine the factor that primarily influenced the crash, whether a CMV was fault, and whether a work-related CMV was involved. In addition, the research team used two statistical modeling techniques to identify the association between critical factors. The research team also conducted field studies in Phase 2 to observe the operational and safety impact of workspace access points. Based on the crash analysis and field study findings, the research team made 10 recommendations for improving CMV safety in work zones.

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PROBLEM STATEMENT

For many years, the Federal Highway Administration (FHWA) has led efforts to reduce the risk of commercial motor vehicle (CMV) (i.e., large trucks and buses with gross vehicle weight or gross combination weight of 10,001 or more pounds) crashes in work zones because relative to fatal crashes occurring outside of work zones, CMVs are consistently overrepresented in fatal work zone crashes. In 2018, FHWA sponsored research to identify the 10 states with the highest number of fatal work zone crashes and associated work zone fatalities involving CMVs. The identified states included Ohio. In November 2020, FHWA led a targeted state-level workshop for Ohio stakeholders, which resulted in the development of a voluntary Ohio state-specific action plan. While this effort also included a high-level analysis of fatal and serious injury CMV crashes in work zones, it did not include more in-depth statistical analysis to better understand causation trends and factors that contribute to these crashes in Ohio. Therefore, The Ohio Department of Transportation (ODOT) wanted to conduct additional research about CMV crashes in Ohio work zones to help prioritize the proposed mitigation strategies and action items and best target limited resources towards reducing these crashes.

RESEARCH BACKGROUND

This section contains the research goal, objectives, and a brief description of the tasks accomplished. This section also includes an overview of the state of the practice.

RESEARCH GOAL AND OBJECTIVES

The goal of this research is to improve the safe movement of CMVs in Ohio's work zones. The objectives of the project are to:

- Collect and analyze data to identify CMV-related crash causation trends or factors adversely impacting CMV-related crashes in Ohio work zones.
- Collect and analyze data to determine if construction access points (as designed and/or implemented) are adversely impacting CMV-related crashes in Ohio work zones.
- Develop recommendations for how to target resources to best address the underlying causes of CMV-related crashes in Ohio work zones using one or more of the following: engineering design/standards, enforcement, and/or education.

STATE-OF-THE-PRACTICE OVERVIEW

As part of the state-of-the-practice review, the research team examined findings from recent crash analyses on CMV-involved work zone crashes conducted for FHWA projects and the National Work Zone Safety Information Clearinghouse. The research team also reviewed published literature on CMV-involved crashes in work zones and identified mitigation strategies that can be used to reduce the risk of CMV crashes in work zones. In addition, the research team met with ODOT staff to discuss current ODOT work zone practices and procedures used to improve CMV safety in work zones. A summary of the key findings is below. Detailed findings from the state-of-the-practice assessment are in Appendix A.

CMV-Involved Work Zone Crashes

Based on crash analyses conducted for previous efforts and the literature review, the research team found that CMVs are consistently overrepresented in fatal work zone crashes on interstates and freeways (urban and rural areas). Rear-end collisions are also overrepresented in CMV-involved fatal crashes in work zones.

Lane closures that result in vehicle queues are known to contribute to rear-end crashes for CMVs and non-CMVs at or near the back of the queue. In addition, difficulty merging at lane closures, especially under high-speed, high-volume conditions where there are limited gaps in traffic, can lead to CMV-involved crashes. Late or forced lane changes may result in rear-end or sideswipe collisions.

Sudden speed drops at construction vehicle access points for large trucks re-entering the travel lanes and at entrance ramps with reduced acceleration lane lengths (especially those with barriers that constrain acceleration lane length) also contribute to CMV-involved rear-end and sideswipe crashes in work zones. In addition, rear-end collisions can involve large trucks hitting slow-moving mobile operations.

Other changes in lane configurations, such as crossovers and lane shifts, are also known to contribute to CMV-involved work zone crashes. Even though crossover and lane shift design details are typically unavailable once a construction project is completed, these geometric changes are typically designed for passenger vehicles. In addition, some crossovers are designed for the reduced work zone speed limit. Yet, research has shown that drivers do not normally travel at the reduced work zone speed limit. Thus, some crossovers may be under-designed from a speed perspective.

Mitigation Strategies

The overrepresentation of CMVs in fatal work zone crashes has been a major area of concern throughout the United States Department of Transportation (USDOT). Many resources including guidance documents, fact sheets, webinars, conference sessions, driver training resources, and driver outreach (CMV and non-CMV) have been developed by FHWA, the Federal Motor Carrier Safety Administration (FMCSA), other federal agencies, and various stakeholders to reduce the risk of CMV crashes in work zones. These materials include information on strategies for designing work zones to better accommodate CMVs and helping CMV drivers better navigate work zones. The following is an abbreviated list that contains design and operation practices included in publications and recently highlighted at workshops with state departments of transportation (DOTs).

- Incorporate CMV effects into work zone traffic impact analyses.
- Maintain sufficient lane widths (11 ft minimum; 12 ft desirable).
- Avoid short or no acceleration lane entrance ramps.
- Use appropriate design speed.
- Alter lane shift design to better accommodate CMVs.
- Maintain good sign, device, and pavement marking retroreflectivity.
- Deploy temporary portable rumble strips upstream of lane closures to increase driver alertness and awareness.
- Deploy sequential warning light systems on channelizing devices used in the taper of nighttime lane closures.
- Avoid the creation of traffic queues.
- Deploy active work zone queue warning and/or dynamic lane merge warning systems where queues are expected to develop.
- Utilize law enforcement to increase speed limit compliance and/or assist with queue warning.
- Encourage trucks to use alternate routes (if acceptable).
- Create a truck-only lane through the work zone or encourage trucks to use only certain lanes.
- Provide good workspace ingress and egress design.
- Deploy active work zone technology to warn approaching motorists about construction vehicles entering or exiting the workspace.
- Use in-cab notifications to send work zone safety messages (e.g., sudden slowdowns) to CMV drivers.

Over the years, ODOT has implemented many design and operational strategies to reduce the risk of CMV-involved crashes in work zones, including but not limited to:

- Using work zone metrics to identify issues impacting CMV safety.
- Establishing a lane closure policy based on an allowable queue length threshold.
- Increasing offset from 1 to 2 ft between the barrier toe and adjacent travel lane and establishing a 2 ft offset between the barrier toe and work area.
- Using a 12 ft preferred lane width on freeways and expressways. If a lane width reduction is necessary, it is desirable to maintain 11 ft lane width.
- Posting lane use signing for trucks if the shoulder pavement cannot adequately accommodate trucks when traffic is shifted onto the shoulder.
- Publishing standards for the use of a work zone queue detection warning system (WZQDWS).
- Publishing a standard construction drawing for construction access points (ingress/egress) and designer guidance in the *Ohio Traffic Engineering Manual*.

- Publishing guidance on the use of work zone egress warning systems that warn drivers of slow-moving construction vehicles entering the travel lanes from the workspace.
- Sending in-cab alerts about slowdowns and congestion to large trucks via Drivewyze®.
- Updating the Permitted Lane Closure Schedule (PLCS) system to better leverage percent truck data for capacity calculation purposes (half hourly rather than one average percent truck value), where such data is available for use.

RESEARCH APPROACH

In addition to conducting the state-of-the-practice review, the research team:

- Conducted a preliminary crash analysis to identify trends and overrepresentation of CMV-involved crashes in work zone areas compared to non-work zone areas (see Appendix B).
- Conducted a more comprehensive crash analysis of fatal (K), serious injury suspected (A), and minor injury suspected (B) CMV-involved work zone crashes to identify causation trends and common factors contributing to these crashes (see Appendix B).
- Conducted field studies to observe the operational and safety impacts of construction access points (see Appendix C).

For the preliminary crash analysis, the research team acquired crash data for the latest five years (2017–2021) and roadway inventory data from ODOT. The research team looked at general trends for non-CMV-involved and CMV-involved non-work zone and work zone crashes. The research team also computed and analyzed descriptive statistics for CMV crashes (work zone and non-work zone locations), work zone crashes (CMV-involved and non-CMV-involved), and CMV-involved work zone crashes.

For the more comprehensive crash analysis, the research team devised a process for transferring crash report narratives from a PDF format to a readable spreadsheet utilizing an open-source toolkit. The research team reviewed the crash narratives, diagrams, and characteristics for the KAB CMV-involved work zone crashes from 2017–2021 to determine the following:

- Did the crash involve a CMV?
- Was a CMV at fault?
- Was a work-related CMV involved in the crash (e.g., shadow vehicles with impact attenuators or those delivering materials to and from the work site)?
- What factor primarily influenced the crash (see Table 1)?

In addition, the research team used two statistical modeling techniques (i.e., nested logit and cluster correspondence analysis [CCA]) to identify the association between critical factors.

For the field studies, the research team identified and reviewed potential projects and data sources and developed an experimental plan for data collection. Ultimately, the research team, in concert with ODOT, selected three projects for the field studies. One of the projects was located southwest of Columbus on I-71 in a rural area, while the other two projects were located on I-75 in Dayton in urban areas.

Table 1. Factors Primarily Influencing KAB CMV-Involved Work Zone Crashes.

Factor Name	Description of Factor
CMV Operator Error	Improper operation of CMV
Failure to Yield ROW	Driver failed to yield the proper right of way
Following Too Close	Driver following too close to another vehicle
Geometry	Roadway geometry
Ingress/Egress	Construction vehicle entering/exiting the work area
Intrusion—Mobile	Slow-moving work vehicle or related equipment struck
Intrusion—Stationary	Intrusion into a stationary work zone operation
Lane Change	Vehicle making a lane change not associated with a lane closure
Lane Departure	Vehicle leaving a travel lane
Malfunction	Vehicle malfunctioned
Medical	Driver medical emergency
Merge	Vehicle merging due to a lane reduction/closure
Object	Debris, animal, or another object present in or near the roadway
Passing	Vehicle attempting to pass another vehicle
Queuing	Traffic slowing down or stopped
Secondary Crash	Traffic conditions because of a primary crash
Turning	Vehicle making a turn
View Obstructed	Driver's view obstructed
Weather	Inclement weather
Work Site	Occurred within the work area
Worker/Equipment Encroachment	Worker or construction equipment encroached into the open travel lanes
Wrong Way	Wrong-way driver

Note: ROW = Right of Way.

The research team collected field data in October 2023 at multiple workspace access points designed according to the ODOT standard construction drawing (MT-103.10). Data collection included physical measurements of the workspace access points, speed profiles of construction vehicles using the workspace access point, spot speed measurements of the vehicles in the open travel lanes, global positioning system (GPS) mapping of the work zones, documentation of various site characteristics, and video data from cameras mounted on two portable trailers that recorded CMVs entering and exiting the workspace access points and the vehicles in the open travel lanes. In total, the research team collected approximately 606 hours (25 days) of video data across all the sites, with most video data recorded at the project on I-71 due to that project's extensive use of many workspace access points. In total, 1,304 CMVs were recorded entering or exiting the workspace across all sites, with 1,271 of those from the I-71 project. From these data, the research team:

- Compared the workspace access point designs used at the three projects to the ODOT standard construction drawing (MT-103.10).
- Reviewed each construction vehicle's entry or exit path and organized them into 10 categories (i.e., three for entries, six for exits, and one for all the maneuvers that did not fit into the other nine categories).
- Computed the post encroachment time (PET) (i.e., time gap) between construction vehicles entering and exiting the workspace and vehicles immediately following and/or leading at the I-71 project to use as a surrogate safety measure to assess construction vehicle diverging and merging behaviors.
- Computed average speeds for main lane traffic for the I-71 project.
- Created speed deceleration and acceleration profiles for select construction vehicles at the I-71 project.
- Measured the number of lane changes (i.e., inside lane to outside lane and vice versa) and last-minute lane changes when a construction vehicle was entering or exiting the workspace at the I-71 project to use as a surrogate safety measure to assess other vehicles' behavior around the construction vehicle.
- Computed lane level volume counts for the I-71 project.

See Appendix C for additional information.

RESEARCH FINDINGS AND CONCLUSIONS

CRASH ANALYSES

The findings from the preliminary crash analysis revealed that CMVs were involved in a higher percentage of sideswipe-passing injury crashes and rear-end fatal crashes in work zones compared to non-work zones. About two-thirds of the CMV-involved work zone crashes occurred in the activity area and almost half happened during a lane closure. While most of the lane closure-related CMV-involved work zone crashes occurred in the activity area, one-quarter of them took place in the transition area and 15 percent happened in the advance warning area or before the first work zone warning sign.

Based on these findings, the research team speculated that the sideswipe-passing crashes were attributed to temporary changes in the roadway geometrics that make it more difficult for CMV drivers to maintain lane position or merge (e.g., reduced shoulder or lane width, shortened merge and diverge areas, lane shifts, or crossovers), and that the rear-end crashes were likely the result of sudden slowdowns due to lane closures, restrictive geometries, or slow-moving operations. Researchers also hypothesized that construction vehicles entering or exiting the travel lanes to access the workspace may contribute to CMV-involved sideswipe-passing and rear-end crashes in work zones.

Table 2 summarizes the key findings from the more comprehensive crash analysis of KAB CMV-involved work zone crashes from 2017–2021 by roadway type. In general, the trends for ODOT-maintained and non-ODOT maintained roadways were similar except for the third most common crash cause. This will be discussed briefly later in this section. Additional details can be found in Appendix B.

Table 2. Key Findings by Roadway Type.

Key Findings	ODOT Maintained Roadways (n = 420)	Non-ODOT Maintained Roadways (n = 212)	All Roadways (n = 632)
Percent that occurred on a freeway	83%	60%	75%
Percent where a CMV was at fault	56%	56%	56%
Percent that involved a work-related CMV	19%	33%	23%
First most common cause	Queuing	Queuing	Queuing
Second most common cause	Lane Departure	Lane Departure	Lane Departure
Third most common cause	Lane Change	Intrusion—Stationary	Lane Change
Percent contributed to a construction vehicle entering or exiting the workspace	2%	4%	3%

The review of the crash narratives, diagrams, and characteristics found that on ODOT maintained roadways:

- Of the KAB CMV-involved work zone crashes, 83 percent occurred on freeways (54 percent in urban areas, and 29 percent in rural areas).
- A CMV was at fault in 56 percent of the KAB CMV-involved work zone crashes.
- Of the KAB CMV-involved work zone crashes, 19 percent involved a work-related CMV and most of those were the result of a work zone intrusion.
- The three most common causes of the KAB CMV-involved work zone crashes were queuing (29 percent), lane departure (19 percent), and lane changes (15 percent).
- Construction vehicles entering or exiting the workspace contributed to 2 percent of the KAB CMV-involved work zone crashes.

Queuing-Related Crashes

A deeper dive into the 121 queuing-related KAB CMV-involved work zone crashes on ODOT-maintained roadways revealed that 54 percent occurred in an urban area, 94 percent resulted in rear-end collisions, a CMV was at fault in 65 percent of the crashes, and more than half (52 percent) occurred when a lane closure was present. A work-related CMV was only involved in 8 percent of these crashes. The research team found similar trends on the non-ODOT maintained roadways, except more queuing-related crashes occurred in rural areas (60 percent).

For ODOT-maintained roadways, 26 percent of traffic slowdowns associated with lane closures happened in the advance warning area or before the first warning sign, where motorists may not be expecting congestion. Queuing because of a lane closure also caused crashes to occur in the activity area (17 percent) and transition area (7 percent). The statistical analysis of all 632 KAB CMV-involved work zone crashes supported these findings, since 43 percent of these crashes were associated with freeways or expressways with reduced capacity due to lane closures that resulted in rear-end crashes.

Queuing-related KAB CMV-involved work zone crashes on ODOT-maintained roadways were also influenced by work on the shoulder or median (22 percent), lane shifts/crossovers (15 percent), and intermittent/moving work (7 percent). Since most of the crash narratives and diagrams only mentioned slowing or stopped traffic, researchers can only speculate as to the cause of the slowdown when work was occurring on the shoulder or median. Possible causes could be reduced lane width, reduced or no shoulder, presence of barrier on one or both sides of the roadway, merging traffic from ramps, unexpected hazards in the travel lane, or confusion about the proper driving action. While specifics about the design of the lane shifts or crossovers were not readily available, such features are typically designed for passenger vehicles and sometimes for lower design speeds to accommodate road users traveling through the work zone and project constructability. CMVs and passenger vehicles may approach such features at speeds higher than the posted speed limit and be surprised by the severity of the change in the travel path, resulting in sudden slowdowns. Intermittent/moving work by nature can cause slowdowns since these operations typically progress down the roadway at slow speeds.

To further explore the 121 queuing-related KAB CMV-involved work zones crashes on ODOT-maintained roadways, the research team completed the following actions:

- Matched each crash to a past project using data from ODOT's Transportation Information Mapping System (TIMS).
- Reviewed ODOT's Traffic Management in Work Zone Exceptions database to determine whether each project obtained a maintenance of traffic (MOT) exception.
- Reviewed project plans, addenda files, and bid data to determine if a WZQDWS was included.
- Reviewed daily diaries to obtain insights, if any, about the temporary traffic control at the time of the crash for the top 10 projects with the most crashes.

The research team was able to match 108 of the KAB CMV-involved work zone crashes on ODOT-maintained roadways to a project. Some projects experienced multiple queue-related KAB CMV-involved work zone crashes. One project was matched to five crashes, two projects were linked to four crashes each, seven projects were connected to three crashes each, and 10 projects were attributed to two crashes each. The remaining 54 projects were matched to one crash each. The research team identified 37 MOT exceptions that corresponded to a project matched with one of these crashes. Of these 37 MOT exceptions, 20 were for lane closures, eight for ramp closures, five for one direction of travel being closed (i.e., partial road closures), three for both directions of travel being closed (i.e., full road closure), and one for a crossover. The research team found a WZQDWS in one set of project plans, in the bid data for another project, and as part of the MOT exception for another project.

Further review of top 10 projects with the most queuing-related KAB CMV-involved work zone crashes revealed that 8 percent occurred when lane closures were present but not permitted by the PLCS, plans, or MOT exception, and 29 percent happened when lane closures were active and permitted by the PLCS, plans, or MOT exception. In addition, 29 percent occurred during shoulder or median work and 6 percent took place when a lane shift or crossover was present. MOT exceptions were approved for four of the top 10 projects. The MOT exceptions included closing lanes, closing an auxiliary lane, and closing a system ramp. All three projects that included a WZQDWS were identified as being in the top 10. However, the research team was unable to confirm whether the system was deployed and functioning properly at the time of the crash.

Lane Departure-Related Crashes

The second most common cause of KAB CMV-involved work zone crashes on ODOT-maintained roadways was a vehicle departing its travel lane. These crashes happened most often during the day (62 percent) and in urban areas (52 percent). A CMV was at fault in 68 percent of these crashes, but a work-related CMV was involved in only 5 percent of the crashes. The most prevalent crash types were fixed object (37 percent) and sideswipe passing (33 percent). Based on a review of the crash narratives, the research team determined that in two-thirds of the lane departure-related KAB CMV-involved work zone crashes on ODOT-maintained roadways, a vehicle left the roadway. In most cases, the vehicle hit a fixed object (e.g., barrier, guardrail, sign, or work zone device) and/or another vehicle. The remaining one-third of the lane departure-related KAB CMV-involved work zone crashes were attributed to a vehicle leaving its lane but not the roadway (e.g., drifting, swerving, or crossing into another travel lane). Forty-one percent of the lane departure-related KAB CMV-involved work zone crashes on ODOT-maintained roadways occurred when there was work on the shoulder or median, 23 percent during a lane closure, 22 percent when there was a lane shift or crossover, and 8 percent with intermittent or moving work. Most of these crashes occurred in the activity area (73 percent). The research team found similar trends on the non-ODOT maintained roadways, except more lane departure-related crashes occurred in rural areas (59 percent) and during intermittent or moving work (67 percent).

While details regarding the work zone conditions at the time of the crash were not readily available, these lane departure-related KAB CMV-involved work zone crashes may be indicative of physical constraints due to temporary changes in roadway geometrics (e.g., reduced or no shoulder width, reduced lane width, shortened merge and diverge areas, lane shifts, and crossovers). Three crash narratives specifically mentioned such constraints. Two crash narratives noted that the CMV was approaching or in a lane shift at the time of the lane departure, and one crash narrative mentioned that the CMV had just come out of a crossover. In addition, one crash narrative noted that a CMV departed the lane onto a low shoulder due to paving and then overcorrected. Also, 35 percent of the crash narratives mentioned the vehicle hitting a guardrail, barrier, or attenuator, which could be indicative of vehicles having less room to maneuver in their lane.

The statistical analysis of all 632 KAB CMV-involved work zone crashes supported these findings, since 31 percent of the crashes were associated with driver behavior related to sideswipe-passing and run-off roadway crashes. Factors associated with these types of crashes included work on the shoulder or median, vehicle moving at unsafe speeds, interstate routes, roadway curvature, crashes with fixed objects, and the presence of a work zone lane shift or crossover.

Lane Change-Related Crashes

The third most common cause of KAB CMV-involved work zone crashes on ODOT-maintained roadways was a vehicle changing lanes but not because of merging due to a lane reduction/closure. The research team categorized the latter maneuver separately in the comprehensive crash analysis. The lane change-related crashes happened most often during the day (74 percent) and in urban areas (82 percent). A CMV was at fault in 64 percent of these crashes, but a work-related CMV was involved in only 7 percent of the crashes. The most prevalent crash type was sideswipe-passing collisions (90 percent). Forty-six percent of the lane-change-related crashes occurred when there was work on the shoulder or median, 21 percent when there was a lane shift or crossover, 16 percent during a lane closure, and 8 percent with intermittent or moving work. Most of these crashes occurred in the activity area (82 percent).

While the crash narratives did not contain any additional details that provided insight into the work zone conditions that contributed to these crashes, the statistical analysis of all 632 KAB CMV-involved work zone crashes supported these findings. The same cluster of crashes associated with sideswipe-passing and run-off roadway crashes was highly correlated with lane change behavior and the presence of work on the shoulder or median. Improper lane changes that lead to vehicle conflicts can result in sideswipe-passing crashes in the activity area when there is work on the shoulder or median since the presence of such work can physically constrain the traveled way and limit available recovery room for vehicles (e.g., reduced or no shoulder, presence of barrier on one or both sides of the roadway, merging traffic from ramps, unexpected hazards in the travel lane, or confusion about the proper driving action). While not included in this category, construction vehicles entering or exiting the workspace also led to lane change conflicts that resulted in sideswipe-passing collisions.

Intrusion Crashes

As mentioned previously, the third most common cause of KAB CMV-involved crashes on non-ODOT maintained roadways (intrusions into stationary work zones) differed from ODOT-maintained roadways (lane change). On non-ODOT maintained roadways, stationary-intrusion crashes occurred most often during the day (74 percent) and in urban areas (82 percent). A CMV was at fault in only 7 percent of these crashes. The most common crash types were parked vehicle (56 percent) and rear-end (22 percent). Due to the nature of the crashes, a work-related CMV was involved in 100 percent of the crashes. For 82 percent of the crashes, a passenger vehicle hit a work-related CMV (typically a shadow vehicle with an impact attenuator or piece of equipment). In 7 percent of the crashes, a non-work related CMV hit a work-related CMV. Seven percent of these crashes involved workers. The crash narratives associated with these crashes did not offer any additional insights, except that flagging operations were present for three crashes.

The statistical analysis of all 632 KAB CMV-involved work zone crashes supported these findings, since two clusters of crashes (18 percent and 4 percent) were associated with non-interstate roadways and intermittent or moving work zones. Other positive associations included pedestrians, vehicle entering the traffic lanes, improper driving behavior, and driving improper speed.

In work zones, equipment, traffic control devices, and workers are commonly placed near travel lanes. This positioning elevates the likelihood of vehicles colliding with equipment or accidentally hitting people working on the roadway. The close arrangement of these elements near travel lanes creates a situation where drivers face increased challenges in navigating through confined spaces and workers must be diligent to keep themselves and equipment inside the constrained workspace. This also emphasizes the critical need for effective traffic control measures, clear signage, and increased driver awareness within work zones to minimize the potential for collisions and ensure the safety of both road workers and drivers.

Construction Vehicle Ingress/Egress Crashes

The research team found that only a small portion (2 percent) of the KAB CMV-involved work zone crashes on ODOT-maintained roadways were attributed to construction vehicles (i.e., CMVs) entering or exiting the workspace. Based on a review of the crash narratives, 70 percent of these crashes occurred when a construction vehicle was exiting the workspace into the open travel lanes. The remaining crashes (30 percent) resulted from a construction vehicle slowing down in the open travel lanes or the deceleration lane. A construction vehicle was involved in 90 percent of these crashes and was found to be at fault in 50 percent of these crashes. The most frequent crash types were rear-end (50 percent) and sideswipe passing (50 percent). The research team found similar trends on the non-ODOT maintained roadways, except more lane change-related crashes occurred in urban areas (88 percent) and also resulted in turning collisions.

FIELD STUDY

The field studies showed that most construction vehicle (i.e., CMVs) drivers used the dedicated lane in the standard construction drawing of construction access points for deceleration and acceleration, as intended. However, the research team did observe some instances where the standard workspace access point design was used differently than envisioned to facilitate material delivery. The research team also observed other types of workspace access point designs being used by contractors at the beginning or end of the workspace or to expediate material delivery.

Even with the dedicated lane, construction drivers entering the workspace had to slow down in the travel lanes prior to moving into the dedicated lane. Deceleration profiles of 30 fully loaded dump trucks showed that the drivers began decelerating in the inside travel lane between 800 and 1200 ft upstream of Opening A (i.e., 400 to 800 ft before entering the dedicated lane). Their initial average speed was 55 mph, with a range from 41 to 62 mph, and their average speed when they entered the dedicated lane was 43 mph, with a range of 29 to 59 mph. In comparison, the average speed of the vehicles in the travel lanes was 66 mph even though the posted speed limit was 60 mph. On average, the dump trucks reduced their speed by 13 mph in the inside lane before entering the dedicated lane.

These types of unexpected slowdowns in the inside lane resulted in 219 lane changes of which 43 percent were last-minute lane changes from the inside to the outside lane. The average PET for the vehicle following the construction vehicle that was decelerating to enter the workspace was 3.31 seconds and ranged from 0.26 to 21.11 seconds. Based on the PET distribution, the research team defined a serious conflict as less than or equal to 0.86 second (15th percentile value). PET values between 0.86 and 2.04 seconds (50th percentile value) were considered general conflicts, PET values between 2.04 and 5.97 seconds were considered slight conflicts, and PET values greater than 5.97 seconds were considered potential conflicts.

The research team also observed construction vehicles exiting the workspace. Typically, the construction vehicle driver would stop at the workspace exit point (i.e., Opening B) and wait for a gap in the main lane traffic before accelerating and merging into the travel lanes. Acceleration profiles of 19 empty and 32 fully loaded dump trucks showed that most of construction vehicle drivers used the dedicated lane to accelerate. The average speed of the empty dump trucks when they entered the inside travel lane was 42 mph with a range of 33 to 48 mph. On average, the empty dump trucks increased their speed by 30 mph in the dedicated lane before entering the inside lane. In contrast, the fully loaded dump trucks tended to enter the inside lane at a lower speed (average was 27 mph with a range of 17 to 34 mph). On average, the fully loaded dump trucks increased their speed by 16 mph in the dedicated lane before entering the inside lane. In comparison, the average speed of the vehicles in the travel lanes was 69 mph even though the posted speed limit was 60 mph.

For 127 such slow-moving construction vehicles, the speed differential between them and the vehicles in the inside lane resulted in 115 lane changes, of which 22 percent were last-minute lane changes from the inside to the outside lane. The average PET for the vehicle in front of the construction vehicle that was accelerating to enter the travel inside lane was 5.77 seconds and ranged from 0.01 to 21.35 seconds, while the PET for the vehicle following the construction vehicle was 9.64 seconds and ranged from 1.07 to 21.88 seconds. The average gap (i.e., difference between the PET for the vehicle following the construction vehicle and the PET for the vehicle in front of the construction vehicle) was 15.20 seconds and ranged from 1.15 to 36.02 seconds. Based on the gap distribution, the research team defined a serious conflict as less than or equal to 7.41 seconds (15th percentile value). PET values between 7.41 and 13.84 seconds (50th percentile value) were considered general conflicts, PET values between 13.84 and 24.20 seconds were considered slight conflicts, and PET values greater than 24.20 seconds were considered potential conflicts.

RECOMMENDATIONS

Based on the findings from the crash analyses and the field study, the research team recommends the following:

- **Monitor the implementation of the new Permitted Lane Closure Schedule that was made available in February 2024.** Since ODOT made recent improvements to the PLCS, the use of the new lane closure schedules for freeway and expressways was not reflected in the crash analysis. Even so, many of the queue-related crashes occurred when lane closures were permitted. To determine if the new PLCS has reduced the risk of queue-related crashes, ODOT should monitor crashes and use vehicle probe-based data sources to vet the anticipated queue length (≤ 0.75 miles) versus actual queue length for allowable lane closures. This information should be used to make further improvements to the PLCS, as needed.
- **Closely monitor projects with approved MOT exceptions that reduce capacity.** Since several of the projects related to multiple queue-related crashes had approved MOT exceptions, ODOT should periodically review crashes and operational conditions (e.g., speed, sudden slowdowns, etc.) for projects with approved MOT exceptions (by district deputy directors and the Maintenance of Traffic Exception Committee) to determine the impact of queuing on safety. Reports could be developed and autogenerated from crash databases and vehicle probe-based data sources to assist with this task. This information should be used to support the consideration of mitigation strategies on the current project and future projects, as well as the MOT exception process.
- **Consider using other data-driven performance metrics to determine when lane closures are allowed.** In addition to predicting queue length based on available capacity (supply) versus traffic volumes (demand), sensitivity analysis could be used to provide additional insights into potential impacts, especially for projects where a queue length study is needed for the MOT exception process. The sensitivity analysis could include variations in traffic volumes, the likelihood that a queue will occur (probability), and how long a queue exists if it does occur (duration). These metrics could be incorporated into ODOT's Lane Closure Queue Analysis Tool, and thresholds for these metrics could also be developed and included in the ODOT Traffic Management in Work Zones Standard Procedure (123-001[SP]).
- **Develop a criteria-based tool for selecting when a WZQDWS should be used.** Currently, WZQDWSs are recommended for use where there is

potential for queuing and are required for some projects with an approved MOT exception. Only three of the top 10 projects with multiple queue-related crashes included a WZQDWS. A tool that incorporates specific data-driven scoring factors, such as estimated queue length, probability that a queue will occur, estimated queue duration, and percent of CMVs, would result in a more consistent use of WZQDWSs and facilitate a mechanism for evaluating potential safety improvements. Results from such evaluations could also be used to continually improve the tool.

- **Avoid reducing the design speed for lane shifts and crossovers more than 10 mph below the normal speed limit.** Many of the queue-related and lane departure-related crashes were associated with lane shifts and crossovers. CMVs and passenger vehicles may approach such features at speeds higher than the posted speed limit and be surprised by the severity of the change in the travel path, resulting in sudden slowdowns, vehicle encroachments into adjacent lanes, or vehicles running off the road. The *Ohio Traffic Engineering Manual* supports designing work zones to the original posted speed limit.
- **Consider implementing slightly wider lanes in lane shifts to better accommodate the off-tracking tendencies of CMVs.** Indiana DOT is using a method that offsets the start of the lane shift for each lane, which slightly widens the width of the lanes within the transition. See the factsheet referenced in Appendix A for more details.
- **Lengthen the dedicated lane in the ODOT Construction Access Point standard construction drawing (MT-103.10) to provide additional pavement for loaded construction vehicles to accelerate and decelerate.** The field studies found that construction vehicles are decelerating in the travel lanes before entering the dedicated lane. Construction vehicles are also exiting the dedicated lane and merging with traffic at low speeds. These findings indicate that the dedicated lane in the current ODOT standard does not provide adequate distance for construction vehicles to decelerate and accelerate. Guidance on designing workspace access points suggests that 1,500 ft is needed for a fully loaded truck to accelerate to 55 mph. Several other state DOTs provide between 1,320 and 1,620 ft for acceleration. Changing the distance between Opening B and Opening A from 650 ft to 1,360 ft would provide 1,500 ft of acceleration and 1,360 ft for deceleration.
- **Add a drawing to the ODOT Construction Access Point standard construction drawing (MT-103.10) that shows how the construction access points should be used.** The field studies revealed that construction vehicles were utilizing the dedicated lane in a variety of ways to enter and exit the workspace. Developing a graphic that depicts the information in Note 5 could help specify the intended construction vehicle paths.
- **Continue to encourage the use of work zone egress warning systems to warn approaching drivers about slow-moving construction vehicles merging with traffic**. The field studies found that fully loaded construction vehicles are exiting the workspace, accelerating in the dedicated lane, and

entering the travel lanes at speeds much lower than the other vehicles. This speed differential can result in merging conflicts and last-minute lane changes to avoid collisions, especially as traffic volumes increase. While the effectiveness of work zone egress warning systems is still under investigation, the researchers hope that providing real-time, focused warnings will better prepare drivers to slow down or change lanes, provide more time for drivers to react to slow-moving construction vehicles, and reduce crash risk by reducing conflicts between slow-moving construction vehicles and traffic in the travel lanes.

- **Continue to use law enforcement judiciously in work zones to help encourage speed limit compliance and reduce speed differentials between slow-moving construction vehicles and high-speed traffic.** The field studies documented the low speeds at which fully loaded construction vehicles enter the travel lanes. Having law enforcement present upstream of active workspace access points could help decrease operational speeds and reduce conflicts between traffic and slow-moving construction vehicles. However, the placement of the law enforcement vehicle should be such that it does not push traffic into the lane where the slow-moving construction vehicles are entering the travel lanes. For example, a law enforcement vehicle located on the outside shoulder upstream of an active workspace access point in the median would cause vehicles in the outside lane to move to the inside lane. This could result in increased lane changes (i.e., vehicles having to move back into the outside lane to avoid a slow-moving construction vehicle entering the roadway) and vehicle conflicts in the vicinity of the workspace access point.

APPENDIX A:
STATE OF THE PRACTICE

This appendix contains findings from recent unpublished crash analyses on CMV-involved work zone fatal crashes and a summary of published literature on CMV-involved crashes in work zones and mitigation strategies that can be used to reduce the risk of CMV crashes in work zones. In addition, it includes an overview of ODOT's current work zone practices and procedures that reduce the risk of CMV-involved work zone crashes, a summary of the 2020 Ohio CMV Safety in Work Zones Workshop sponsored by FHWA, and a review of other state practices concerning the design of construction vehicle access points.

CRASH STUDIES

National Findings

According to the National Highway Traffic Safety Administration's (NHTSA) Fatality Analysis Reporting System (FARS), since 2016 over 2 percent of all fatal crashes in the United States every year occur in work zones. Figure 1 shows CMV-involved fatal work zone crashes (i.e., those involving large trucks[1] and buses[2]) have generally been trending upward, while the percentage of all fatal work zone crashes that involve a CMV has remained relatively steady. From 2013 to 2019, the number of fatal work zone crashes involving a CMV increased from 153 to 252. In 2020, there was a decrease in the number (211) and percent of fatal work zone crashes involving a CMV (27 percent). However, this was likely due to pandemic-related decreases in overall vehicle travel that year. In 2021, the number of fatal work zone crashes involving a CMV rose to 295 (34 percent), but in 2022 the number declined to 248 (33 percent).

For comparison purposes, CMV involvement in non-work zone fatal crashes has remained fairly constant at about 10 to 13 percent during the same time period. So relative to fatal crashes occurring outside of work zones, CMVs are consistently overrepresented in fatal work zone crashes. This is why FHWA and other federal agencies have placed an emphasis on improving CMV safety in work zones.

Several possible reasons exist for this overrepresentation of CMVs in fatal work zone crashes, relative to CMV involvement in non-work zone fatal crashes, including:

- More work zones occurring on roadways that CMVs use.
- Work zone designs can be more challenging for CMVs.

[1] Large trucks were defined as vehicles with a gross vehicle weight rating (GVWR) more than 10,000 pounds (lb) (FARS body type codes 60–64, 66–67, 71–72, and 78). Large trucks do not include motor homes.

[2] Buses were defined as school buses, cross country/intercity buses, transit (city) buses, van-based buses (GVWR more than 10,000 lb), and other types of buses (e.g., FARS body type codes 50–59). Buses do not include van-based buses with a GVWR of 10,000 lb or less.

- CMVs delivering and removing materials and equipment to and from the work zone.
- Driver distraction (CMV and non-CMV).

However, to date it is not clear from available data how these reasons interact and impact CMV safety in work zones.

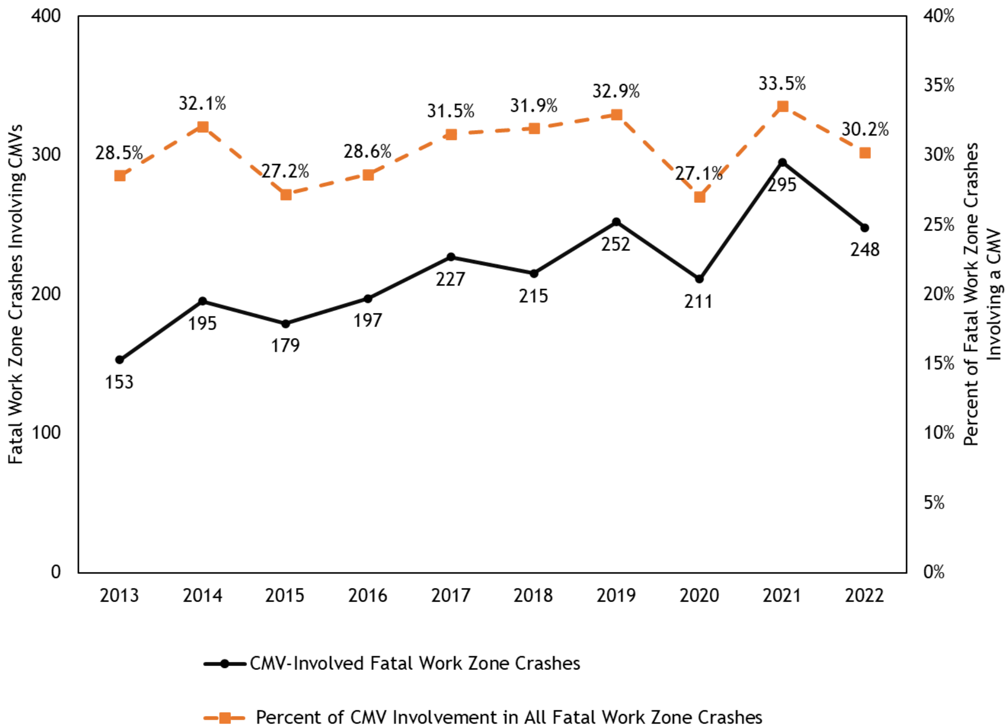


Figure 1. CMV-Involved Fatal Work Zone Crashes (Source: NHTSA FARS 2013–2022).

Further investigation of CMV-involved fatal work zone crashes from NHTSA FARS from 2016 to 2020 found most CMV-involved fatal work zone crashes occurred on interstates (52 percent), and the most common type of crash involving a CMV was a rear-end collision (46 percent). In 47 percent of all CMV-involved fatal work zone crashes, the front of the CMV was the initial point of contact. These most likely represent the CMV hitting another vehicle. The back of the CMV was the initial point of contact in 38 percent of all CMV-involved fatal work zone crashes. These presumably include other vehicles hitting the CMV. CMV-involved work zone crash fatalities were most often occupants of non-CMVs (71 percent).

Figure 2 shows the percent of fatal crashes involving a CMV for work zones and non-work zones by facility type (i.e., combination of land use and functional classification) from another recent analysis of NHTSA FARS data. CMV involvement is overrepresented on all types of roadways, but especially on interstates. More than 50 percent of all fatal work zone crashes on rural interstates involved a CMV, and

36 percent of all fatal work zone crashes on urban interstates involved a CMV. Overall, about 30 percent of fatal work zone crashes nationally involved a CMV.

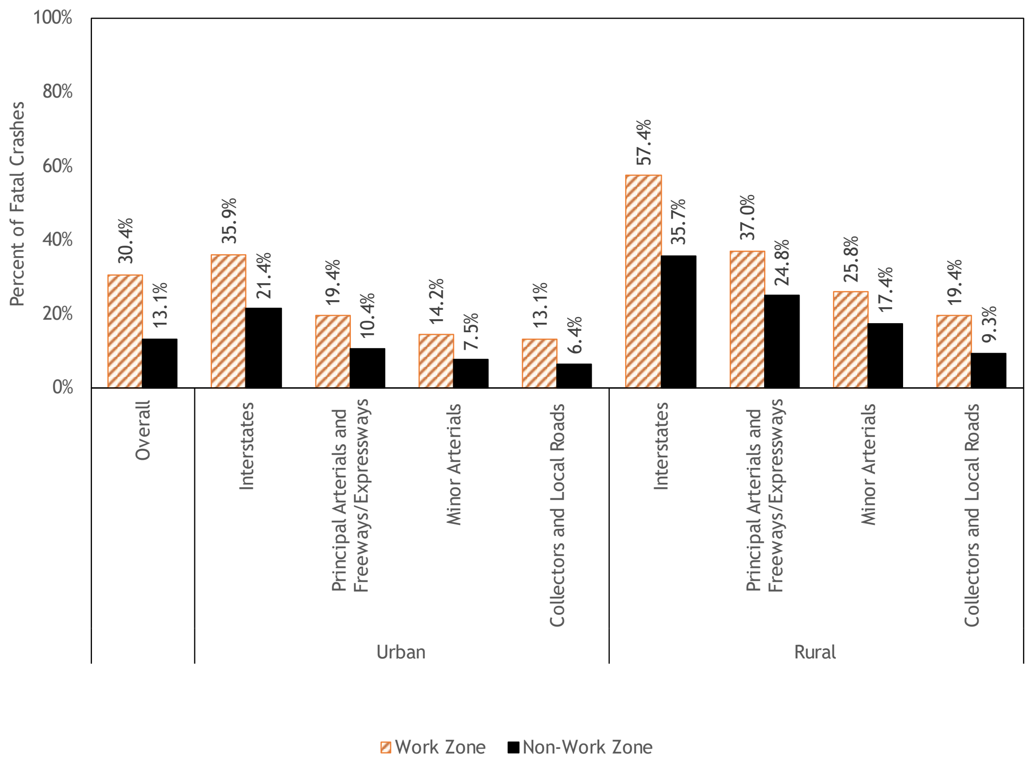


Figure 2. CMV Involvement in Fatal Work Zone and Non-Work Zone Crashes by Facility Type (Source: NHTSA FARS 2020-2022).

Ohio Findings

In 2018, Ohio was identified by FHWA as an "opportunity state" to improve CMV safety in work zones because it was one of the top 10 states with the highest number of fatal work zone crashes and associated work zone fatalities involving CMVs. Over a six-year period from 2012 to 2017, 49 fatal work zone crashes involved a CMV and resulted in 53 fatalities in Ohio based on an analysis of NHTSA FARS data.

As part of the recent FHWA Work Zone Management Program CMV task order, Texas A&M Transportation Institute (TTI) researchers analyzed NHTSA FARS data from 2012 to 2018 to identify trends in fatal motor vehicle crashes involving CMVs in work zones and non-work zones in Ohio. Figure 3 shows the percent of fatal crashes involving a CMV in work zones and the percent of fatal crashes involving a CMV in non-work zones for Ohio and nationally. It is evident from this figure that fatal work zone crashes involving CMVs are overrepresented in Ohio, and that Ohio has a higher percentage of fatal crashes involving CMVs in work zones compared to national trends.

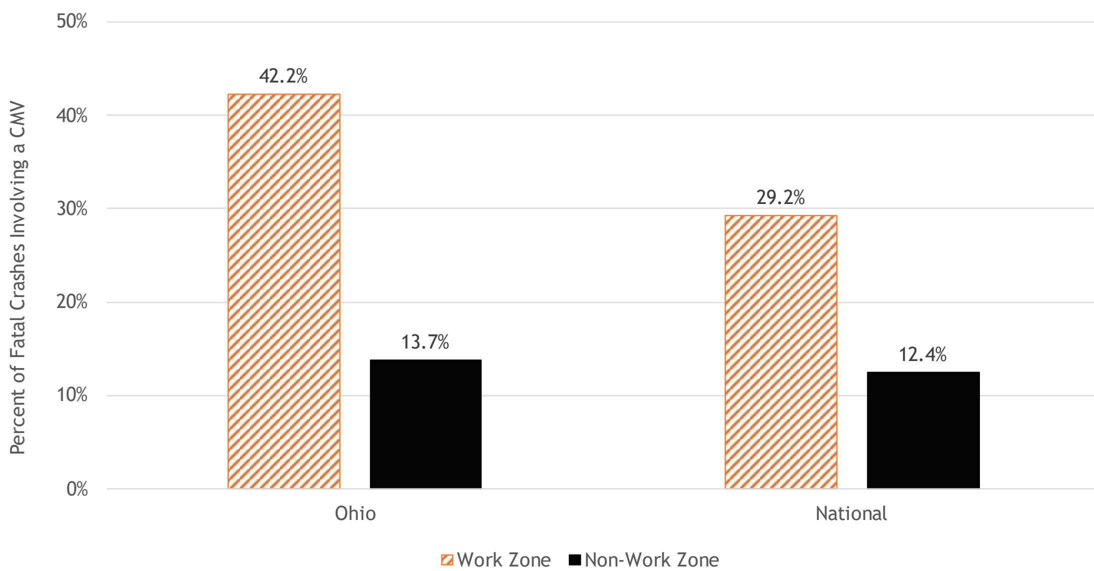


Figure 3. CMV Involvement in Fatal Work Zone and Non-Work Zone Crashes (Source: NHTSA FARS 2012–2018).

Figure 4 shows the distribution of Ohio CMV-involved fatal crash trends for work zones and non-work zones by facility type. The percent of CMV-involved fatal work zone crashes occurring on urban interstates and freeways is almost triple the percentage of non-work zone CMV-involved fatal crashes on those facility types. In addition, the percent of CMV-involved fatal work zone crashes occurring on rural interstates and freeways is more than double the percentage of non-work zone CMV-involved fatal work zone crashes on those facility types. About two-thirds of the CMV-involved fatal work zone crashes on urban interstates and freeways occurred at night. In contrast, almost 80 percent of the CMV-involved fatal work zone crashes on rural interstates and freeways happened during the day.

Figure 5 contains the Ohio CMV-involved fatal crash trends for work zones and non-work zones by manner of collision. Rear-end collisions (i.e., front to rear) appear to be overrepresented in CMV-involved fatal crashes in Ohio work zones in rural and urban areas. However, the percent of CMV-involved fatal rear-end crashes in work zones was higher in rural areas (71 percent) compared to urban areas (61 percent). In addition, 70 percent of rural CMV-involved fatal rear-end work zone crashes occurred during the day. These findings are intuitive since rural interstates and freeways typically have higher speeds and most work activity is conducted during the day. Thus, unexpected slowdowns and queues from work zone related activities can contribute to more rear-end collisions. In contrast, 65 percent of urban CMV-involved fatal rear-end work zone crashes happened at night. On urban interstates and freeways, road work that requires reduced capacity (i.e., lane closures) is typically conducted at night to reduce operational impacts. Additional analysis found the front and back of the CMV were the initial point of contact in 46 and 38 percent of CMV-involved fatal rear-end work zone crashes, respectively.

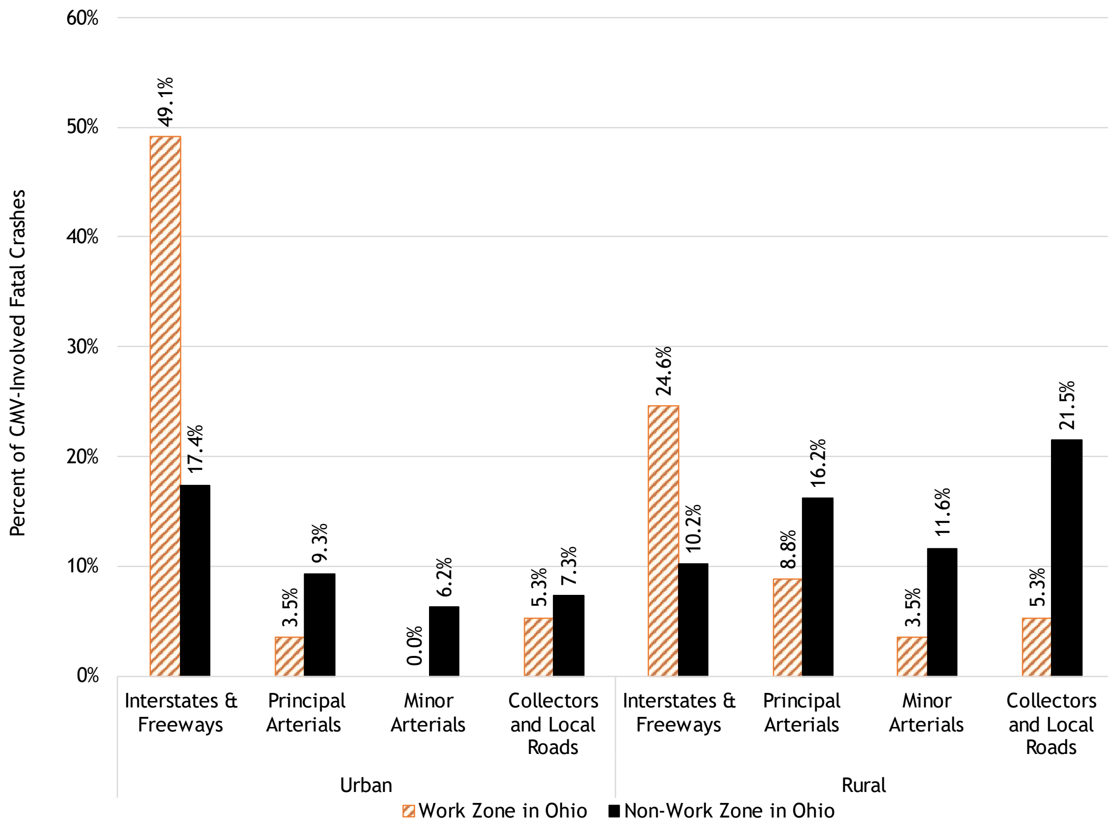


Figure 4. Distribution of Ohio CMV-Involved Fatal Work Zone and Non-Work Zone Crashes by Facility Type (Source: NHTSA FARS 2012–2018).

As part of the recent FHWA task order, TTI researchers further explored CMV-involved work zone crash trends by obtaining serious injury crash data from ODOT. Focusing on CMV-involved serious injury crashes in work zones from 2012 to 2018, researchers found that 38 percent occurred when a lane closure was present. For the lane closure-related serious injury crashes, 47 percent occurred in the activity area, 24 percent in the transition area, 19 percent in the advance warning area, and 8 percent before the first warning sign. The latter two categories could be indicative of traffic queues forming due to the reduced capacity. More than 80 percent of the lane closure-related crashes happened during the day. Following too close (58 percent) and improper lane change (20 percent) were the primary contributing actions. Distracted driving (23 percent) and speed (21 percent) were the top contributing factors.

Work activities outside of the travel lanes (i.e., on the shoulder or median) contributed to 36 percent of CMV-involved work zone serious injury crashes. Eighty-five percent of these crashes occurred in the activity area, 7 percent in the transition area, 4 percent in the advance warning area, and 2 percent before the first warning sign. About two-thirds of all the serious injury crashes related to work activity outside of the travel lanes happened during the day. Improper lane change (36 percent) and following too close (30 percent) were the primary contributing actions. Speed (40 percent) was the top contributing factor.

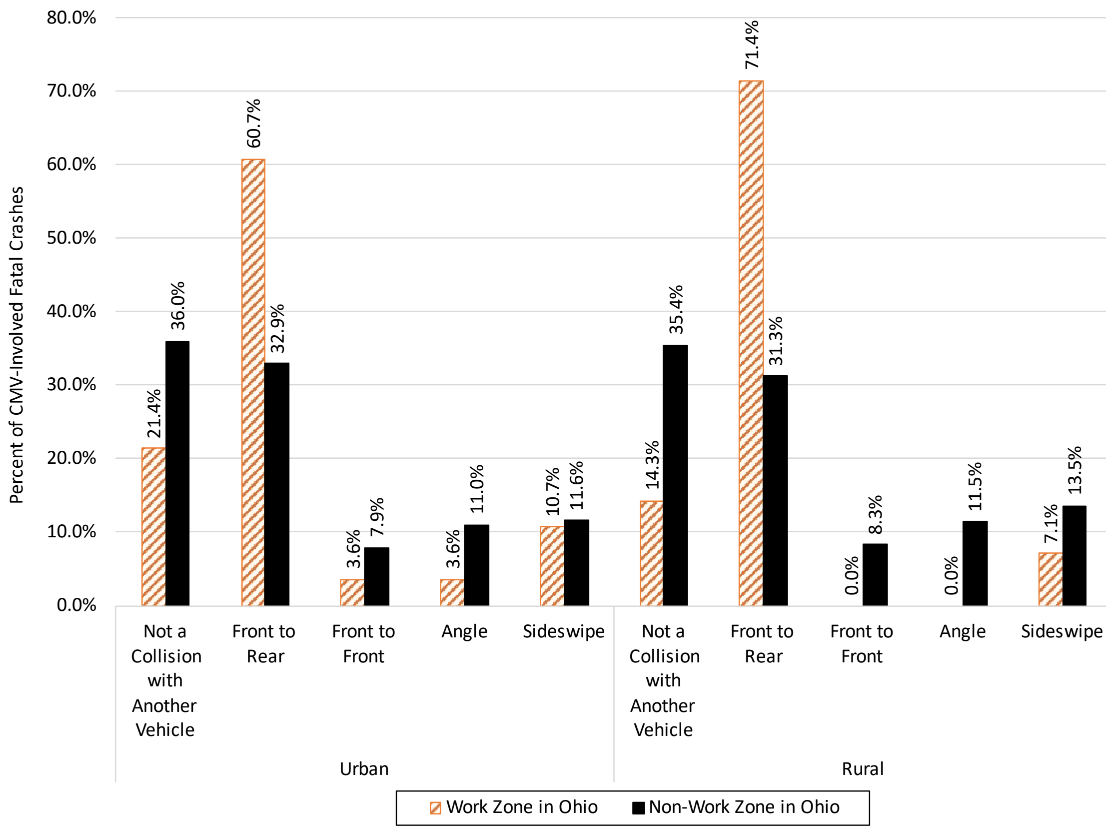


Figure 5. Distribution of Ohio CMV-Involved Fatal Work Zone and Non-Work Zone Crashes by Manner of Collision (Source: NHTSA FARS 2012–2018).

Literature Review

Several studies have also concluded that CMVs are typically overrepresented in work zone crashes (*1*, *2*, *3*, *4*, *5*, *6*, *7*). Other studies have attempted to better understand the additional risks that large trucks experience in work zones. Benekohal et al. (*8*) conducted interviews with truck drivers in Illinois to assess their experiences in work zones. Approximately 6 percent of the truck drivers surveyed had been involved in a work zone crash. About one-third of those crashes occurred in the advance warning area and two-thirds happened in the transition area. Poor driving conditions were cited as a key contributor to work zone crashes. Harb et al. (*9*) used a relative accident involvement ratio and various logistical regression models to conclude that large trucks were 44.6 percent more likely to be involved in a work zone single-vehicle crash compared to non-work zone locations in Florida.

In 2012, TTI led National Cooperative Highway Research Project (NCHRP) 17-61 (*10*) to develop new information and comprehensive guidance on work zone crash characteristics and the effectiveness of countermeasures intended to reduce work zone crash frequency and severity. As part of this project, Ullman et al. examined the combined NHTSA/FMCSA Large Truck Crash Causation Study database for insights into large truck-involved work zone crashes. The database included 1,070 crashes from 17 states between April 2001 and December 2003 that involved at least one large truck (i.e., gross vehicle weight of more than 10,000 lb) and one or more fatalities or injuries. Out of these crashes, 77 (7.2 percent) were associated with a work zone. An analysis of freeway crashes found that 65 percent were rear-end crashes and the majority of those occurred at or near the back of queue. Other rear-end crashes involved vehicles re-entering the travel lanes from the construction area, a slow-moving mobile operation, disabled vehicles, driver overreaction to misaligned barrels, and illegal driving maneuvers. Other large truck-involved work zone freeway crashes were attributed to vehicles performing a late or forced lane change (13 percent), sideswipe (13 percent), or roadway departure (9 percent). Ullman et al. found that sudden speed drops and congestion contributed to 60 percent of the crashes directly related to work zones. Other contributing factors included changes in the lane configuration (36 percent) and changes in the surface conditions (4 percent). The analysis of non-freeway crashes identified similar trends except that 38 percent of the crashes were due to driver physical condition and/or vehicle mechanical condition instead of vehicle-roadway or vehicle-vehicle interaction.

Ullman et al. also found that a sizeable portion of rear-end collisions and sideswipe crashes could be attributed to work vehicles entering or exiting the travel lane from the workspace. One of the databases analyzed showed that 10 percent of the crashes on interstates/freeways appeared to result from such work vehicle maneuvers. Further investigation revealed that the third most common cause for crashes involving work vehicles was when they were entering/exiting the workspace (18 percent). Ullman et al. noted that the findings suggested it is more difficult for work zone vehicles to merge into and out of interstate work zones. Another database analyzed found that crashes involving work vehicles entering the travel lanes from the workspace was the fifth most common crash category. Speed differentials between the main lane traffic and work vehicles entering the travel lanes were a significant factor, causing vehicles to rear-end the work vehicles.

In 2022, Dunn et al. (*11*) analyzed naturalistic driving data to gain insight into the characteristics of work zones, roadways, vehicles, and environments that are associated with a truck driver being involved in a safety-critical event (SCE) (i.e., crash, near-crash, or crash-relevant conflict). Items that increased SCE risk included the use of traffic cones (presumably due to their smaller size), single-lane roadways (three times greater risk than four-lane roadways), and active work zones (twice the risk of inactive work zones). Features that decreased SCE risk included retroreflective signs, retroreflective barrels, and concrete barriers. Light traffic compared to moderate or heavy traffic also reduced SCE risk.

Other prior studies have focused on the severity of crashes in work zones and found that large truck-involved work zone collisions tend to be more severe than non-large truck-involved work zone collisions (4, *12*, *13*, *14*). Such findings are intuitive, since large trucks have significantly more kinetic energy to dissipate in the event of a crash than passenger vehicles. Since large trucks are heavier than passenger vehicles, several studies have also found that work zone crashes involving large trucks and pedestrians tend to be more severe. Fatal work zone crashes involving large trucks and pedestrians occurred at almost three times the rate of all crashes with pedestrian fatalities (*15*, *16*). Gupta et al. (*16*) found that dark not lighted conditions, distracted truck drivers, airbag deployment, and truck driver age were factors that significantly increased the probability of a fatality in crashes involving large trucks and pedestrians based on seven years of Florida crash data (2010–2016). For non-pedestrian crashes, Gupta et al. found that front air bag deployment without full restraint (i.e., shoulder and belt) and abnormal driver conditions (e.g., fatigue and alcohol/drug influence) contributed to large truck-involved work zone fatal crashes. No roadway conditions (e.g., road type, median type, etc.), environmental factors (e.g., weather), vehicle maneuvers, or driver actions were found to be primary contributors in either model.

A more recent analysis of Florida single-vehicle large truck crashes (2011-2019) by Islam (*17*) found the likelihood of large truck drivers' injury severity is about 14 times higher on rural interstates and six times higher on urban interstates in work zones versus non-work zones. Islam also determined that driving 10 mph below the posted speed limit resulted in 1.3 times lower risk for large truck drivers inside work zones relative to non-work zones. Likelihood ratio tests showed the estimated model parameters for work zone crashes were statistically different from those for non-work zone crashes. The single-vehicle large truck work zone crash model indicated the likelihood of severe truck driver injury was higher for heavy trucks (i.e., GVWR more than 26,000 lb), crossovers (i.e., travel lanes cross over to the other direction of travel), and careless driving.

Khattak et al. (*13*) found that truck-involved, multivehicle crashes caused the most injuries when they occurred on two-way undivided roadways, at crossovers, adjacent to the work activity, and when the posted speed limit was higher. Osman et al. (*18*) developed several econometric models based on 10 years of large truck work zone crash data in Minnesota and found that crashes occurring during the day on roads with no access control and higher speed limits (i.e., rural principal arterials) increased the risk of severe large truck crashes in work zones. Theiss et al. (*19*) examined rear-end work zone crashes associated with flagging operations on two-lane roadways in Texas. Fifty-two percent of the fatal and serious injury crashes involved at least one CMV, and in the majority of those crashes, the CMV was stopped or coming to a stop.

More recently, Ahmed et al. (*20*) examined large truck-involved work zone crashes in South Carolina and found the top ranked factors that contributed to injuries were airbags deployed, rear-end crashes, crashes on primary roadways, and crashes in dark conditions. Yu et al. (*21*) analyzed truck-involved crashes in work zones in North Carolina over a 10-year period and developed models for rural and urban highways. Yu et al. identified significant factors among the following characteristics: driver, environmental, work zone, road, and vehicle. The likelihood of severe injury increased for truck-involved work zone crashes on rural roadways for young drivers, maintenance activities, and principal arterials. Middle-aged drivers, dark conditions, upstream of the work zone, and undivided highways were factors found to increase the likelihood of possible injury from truck-involved work zone crashes on urban roadways. For both models, driver alcohol/drug use, unrestrained driver, and dawn conditions significantly increased the likelihood of injury severity. Ongoing work activity was associated with a lower likelihood of injury for both models.

MITIGATION STRATEGIES

National Guidance

The overrepresentation of CMVs in fatal work zone crashes has been a major area of concern for USDOT. Many resources including guidance documents, fact sheets, webinars, conference sessions, driver training resources, and driver outreach (CMV and non-CMV) have been developed by FHWA, FMCSA, other federal agencies, and various stakeholders to reduce the risk of CMV crashes in work zones (*22*, *23 24*, *25*). These materials include information on strategies for designing work zones to better accommodate CMVs and helping CMV drivers better negotiate work zones. The *Design and Operation of Work Zone Strategies to Improve Large Truck Safety* (*26*) summarizes available methods to reduce CMV crashes through work zone design and operational practices. Below is an abbreviated list that contains some practices recently highlighted by FHWA in its work with the "opportunity states."

- Properly incorporate CMV effects into work zone traffic impact analyses.
- Maintain sufficient lane widths (11 ft minimum; 12 ft desirable).
- Avoid short or no acceleration lane entrance ramps.
- Use appropriate design speed.
- Maintain good sign, device, and pavement marking retroreflectivity.
- Encourage trucks to use alternate routes (if acceptable).
- Create a truck-only lane through the work zone or encourage trucks to use only certain lanes.
- Avoid the creation of traffic queues.
- Deploy active work zone queue warning and/or dynamic lane merge warning systems where queues are expected to develop.
- Utilize law enforcement to increase speed limit compliance and/or assist with queue warning.
- Deploy temporary portable rumble strips upstream of lane closures to increase driver alertness and awareness.
- Deploy sequential warning light systems on channelizing devices used in the taper of nighttime lane closures.
- Provide good workspace ingress and egress design.
- Deploy active work zone technology to warn approaching motorists about construction vehicles entering or exiting the workspace.

The *Guidelines on Work Zone Access and Egress* publication (*27*) contains additional guidelines for planning and implementing safe access and egress into the workspace for work vehicles. This guide notes several challenges with providing safe and efficient passage of work vehicles into and out of the workspace, especially on high-volume roadways. These include the potential for drivers to follow work vehicles into the workspace, the acceleration and deceleration of work vehicles as they exit and enter the open travel lanes, the proximity of workers to work vehicle access points, and the proximity of parked or staged equipment near open travel lanes. The guide also contains recommended practices for planning and designing the work zone to minimize the impact on traffic flow from accelerating and decelerating work vehicles, managing access and egress points during construction, and incorporating access and egress into internal traffic control plans. This publication also highlighted examples of innovative ideas regarding workspace access points, including the development of a standard workspace access point design by ODOT to reduce conflicts between construction vehicles and the traffic in the open travel lanes, and the use of intelligent transportation system technology by the Minnesota Department of Transportation (MnDOT) to automatically detect construction vehicles entering, exiting, or crossing the workspace and warn approaching drivers about possible slowdowns and merging conflicts. MnDOT's Intelligent Work Zone Toolbox identifies when to use such a system and specifies how to configure the PCMS.

The *Work Zone Operation Best Practices Guidebook* (*Third Edition*) (*28*) is a compilation of work zone operations practices used and recommended by various states and localities in the United States. It includes noteworthy practices to address slow-moving construction vehicles entering, leaving, and crossing open travel lanes to deliver materials and perform other job duties in the workspace. Examples include documents from the Virgina Department of Transportation (VDOT), the Texas Department of Transportation, and the Maryland State Highway Administration. In general, these documents provide information about the location of signs to warn drivers about construction vehicles entering the roadway, requirements for construction vehicle access/egress to be in the same direction of travel as open lanes, and additional strategies that could be considered on a project-by-project basis.

More recently, the *Designing Work Space Access Points to Better Accommodate Large Trucks* factsheet was released (*29*). It acknowledges that speed differentials between CMVs entering and exiting the workspace and high-speed traffic may contribute to CMV-involved crashes in work zones. CMVs entering the workspace must significantly slow down to turn into a construction workspace access point. Also, when exiting the workspace, CMVs need time to accelerate from very slow speeds. The factsheet provides information about incorporating acceleration and deceleration lanes into the temporary traffic control plan and the appropriate length for acceleration and deceleration lanes. The factsheet also includes examples from VDOT and ODOT.

Another factsheet introduces smart work zone warning systems available for vehicles entering and exiting the workspace (*30*). Primarily these systems actively warn approaching drivers of the presence of slow-moving CMVs exiting the workspace (i.e., entering the travel lanes), although the technology can also be used to warn of CMVs slowing down to enter the workspace. The factsheet contains a description of these systems and key considerations. Entering/exiting construction vehicle notification systems are further discussed in the *Use of Technology and Data for Effective Work Zone Management: Work Zone Intelligent Transportation Systems Implementation Guide* (*31*) and *Work Zone Intelligent Transportation Systems—Technology Supplement* (*32*).

In 2023, FHWA, FMCSA, and NHTSA released a *Commercial Vehicle Safety in Work Zones Targeted Action Plan* (*33*) to provide a coordinated strategy that stakeholders could use to reduce the risk of CMV crashes in work zones. While many CMV and work zone safety initiatives benefit CMV safety in work zones indirectly, this plan is centered on voluntary actions that can be taken to address CMV safety specifically in work zones. The optional actions fall into three key emphasis areas: engineering, enforcement, and driver education.

FHWA also developed a factsheet on the use of in-cab notifications to warn CMV drivers about traffic slowdowns and queues attributed to work zones (*34*). While roadside queue warning systems are an effective means of providing such warnings (*35*), these systems are not used at every work zone, and it is desirable to provide similar warnings directly to CMV drivers through electronic logging devices. The factsheet documents an early demonstration of the concept in North Carolina, but due to a low sample size, the effects of the alerts upon driver behavior could not be assessed.

FHWA recently released a factsheet on designing work zone lane shifts to improve CMVs' ability to navigate through these temporary changes in the roadway alignment (*36*). The traditional method of designing lane shifts can create challenges for CMV drivers of tractor-trailer combinations trying to maintain proper lane positioning and may result in vehicle encroachments into adjacent lanes or work zones, which can increase sideswipe crashes and crashes with fixed objects (e.g., barrier). To provide slightly wider lanes within lane shifts to better accommodate CMVs, the Indiana DOT is offsetting the start of the shift for each lane. Using this method, a 12 ft lane width can be increased to more than 13 ft within the transition by staggering the start of each lane's shift by 40 ft.

Current ODOT Practices and Procedures

Over the years, ODOT has implemented many strategies to reduce the risk of CMV-involved work zone crashes, including but not limited to:

- Using work zone metrics to identify issues impacting CMV safety.
- Establishing a policy and standard procedure for traffic management in work zones on all ODOT-maintained highways and on all federal-aid highway projects (Policy 21-008[P] [*37*] and Standard Procedure 123-001[SP] [*38*], respectively). The procedure instituted a lane closure policy based on an allowable queue length threshold (less than or equal to 0.75 miles) and includes the use of a searchable capacity-based tool (PLCS) for identifying which hours of the day lane closure(s) should not exceed the allowable queue length threshold. Large truck volume data will be used more in the updated system, but there is currently a limited amount of large truck classification and volume information available.
- Posting lane use signing for trucks if the shoulder pavement cannot adequately accommodate trucks when traffic is shifted onto the shoulder.
- Publishing a plan insert sheet (PIS) for construction access points (ingress/egress) and designer guidance in the *Ohio Traffic Engineering Manual* in April 2009. The PIS became a standard construction drawing (MT-103.10) in January 2015 (most recently revised in January 2022) (*39*, *40*) and is intended for use on freeways, expressways, and multi-lane highways with an original speed limit of 45 mph or greater to provide a dedicated lane outside the travel lanes for the deceleration and acceleration of construction vehicles.

- Publishing guidance on the use of work zone egress warning systems that warn drivers of slow-moving construction vehicles entering the travel lanes from the workspace in January 2017 (*39*, *40*).
- Increasing offset from 1 to 2 ft between the barrier toe and adjacent travel lane and establishing a 2 ft offset between barrier toe and work area in July 2017 (most recently revised in January 2018) (*39*, *40*, *41*). The former application provides more space between the lane and the barrier for CMVs.
- Using a 12 ft preferred lane width on freeways and expressways. If a lane width reduction is necessary, it is desirable to maintain 11 ft lane width (*40*).
- Sending in-cab alerts about slowdowns and congestion to large trucks via Drivewyze® since 2021.
- Updating the PLCS system to better leverage percent truck data for capacity calculation purposes (half hourly rather than one average percent truck value), where such data is available for use, in January 2024.

Other strategies that may indirectly impact CMV safety in work zones include:

- Publishing standards for the use of a WZQDWS in July 2016 (*40*).
- Adding a plan note for traffic incident management during maintenance of traffic in July 2018 to enhance coordination and planning (*40*).
- Using enforcement to increase compliance with work zone speed limits.
- Providing real-time traffic information through personalized route notifications on the OHGO app.

2020 Ohio CMV Safety in Work Zones Virtual Workshop

As previously mentioned, Ohio was identified as an “opportunity state” for improving CMV safety in work zones by FHWA in 2018. FHWA recently worked hand in hand with agencies and entities in the 10 opportunity states to conduct workshops and develop voluntary state-specific action plans of methods to employ to improve CMV safety.

The Ohio virtual workshop was held on November 19, 2020. Forty-three participants from federal and state transportation agencies, public safety offices, associations, and academia participated. During the workshop, stakeholders discussed previous and ongoing efforts to improve CMV safety in work zones, learned about other strategies that could be used to address the issue, and prioritized strategies that should be implemented to improve CMV safety in work zones. Based on the workshop findings and other related resources, TTI researchers developed the Ohio State Specific Action Plan. This plan contains voluntary action items related to three priority strategies and additional action items that Ohio stakeholders may consider to reduce the risk of CMV crashes in work zones. The priority strategies identified were:

- Strengthen use of WZQDWSs that detect queuing and warn upstream drivers of slowed/stopped traffic via portable changeable message signs.
- Explore use of in-vehicle communications to send work zone safety messages to CMV drivers.

- Deploy enforcement upstream of active work zone access points to reduce speed differentials between slow-moving work vehicles and high-speed traffic.

Based on the voluntary action plan, ODOT sponsored the research documented herein to determine if construction access points are adversely impacting CMV-related crashes in Ohio work zones and if so, to recommend mitigation strategies. ODOT also sponsored a research study to investigate commercial vehicle safety alert (CVSA) systems (*42*, *43*). Researchers utilized surveys to gather feedback from CMV drivers, truck companies, and DOTs on available CVSA systems and their effectiveness. Researchers also used a data-driven analysis to evaluate CVSAs' impact on congestion-related and secondary crashes. The survey results found that CMV drivers use a variety of CVSA systems, with Drivewyze® being the most common. The data-driven analysis found the CVSAs reduced secondary crashes, with reductions in all injury categories except serious injury crashes and reduced delay. Researchers also determined that CVSAs yielded a benefit-cost ratio of 22.56 for CMV congestion-related crashes. Based on the findings, researchers recommended that ODOT continue to partner with entities that provide CVSAs.

Other State Practices

Recently, as part of another FHWA effort, TTI identified four other state DOTs (i.e., Tennessee, Wisconsin, North Carolina, and Virginia) that have developed detailed standard drawings for how workspace access points are to be accommodated on construction projects. These state DOTs developed their drawings more recently than ODOT and have only used them on a small number of projects with varying degrees of success.

Figure 6 shows the standard drawing developed by the Tennessee Department of Transportation (TDOT) for both construction access and emergency pull-off areas. Like the ODOT standard drawing, the TDOT workspace access point drawing includes a dedicated lane separate from the open travel lanes for construction vehicles to decelerate and accelerate. However, the deceleration and acceleration areas are longer (approximately 1190 ft and 1320 ft, respectively). The minimum width of the dedicated lane is 11 ft. The shoulder or roadway segment used for the deceleration/acceleration lane must be either asphalt or concrete.

The Wisconsin Department of Transportation (WisDOT) standard drawings provide options with and without barrier (see Figure 7 and Figure 8, respectively). The WisDOT drawing also separates ingress and egress movements and specifically prohibits workspace access points on freeways to be used for ingress and egress at the same time. The lengths of the deceleration and acceleration lanes vary based on speed. For the design without barrier, drums are used to close a travel lane.

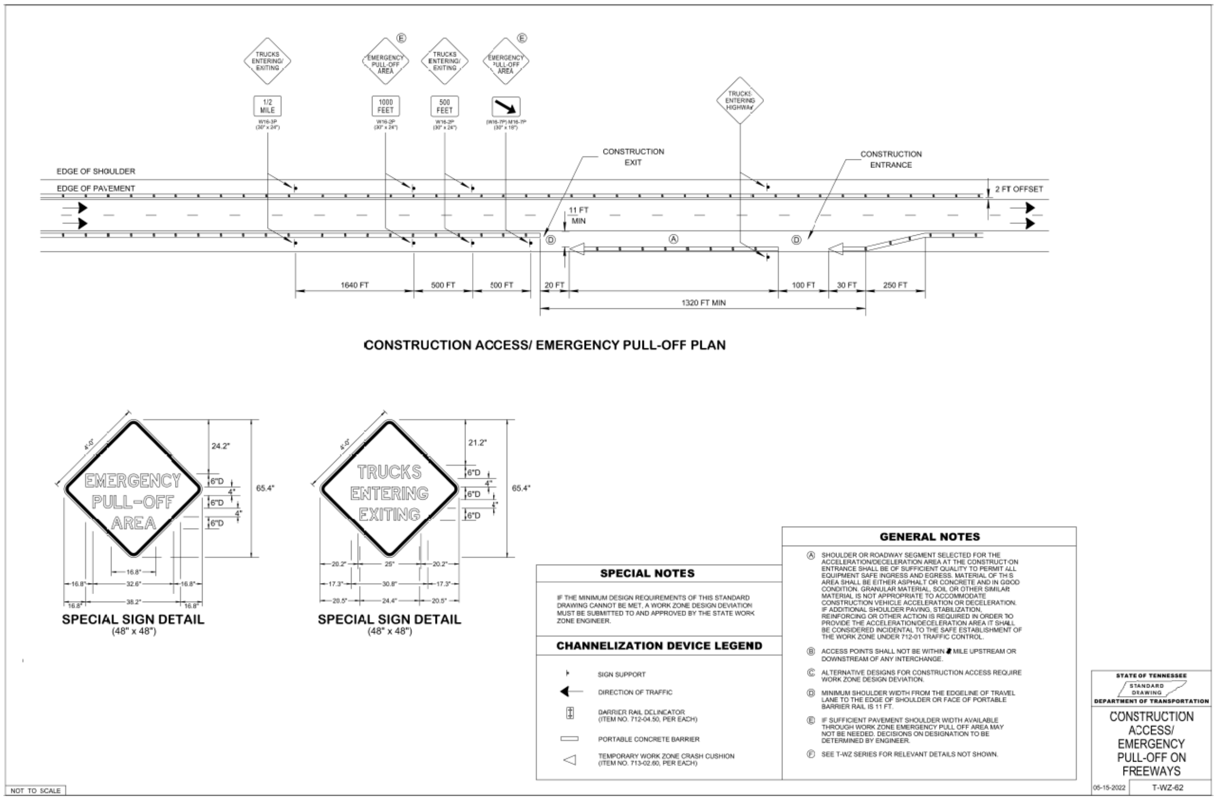


Figure 6. TDOT Construction Access Point Drawing T-WZ-82 (*44*).

North Carolina Department of Transportation (NCDOT) primarily uses a closed travel lane to provide an area for construction vehicles to accelerate when exiting the workspace (see Figure 9). Since daytime lane closures are not always feasible due to traffic volumes, NCDOT developed a standard drawing for median workspace access points (see Figure 10). However, this configuration is only used when an entering/exiting construction vehicle notification system is also deployed. Like the ODOT standard drawing, the NCDOT median access point drawing includes a dedicated lane separate from the open travel lanes for construction vehicles to decelerate and accelerate. The NCDOT deceleration and acceleration areas are approximately 820 ft and 1420 ft, respectively. In addition, the beginning of the acceleration area includes a 500 ft channelized lane. The special provision associated with the NCDOT median access drawing states that the deceleration/acceleration lane must use either existing or proposed pavement. If not available, temporary pavement must be constructed.

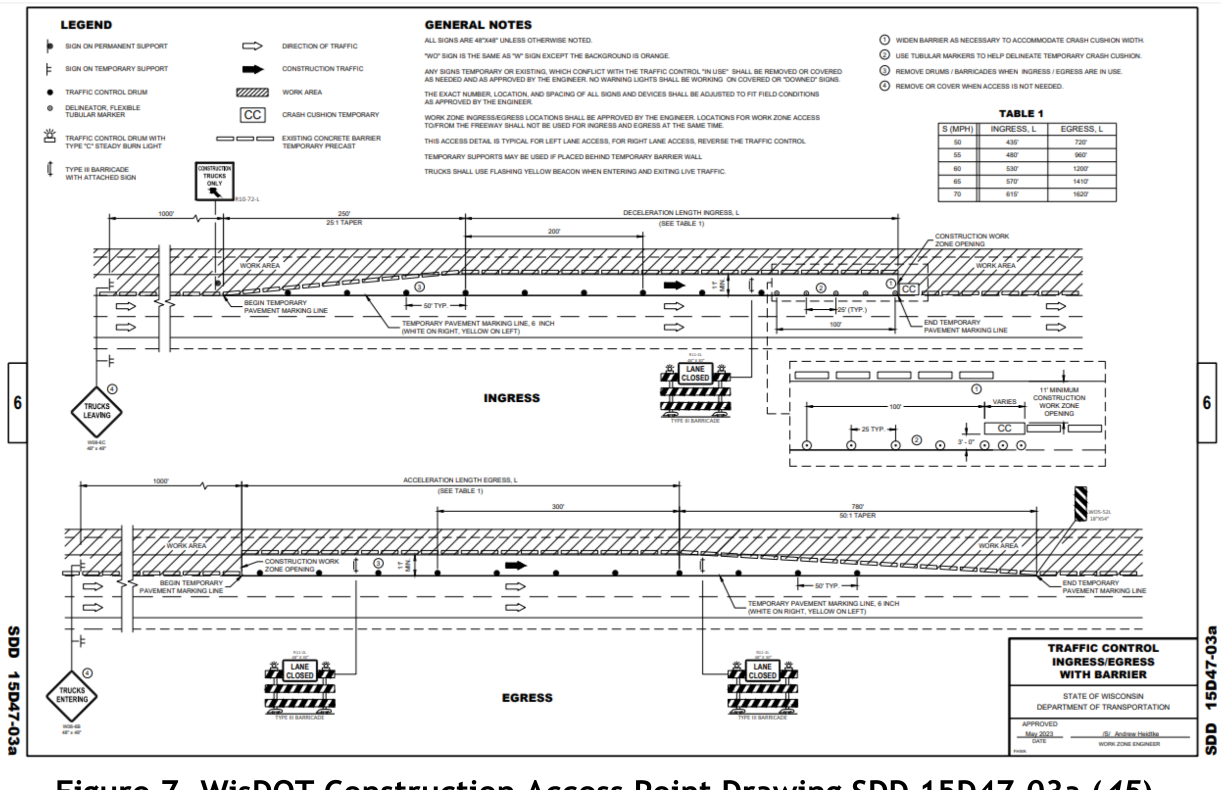


Figure 7. WisDOT Construction Access Point Drawing SDD 15D47-03a (*45*).

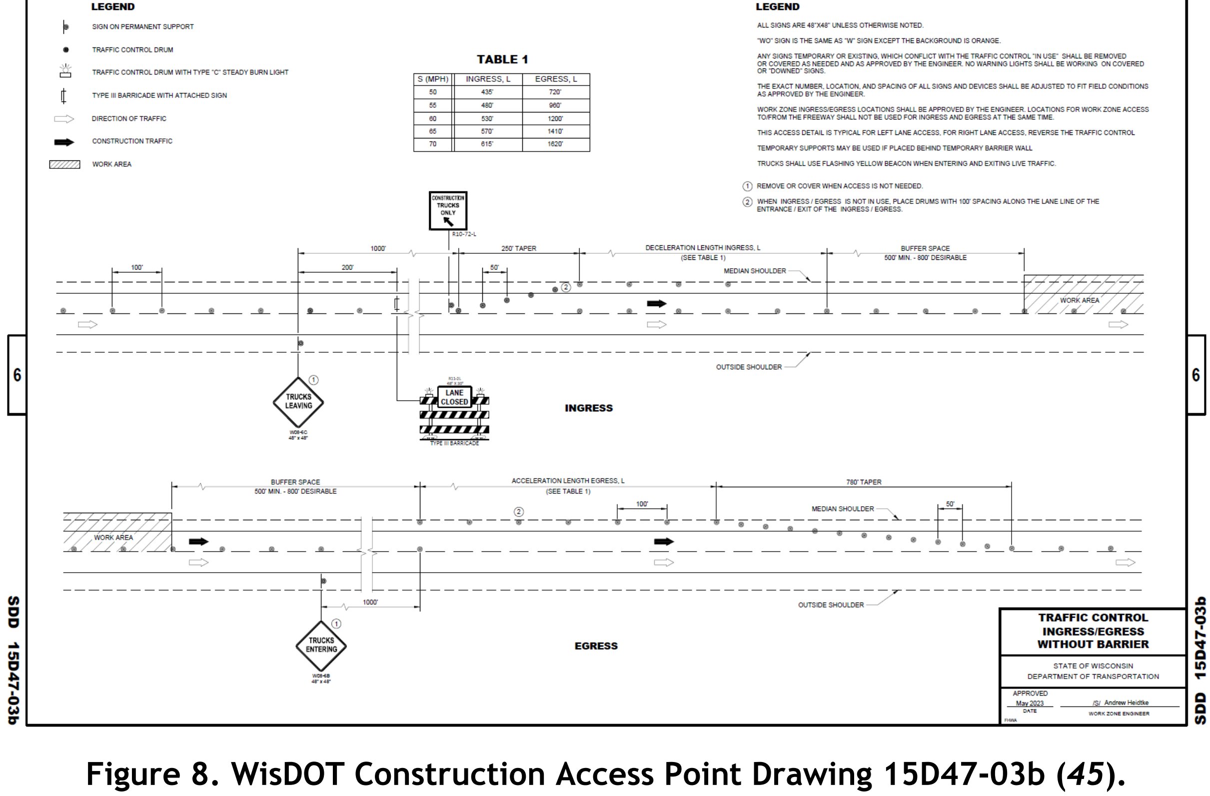


Figure 8. WisDOT Construction Access Point Drawing 15D47-03b (*45*).

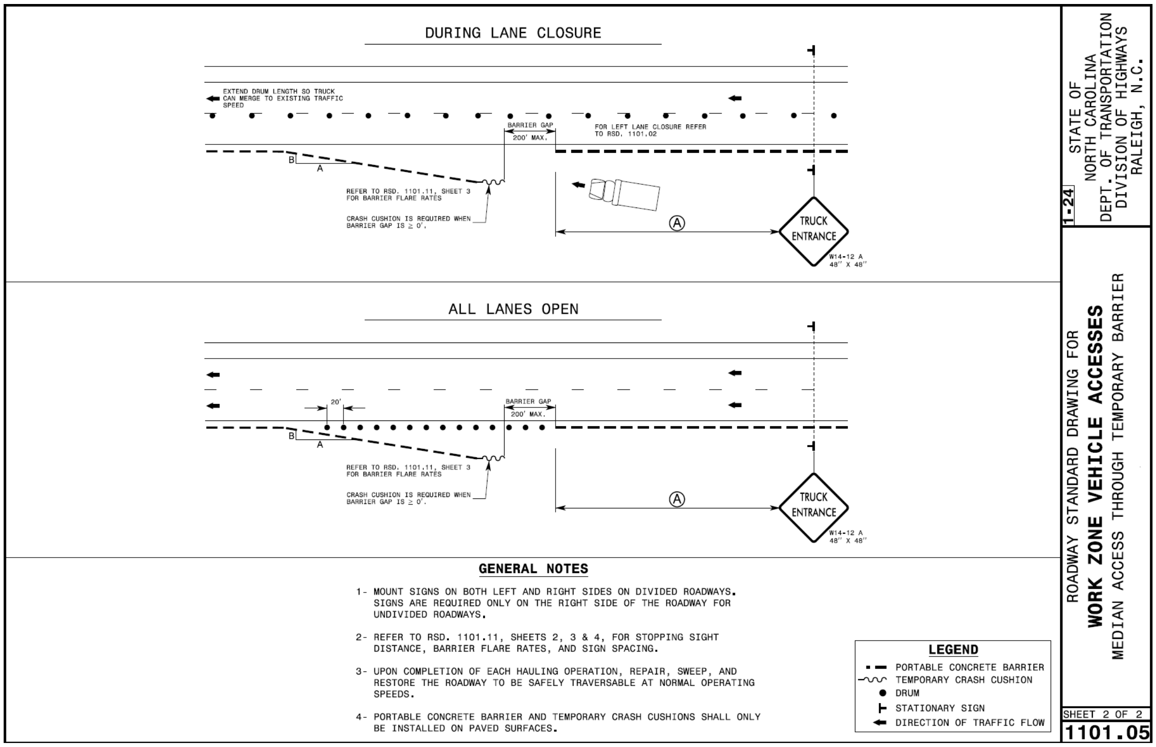


Figure 9. NCDOT Construction Access Point Drawing (*46*).

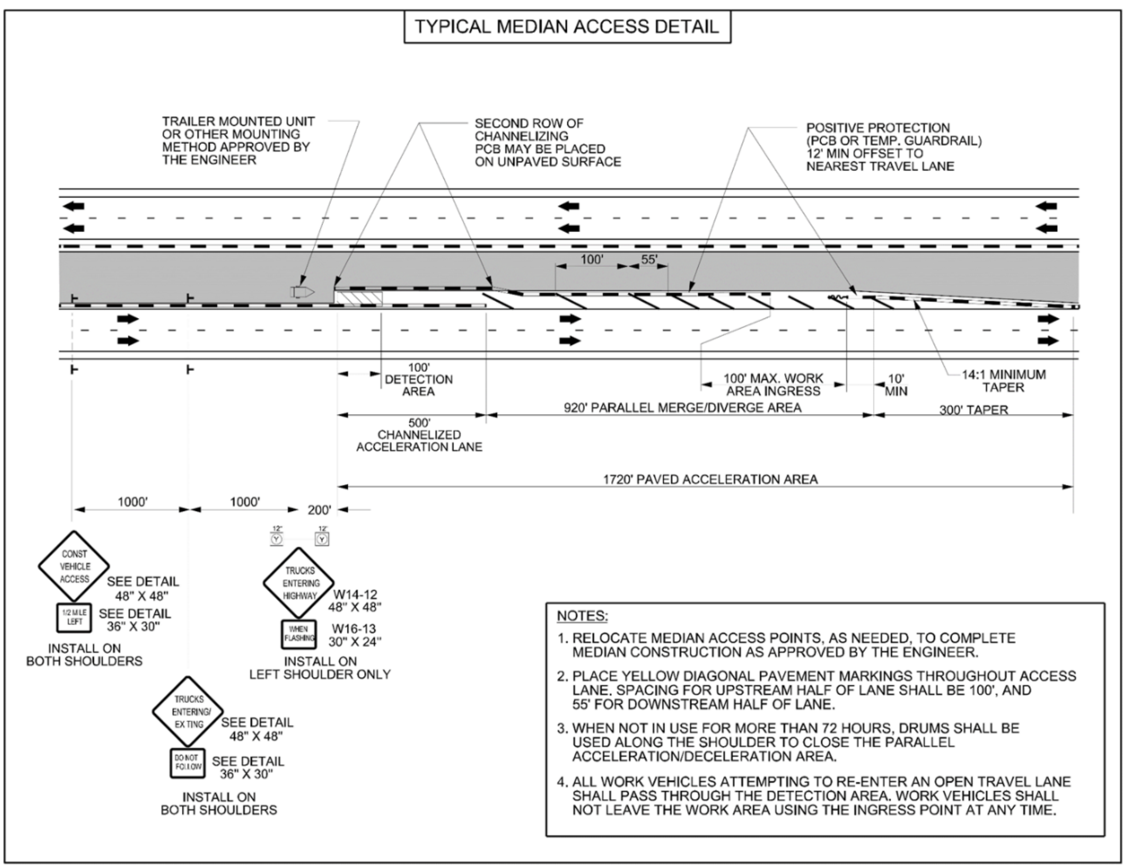


Figure 10. NCDOT Construction Access Point Drawing (*47*).

The 2011 edition of the *Virginia Work Area Protection Manual* (*48*) contains an entire section on work area ingress/egress. This section notes the need for addressing the safe movement of materials and equipment into and out of the work zone with minimal disruption to traffic in the temporary traffic control plan. The manual also states that internal traffic control plans identifying workspace access points for equipment and materials, as well as parking areas for workers' private vehicles, should be submitted and approved. Ingress workspace access points must be designed such that heavy trucks can exit the open travel lanes and decelerate safely into the workspace. Egress workspace access points must be designed so loaded trucks can accelerate to roadway speeds and merge safely into the open travel lanes. The location of the workspace access points should meet the sight distance requirements included in the manual. The deceleration/acceleration lane should be a minimum of 1320 ft long and 15 ft wide, but the width may be reduced to 12 ft on roadways with limited right of way. The spacing of workspace access points is every 0.5 to 0.75 mile for projects with activity areas up to 2 miles in length and one every mile for projects with activity areas greater than 2 miles in length.

VDOT wanted to conduct a pilot study of an entering/exiting construction vehicle notification system on a project (I-81), so it developed the median access detail shown in Figure 11. In this draft drawing, construction vehicles have approximately 1320 ft of dedicated lane outside the open travel lanes for deceleration and approximately 1420 ft for acceleration. Barrier openings must be a minimum of 14 ft wide and maximum of 18 ft wide. Median workspace access points cannot be located within ½ mile of the beginning of a deceleration lane or the end of an acceleration lane for an existing interchange.

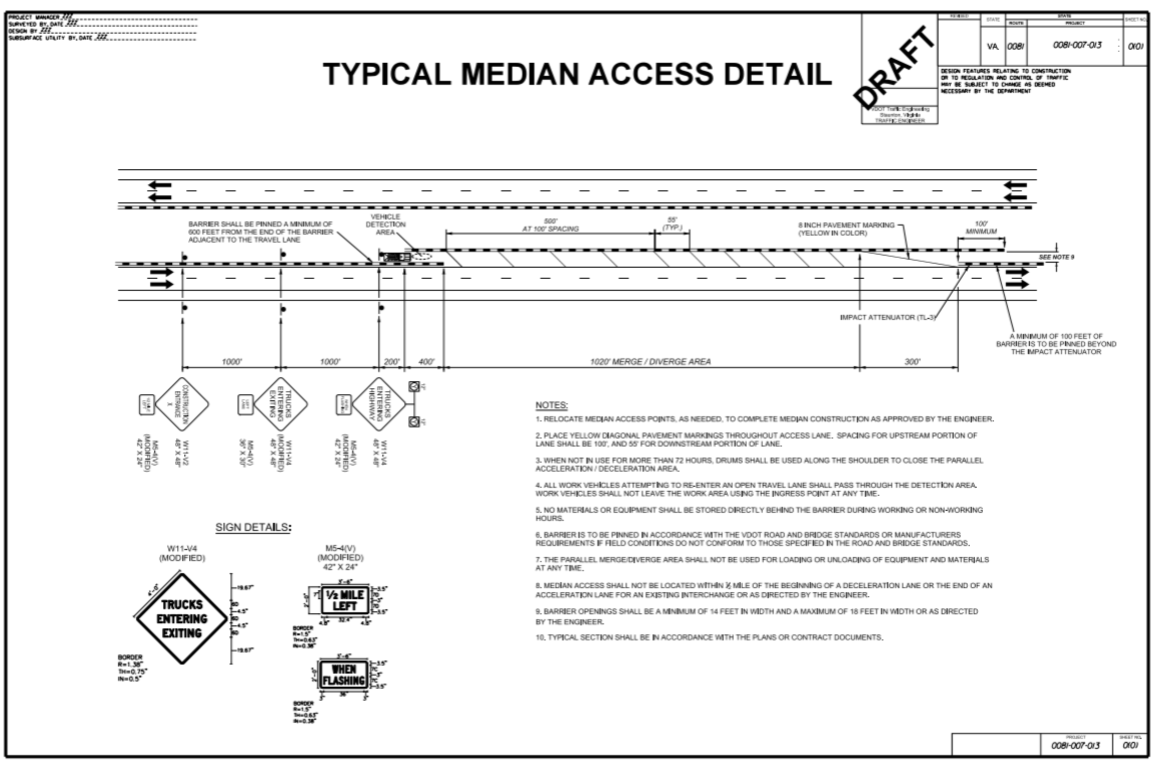


Figure 11. VDOT Draft Construction Access Point Drawing for I-81 (*49*).

Other Relevant Published Literature

Wang and Lee (*50*) built a microsimulation network of a freeway work zone in Florida to investigate the safety impact of the speed of construction trucks exiting the workspace into open travel lanes. The work zone had two open travel lanes and an acceleration lane for the construction trucks adjacent to the outside travel lane. The simulations included scenarios with five magnitudes of truck egress speeds (30 mph, 35 mph, 40 mph, 45 mph, and 50 mph) and three traffic volumes (1000 vehicle per hour [vph], 2000 vph, and 3000 vph). Wang and Lee found that increasing the truck egress speed significantly reduced the number of vehicle conflicts. Thus, Wang and Lee concluded that providing sufficient acceleration distance for construction trucks merging into open travel lanes can positively impact safety. Wang and Lee also developed the concept for a truck egress system that functioned like a ramp meter.

NCHRP Synthesis 587 (*51*) documented state practices regarding the use of smart work zone technologies, including entering/exiting construction vehicle notification systems. A survey of all 50 state DOTs and the Washington DC DOT revealed that 18 percent had already implemented entering/exiting construction vehicle notification systems, 33 percent were planning to implement such systems in the future, 47 percent did not have plans to implement such systems, and 2 percent did not respond. The performance of entering/exiting construction vehicle notification systems was rated as a 2.71 (average of seven responses), with one being poor and five being outstanding.

El-Rayes et al. (*52*) also surveyed state DOTs about their experiences with smart work zone systems, including entering/exiting construction vehicle notification systems. Nine out of the 18 state DOTs (50 percent) that responded to the survey indicated that they use entering/exiting construction vehicle notification systems (i.e., Arizona, Iowa, Michigan, Missouri, North Carolina, Ohio, Pennsylvania, South Carolina, and Wisconsin). In addition, four other state DOTs (i.e., Arkansas, Nevada, South Dakota, and Washington) reported the future planned use of entering/exiting construction vehicle notification systems. Entering/exiting construction vehicle notification systems were typically used on projects with defined workspace access points that frequently have construction vehicles entering or exiting the workspace. Documented challenges included finding available equipment and frequent malfunctions. State DOTs noted that there is inadequate information about the effectiveness of entering/exiting construction vehicle notification systems to reduce crash severity, frequency, delay, and queue lengths.

Desai e al. (*53*) evaluated driver response to CVSAs by measuring statistical trends of vehicle speeds for trucks traveling on interstates in Ohio before and after an alert was received. Thirty seconds after receiving a dangerous slowdown alert, 22 percent of the truck drivers reduced their speed by at least 5 mph. In addition, 26 percent of truck drivers traveling at or above 70 mph at the time of an alert reduced their speed by at least 5 mph. Desai et al. concluded that truck drivers do act as a result of receiving a CVSA.

APPENDIX B: CRASH ANALYSIS

In Phase 1, the research team performed a preliminary crash analysis to look at general trends and CMV involvement in work zone crashes. In Phase 2, the research team conducted a more detailed analysis of the Ohio crash data to identify key contributing factors and combinations of factors that contribute to CMV-involved work zone crashes. This appendix is divided into the following sub-sections:

- Data collection and analysis methods.
- Preliminary analysis.
  - Overview of Ohio crash trends.
  - CMV-involved crash factors.
  - Work zone crash factors.
  - CMV-involved work zone crash factors.
- Detailed analysis.
  - Characteristics of KAB CMV-involved work zone crashes.
  - CCA of KAB CMV-involved work zone crashes.

DATA COLLECTION AND ANALYSIS METHODS

At the beginning of the project, the research team acquired crash data for the latest five years (2017–2021) and roadway inventory data from ODOT to perform crash analyses. In the preliminary crash analysis, three injury severity levels were used in the analysis: fatal, injury, and no injury or property damage only (PDO). Serious injury, moderate injury, and minor injury crashes were collectively considered as injury crashes. The database included many variables that were used to identify CMV and non-CMV crashes, as well as work zone and non-work zone crashes (see Table 3). Specifically, the research team used the following filters for the preliminary crash analyses:

- Work zone related CMV crashes (IF ODPS_WORK_ZONE_IND = Y and IS_COMMERCIAL_RELATED = Y).
- Work zone related non-CMV crashes (IF ODPS_WORK_ZONE_IND = Y and IS_COMMERCIAL_RELATED = N).
- Non-work zone related CMV crashes (IF ODPS_WORK_ZONE_IND = N and IS_COMMERCIAL_RELATED = Y).
- Non-work zone related non-CMV crashes (IF ODPS_WORK_ZONE_IND = N and IS_COMMERCIAL_RELATED = N).

To perform a more comprehensive analysis, the research team examined three significant categories of injury crashes related to CMV-involved work zone incidents: fatal (K), serious injury suspected (A), and minor injury suspected (B) crashes. The team devised a process for transferring crash report narratives from a PDF format to a readable spreadsheet utilizing an open-source toolkit (i.e., ‘pdftools’ in the R open-source software). The research team reviewed the crash narratives, diagrams, and characteristics to determine the following:

- Did the crash involve a CMV per the definition agreed upon by FHWA, FMCSA, and NHTSA (i.e., large trucks and buses with a gross vehicle weight or gross combination weight of 10,001 lb or more)?
- Was a CMV at fault?
- Was a work-related CMV involved in the crash (e.g., shadow vehicles with impact attenuators or those delivering materials to and from the work site)?
- What factor primarily influenced the crash (see Table 1)?

Table 3. Primary Crash Data Variables Used.

No.	Variable	Variable Code	Code	Description
17	Commercial vehicle involvement	IS_COMMERCIAL_RELATED	Y	CMV related
17	Commercial vehicle involvement	IS_COMMERCIAL_RELATED	N	Not CMV related
34	Work zone indicator	ODPS_WORK_ZONE_IND	Y	Work zone related
34	Work zone indicator	ODPS_WORK_ZONE_IND	N	Not work zone related
35	Work zone type	ODPS_TYPE_OF_WORK_ZONE_CD	1	Lane closure
35	Work zone type	ODPS_TYPE_OF_WORK_ZONE_CD	2	Lane shift/crossover
35	Work zone type	ODPS_TYPE_OF_WORK_ZONE_CD	3	Work on shoulder or median
35	Work zone type	ODPS_TYPE_OF_WORK_ZONE_CD	4	Intermittent or moving work
35	Work zone type	ODPS_TYPE_OF_WORK_ZONE_CD	5	Other
36	Location of crash in work zone	ODPS_LOC_IN_WORK_ZONE_CD	1	Before the first work zone warning sign
36	Location of crash in work zone	ODPS_LOC_IN_WORK_ZONE_CD	2	Advance warning area
36	Location of crash in work zone	ODPS_LOC_IN_WORK_ZONE_CD	3	Transition area in a work zone
36	Location of crash in work zone	ODPS_LOC_IN_WORK_ZONE_CD	4	Activity area in a work zone
36	Location of crash in work zone	ODPS_LOC_IN_WORK_ZONE_CD	5	Termination area

Of the 736 KAB CMV-involved work zone crashes, the research team determined that 104 (14 percent) did not meet the FHWA, FMCSA, and NHTSA definition of a CMV (i.e., tractor-trailers, semi-trucks, dump trucks, school buses, and large vans). These non-CMV vehicles were typically business-related ("commercial") vehicles that did not meet the weight requirements. The more detailed analysis focused on the remaining 632 crashes.

The research team attempted to assess whether each crash was influenced by the presence of the work zone but found that the process was too subjective based on the available information in the crash database, narratives, and diagrams. So, the research team retained all crashes with ODPS_WORK_ZONE_IND = Y.

In addition to descriptive statistics, the research team used two statistical modeling techniques (i.e., nested logit and CCA) to identify the association between critical factors. The nested logit tree approach is adapted to illustrate a heuristic sequence of attributes of infrastructural facilities or other conditions which are mostly associated with the concerned crashes. At each level of the organized hierarchy of the chained-correlated factors or attributes, the frequencies measured are used to identify the critical correlated factors to crashes at that level. The series of the critical factors forms the chain to identify or imply the potential causality mechanism. In other words, it is a top-down systemic analysis process to demonstrate a visual representation of the contexts of highly associated contributing attributes at different layers of the heuristic causality chain. For the preliminary analysis, nested logit models were used for analysis of CMV-involved crashes and analysis of work zone crashes. For the more detailed analysis, nested logit models were used to support the CCA.

CCA is a statistical technique used to examine the relationships between clusters of categorical variables. The primary objective of CCA is to create meaningful groups within the data, relying on a specified set of observable variables. In CCA, a set of categorical variables are grouped into clusters based on their similarities or differences. The clusters are then analyzed using CCA to identify the underlying patterns of association between them. The analysis produces a graphical representation of the relationships between the clusters, which can be used to visualize the structure of the data and identify any underlying patterns or trends. For the more detailed analysis, CCA was applied on the CMV-involved work zone crashes dataset. The subsequent explanation will delve into the mathematical algorithm employed in CCA.

Initially, a normal data matrix X that has n observations containing q number of categorical variables needs to be converted to a new matrix Z, which is named as super indicator matrix. This matrix will be generated through a one-hot encoding process which transforms each categorical variable to a binary matrix (i.e., $Z = [\boldsymbol{Z_1}, \boldsymbol{Z_2}, \ldots, \boldsymbol{Z_q}]$, where Zj is an $\mathrm{n} \times \mathrm{pj}$ matrix of the encoded j- categorical variable with pj number of categories). The indicator matrix Z has the same n number of rows and $Q = \sum_{j=1}^{q} Pj$ number of columns. One can define Zk as a $\mathrm{n} \times \mathrm{K}$ binary matrix indicating the memberships of each observation into the K number of clusters. To take into account the clusters' relationship with categorical variables, cross-tabulation of the indicator matrix and membership matrix will be constructed as a $\mathrm{K} \times \mathrm{pj}$ matrix (i.e.,$F = \boldsymbol{Z_K^{\mathsf{T}} Z}$). By applying CCA to contingency matrix F, scaling values corresponding to clusters and categories that maximize the inter-group variances will be optimized. In the optimal condition, the clusters separate the observations in a way that maximum variances from distributions over categorical variables and simultaneously distributions of categories in each variable will be obtained (*54*).

The process of CCA can be briefly presented as:

- Randomly assigning observations to clusters and creating an initial membership matrix Zk and contingency matrix F.
- Applying the corresponding analysis to F and finding the category quantifications matrix B.
- Calculating object coordinate matrix $\boldsymbol{Y} = \frac{\boldsymbol{1}}{\boldsymbol{q}}\left(\boldsymbol{I_n} - \frac{\boldsymbol{1_n 1_n'}}{\boldsymbol{n}}\right)\boldsymbol{ZB}$.

- Applying k-means clustering to Y and updating Zk.
- Repeating the process until Zk values converge to a fixed number.

The resulting Zk gives G, which is the optimum cluster centroid matrix and category quantification matrix B. The coordinate matrix G, B is used to present a biplot of the clusters and categories. However, to facilitate the interpretation of the biplots, the two matrices will be scaled by a constant value of $\boldsymbol{\gamma} = \left(\frac{\boldsymbol{K}}{\boldsymbol{Q}} . \frac{\boldsymbol{TrB^TB}}{\boldsymbol{TrG^TG}}\right)^{\mathbf{1/4}}$. The new coordinate matrices $\boldsymbol{G_s} = \boldsymbol{\gamma G}$ and $\boldsymbol{B_s} = \frac{\mathbf{1}}{\boldsymbol{\gamma}}\boldsymbol{B}$ have the same average squared deviation from the origin that will be used for biplot presentations of analysis (*54*).

PRELIMINARY ANALYSIS

Overview of Ohio Crash Trends

Table 4 provides information about the total yearly crashes in work zones and non-work zones with and without CMV involvement. Most crashes did not involve CMVs or work zones (about 90 percent of total crashes). Overall, work zone crashes comprised about 2 percent of total crashes, and CMV-involved crashes comprised about 9 percent of total crashes. Less than 1 percent of total crashes involved a CMV in a work zone. While the total number of CMV-involved crashes in work zones exhibited a slight decreasing trend from 1,503 in 2017 to 1,095 in 2021, the percentage of yearly crashes remained relatively stable. In contrast, there was an obvious decline in CMV-related crashes in non-work zones from 32,245 (11 percent) in 2017 to 17,852 (7 percent) in 2021.

Table 4. Total Yearly Crashes by Work Zone and CMV Involvement.

Work Zone	CMV	2017	2018	2019	2020	2021	Total
Yes	Yes	1,503 (0.50%)	1,450 (0.49%)	1,471 (0.50%)	1,096 (0.45%)	1,095 (0.41%)	6,615 (0.47%)
No	Yes	32,245 (10.63%)	32,247 (10.82%)	20,102 (6.78%)	15,561 (6.33%)	17,852 (6.62%)	118,007 (8.35%)
Yes	No	3,395 (1.12%)	3,234 (1.08%)	5,091 (1.72%)	3,444 (1.40%)	3,702 (1.37%)	18,866 (1.33%)
No	No	266,140 (87.75%)	261,162 (87.61%)	269,918 (91.01%)	225,737 (91.82%)	247,034 (91.60%)	1,269,991 (89.85%)
Total		303,283	298,093	296,582	245,838	269,683	1,413,479

Table 5 presents data on the total number of fatal crashes for the four categories of interest. The findings show that the percentage of fatal crashes was higher when a CMV is involved. In 2017 and 2018, CMV involvement resulted in a larger percentage of fatal crashes in work zones than non-work zones. However, in 2019 that trend changed and continued through 2021, resulting in a higher percentage of CMV-involved fatal crashes occurring in non-work zones.

Table 5. Total Yearly Fatal Crashes by Work Zone and CMV Involvement.

Work Zone	CMV	2017	2018	2019	2020	2021
Yes	Yes	11	9	8	6	9
% out of total crashes[a]		**0.73%**	**0.62%**	**0.54%**	**0.55%**	**0.82%**
No	Yes	186	171	143	112	174
% out of total crashes[a]		0.58%	0.53%	0.71%	0.72%	0.97%
Yes	No	6	4	7	12	16
% out of total crashes[a]		**0.18%**	**0.12%**	**0.14%**	**0.35%**	**0.43%**
No	No	891	810	883	1023	1045
% out of total crashes[a]		0.33%	0.31%	0.33%	0.45%	0.42%
Total		**1,094**	**994**	**1,041**	**1,153**	**1,244**

[a] Compared with the total crashes under the same category. For example, fatal CMV-involved work zone crashes over total CMV-involved work zone crashes in 2017 = 11/1503 = 0.73%.

Table 6 lists the total number of injury crashes that occurred for the four categories of interest. There was no obvious change in the trends during the five years measured by the percentage of injury crashes in either work zones or non-work zones, regardless of CMV involvement or non-CMV involvement. However, in contrast to fatal crashes, the percentage of injury crashes was higher when a CMV was not involved.

Table 6. Total Yearly Injury Crashes by Work Zone and CMV Involvement.

Work Zone	CMV	2017	2018	2019	2020	2021
Yes	Yes	276	260	252	242	216
% out of total crashes[a]		18.36%	17.93%	17.13%	22.08%	19.73%
No	Yes	6,624	6,538	4,214	3,388	3,927
% out of total crashes[a]		20.54%	20.27%	20.96%	21.77%	22.00%
Yes	No	883	879	1,304	966	1,000
% out of total crashes[a]		26.01%	27.18%	25.61%	28.05%	27.01%
No	No	67,897	64,764	68,769	59,984	64,914
% out of total crashes[a]		25.51%	24.80%	25.48%	26.57%	26.28%
Total		**75,680**	**72,441**	**74,539**	**64,580**	**70,057**

[a] Compared with the total crashes under the same category. For example, injury CMV-involved work zone crashes over total CMV-involved work zone crashes in 2017 = 276/1503 = 18.36%.

CMV-Involved Crash Factors

This section presents descriptive statistics for critical factors linked to CMV-involved crashes in work zones and non-work zones. The primary focus of the descriptive statistics was to examine the impact of the presence or absence of a work zone on various crash characteristics.

Land Use

Table 7 displays the percentage distribution of total, fatal, and injury crashes involving CMVs by land use without and with work zones. On rural roadways, non-work zone locations accounted for a slightly higher percentage of total CMV-involved crashes (31 percent) compared to work zone locations (29 percent). Additionally, fatal and injury CMV-involved crashes were more frequent in non-work zone locations (59 percent and 35 percent, respectively) than in work zone locations (56 percent and 30 percent, respectively). In contrast, on urban roadways, the percentage of total CMV-involved crashes was slightly higher in work zone locations (72 percent) compared to non-work zone locations (69 percent). Fatal and serious CMV-involved crashes were also more prevalent in work zone locations (44 percent and 70 percent, respectively) compared to non-work zone locations (41 percent and 65 percent, respectively).

Table 7. Distribution of Total, Fatal, and Injury CMV-Involved Crashes by Land Use Type.

Land Use	Total		Fatal		Injury	
	Non-Work Zone	Work Zone	Non-Work Zone	Work Zone	Non-Work Zone	Work Zone
Rural	31.05%	28.54%	58.78%	55.81%	35.01%	30.18%
Urban	68.95%	71.46%	41.22%	44.19%	64.99%	69.82%

Functional Class

To further explore the land use trends, the research team computed descriptive statistics by functional classification for rural and urban roadways (see Table 8 and Table 9, respectively). The functional classes were freeways (i.e., interstate routes and other freeways or expressways), arterials (i.e., minor arterial roads and other principal arterial roads), collectors (i.e., major and minor collector roads), and local roads.

Table 8. Total, Fatal, and Injury CMV-Involved Crashes in Non-Work Zone and Work Zone Locations on Rural Roads by Functional Class.

Functional Class	Total		Fatal		Injury	
	Non-Work Zone	Work Zone	Non-Work Zone	Work Zone	Non-Work Zone	Work Zone
Freeways	33.69%	71.61%	23.86%	58.33%	28.46%	72.53%
Arterials	27.74%	14.83%	41.87%	33.33%	34.15%	17.07%
Collectors	25.40%	9.94%	27.11%	4.17%	27.75%	9.33%
Local Roads	13.16%	3.62%	7.16%	4.17%	9.64%	1.07%

For rural roadways, the highest percentage of CMV-involved crashes occurred on freeway routes in both non-work zone (34 percent) and work zone locations (72 percent). Similarly, fatal and injury CMV crashes were highest on freeways with work zones. For all three categories of CMV-involved crashes, the percentage for freeways was more than two times higher in work zones than in non-work zones.

Table 9. Total, Fatal, and Injury CMV-Involved Crashes in Non-Work Zone and Work Zone Locations on Urban Roads by Functional Class.

Functional Class	Total		Fatal		Injury	
	Non-Work Zone	Work Zone	Non-Work Zone	Work Zone	Non-Work Zone	Work Zone
Freeways	27.75%	66.15%	41.49%	68.42%	32.47%	71.25%
Arterials	44.24%	22.83%	39.63%	21.05%	47.98%	20.67%
Collectors	12.60%	5.57%	11.76%	5.26%	11.31%	5.31%
Local Roads	15.41%	5.44%	7.12%	5.26%	8.23%	2.77%

Similar trends were found for CMV-involved crashes on urban roads. While the total percentage of CMV-involved work zone crashes on freeways was lower on urban roads (66 percent) compared to rural roads (72 percent), the percentage of fatal crashes was higher (68 percent on urban roads compared to 58 percent on rural roads).

Crash Types

Table 10 provides information on the type of crashes and their involvement in total, fatal, and injury CMV-involved crashes in both non-work zone and work zone locations on all roadways. With respect to total crashes, sideswipe passing was the most frequent type of crash in work zones (48 percent) and non-work zones (27 percent). The larger percentage of sideswipe-passing CMV-involved crashes in work zones may be indicative of physical constraints due to temporary changes in roadway geometrics (e.g., reduced shoulder or lane width, shortened merge and diverge areas, lane shifts, or crossovers). The second most common type of crash for both non-work zone and work zone locations was rear-end (21 percent).

Table 10. Total, Fatal, and Injury CMV-Involved Crashes in Non-Work Zone and Work Zone Locations by Crash Type on All Roadways.

Crash Type	Total		Fatal		Injury	
	Non-Work Zone	Work Zone	Non-Work Zone	Work Zone	Non-Work Zone	Work Zone
Sideswipe passing	27.23%	48.13%	7.76%	6.98%	20.61%	30.42%
Rear end	20.63%	21.42%	18.70%	44.19%	30.40%	41.25%
Fixed object	11.45%	9.80%	7.38%	0.00%	7.85%	8.35%
Parked vehicle	4.54%	4.25%	2.93%	13.95%	2.45%	4.98%
Angle	10.20%	2.49%	20.61%	0.00%	17.52%	3.21%
Head-on	1.91%	1.18%	19.85%	4.65%	3.45%	2.17%
Pedestrian	0.38%	0.62%	8.91%	20.93%	1.43%	2.33%

For fatal CMV-involved crashes, angle collisions were the most frequent type of crash in non-work zone locations (21 percent), while rear-end collisions were the most frequent in work zone locations (44 percent). For injury crashes, rear-end collisions were the most frequent type of crash in both non-work zone and work zone locations

(30 percent and 41 percent, respectively). In work zones, rear-end crashes are likely the result of unexpected slowdowns and queues from work zone related activities.

Other CMV-involved crash types overrepresented in work zones included parked vehicle and pedestrian crashes. These could be indicative of stranded motorists exiting their vehicle and being hit. Such crashes could also include work zone intrusions that involve CMVs hitting workers on foot or parked work vehicles/equipment, or passenger vehicles hitting work-related CMVs (e.g., shadow vehicles or construction vehicles delivering materials to the work area). Similar trends were found when reviewing only freeway facilities (see Table 11).

Table 11. Total, Fatal, and Injury CMV-Involved Crashes in Non-Work Zone and Work Zone Locations by Crash Type on Freeways.

Crash Type	Total		Fatal		Injury	
	Non-Work Zone	Work Zone	Non-Work Zone	Work Zone	Non-Work Zone	Work Zone
Sideswipe passing	50.36%	57.20%	16.80%	7.41%	41.18%	36.37%
Rear end	22.29%	23.66%	33.20%	55.56%	36.04%	45.16%
Fixed object	9.44%	9.95%	12.30%	0.00%	9.10%	9.01%
Animal	3.55%	0.77%	0.41%	0.00%	0.52%	0.00%
Other non-collision	3.41%	1.44%	0.41%	0.00%	0.62%	0.23%
Parked vehicle	2.41%	1.31%	5.74%	14.81%	1.86%	2.48%
Head-on	1.00%	0.70%	13.93%	3.70%	1.55%	1.58%
Pedestrian	0.22%	0.25%	9.84%	14.81%	0.64%	0.68%

Lighting Condition

Table 12 provides information on the percentage of total, fatal, and injury CMV-involved crashes in non-work zone and work zone locations by lighting condition. The majority of CMV crashes occurred during daylight hours in both non-work zones (76 percent) and work zones (75 percent). In general, similar trends were observed in non-work zones and work zones regarding lighting condition. One exception was at night on lighted roadways where slightly more total, fatal, and injury CMV-involved crashes occurred in work zones than in non-work zones. Another area where work zones were overrepresented was for fatal CMV-involved crashes during dawn/dusk hours. Similar trends were found when reviewing only freeway facilities (see Table 13).

Table 12. Total, Fatal, and Injury CMV-Involved Crashes in Non-Work Zone and Work Zone Locations by Lighting Condition on All Roadways.

Lighting Condition	Total		Fatal		Injury	
	Non-Work Zone	Work Zone	Non-Work Zone	Work Zone	Non-Work Zone	Work Zone
Daylight	75.85%	74.66%	65.52%	67.44%	75.88%	74.96%
Dark—roadway not lighted	9.51%	9.74%	19.85%	13.95%	9.60%	9.87%
Dark—lighted roadway	9.44%	11.22%	10.05%	11.63%	9.75%	11.40%
Dawn/dusk	4.37%	3.87%	4.33%	6.98%	4.16%	3.29%
Dark—unknown roadway lighting	0.26%	0.26%	0.13%	0.00%	0.20%	0.24%

Table 13. Total, Fatal, and Injury CMV-Involved Crashes in Non-Work Zone and Work Zone Locations by Lighting Condition on Freeways.

Lighting Condition	Total		Fatal		Injury	
	Non-Work Zone	Work Zone	Non-Work Zone	Work Zone	Non-Work Zone	Work Zone
Daylight	66.13%	68.29%	52.05%	59.26%	66.47%	70.64%
Dark—roadway not lighted	15.63%	12.75%	25.82%	14.81%	15.47%	12.04%
Dark—lighted roadway	12.94%	14.10%	17.62%	18.52%	13.00%	13.27%
Dawn/dusk	4.65%	4.34%	3.69%	7.41%	4.45%	3.49%
Dark—unknown roadway lighting	0.28%	0.31%	0.41%	0.00%	0.31%	0.34%

Weather and Surface Conditions

Table 14 and Table 15 contain the percentage distribution of total, fatal, and injury crashes involving CMVs in non-work zone and work zone locations, categorized by weather condition and road surface condition, respectively. Overall, the data showed that the majority of CMV-involved crashes occurred during clear weather and dry surface conditions for both non-work zone and work zone locations. However, work zone locations had a higher percentage of clear, dry road condition CMV-involved crashes compared to non-work zone locations, especially for fatal crashes.

Table 14. Total, Fatal, and Injury CMV-Involved Crashes in Non-Work Zone and Work Zone Locations by Weather Condition.

Weather Condition	Total		Fatal		Injury	
	Non-Work Zone	Work Zone	Non-Work Zone	Work Zone	Non-Work Zone	Work Zone
Clear	55.47%	62.04%	58.40%	79.07%	54.72%	61.40%
Cloudy	27.35%	27.45%	28.12%	16.28%	27.27%	25.92%
Rain	10.62%	7.98%	9.16%	2.33%	11.39%	9.63%
Snow	4.77%	1.47%	2.16%	2.33%	4.67%	1.61%

Table 15. Total, Fatal, and Injury CMV-Involved Crashes in Non-Work Zone and Work Zone Locations by Road Surface Condition.

Surface Condition	Total		Fatal		Injury	
	Non-Work Zone	Work Zone	Non-Work Zone	Work Zone	Non-Work Zone	Work Zone
Dry	74.46%	84.60%	79.52%	93.02%	73.69%	82.66%
Wet	19.65%	13.42%	16.54%	4.65%	20.80%	14.69%
Snow	3.82%	0.80%	1.65%	2.33%	3.51%	1.12%

Number of Involved Vehicles

Table 16 presents the percentage distribution on the number of units involved in total, fatal, and injury CMV crashes at both non-work zone and work zone locations. In terms of total CMV-involved crashes, multiple-unit crashes were more common than single-unit crashes in both non-work zone and work zone locations. However, slightly more multiple-unit crashes occurred in work zones than non-work zones. This was also true for fatal and injury crashes.

Table 16. Total, Fatal, and Injury CMV-Involved Crashes in Non-Work Zone and Work Zone Locations by Number of Units Involved.

Number of Units Involved	Total		Fatal		Injury	
	Non-Work Zone	Work Zone	Non-Work Zone	Work Zone	Non-Work Zone	Work Zone
Single	19.17%	13.98%	6.75%	0.00%	11.84%	10.43%
Multiple	80.83%	86.02%	93.25%	100.00%	88.16%	89.57%

Roadway Alignment

Table 17 shows the percentage of total, fatal, and injury CMV-involved crashes categorized by roadway alignment in non-work zone and work zone locations. Most CMV-involved crashes occurred on roads with a straight level alignment for both non-work zones and work zones, and the trends were similar between non-work zone and work zone locations.

Table 17. Total, Fatal, and Injury CMV-Involved Crashes in Non-Work Zone and Work Zone Locations by Road Alignment.

Road Alignment	Total		Fatal		Injury	
	Non-Work Zone	Work Zone	Non-Work Zone	Work Zone	Non-Work Zone	Work Zone
Straight level	74.04%	68.95%	67.30%	67.44%	72.33%	70.14%
Straight grade	15.81%	17.29%	17.18%	20.93%	16.14%	17.01%
Curve level	5.02%	6.70%	7.76%	4.65%	5.41%	5.94%
Curve grade	4.99%	6.89%	7.76%	6.98%	6.03%	6.58%

Critical Correlated Factors to CMV Crashes

The nested logit tree diagram in Figure 12 visualizes the sequence of the identified critical chained-correlated factors to CMV-involved work zone and non-work zone crashes. The findings reinforce those discussed in the previous individual sections.

Only 5 percent of CMV-involved crashes occurred in work zones. Most of these crashes occurred in urban areas on freeways (66 percent). Those occurring in rural areas were also predominantly on freeways (72 percent). In contrast, most CMV-involved non-work zone crashes happened on non-freeway facilities (72 percent and 66 percent for urban and rural areas, respectively).

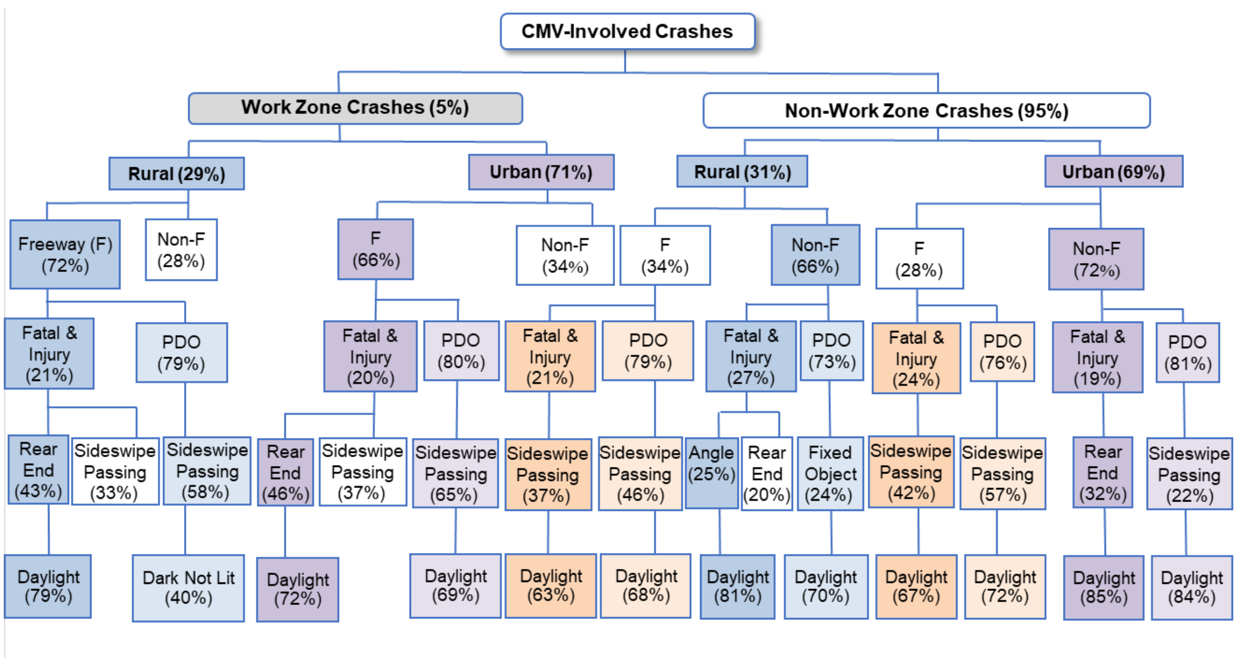


Figure 12. Nested Logit Tree Diagram for CMV-Involved Crashes.

For both work zone and non-work zone locations, the majority of CMV-involved crashes were PDO (73–81 percent). For CMV-involved PDO crashes, sideswipe passing was the most frequent type of crash for both work zone and non-work zone locations, but the percentage of sideswipe-passing crashes was higher in work zones than non-work zones. As discussed previously, these crashes may be indicative of physical constraints due to temporary changes in roadway geometrics (e.g., reduced shoulder or lane width, shortened merge and diverge areas, lane shifts, or crossovers).

For both work zone and non-work zone locations, about one-quarter of CMV-involved crashes were fatal and injury crashes. On freeways, in work zones the most predominant type of fatal and injury crash was rear-end collisions (46 percent and 43 percent for urban and rural areas, respectively). These crashes are likely the result of unexpected slowdowns and queues from work zone related activities. In contrast, on freeways without work zones, sideswipe passing was the most frequent type of crash (42 percent and 37 percent for urban and rural areas, respectively) for CMV-involved fatal and serious injury crashes on freeways.

Most of the critical path CMV-involved crashes occurred during the day. The one exception was sideswipe-passing crashes in work zones on rural freeways that resulted in PDO. Forty percent of those crashes occurred at night in a non-lighted area.

Work Zone Crash Factors

This section provides descriptive statistics on the critical factors associated with CMV and non-CMV crashes in work zones. The primary focus of the descriptive statistics was to examine the impact of the presence or absence of a CMV on various crash characteristics.

Table 18 lists the number of total work zone crashes by year, along with the number and percentage of non-CMV involved crashes and CMV-involved crashes. In 2017 and 2018, the total number of work zone crashes remained relatively stable. There was a significant increase in work zone crashes in 2019; however, this was most likely due to crash reporting changes. The decrease in 2020 was likely due to the pandemic reducing traffic volumes and the number of work zones. In 2021, the number of work zone crashes increased but remained lower than the pre-pandemic levels.

Table 18. Total Work Zone Crashes by Year.

Year	Total Work Zone Crashes	Non-CMV Involved Work Zone Crashes	Percentage of Non-CMV Involved Work Zone Crashes	CMV-Involved Work Zone Crashes	Percentage of CMV-Involved Work Zone Crashes
2017	4,898	3,395	69.31%	1,503	30.69%
2018	4,684	3,234	69.04%	1,450	30.96%
2019	6,562	5,091	77.58%	1,471	22.42%
2020	4,540	3,444	75.86%	1,096	24.14%
2021	4,797	3,702	77.17%	1,095	22.83%
Total	25,481	18,866	74.04%	6,615	25.96%

The percentage of non-CMV involved work zone crashes was higher than the percentage of CMV-involved work zone crashes in all years. This is not surprising since there are generally more non-CMV vehicles on the road than CMV vehicles, resulting in a higher exposure and likelihood of being involved in work zone crashes. Interestingly, the percentage of CMV-involved work zone crashes generally decreased from 2017 to

2021 (from 31 percent down to 23 percent). This trend may indicate that the strategies ODOT has been implementing to improve CMV safety in work zones have made an impact.

Table 19 lists the number of fatal work zone crashes by year, along with the number and percent of non-CMV involved crashes and CMV-involved crashes. The number of fatal work zone crashes remained relatively stable from 2017 to 2020 but increased in 2021. Over the five-year period, the percentage of CMV-involved fatal work zone crashes (51 percent) was slightly higher than the percentage of non-CMV involved fatal work zone crashes (49 percent). However, from 2017 to 2021, the percentage of CMV-involved fatal work zone crashes decreased from 65 percent to 36 percent. In contrast, the percentage of non-CMV involved fatal work zone crashes increased from 35 percent to 64 percent. Again, this may indicate that strategies being implemented by ODOT to improve CMV safety in work zones are having an impact on fatal crashes.

Table 19. Fatal Work Zone Crashes by Year.

Year	Fatal Work Zone Crashes	Non-CMV Involved Work Zone Crashes	Percentage of Non-CMV Involved Work Zone Crashes	CMV-Involved Work Zone Crashes	Percentage of CMV-Involved Work Zone Crashes
2017	17	6	35.29%	11	64.71%
2018	13	4	30.77%	9	69.23%
2019	15	7	46.67%	8	53.33%
2020	18	12	66.67%	6	33.33%
2021	25	16	64.00%	9	36.00%
Total	88	45	48.68%	43	51.32%

Table 20 lists the number of injury work zone crashes by year, along with the number and percent of non-CMV involved crashes and CMV-involved crashes. The number of injury work zone crashes remained stable from 2017 to 2018, increased in 2019, and then remained stable from 2020 to 2021. Both the percentage of CMV-involved and non-CMV involved injury work zone crashes remained relatively stable over the five-year period. Overall, the percentage of non-CMV involved injury work zone crashes (80 percent) was higher than the percentage of CMV-involved injury work zone crashes (20 percent).

The nested logit tree diagram in Figure 13 visualizes the sequence of the identified critical chained-correlated factors to work zone CMV and non-CMV crashes. About one-quarter of the total work zone crashes involve a CMV. Most CMV-involved work zone crashes resulted in PDO (80 percent), while 20 percent resulted in a fatality or injury. For all severity categories, most CMV-involved work zone crashes occurred on freeways. Compared with non-CMV work zone crashes, there were more CMV-involved work zone crashes on freeways and less on non-freeways (i.e., minor arterial roads, other principal arterial roads, major and minor collector roads, and local roads).

Table 20. Injury Work Zone Crashes by Year.

Year	Injury Work Zone Crashes	Non-CMV Involved Work Zone Crashes	Percentage of Non-CMV Involved Work Zone Crashes	CMV-Involved Work Zone Crashes	Percentage of CMV-Involved Work Zone Crashes
2017	1,159	883	76.19%	276	23.81%
2018	1,139	879	77.17%	260	22.83%
2019	1,556	1,304	83.80%	252	16.20%
2020	1,208	966	79.97%	242	20.03%
2021	1,216	1,000	82.24%	216	17.76%
Total	6,278	5,032	79.87%	1,246	20.13%

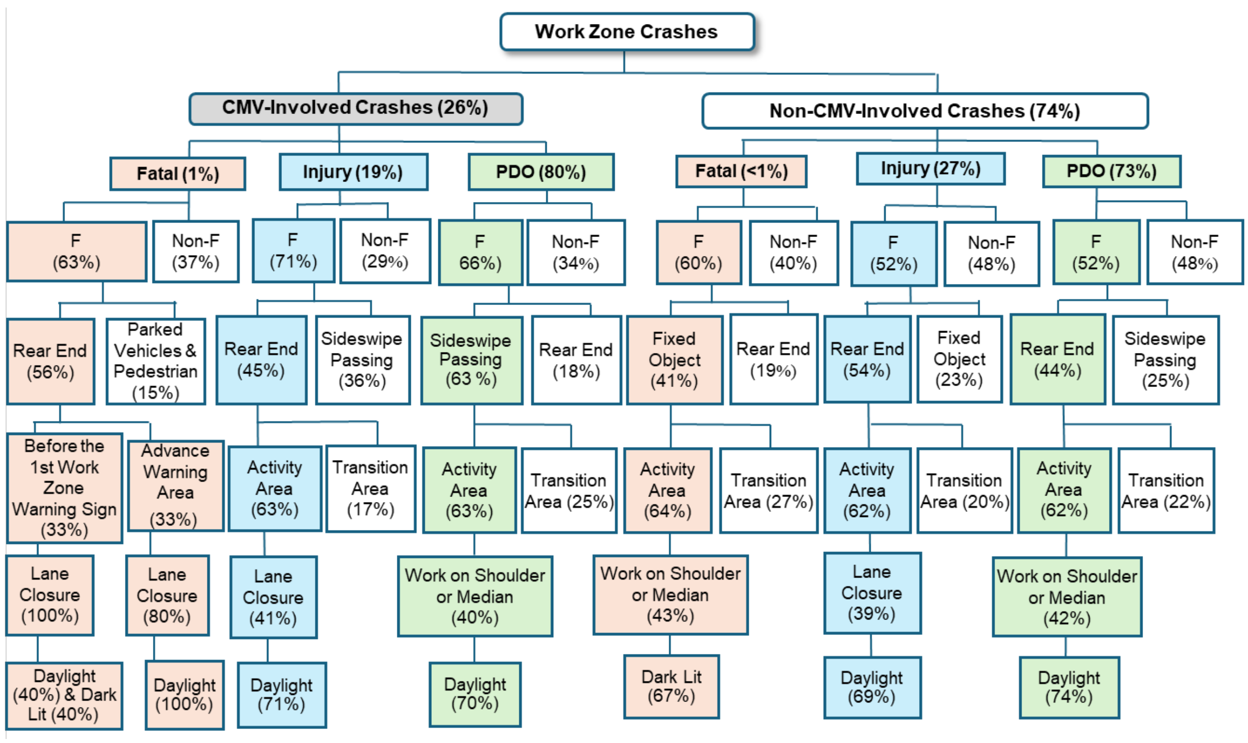


Figure 13. Nested Logit Tree Diagram for Work Zone Crashes.

Rear-end crashes accounted for most of the CMV-involved fatal and injury work zone crashes on freeways (56 percent and 45 percent, respectively). Two-thirds of the fatal rear-end CMV-involved work zone crashes on freeways occurred before the first work zone warning sign or in the advance warning area (i.e., upstream of the work area). Since most of these crashes occurred during a lane closure, they were likely the result of traffic queues forming due to reduced capacity and extending further upstream than expected. Two-thirds of the injury rear-end CMV-involved work zone crashes on freeways occurred in the activity area. Many of these crashes also occurred when a lane closure was present. Sudden speed drops due to constrictive roadway geometry (e.g., reduced shoulder or lane width, lane shifts, or crossovers) or construction vehicles entering/exiting the work area may contribute to CMV-involved rear-end crashes in the activity area. While rear-end collisions were also prevalent for non-CMV involved injury and PDO crashes (54 percent and 44 percent, respectively), fixed object crashes were the leading cause of fatal non-CMV involved work zone crashes (41 percent).

For PDO CMV-involved work zone crashes on freeways, the primary manner of collision was sideswipe passing (63 percent). Since most of these crashes occurred in the activity area, they may be indicative of physical constraints due to temporary changes in roadway geometrics.

Most of the critical path CMV-involved and non-CMV involved work zone crashes occurred during the day. The one exception was fatal non-CMV involved crashes with a fixed object in the activity area when work was on the shoulder or median. Two-thirds of these crashes occurred at night in a lit area.

CMV-INVOLVED WORK ZONE CRASH TRENDS

Table 21 presents data on where CMV-involved work zone crashes occurred within the temporary traffic control zone (i.e., before the first work zone warning sign, advance warning area, transition area, activity area, and termination area) over the five-year period. Table 22 presents data on these same crashes by severity.

Table 21. Total CMV-Involved Work Zone Crashes by Temporary Traffic Control Zone Part.

Year	Before First Work Zone Warning Sign	Advance Warning Area	Transition Area	Activity Area	Termination Area	Grand Total
2017	52	129	351	931	40	1,503
2018	49	119	273	965	44	1,450
2019	50	139	250	986	46	1,471
2020	39	82	222	713	40	1,096
2021	47	81	230	704	33	1,095
Grand Total	237	550	1,326	4,299	203	6,615

Most CMV-involved work zone crashes occurred in the activity area, where the work takes place (65 percent), and resulted in PDO (52 percent). The highest percentage of injury and fatal crashes also happened in the activity area. What is not known is whether active work was taking place in the immediate vicinity of the crash and what temporary traffic control measures were in place. In addition, it is not known if these crashes were related to construction vehicles delivering materials to or removing materials from the work zone.

The transition area had the second highest number of total crashes (1,326 or 20 percent). This area is where traffic is moved out of the normal travel path (e.g., lane shifts, lane closures, and/or crossovers). PDO crashes were also the most frequent type of crash in this area.

Table 22. Total CMV-Involved Work Zone Crashes by Temporary Traffic Control Zone Part and Crash Severity.

Severity	Before First Work Zone Warning Sign	Advance Warning Area	Transition Area	Activity Area	Termination Area	Grand Total
Fatal	0.09%	0.17%	0.06%	0.30%	0.03%	0.65%
Injury	0.60%	1.80%	3.40%	12.40%	0.70%	12.40%
PDO	2.89%	6.34%	16.59%	52.29%	2.34%	86.95%
Grand Total	3.58%	8.31%	20.05%	64.99%	3.07%	100.00%

About 12 percent of the CMV-involved work zone crashes occurred in the advance warning area (where drivers are alerted to downstream work zone conditions) and before the first work zone warning sign. Crashes in these areas are concerning and typically thought to be a result of unexpected slowdowns and queues from work-related activities such as lane closures.

Overall, the number of CMV-involved work zone crashes in the activity area, transition area, and advance warning area decreased over the five-year period. In contrast, the number of CMV-involved work zone crashes before the first warning sign remained relatively stable.

Table 23 shows the total number of CMV-involved work zone crashes by type of work zone (i.e., lane closure, work on shoulder/median, lane shift/crossover, intermittent/moving work, and other) over the five-year period. Table 24 presents data on these same crashes by severity. The number of CMV-involved work zone crashes for all work zone types decreased over the five-year period. The highest percentage of CMV-involved work zone crashes occurred when a lane closure was present (45 percent), followed by work on the shoulder or median (25 percent), lane shift/crossover (18 percent), intermittent or moving work (6 percent), and other work (5 percent). Lane closures had the highest percentage of fatal, injury, and PDO crashes.

Table 23. Yearly Total CMV-Involved Work Zone Crashes by Work Zone Type.

Year	Lane Closure	Work on Shoulder/ Median	Lane Shift/ Crossover	Intermittent/Moving Work	Other	Grand Total
2017	667	355	283	112	86	1,503
2018	652	384	231	99	84	1,450
2019	626	459	257	73	56	1,471
2020	517	269	191	69	50	1,096
2021	538	212	214	70	61	1,095
Grand Total	3,000	1,679	1,176	423	337	6,615

Table 24. CMV-Involved Work Zone Crashes by Work Zone Type and Crash Severity.

Severity	Lane Closure	Work on Shoulder/ Median	Lane Shift/ Crossover	Intermittent/Moving Work	Other	Grand Total
Fatal	0.36%	0.12%	0.05%	0.06%	0.06%	0.65%
Injury	8.59%	5.09%	2.89%	1.41%	0.86%	18.84%
PDO	36.40%	20.17%	14.84%	4.92%	4.17%	80.51%
Grand Total	45.35%	25.38%	17.78%	6.39%	5.09%	100.00%

Focusing on CMV-involved lane closure crashes (see Table 25), most occurred in the activity area (58 percent), followed by the transition area (24 percent). Crashes in the activity area may be attributed to temporary changes in the lane configurations, while crashes in the transition area may be caused by difficulty merging. About 15 percent happened in the advance warning area or before the first work zone warning signing. Such crashes were likely the result of traffic queues forming due to reduced capacity and extending further upstream than expected.

Table 25. Lane Closure-Related CMV-Involved Work Zone Crashes by Temporary Traffic Control Zone Part and Crash Severity.

Severity	Before First Work Zone Warning Sign	Advance Warning Area	Transition Area	Activity Area	Termination Area	Grand Total
Fatal	0.17%	0.20%	0.03%	0.37%	0.03%	0.65%
Injury	0.83%	2.00%	4.00%	11.40%	0.70%	12.40%
PDO	3.63%	8.23%	20.10%	46.23%	2.07%	86.95%
Grand Total	4.63%	10.43%	24.13%	58.00%	2.80%	100.00%

Table 26 reveals that rear-end CMV-involved work zone crashes occurred most frequently with lane closures (21 percent), followed by work on the shoulder or median (14 percent) and lane shifts/crossover (10 percent). Sudden slowdowns from lane closures, especially in the advance warning area or before the first work zone warning sign, can lead to rear-end collisions (see Table 27). Sudden speed drops at construction vehicle access points for large trucks re-entering the travel lanes from work in the median may contribute to CMV-involved rear-end crashes in the activity area.

The nested logit tree diagram in Figure 14 visualizes the sequence of the identified critical chained-correlated factors for CMV-involved work zone crashes. Most of the CMV-involved work zone crashes occurred on urban freeways in the activity area when work was on the shoulder or in the median. The resulting sideswipe-passing and rear-end crashes may be attributed to changes in the roadway alignment (e.g., lane closures, lane shift, or crossovers) or sudden slowdowns for construction vehicles entering the travel lanes from construction vehicle access points.

Table 26. Total CMV-Involved Work Zone Crashes by Work Zone Type and Crash Type.

Crash Types	Lane Closure	Work on Shoulder/ Median	Lane Shift/ Crossover	Intermittent/Moving Work	Other	Grand Total
Rear End	20.54%	13.59%	9.92%	2.07%	1.06%	47.19%
All Other Manners of Collision	24.81%	11.79%	7.86%	4.32%	4.03%	52.81%
Grand Total	45.35%	25.38%	17.78%	6.39%	5.09%	100.00%

Table 27. Lane Closure-Related CMV-Involved Work Zone Crashes by Temporary Traffic Control Zone Part and Crash Type.

Crash Types	Before First Work Zone Warning Sign	Advance Warning Area	Transition Area	Activity Area	Termination Area	Grand Total
Rear end	20.83%	20.83%	4.17%	12.50%	4.17%	62.50%
All Other Manners of Collision	0.00%	4.17%	0.00%	33.33%	0.00%	37.50%
Grand Total	20.83%	25.00%	4.17%	45.83%	4.17%	100.00%

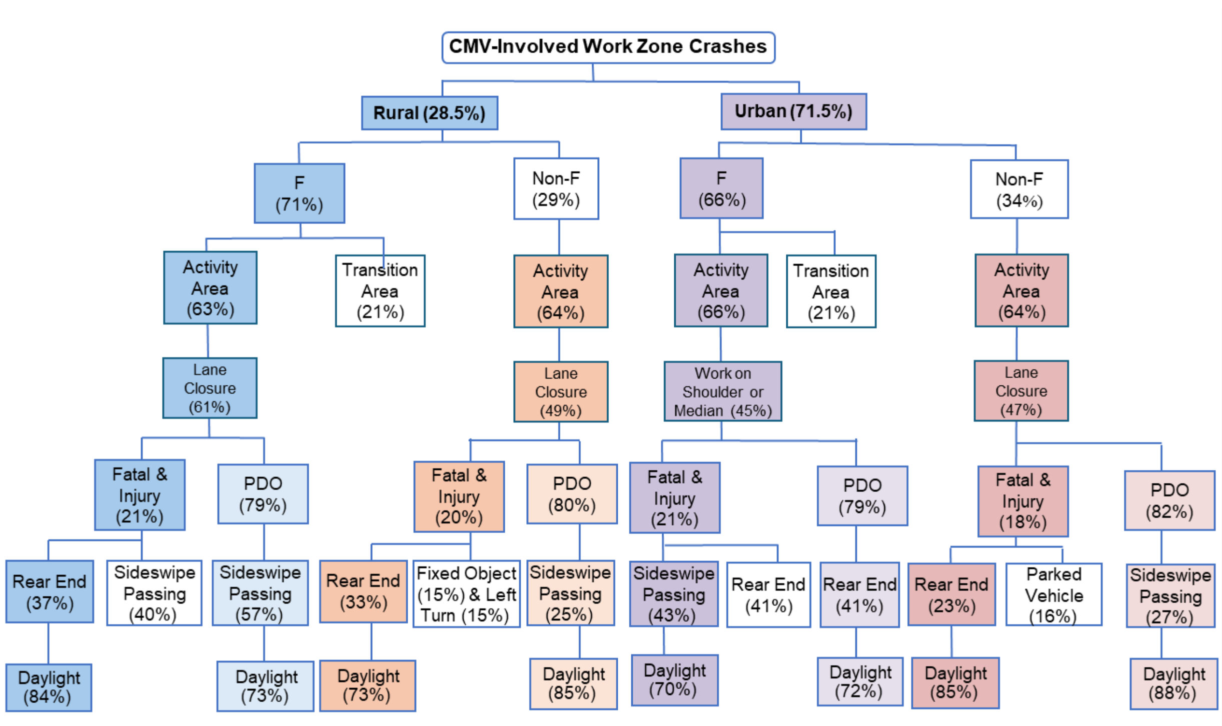


Figure 14. Nested Logit Tree Diagram for CMV-Involved Work Zone Crashes.

CMV-involved work zone crashes on rural freeways also predominantly occurred in the activity area but were largely correlated to the presence of a lane closure. The resulting rear-end and sideswipe crashes could be from unexpected vehicle queues or difficulty merging, especially under high-speed, high-volume conditions where adequate gaps in traffic are more difficult.

CMV-involved work zone crashes on non-freeways in both urban and rural areas mostly occurred in the activity area when lane closures were present. Sudden slowdowns, unexpected queues, and late or forced lane changes could have led to the prevalence of rear-end and sideswipe-passing crashes.

DETAILED ANALYSIS

As discussed previously, to perform a comprehensive analysis, the research team used several data mining and statistical techniques to extract the causal patterns of KAB work zone crashes involving CMVs, including trends, anomalies, and contributing factors. Table 28 contains the yearly KAB CMV-involved work zone crashes from 2017 to 2021. In this period, 632 crashes occurred across all roadway types, including 36 fatal crashes, 106 serious injury suspected crashes, and 490 minor injury suspected crashes.

Table 28. Total Yearly KAB CMV-Involved Work Zone Crashes.

Roadways	2017	2018	2019	2020	2021	Total
ODOT Maintained	88	76	94	89	73	420
Non-ODOT Maintained	31	29	52	39	61	212
All	119	105	146	128	134	632

The research team used the ODOT_MAINTAINED_HWY_IND flag to distinguish between facilities maintained by ODOT (if the variable was flagged with YES) and non-ODOT agencies (if the variable was flagged with NO). Out of the 632 total crashes analyzed, 420 crashes occurred on an ODOT-maintained roadway and the remaining 212 crashes occurred on a non-ODOT maintained roadway. Of the 212 crashes on roadways maintained by other agencies, 100 (47 percent) were on Ohio Turnpike roadways.

Characteristics of KAB CMV-Involved Work Zone Crashes

Land Use and Functional Class

First, the research team explored the land use and functional classification trends for the KAB CMV-involved work zone crashes on all roadways (see Table 29), ODOT-maintained roadways (see Table 30), and non-ODOT maintained roadways (see Table 31). The functional classes were freeways (i.e., interstate routes and other freeways or expressways), arterials (i.e., minor arterial roads and other principal arterial roads), collectors (i.e., major and minor collector roads), and local roads. The main findings are as follows:

- The CMV-involved work zone crashes predominantly occurred in urban areas on both ODOT-maintained roadways (57 percent) and non-ODOT maintained roadways (60 percent).
- For ODOT-maintained roadways, the majority (83 percent) of KAB CMV-involved work zones crashes occurred on freeways (54 percent in urban areas, and 29 percent in rural areas). This is not surprising since ODOT is the primary transportation agency over freeway facilities in Ohio.
- For roadways maintained by non-ODOT agencies, 60 percent of KAB CMV-involved work zones crashes occurred on freeways, 26 percent on arterial roads, 10 percent on collector roads, and 4 percent on local roads. The large number of freeway crashes is due to the Ohio Turnpike being classified as a non-ODOT agency.

Table 29. Percent of KAB CMV-Involved Work Zone Crashes by Functional Class—All Roadways.

Land Use	Freeways	Arterials	Collectors	Local Roads	Grand Total
Rural	31%	7%	4%	< 1%	42%
Urban	44%	10%	3%	1%	58%
Grand Total	75%	17%	7%	1%	100%

Table 30. Percent of KAB CMV-Involved Work Zone Crashes by Functional Class—ODOT-Maintained Roadways.

Lane Use	Freeways	Arterials	Collectors	Local Roads	Grand Total
Rural	29%	10%	4%	0%	43%
Urban	54%	3%	<1%	0%	57%
Grand Total	83%	13%	4%	0%	100%

Table 31. Percent of KAB CMV-Involved Work Zone Crashes by Functional Class—Non-ODOT Maintained Roadways.

Land Use	Freeways	Arterials	Collectors	Local Roads	Grand Total
Rural	35%	2%	2%	1%	40%
Urban	25%	24%	8%	3%	60%
Grand Total	60%	26%	10%	4%	100%

Table 32 shows the percent of KAB CMV-involved work zone crashes where a CMV was at fault for ODOT-maintained roadways, non-ODOT maintained roadways, and on all roadways. In total, a CMV was found to be at fault in 56 percent of the KAB CMV-involved work zone crashes. While the percent fluctuated over time, in general there were only slight differences between ODOT-maintained and non-ODOT maintained roadways.

Table 32. Percent of KAB CMV-Involved Work Zone Crashes Where a CMV Was at Fault.

Roadways	2017	2018	2019	2020	2021	Grand Total
ODOT Maintained	51%	59%	63%	56%	52%	56%
Non-ODOT Maintained	58%	52%	54%	56%	57%	56%
All	53%	57%	60%	56%	54%	56%

Table 33 contains the percent of KAB CMV-involved work zone crashes where a work-related CMV was involved for ODOT-maintained roadways, non-ODOT maintained roadways, and on all roadways. Overall, a work-related CMV was involved in about one-quarter of the KAB CMV-involved work zone crashes. Over the five-year period, work-related CMVs were involved in 19 percent of the KAB CMV-involved work zone crashes on ODOT-maintained roadways. In contrast, work-related CMVs were involved in one-third of the KAB CMV-involved work zone crashes on non-ODOT maintained roadways. Additional details of these crashes will be explored in a later section of this report.

Table 33. Percent of KAB CMV-Involved Work Zone Crashes Where a Work-Related CMV Was Involved.

Roadways	2017	2018	2019	2020	2021	Total
ODOT Maintained	20%	25%	12%	22%	14%	19%
Non-ODOT Maintained	42%	45%	23%	44%	25%	33%
All	26%	30%	16%	29%	19%	23%

Primary Influencing Factors

Table 34 shows the factors primarily influencing the KAB CMV-involved work zone crashes on all roadways by whether the CMV was at fault or not and overall. The top three factors that primarily influenced the KAB CMV-involved work zone crashes where a CMV was at fault were queuing (30 percent), lane departures (22 percent), and lane changes (15 percent). Other factors include following too close (5 percent) and ingress/egress into the work zone (4 percent). Queuing, lane changes, lane departures, and following too close also influenced KAB CMV-involved work zone crashes where a CMV was not at fault. However, the top factor for crashes where a CMV was not at fault was a non-CMV intruding into the work zone (21 percent total, 15 percent stationary operations and 6 percent mobile operations). Another factor for crashes where a CMV was not at fault was a non-CMV failing to yield the right of way. Similar trends were found for ODOT-maintained and non-ODOT maintained roadways (see Table 35 and Table 36, respectively). The most notable differences were the larger percentage of intrusions into stationary work zones and the smaller percentage of queuing-related crashes on non-ODOT maintained roadways.

Table 34. Factors Primarily Influencing KAB CMV-Involved Work Zone Crashes on All Roadways.

Factors Primarily Influencing Crash	CMV At Fault (n = 355)	CMV Not At Fault (n = 271)	Grand Total (632)[a]
CMV Operator Error	< 1%	0%	< 1%
Failure to Yield ROW	< 1%	6%	3%
Following Too Close	5%	6%	5%
Geometry	1%	2%	1%
Ingress/Egress	4%	2%	3%
Intrusion—Mobile	2%	6%	4%
Intrusion—Stationary	2%	**15%**	8%
Lane Change	**15%**	11%	**14%**
Lane Departure	**22%**	**12%**	**18%**
Malfunction	2%	< 1%	2%
Medical	< 1%	1%	< 1%
Merge	1%	4%	2%
Object	1%	3%	2%
Passing	2%	2%	2%
Queuing	**30%**	**18%**	**25%**
Secondary Crash	< 1%	1%	< 1%
Turning	3%	4%	3%
View Obstructed	< 1%	0%	< 1%
Weather	1%	3%	2%
Work Site	1%	< 1%	1%
Worker/Equipment Encroachment	3%	1%	2%
Wrong Way	< 1%	2%	1%

Bold text indicates a top three factors.
[a] The determination of fault could not be determined for six crashes (1 percent).

Queuing

The research team determined that 121 of the 420 (29 percent) KAB CMV-involved work zone crashes on ODOT-maintained roadways and 37 of the 212 (18 percent) KAB CMV-involved work zone crashes on non-ODOT maintained roadways were primarily influenced by slowing or stopped traffic. Table 37 shows that the number of queuing-related crashes on ODOT-maintained roadways remained relatively constant over the five-year period. Conversely, queuing-related crashes on non-ODOT maintained roadways drastically increased in 2021. On ODOT-maintained roadways, 54 percent of the queuing-related crashes occurred in urban areas and 94 percent were rear-end collisions. A CMV was at fault in 65 percent of the queuing-related crashes on ODOT-maintained roadways. On non-ODOT maintained roadways, 60 percent of the queuing-related crashes occurred in rural areas and 95 percent were rear-end collisions. A CMV was at fault in 81 percent of the queuing-related crashes on non-ODOT maintained roadways.

Table 35. Factors Primarily Influencing KAB CMV-Involved Work Zone Crashes on ODOT-Maintained Roadways.

Factors Primarily Influencing Crash	CMV At Fault (n = 237)	CMV Not At Fault (n = 179)	Grand Total (420)[a]
CMV Operator Error	0%	0%	0%
Failure to Yield ROW	1%	6%	3%
Following Too Close	4%	6%	5%
Geometry	1%	2%	2%
Ingress/Egress	3%	1%	2%
Intrusion—Mobile	2%	7%	4%
Intrusion—Stationary	3%	9%	5%
Lane Change	**17%**	**11%**	**15%**
Lane Departure	**23%**	**12%**	**19%**
Malfunction	2%	< 1%	1%
Medical	< 1%	< 1%	< 1%
Merge	< 1%	4%	2%
Object	1%	3%	2%
Passing	1%	1%	1%
Queuing	**33%**	**24%**	**29%**
Secondary Crash	0%	1%	< 1%
Turning	2%	3%	2%
View Obstructed	< 1%	0%	< 1%
Weather	2%	4%	3%
Work Site	< 1%	0%	< 1%
Worker/Equipment Encroachment	2%	1%	1%
Wrong Way	< 1%	3%	1%

Bold text indicates a top three factors.
[a] The determination of fault could not be determined for four crashes (1 percent).

Table 38 presents data on where the queuing-related KAB CMV-involved work zone crashes occurred within the temporary traffic control zone and the work zone type for ODOT-maintained roadways. More than half were the result of a reduction in capacity due to a lane closure (52 percent). Twenty-six percent of the traffic slowdowns associated with lane closures resulted in KAB CMV-involved crashes in the advance warning area and before the first work zone sign, indicating that queues may have extended further upstream than expected. Lane closures also resulted in queuing-related KAB CMV-involved crashes in the transition area (7 percent) and activity area (17 percent). Slowing or stopped traffic also resulted in KAB CMV-involved crashes when there was work on the shoulder or median (22 percent), a lane shift or crossover (15 percent), and intermittent or moving work (7 percent). The research team found similar trends for the non-ODOT maintained roadways (see Table 39). A notable difference was the larger percentage of queuing-related crashes due to a lane closure that occurred in the activity area.

Table 36. Factors Primarily Influencing KAB CMV-Involved Work Zone Crashes on Non-ODOT Maintained Roadways.

Factors Primarily Influencing Crash	CMV At Fault (n = 118)	CMV Not At Fault (n = 92)	Grand Total (212)[a]
CMV Operator Error	3%	0%	1%
Failure to Yield ROW	0%	6%	2%
Following Too Close	7%	4%	6%
Geometry	< 1%	1%	< 1%
Ingress/Egress	4%	3%	4%
Intrusion—Mobile	3%	3%	3%
Intrusion—Stationary	2%	**27%**	**13%**
Lane Change	**13%**	**11%**	12%
Lane Departure	**20%**	**11%**	**16%**
Malfunction	3%	1%	2%
Medical	< 1%	2%	1%
Merge	2%	4%	3%
Object	2%	1%	1%
Passing	3%	4%	3%
Queuing	**25%**	8%	**18%**
Secondary Crash	2%	1%	1%
Turning	4%	7%	5%
View Obstructed	< 1%	0%	< 1%
Weather	< 1%	1%	2%
Work Site	2%	2%	2%
Worker/Equipment Encroachment	4%	2%	3%
Wrong Way	0%	0%	0%

Bold text indicates a top three factors.
[a] The determination of fault could not be determined for two crashes (1 percent).

Table 37. Number of KAB CMV-Involved Work Zone Crashes Where the Primary Factor Influencing the Crash Was Queuing.

Roadways	2017	2018	2019	2020	2021	Grand Total
ODOT Maintained	26	25	30	18	22	121
Non-ODOT Maintained	5	2	7	3	20	37
All	31	27	37	21	42	158

Table 38. Queuing-Related KAB CMV-Involved Work Zone Crashes on ODOT-Maintained Roadways by Temporary Traffic Control Zone Part and Work Zone Type.

Work Zone Type	Before First Work Zone Warning Sign	Advance Warning Area	Transition Area	Activity Area	Termination Area	Grand Total
Lane Closure	11%	15%	7%	17%	2%	52%
Lane Shift/ Crossover	0%	2%	1%	12%	0%	15%
Work on Shoulder/Median	2%	2%	3%	15%	<1%	22%
Intermittent/ Moving Work	<1%	2%	2%	2%	0%	7%
Other	0%	2%	1%	1%	0%	4%
Grand Total	13%	23%	14%	47%	3%	100%

Table 39. Queuing-Related KAB CMV-Involved Work Zone Crashes on Non-ODOT Maintained Roadways by Temporary Traffic Control Zone Part and Work Zone Type.

Work Zone Type	Before First Work Zone Warning Sign	Advance Warning Area	Transition Area	Activity Area	Termination Area	Grand Total
Lane Closure	3%	8%	11%	46%	0%	68%
Lane Shift/ Crossover	0%	0%	0%	22%	0%	22%
Work on Shoulder/Median	0%	0%	0%	5%	0%	5%
Intermittent/ Moving Work	0%	0%	0%	5%	0%	5%
Other	0%	0%	0%	0%	0%	0%
Grand Total	3%	8%	11%	78%	0%	100%

To further explore the 121 queuing-related KAB CMV-involved work zones crashes on ODOT-maintained roadways, the research team completed the following actions:

- Matched each crash to a past project using data from ODOT's TIMS.
- Reviewed ODOT's Traffic Management in Work Zone Exceptions database to determine whether each project obtained an MOT exception.
- Reviewed project plans, addenda files, and bid data to determine if a WZQDWS was included.
- Reviewed daily diaries to obtain insights, if any, about the temporary traffic control at the time of the crash for the top 10 projects with the most crashes.

First, the research team imported the crash details into ArcGIS Pro and plotted them on a map (see Figure 15). Next, the research team obtained shapefiles containing historical project information from ODOT's TIMS online resources. The shapefiles allowed the research team to plot the historical project information on a map either in the form of a line on a road (linear) or a point on the map. In addition, the attribute tables included in the shapefiles allowed the research team to determine when each project was active, what type of work was being done, and other project information.

Map Source: Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, NPS, USFWS.

Figure 15. Base Map of Queuing-Related KAB CMV-Involved Work Zone Crashes on ODOT-Maintained Roadways (2017–2021).

With the historical project information obtained and added to the ArcGIS Pro map, the process of matching crashes to specific projects could begin. For each crash, the research team searched the area around the crash for potential projects and then reviewed the attribute information for each potential project to determine if the project was ongoing at the time of the crash. The research team also considered the location of the crash and the type of work being performed. Some crashes occurred outside of a project's limits but matched the time frame. Since the crash data results showed that a percentage of the queue-related crashes occurred before the first sign, if the distance from that crash to the project limits was within reason, then the research team matched the crash with that project. In some instances, crashes matched to more than one project. For these crashes, the research team used the type of work being performed to select a primary project but labeled the secondary project in the data files for further consideration. Sixty-five percent of the queuing-related KAB CMV-involved work zone crashes on ODOT-maintained roadways were matched to one project and 24 percent were linked to two projects (primary and secondary projects). The remaining 11 percent could not be matched to a project with the information provided.

For the 108 KAB CMV-involved work zone crashes that were associated with at least one project, the research team produced a list of unique primary project identification numbers (PIDs) and determined that the crashes were associated with 74 primary projects. Thus, some projects experienced multiple queue-related KAB CMV-involved work zone crashes (see Table 40). One project was matched to five crashes, two projects were linked to four crashes each, seven projects were connected to three crashes each, and 10 projects were attributed to two crashes each. The remaining 54 projects were matched to one crash each.

Table 40. Number of Primary Projects versus the Number of Queuing-Related KAB CMV-Involved Work Zone Crashes.

Number of Primary Projects	Number of Crashes
1	5
2	4
7	3
10	2
54	1

Next, the research team obtained a shapefile containing ODOT's Traffic Management in Work Zone Exceptions database and imported it into ArcGIS Pro. Using the PID, the research team linked the attribute table for the queuing-related crashes to the attribute table for the MOT exceptions. More specifically, the ArcGIS join feature filtered through the PID values tied to the queuing-related crashes and joined the related data of matching PID values to the PID values in the MOT exception attribute table. This allowed the research team to easily filter through the new table and identify which MOT exceptions were tied to the projects that the research team identified as being related to the queuing-related crashes.

MOT exceptions that had been submitted but denied or withdrawn were present in the shapefile's attribute table, but the PID for most of those MOT exceptions was omitted (i.e., shown as zero in the attribute table) so they could not be matched up to a specific project. Only MOT exceptions that had been approved were tied to the projects that the research team identified. The approved MOT exceptions included details of the exception, such as what the exception would entail, when it would go into effect, and why the exception was submitted. In total, there were 35 crashes linked to 18 primary projects that had at least one MOT exception. In some cases, the primary project had more than one MOT exception. This could be for multiple exceptions over a period of time or multiple exceptions happening at the same time. Only one of the secondary projects was linked to a MOT exception. Since the secondary project was listed as a primary project for other crashes, the research team included the exception in the filtered dataset. In total, the research team identified 37 MOT exceptions that corresponded to a project matched with a crash. Of these 37 exceptions, 20 were for lane closures, eight for ramp closures, five for one direction of travel being closed (i.e., partial road closures), three for both directions of travel being closed (i.e., full road closure), and one for a crossover.

Next, the research team reviewed project plans, addenda files, and bid data (Items 896E00010, 896E00012, 896E00020 and 896E00021) to determine if a WZQDWS was included on the project. Out of the 108 queue-related crashes matched to a PID (74 primary projects and 15 secondary projects), only one project included a WZQDWS in the project plans and Item 896E00010 in the bid data. For another project, the research team identified Item 896E00010 in the bid data only. Another project included a WZQDWS as part of a MOT exception. Interestingly, all three projects were identified as being in the top 10 projects in terms of how many crashes were linked to them.

Figure 16 shows the queuing-related KAB CMV-involved work zone crashes on ODOT-maintained roadways with additional details found through further exploration. Overall, 11 percent of the crashes could not be matched to a project (black cross), 60 percent of the crashes were matched to a project without an exception (red circle), 26 percent of the crashes were matched to a project with an exception but no WZQDWS (yellow triangle), and 3 percent of the crashes were matched to a project with an exception with a WZQDWS (teal square).

Table 41 contains the top 10 projects with the most queuing-related KAB CMV-involved work zone crashes on ODOT-maintained roadways. Of these 10 projects, only four had an approved MOT exception and only three projects included a WZQDWS. Seven projects involved major construction, such as adding through lanes or roadway rehab. The other three projects were for pavement maintenance, traffic control maintenance, and traffic control (safety). Interestingly, six out of the 10 projects (60 percent) were located on I-75.

Five queue-related KAB CMV-involved work zone crashes were linked to PID 87005, which involved adding through lanes on a section of I-75 that runs through Findlay, Ohio. This project was granted a MOT exception that involved closing one of the system ramps (i.e., 75N to 68) for three years. The project plans noted that the lane closures could only be implemented at times permitted by the district, and it had been determined that I-75 lane closures were not permitted between 7:00 a.m. and 9:00 p.m. on weekdays and weekends unless approved by the project engineer. The ODOT-permitted lane closure system supported the use of lane closures (2:1) outside of the restricted times but noted that backups were possible during off-peak hours. Four of the queue-related crashes occurred between 2:30 p.m. and 5:30 p.m. (i.e., when lane closures were not typically allowed). The remaining crash occurred when lane closures were permitted (12:45 a.m.). The daily diary for that late night crash mentioned that a rolling roadblock was being used to set up temporary traffic control to close the northbound inside (left) lane for spot pavement repairs when the crash occurred. The daily dairies for the other four crashes did not mention the type of work activity, but the crash report noted that work was being conducted on the shoulder or in the median. The project plans did not contain any reference to a WZQDWS, but the bid data contained Item 896E00010. Project documentation indicated that WZQDWS was placed on I-75 on May 8, 2017, and eight sensors were paid for from June 2017 to November 2019. However, the daily diaries did not indicate whether a WZQDWS was in use and functioning properly on the dates of the crashes.

Map Source: Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, NPS, USFWS.

Figure 16. Detailed Map of Queuing-Related KAB CMV-Involved Work Zone Crashes on ODOT Roadways (2017–2021).

Table 41. Top 10 Projects with Queuing-Related KAB CMV-Involved Work Zone Crashes on ODOT-Maintained Roadways.

PID	Roadway	Start/End of Construction	Number of Crashes	Project Description	Exception	WZQDWS
87005	I-75	3/20/2017—8/3/2022	5	Add Through Lane(s)	Yes	Yes
83663	I-70	7/18/2018—2/5/2024	4	Add Through Lane(s)	No	No
94206	I-75	6/26/2019—5/27/2020	4	Roadway Minor Rehab	Yes	Yes
101998	I-76 I-680 Route 183	5/15/2017—8/20/2018	3	Pavement Maintenance	No	No
25594	I-70	9/28/2015—6/28/2019	3	Roadway Major Rehab	Yes	No
96631	I-75	9/10/2018—5/20/2019	3	Traffic Control Maintenance	No	No
104799	I-71	8/10/2017—6/30/2020	3	Roadway Major Rehab	No	No
82288	I-75	5/23/2017—1/14/2022	3	Roadway Major Rehab	No	No
108054	I-75	12/17/2020—10/8/2021	3	Traffic Control (Safety)	No	No
104667	I-75	8/2/2018—1/3/2024	3	Add Through Lane(s)	Yes	Yes

PID 83663 and PID 94206 were both linked to four queue-related KAB CMV-involved work zone crashes. PID 83663 involved adding through lanes on a section of I-70 just south of Springfield, Ohio. This project was not granted any MOT exceptions. The project plans noted that lane closures were permitted in accordance with times listed on the permitted lane closure website. The permitted lane closure website noted that no lane closures were allowed between 6:00 a.m. and 7:00 p.m. on weekdays (except between 9:00 a.m. and 12:00 p.m. during the winter) and between 6:00 a.m. and 8:00 p.m. on weekends. The ODOT-permitted lane closure system allowed for the use of lane closures (2:1) outside of the restricted times. All four of the queue-related crashes occurred between 7:00 a.m. and 6:30 p.m., which falls within the timeframe that lane closures were not permitted. Two of the project daily diaries mentioned the queuing-related crashes they were linked to, but did not include any additional information about the work activity or temporary traffic control. The crash reports for three of the crashes indicated that work was on the shoulder or median. The other crash report indicated that a lane closure was present. The project plans, addenda files, bid data, and daily diaries did not include any reference to a WZQDWS.

PID 94206 involved minor roadway rehabilitation on a section of I-75 between Lima and Beaverdam, Ohio. The project was granted a work zone exception for a single lane closure per ODOT Standard Construction Drawing MT-95.30. However, the contractor was required to maintain at least one 11 ft lane in each direction, and lane closures were not allowed from noon Friday until 7:00 p.m. on Sunday per the project plans. The ODOT-permitted lane closure system allowed for the use of lane closures (2:1) outside of the restricted times but noted that backups were possible during off-peak hours. The four queue-related crashes occurred between 1:00 p.m. and 6:30 p.m. on weekdays when a lane closure was permitted. Three of the daily dairies mentioned the work activity involved paving, but did not mention a lane closure. However, all three of the crash reports noted that a lane closure present. Another diary entry referenced a crash that occurred possibly due to the road construction (milling) that caused traffic to back up. While the daily diary does not give a time for when the crash happened, it does give a time (9:30 p.m.) for when the crash was cleared. The linked crash occurred at 6:15 p.m. and involved two semi-trucks, so it could have taken three hours to clear. The crash report also stated that traffic had started to queue due to the road construction, so it is very likely that the crash referenced in the daily diary is the same crash. A WZQDWS was specified in the project plans and project documentation indicated that eight sensors were paid for from July 2019 to October 2019, but the daily diaries did not indicate whether a WZQDWS was in use and functioning properly on the dates of the crashes.

Three queue-related KAB CMV-involved work zone crashes were linked to the remaining seven projects included in Table 41. PID 101998 involved pavement maintenance (i.e., crack sealing) across the northeastern end of the state. One crash each occurred on different sections of I-76, I-680, and Route 183 between the time of 8:30 a.m. and 2:00 p.m. This project was not granted a MOT exception, and the plans, addenda, and bid item data did not mention the use of a WZQDWS. Lane closures, if needed, were to follow the permitted lane closure website on the date the project sold. At least one lane was to always be maintained on both two-lane and three-lane sections, with lane restrictions/reductions not permitted at all after normal working hours. Daily diaries were not available for this project.

PID 25594 involved major roadway rehabilitation on a section of I-70 west of Columbus, Ohio. This project was granted a MOT exception that involved closing an auxiliary lane during daytime, non-peak periods. The project plans contained an unauthorized lane use table, which showed when lane closures were not permitted. For the section of I-70 where two of the queue-related crashes occurred, times for permissible lane closures depended on the number of lanes available and closed. In this three-lane section of roadway, a single lane closure was not allowed from 5:00 a.m. to 7:00 p.m. on Monday through Friday and from 3:00 p.m. to 6:00 p.m. on Saturday and Sunday. Closing two lanes was not permitted from 5:00 a.m. to 10:00 p.m. on Monday through Friday, from 6:00 a.m. to 9:00 p.m. on Saturday, and from 6:00 a.m. to 11:00 p.m. on Sunday. The two queue-related crashes in this section of roadway occurred between 9:00 a.m. and 3:00 p.m. on a weekday, when lane closures were not permitted. However, one of the crash reports indicated a lane closure was present at the time of crash. In the two-lane section of I-70 where the remaining crash occurred, a single lane closure was not allowed from 5:00 a.m. to 11:00 p.m. on Monday through Friday, from 6:00 a.m. to 9:00 p.m. on Saturday, and from 6:00 a.m. to 11:00 p.m. on Sunday. The queue-related crash that occurred in this section happened at 12:06 a.m., when a lane closure was permitted. The crash report noted that there was an active lane closure, which caused queuing that contributed to the crash. The review of the daily diaries did not provide any additional information. The project plans, addenda, and bid data did not contain any reference to a WZQDWS.

PID 96631 involved traffic control maintenance on a section of I-75 between Lima and Beaverdam, Ohio. Specifically, this project included raised pavement marker replacement in various counties throughout northeast Ohio, but the crashes linked to this project occurred on I-75. This project was not granted a MOT exception, and the plans, addenda, and bid item data did not mention the use of a WZQDWS. Per the project plans, lane closures were allowed except during times dedicated as holidays. A minimum of one lane in each direction of travel had to always be maintained. The length and duration of lane closures had to be approved by the engineer. One of the three queue-related crashes occurred in the morning at 9:32 a.m., another happened in the afternoon at 1:05 p.m., and the remaining crash occurred in the early evening at 5:46 p.m. The daily diaries do not provide any significant insights into the work activity or temporary traffic control used that might have influenced any of the crashes. However, all three crash reports indicated that a lane closure was present.

PID 104799 involved major roadway rehabilitation on a section of I-71 that goes through Columbus, Ohio. This project was not granted a MOT exception, and the plans, addenda, and bid item data did not mention the use of a WZQDWS. The project plans contained an unauthorized lane use table that showed when lane closures were not permitted for different sections of the project. For the section of I-71 that the crashes occurred on, permitted lane closures depended on the number of lanes available and closed. In the three-lane section of roadway, a single lane closure was not allowed from 5:00 a.m. to 7:00 p.m. on Monday through Friday and from 7:00 a.m. to 9:00 a.m. and 2:00 p.m. to 7:00 p.m. on Saturday and Sunday. Closing two lanes was not permitted from 5:00 a.m. to 10:00 p.m. on Monday through Friday, from 6:00 a.m. to 8:00 p.m. on Saturday, and from 6:00 a.m. to 10:00 p.m. on Sunday. Two of the crashes occurred between 12:30 p.m. and 6:30 p.m. on weekdays, which would indicate that they happened within the timeframe that permitted lane closures were not allowed. The daily diaries for these two crashes did not provide any additional insights, but the crash reports indicated that one crash happened when a lane shift/crossover was present, and the other crash occurred with shoulder or median work. The third crash occurred at 7:44 p.m. on a weekday. The daily diary included this crash and indicated that the left lane was closed (also noted in crash report). Thus, this crash occurred when a single lane closure was allowed.

PID 82288 involved major roadway rehabilitation on I-75 north of Cincinnati, Ohio. This project was not granted a MOT exception, and the plans, addenda, and bid item data did not mention the use of a WZQDWS. The project plans contained a permitted lane closure table that showed when lane closures were permitted. A single lane closure was allowed from 8:00 p.m. to 6:00 a.m. on Monday through Friday and from 7:00 p.m. to 6:00 a.m. on Saturday and Sunday. Closing two lanes was permitted from 11:00 p.m. to 5:00 a.m. on Monday through Friday and from 10:00 p.m. to 6:00 a.m. on Saturday and Sunday. Closing all three lanes was allowed for 15-minute intervals from 12:00 a.m. to 4:00 a.m. on any day. Furthermore, the table included specifics for lane closures around nearby special event facilities, as well as guidance on when ramp and shoulder closures were allowed. Two of the queue-related crashes happened in the morning between 9:00 a.m. and 10:00 a.m., and the third occurred at 6:20 p.m. All three crashes happened when lane closures were not permitted. The daily diaries do not provide any significant insights into the work activity or temporary traffic control used that might have influenced any of the crashes. The crash reports indicated that a lane closure was present for the crash that occurred at 9:35 a.m. The other two crash reports indicated that one crash happened when a lane shift/crossover was present, and the other crash occurred with shoulder or median work.

PID 108054 involved improvements to traffic control (safety) in western Ohio, specifically the replacement of signage. All three of the queue-related crashes that were linked to this project happened along I-75, with two occurring near Piqua, Ohio, and the third occurring further north near Wapakoneta, Ohio. Two of the crashes occurred between 1:00 p.m. and 3:30 p.m., and the third one happened at 9:30 p.m. This project was not granted a MOT exception, and the plans, addenda, and bid item data did not mention the use of a WZQDWS. Lane closures, if needed, were to be followed according to the most recent guidance provided on the permitted lane closure website 14 calendar days prior to the bid letting date. Like PID 101998, this was a multi-roadway project that covered a large area of western Ohio. Only one daily diary was obtained for a crash linked to this project and it did not contain any insights as to what may have caused the crash. Like PID 101998, the nature of the project meant that there were multiple smaller work zones happening over a large area of Ohio and over a large period of time, which makes it difficult to gain any significant insights from this group of crashes. However, it is significant that all three crashes occurred on I-75, which was a frequently seen roadway in this dataset.

PID 104667 involved adding through lanes throughout an interchange on I-75 north of Cincinnati, Ohio. The three queueing crashes linked to this project all occurred within a 1.5 mile stretch on I-75. All three crashes occurred in 2020 on weekdays with one crash occurring at 12:31 p.m. on May 4, the second crash occurring at 4:55 p.m. on June 15, and the third crash occurring at 5:32 a.m. on July 29. Per the project plans, lane closures on I-75 were permitted based on how many existing lanes there were and which day of the week it was. For three-lane roadways, single lane closures were permitted from 8:00 p.m. to 6:00 a.m. on weekdays and from 7:00 p.m. to 7:00 a.m. on weekends. Two-lane closures were permitted from 11:00 p.m. to 5:00 a.m. on weekdays and from 10:00 p.m. to 6:00 a.m. on weekends. For four-lane roadways, single lane closures were permitted from 8:00 p.m. to 6:00 a.m. on weekdays and from 7:00 p.m. to 7:00 a.m. on weekends. Two-lane closures were permitted from 9:00 p.m. to 6:00 a.m. on weekdays and from 8:00 p.m. to 6:00 a.m. on weekends. For both three-lane and four-lane roadways, 15-minute short duration complete closures were only allowed from 12:00 a.m. to 4:00 a.m. while complete closures exceeding 15 minutes were not allowed at all. Interstate ramp closures were also not allowed. This project did have five approved work zone MOT exceptions that included closing one of two lanes for various periods of time (e.g., 120 days and 1.5 years) and weekend closures. At least one of these exceptions specified the use of a WZQDWS during a lane closure that involved closing one of two lanes on a ramp from northbound I-75 to westbound I-74. The use of a WZQDWS was also found in the addendum files. The daily diaries indicated that lanes were closed on each day that a queue-related crash occurred, but did not indicate if a WZQDWS was in use.

Lane Departure

The research team determined that 79 of the 420 (19 percent) of the KAB CMV-involved work zone crashes on ODOT-maintained roadways and 34 of the 212 (16 percent) KAB CMV-involved work zone crashes on non-ODOT maintained roadways were primarily influenced by a vehicle departing from a travel lane (i.e., failing to keep the vehicle in its lane). Table 42 shows that the number of lane departure crashes on both types of roadways remained relatively constant from 2017 to 2019 and then slightly increased in 2020 and again in 2021. On ODOT-maintained roadways, 52 percent of these crashes occurred in urban areas, while on non-ODOT maintained roadways 59 percent happened in rural areas. A CMV was at fault in 68 percent and 71 percent of the lane departure crashes on ODOT-maintained and non-ODOT maintained roadways, respectively. On both types of roads, the lane departure crashes primarily occurred during the day (62 percent on ODOT-maintained roadways and 77 percent non-ODOT maintained roadways).

Table 42. Number of KAB CMV-Involved Work Zone Crashes Where the Primary Factor Influencing the Crash Was Lane Departure.

Roadways	2017	2018	2019	2020	2021	Grand Total
ODOT Maintained	15	11	15	18	20	79
Non-ODOT Maintained	4	3	6	8	13	34
All	19	14	21	26	33	113

For the ODOT-maintained roadways, the most prevalent crash types were fixed object (37 percent) and sideswipe passing (33 percent). Based on a review of the crash narratives, the research team determined that in two-thirds of the lane departure-related KAB CMV-involved work zone crashes on ODOT-maintained roadways, a vehicle left the roadway. In most cases, the vehicle hit a fixed object (e.g., barrier, guardrail, sign, or work zone device) and/or another vehicle. The remaining one-third of the lane departure-related KAB CMV-involved work zone crashes could be attributed to a vehicle leaving its lane but not the roadway (e.g., drifting, swerving, or crossing into another travel lane). The research team found similar trends for the non-ODOT maintained roadways.

Table 43 presents data on where the lane departure-related KAB CMV-involved work zone crashes occurred within the temporary traffic control zone and the work zone type for ODOT-maintained roadways. Forty-one percent occurred when there was work on the shoulder or median, 23 percent during a lane closure, 22 percent when there was a lane shift or crossover, and 8 percent with intermittent or moving work. Most of these crashes occurred in the activity area (73 percent).

Table 43. Lane Departure-Related KAB CMV-Involved Work Zone Crashes on ODOT-Maintained Roadways by Temporary Traffic Control Zone Part and Work Zone Type.

Work Zone Type	Before First Work Zone Warning Sign	Advance Warning Area	Transition Area	Activity Area	Termination Area	Grand Total
Lane Closure	0%	0%	4%	18%	1%	23%
Lane Shift/ Crossover	0%	0%	9%	13%	0%	22%
Work on Shoulder/Median	1%	1%	3%	35%	1%	41%
Intermittent/ Moving Work	0%	4%	1%	3%	0%	8%
Other	0%	0%	1%	5%	0%	6%
Grand Total	1%	5%	18%	73%	3%	100%

While details regarding the work zone conditions at the time of the crash were not readily available, these lane departure-related KAB CMV-involved work zone crashes may be indicative of physical constraints due to temporary changes in roadway geometrics (e.g., reduced or no shoulder width, reduced lane width, shortened merge and diverge areas, lane shifts, and crossovers). Three crash narratives specifically mentioned such constraints. Two crash narratives noted that the CMV was approaching or in a lane shift at the time of the lane departure, and one crash narrative mentioned that the CMV had just come out of a left lane detour (i.e., crossover). In addition, one crash narrative noted that a CMV departed the lane onto a low shoulder due to paving and then overcorrected. Also, 35 percent of the crash narratives mentioned the vehicle hitting guardrail, barrier, or an attenuator.

Table 44 presents data on where the lane departure-related KAB CMV-involved work zone crashes occurred within the temporary traffic control zone and the work zone type for non-ODOT maintained roadways. Compared to ODOT-maintained roadways, lane departure crashes on non-ODOT maintained roadways occurred more during intermittent or moving work (67 percent) and less during work on the shoulder or median (6 percent) and during lane closures (0 percent). The location of the lane departure crashes on non-ODOT maintained roadways also differed, with more occurring before the first work zone warning sign (50 percent), in the advance warning area (18 percent), or in the transition area (29 percent) instead of the activity area (3 percent).

Table 44. Lane Departure-Related KAB CMV-Involved Work Zone Crashes on Non-ODOT Maintained Roadways by Temporary Traffic Control Zone Part and Work Zone Type.

Work Zone Type	Before First Work Zone Warning Sign	Advance Warning Area	Transition Area	Activity Area	Termination Area	Grand Total
Lane Closure	0%	0%	0%	0%	0%	0%
Lane Shift/ Crossover	9%	3%	3%	0%	0%	15%
Work on Shoulder/Median	3%	3%	0%	0%	0%	6%
Intermittent/ Moving Work	32%	9%	26%	0%	0%	67%
Other	6%	3%	0%	3%	0%	12%
Grand Total	50%	18%	29%	3%	0%	100%

Lane Change

The research team determined that 61 of the 420 (15 percent) of the KAB CMV-involved work zone crashes on ODOT-maintained roadways and 25 of the 212 (12 percent) KAB CMV-involved work zone crashes on non-ODOT maintained roadways were primarily influenced by a vehicle changing lanes, but not because of merging due to a lane reduction/closure. Table 45 shows that the number of these crashes on both types of roads increased from 2017 to 2019 but has since decreased. For ODOT-maintained roadways, 82 percent of the lane change-related crashes occurred in urban areas, and 90 percent were sideswipe-passing collisions. For non-ODOT maintained roadways, 60 percent of the lane change-related crashes happened in rural areas, and 68 percent were sideswipe-passing collisions. On both types of roads, the lane change crashes primarily occurred during the day (74 percent on ODOT-maintained roadways, and 76 percent non-ODOT maintained roadways).

Table 45. Number of KAB CMV-Involved Work Zone Crashes Where the Primary Factor Influencing the Crash Was Lane Change.

Roadways	2017	2018	2019	2020	2021	Grand Total
ODOT Maintained	11	12	16	14	8	61
Non-ODOT Maintained	3	3	9	4	6	25
All	14	15	25	18	14	86

Table 46 presents data on where the lane change-related KAB CMV-involved work zone crashes occurred within the temporary traffic control zone and the work zone type for ODOT-maintained roadways. Forty-six percent occurred when there was work on the shoulder or median, 21 percent when there was a lane shift or crossover, 16 percent during a lane closure, and 8 percent with intermittent or moving work. Most of these crashes occurred in the activity area (82 percent).

Table 46. Lane Change-Related KAB CMV-Involved Work Zone Crashes on ODOT-Maintained Roadways by Temporary Traffic Control Zone Part and Work Zone Type.

Work Zone Type	Before First Work Zone Warning Sign	Advance Warning Area	Transition Area	Activity Area	Termination Area	Grand Total
Lane Closure	0%	0%	3%	13%	0%	16%
Lane Shift/ Crossover	0%	0%	3%	18%	0%	21%
Work on Shoulder/Median	2%	0%	0%	41%	3%	46%
Intermittent/ Moving Work	0%	0%	3%	5%	0%	8%
Other	0%	0%	2%	5%	2%	9%
Grand Total	2%	0%	11%	82%	5%	100%

Table 47 presents data on where the lane change-related KAB CMV-involved work zone crashes occurred within the temporary traffic control zone and the work zone type for non-ODOT maintained roadways. Compared to ODOT-maintained roadways, lane change crashes on non-ODOT maintained roadways occurred more during intermittent or moving work (52 percent) and less during work on the shoulder or median (36 percent) and during lane shifts/crossovers (8 percent). The location of the lane change crashes on non-ODOT maintained roadways also differed, with more occurring before the first work zone warning sign (76 percent) and in the advance warning area (16 percent), instead of the activity area (0 percent). Unfortunately, the narratives did not contain any additional details that provided insight into the work zone conditions on either type of roadway.

Table 47. Lane Change-Related KAB CMV-Involved Work Zone Crashes on Non-ODOT Maintained Roadways by Temporary Traffic Control Zone Part and Work Zone Type.

Work Zone Type	Before First Work Zone Warning Sign	Advance Warning Area	Transition Area	Activity Area	Termination Area	Grand Total
Lane Closure	0%	4%	0%	0%	0%	4%
Lane Shift/ Crossover	4%	4%	0%	0%	0%	8%
Work on Shoulder/Median	32%	4%	0%	0%	0%	36%
Intermittent/ Moving Work	40%	4%	8%	0%	0%	52%
Other	0%	0%	0%	0%	0%	0%
Grand Total	76%	16%	8%	0%	0%	100%

Work Zone Intrusions

The research team determined that 39 of the 420 (9 percent) of the KAB CMV-involved work zone crashes on ODOT-maintained roadways and 33 of the 212 (16 percent) of the KAB CMV-involved work zone crashes on non-ODOT maintained roadways were primarily influenced by a vehicle intruding into a mobile (17 and 6, respectively) or stationary (22 and 27, respectively) work zone. Table 48 shows that on ODOT-maintained roadways, the number of these crashes decreased from 2017 to 2019, increased in 2020, and decreased in 2021. For non-ODOT maintained roadways the number of crashes remained relatively constant over the five-year period. For ODOT-maintained roadways, 59 percent of the work zone intrusion crashes occurred in rural areas. In contrast, on non-ODOT maintained roadways, 79 percent happened in urban areas. On both types of roads, the work zone intrusion crashes primarily occurred during the day (62 percent on ODOT-maintained roadways, and 73 percent non-ODOT maintained roadways).

Table 48. Number of KAB CMV-Involved Work Zone Crashes Where the Primary Factor Influencing the Crash Was Intrusion.

Roadways	2017	2018	2019	2020	2021	Grand Total
ODOT Maintained	12	7	4	10	6	39
Non-ODOT Maintained	7	8	6	6	6	33
All	19	15	10	16	12	72

Based on a review of the crash narratives associated with ODOT-maintained roadways, a passenger vehicle hit a shadow vehicle with an impact attenuator (i.e., the CMV) for 76 percent of the intrusions into mobile operations. For the remaining crashes (4 percent), a CMV hit a shadow vehicle. As expected, the most prevalent crash type was rear-end (82 percent). Work operations mentioned in the narratives included mowing, pothole patching, setting up temporary traffic control, striping, and sweeping. The crash narratives associated with non-ODOT maintained roadways did not offer any additional insights, but did mentioned sweeping, setting up traffic control, and striping.

In 68 percent of the KAB CMV-involved work zone crashes resulting from intrusions into a stationary operation on an ODOT-maintained roadway, a passenger vehicle hit a work vehicle (i.e., the CMV). In 23 percent, CMVs hit either a work vehicle (CMV or non-CMV) or fixed object (e.g., cone or sign). For the remaining crashes (9 percent), a passenger vehicle intruded in the work zone and was then struck by a non-work related CMV. The most common crash types were parked vehicle (41 percent) and rear-end (27 percent). Nine percent of these crashes involved workers. The crash narratives associated with non-ODOT maintained roadways did not offer any additional insights, except that flagging operations were present for three crashes.

Table 49 presents data on where the intrusion-related KAB CMV-involved work zone crashes on ODOT-maintained roadways occurred within the temporary traffic control zone and the work zone type for ODOT-maintained roadways. As expected, most intrusions occurred with lane closures (54 percent) and intermittent or moving work (30 percent) and happened in the activity area (74 percent).

Table 49. Intrusion-Related KAB CMV-Involved Work Zone Crashes on ODOT-Maintained Roadways by Temporary Traffic Control Zone Part and Work Zone Type.

Work Zone Type	Before First Work Zone Warning Sign	Advance Warning Area	Transition Area	Activity Area	Termination Area	Grand Total
Lane Closure	0%	3%	7%	44%	0%	54%
Lane Shift/ Crossover	0%	0%	5%	0%	0%	5%
Work on Shoulder/ Median	0%	0%	3%	5%	0%	8%
Intermittent/ Moving Work	0%	2%	3%	22%	3%	30%
Other	0%	0%	0%	3%	0%	3%
Grand Total	0%	5%	18%	74%	3%	100%

Table 50 presents data on where the intrusion-related KAB CMV-involved work zone crashes occurred within the temporary traffic control zone and the work zone type for non-ODOT maintained roadways. Compared to ODOT-maintained roadways, crashes on non-ODOT maintained roadways occurred more during intermittent or moving work (70 percent) and less during lane closures (6 percent). The location of the lane change crashes on non-ODOT maintained roadways also differed, with more occurring before the first work zone warning sign (48 percent) and in the advance warning area (18 percent), instead of the activity area (12 percent).

Table 50. Intrusion-Related KAB CMV-Involved Work Zone Crashes on Non-ODOT Maintained Roadways by Temporary Traffic Control Zone Part and Work Zone Type.

Work Zone Type	Before First Work Zone Warning Sign	Advance Warning Area	Transition Area	Activity Area	Termination Area	Grand Total
Lane Closure	3%	0%	3%	0%	0%	6%
Lane Shift/ Crossover	0%	3%	3%	0%	0%	6%
Work on Shoulder/ Median	3%	6%	0%	3%	0%	12%
Intermittent/ Moving Work	39%	9%	3%	9%	9%	70%
Other	3%	0%	3%	0%	0%	6%
Grand Total	48%	18%	12%	12%	9%	100%

Ingress/Egress

The research team determined that 10 of the 420 (2 percent) KAB CMV-involved work zone crashes on ODOT-maintained roadways and 8 of the 212 (4 percent) KAB CMV-involved work zone crashes on non-ODOT maintained roadways were primarily influenced by construction vehicles (i.e., CMVs) entering or exiting the workspace. Table 51 shows that the number of these crashes declined from 2017 to 2019 on ODOT-maintained roadways but increased in 2020. For non-ODOT maintained roadways, the number of crashes peaked in 2019, but decreased in the following years. For ODOT-maintained roadways, half of the crashes occurred in rural areas and half happened in urban areas. In contrast, for non-ODOT maintained roadways, 88 percent occurred in urban areas.

Table 51. Number of KAB CMV-Involved Work Zone Crashes Where the Primary Factor Influencing the Crash Was a Construction Vehicle Entering or Exiting the Workspace.

Roadways	2017	2018	2019	2020	2021	Grand Total
ODOT Maintained	2	1	0	4	3	10
Non-ODOT Maintained	0	2	3	2	1	8
All	2	3	3	6	4	18

Based on a review of the crash narratives associated with ODOT-maintained roadways, 70 percent of these crashes occurred when a construction vehicle (i.e., CMV) was exiting the workspace into the open travel lanes. The remaining crashes (30 percent) resulted from a construction vehicle slowing down in the open travel lanes or the deceleration lane. A construction vehicle was involved in 90 percent of these crashes and was found to be at fault in 50 percent of these crashes. The most frequent crash types were rear-end (50 percent) and sideswipe (50 percent).

The crash narrative review for those crashes on non-ODOT maintained roadways were less detailed. Yet, the research team determined that a construction vehicle was involved in 88 percent of the crashes and was found to be at fault in 63 percent of the crashes. Behaviors mentioned when the construction vehicle driver was at fault included striking a passenger vehicle attempting to make a left turn, turning in front of another vehicle, going around another construction vehicle stopped in the closed lane, and exiting the workspace and attempting to merge with traffic.

Work-Related CMVs

The research team determined that 78 of the 420 (19 percent) KAB CMV-involved work zone crashes on ODOT-maintained roadways and 70 out of 212 (33 percent) KAB CMV-involved work zone crashes on non-ODOT maintained roadways involved a work-related CMV. Table 52 shows that the number of these crashes on ODOT-maintained roadways generally declined from 2017 to 2021, while those on non-ODOT maintained roadways remained relatively constant. For ODOT-maintained and non-ODOT maintained roadways, 50 percent and 79 percent of the crashes, respectively, occurred in urban areas.

Table 52. Number of KAB CMV-Involved Work Zone Crashes Where a Work-Related CMV Was Involved.

Roadways	2017	2018	2019	2020	2021	Grand Total
ODOT Maintained	18	19	11	20	10	78
Non-ODOT Maintained	13	13	12	17	15	70
All	31	32	23	37	25	148

Table 53 shows that work-related CMVs are most often involved in crashes when work zone intrusions occur (45 percent). This is expected since shadow vehicles with truck-mounted attenuators (i.e., CMVs) are used by work crews to protect workers in stationary and mobile operations. The second most common influencing factor was construction vehicles entering and exiting the workspace (11 percent). Other notable factors include queuing on ODOT-maintained roadways and worker/equipment encroachment on non-ODOT maintained roadways. A review of the crash narratives revealed that work-related CMVs can be involved in crashes related to sudden slowdowns or stopped traffic. Presumably these are work-related CMVs that are traveling to or from the work zone. A review of the crash narratives for the workers/equipment encroachment found that in most instances equipment was outside of the workspace (e.g., backhoe extended into open travel lane, bucket truck elbow overhanging travel lane, bucket truck bucket over travel lane, excavating arm swung into open travel lane, and crack seal wand extended into open travel lane).

Cluster Corresponding Analysis

For the CCA analysis, the research team used all 632 KAB CMV-involved work zone crashes to examine the relationship between clusters of categorical variables and to identify the association between them. The research team developed six clusters from the dataset. Table 54 shows the locations of the centroids and relevant cluster-based properties. Figure 17 shows the six clusters as a two-dimensional biplot. The locations of the centroid of each cluster are shown in red circles. This plot portrays the nature of attributes and their locations. The centroid of the biplot is nearer to clusters 1–5. Five clusters are located relatively close together, while Cluster 6 is separated from the others.

Table 53. Number of KAB CMV-Involved Work Zone Crashes Where a Work-Related CMV Was Involved.

Factors Primarily Influencing Crash	ODOT Maintained (n = 78)	Non-ODOT Maintained (n = 70)	Grand Total (148)
CMV Operator Error	0%	4%	2%
Failure to Yield ROW	0%	4%	2%
Following Too Close	3%	0%	1%
Geometry	3%	0%	1%
Ingress/Egress	12%	**10%**	**11%**
Intrusion—Mobile	**22%**	9%	**16%**
Intrusion—Stationary	**22%**	**37%**	**29%**
Lane Change	5%	1%	3%
Lane Departure	6%	3%	5%
Malfunction	3%	1%	2%
Medical	0%	4%	2%
Merge	0%	0%	0%
Object	0%	1%	1%
Passing	0%	4%	2%
Queuing	**13%**	0%	7%
Secondary Crash	0%	0%	0%
Turning	3%	4%	3%
View Obstructed	0%	0%	0%
Weather	3%	0%	1%
Work Site	3%	6%	4%
Worker/Equipment Encroachment	5%	**10%**	7%
Wrong Way	0%	0%	0%

Bold text indicates a top three factor.

Table 54. Centroids and Size of the Clusters.

Cluster	Dim 1	Dim 2	Within Cluster Sum of Squares	Size	Percentage
1	0.0045	−0.0056	0.0045	271	42.9
2	0.0074	−0.0168	0.0044	198	31.3
3	−0.0022	0.0116	0.0131	111	17.6
4	−0.0105	0.0529	0.0061	27	4.3
5	−0.0290	0.1262	0.0046	20	3.2
6	−0.3126	−0.0784	0.0296	5	0.8

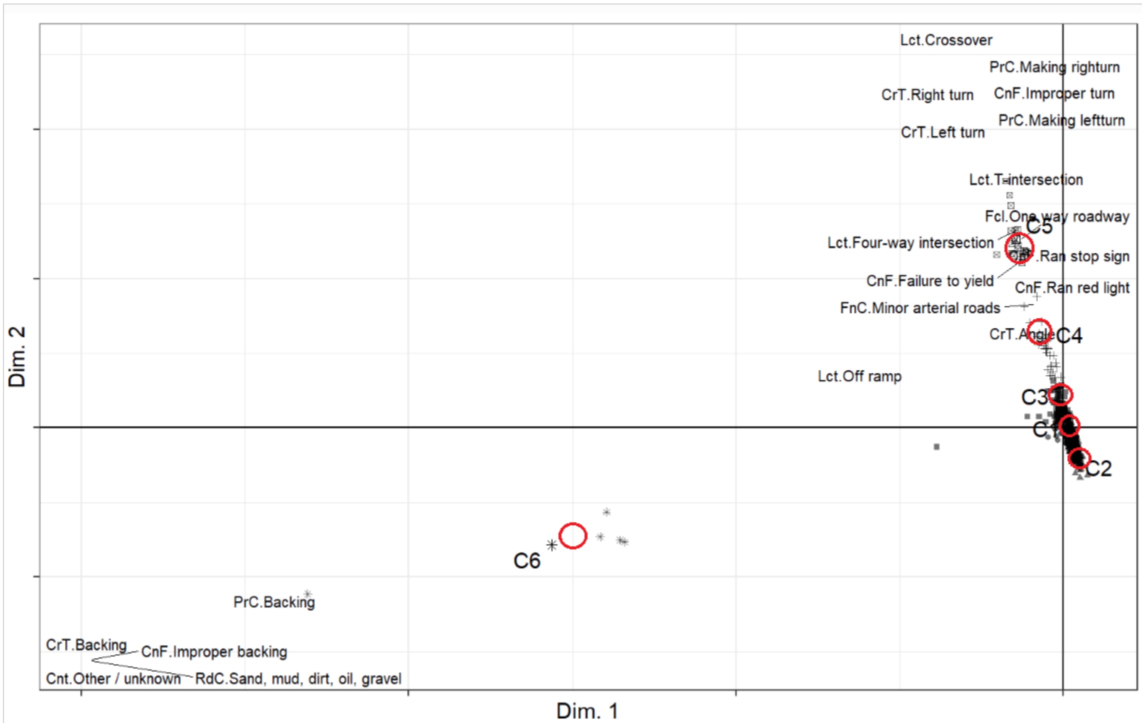


Figure 17. Biplot Showing Clusters Developed from CMV-Involved Work Zone Crash Data.

Cluster 1, Rear-End Crashes at Lane Closures on Freeways or Expressways

Cluster 1 in Figure 18 represents 42.9 percent of the KAB CMV-involved work zone crash data. For the interpretation of clusters, identification of the attributes that deviate most from the independence condition is important. The figure for Cluster 1 is based on the top 20 attributes (e.g., clear condition is an attribute of the weather variable) with the highest residuals. The residuals can be positive or negative. A positive residual signifies that the attribute has above average frequency within the clusters, whereas a negative residual indicates that the attribute has below average frequency. The vertical axis denotes the number of attributes, and the horizontal axis shows the deviation in the frequencies of the attributes from the average frequency (*54*).

Since following too close to other vehicles has the longest bar on the positive side, it signifies that this variable has the strongest association with other categories in Cluster 1. Other positive associations include rear-end crash type, vehicle moving straight ahead before the crash, other freeways or expressways roadway type, and the presence of a lane closure.

Figure 19 shows the nested logit tree diagram for Cluster 1. More crashes occurred in urban areas than in rural areas. For rear-end crashes on rural and urban freeways, more than 50 percent of the crashes occurred in the activity area, and most of those crashes happened during daytime lane closures. The crash narrative analysis revealed that 40 percent of the crashes in this cluster were attributed to queuing.

Overall, the characteristics of this cluster primarily represent conditions on high-speed facilities with reduced capacity due to lane closures that likely resulted in unexpected slowdowns and queues. These conditions coupled with drivers following too close lead to rear-end crashes.

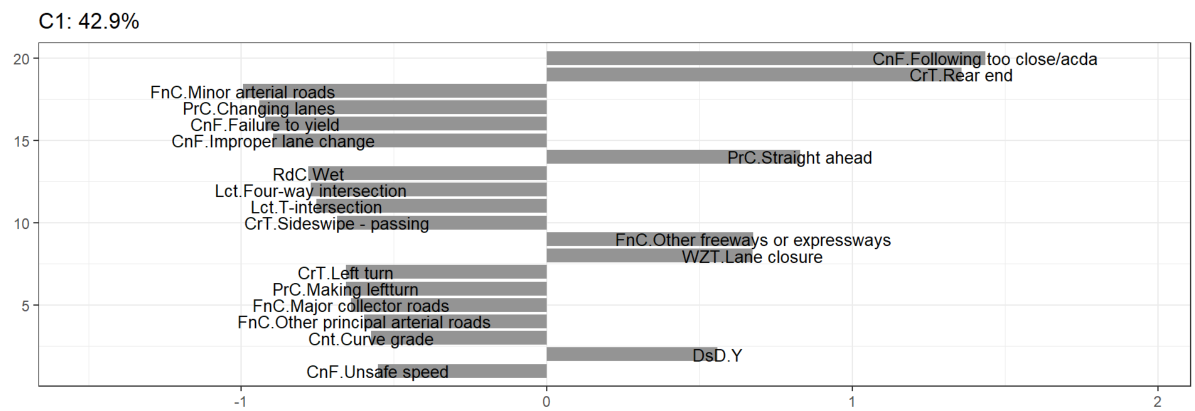


Figure 18. Rear-End Crashes at Lane Closures on Freeways or Expressways.

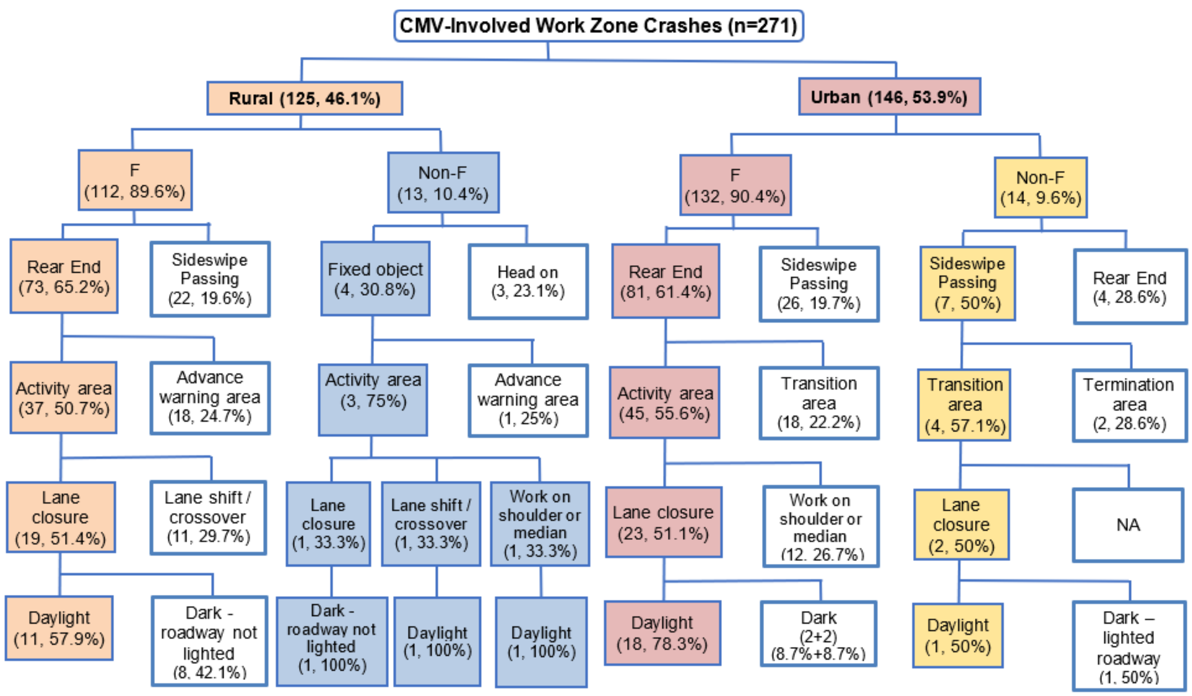


Figure 19. Nested Logit Tree Diagram for CMV-Involved Work Zone Crashes (Cluster 1).

Cluster 2, Driver Behavior Related to Sideswipe-Passing and Run-off Roadway Crashes

Figure 20 contains the correlations for Cluster 2, which includes 31.3 percent of the KAB CMV-involved work zone crashes. This cluster represents the association between the categories for driver behavior related to run-off roadway crashes. The longest bar in Cluster 2 on the positive side is improper lane changing as a precrash action, closely followed by changing lanes. Other positive associations include work on the shoulder or median, sideswipe-passing crashes, wet roadway surface conditions, vehicles moving at unsafe speeds, interstate routes, roadway curvature, rain and snow conditions, crashes with fixed objects, presence of a work zone lane shift or crossover, and lighted roadway conditions.

Figure 20. Driver Behavior Related to Sideswipe-Passing and Run-off Roadway Crashes.

Figure 21 shows the nested logit tree diagram for Cluster 2. About two-thirds of the crashes in this cluster occurred in urban areas. More than 95 percent of the crashes in both rural and urban areas happened on freeways. The most prevalent crash type for urban and rural freeways was sideswipe passing, which for this cluster, is highly correlated with lane changing behavior and the presence of work on the shoulder or median. The latter can physically constrain the traveled way and limit the available recovery room for vehicles. Sideswipe-passing crashes could also lead to one or more vehicles running off the roadway and hitting a fixed object (some of which may be closer to the roadway, such as temporary traffic control devices or work-related vehicles and equipment). Lane shifts and crossovers can also alter the roadway geometry such that there is less room for vehicles to maneuver in their lane.

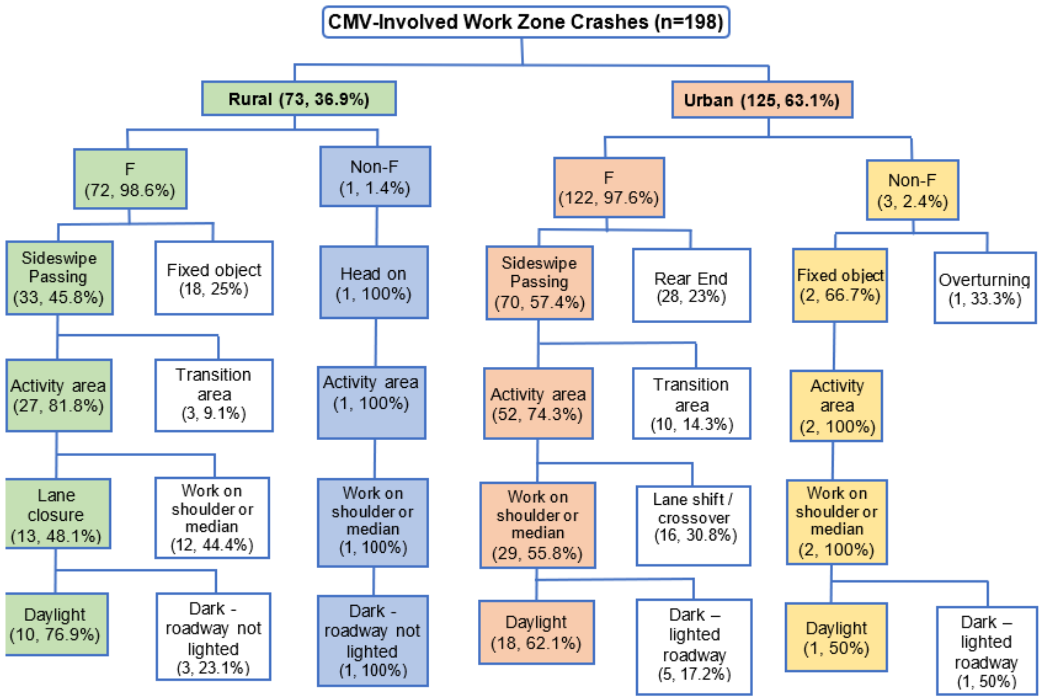


Figure 21. Nested Logit Tree Diagram for CMV-Involved Work Zone Crashes (Cluster 2).

Cluster 3, Pedestrian-Related Serious Injury Suspected Crashes on Non-Interstate Roadways

Cluster 3 includes 17.6 percent of the KAB CMV-involved work zone crashes and represents the association between crashes that occurred on several non-interstate roadways, crash type, precrash action, and work zone type. Figure 22 illustrates that other principal arterial roads had the strongest association in Cluster 3, closely followed by major collector roads and minor arterial roads. Other positive associations include pedestrian, vehicle entering the traffic lanes, vehicle failing to yield, intermittent or moving work zone, and on ramp crash location. The crash narrative analysis found that the primary influencing factors for the crashes included in Cluster 3 were queuing, stationary intrusions, and lane departures.

Equipment, traffic control devices, and workers in work zones are commonly placed near travel lanes. This positioning elevates the likelihood of vehicles colliding with equipment or accidentally hitting people working on the roadway. The close arrangement of these elements near travel lanes creates a situation where drivers face increased challenges in navigating through confined spaces and workers must be diligent to keep themselves and equipment inside the constrained workspace. This also emphasizes the critical need for effective traffic control measures, clear signage, and increased driver awareness within work zones to minimize the potential for collisions and ensure the safety of both road workers and drivers.

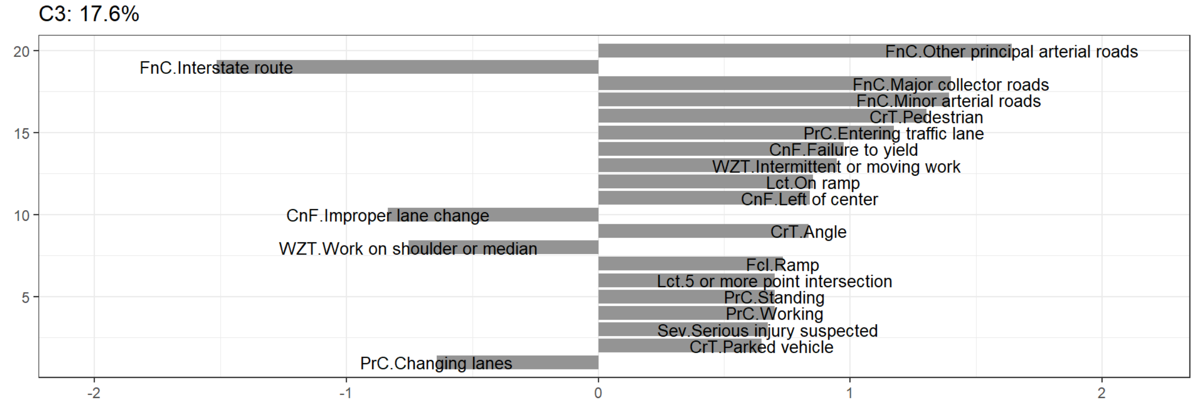


Figure 22. Pedestrian Crashes on Arterial and Major Collector Roadways with Driving Related Contributing Factors.

Figure 23 shows the correlated factors based on the data in Cluster 3. A slightly higher number of crashes occur in urban areas than in rural areas. In both rural and urban areas, most crashes occur on non-freeways, the most frequent crash type is rear-end, and the most frequent location of crashes in work zones is the activity area. The crashes that happened in lane closures and with intermittent or moving work are the same in rural areas, while in urban areas the latter one is the most frequent type of work zone. Most crashes occurred in daylight conditions in all the cases.

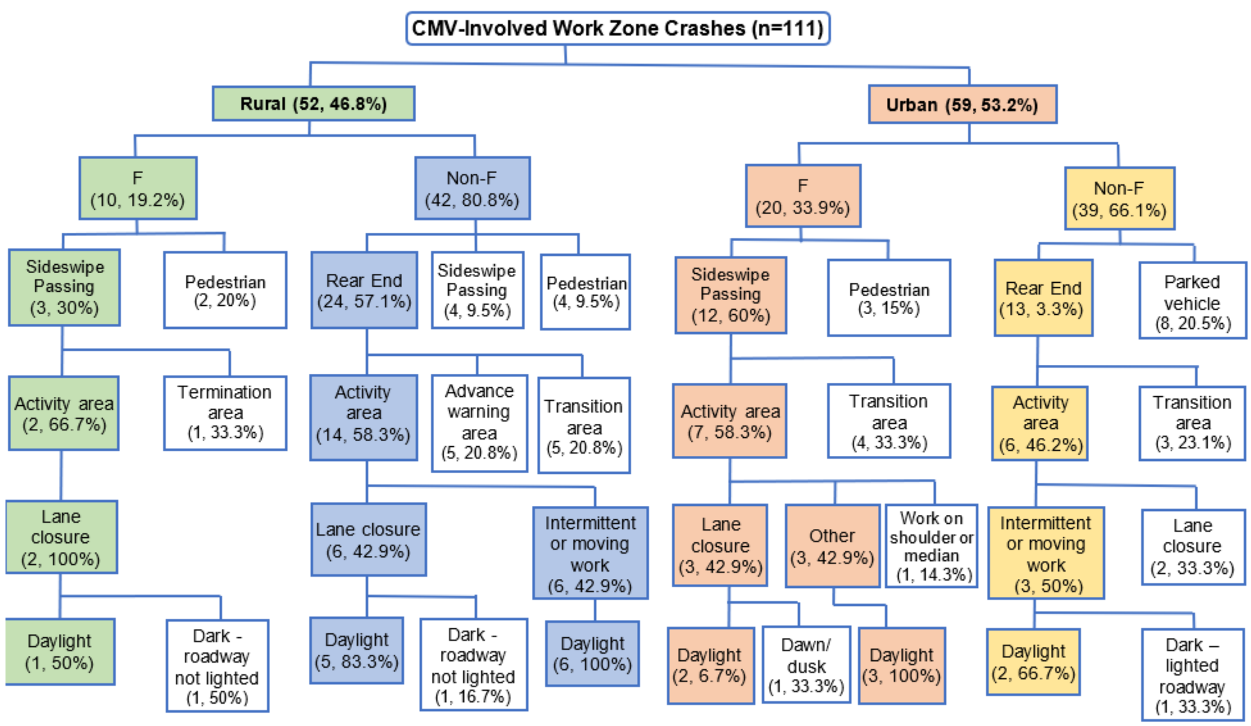


Figure 23. Nested Logit Tree Diagram for CMV-Involved Work Zone Crashes (Cluster 3).

Cluster 4, Vehicle Turning-Related Pedestrian Crashes at Intersections

In Cluster 4, the four-way intersection crash location category has the most positive association (see Figure 24). The association also includes T-intersection, minor arterial roads, major and minor collector roads, angle, pedestrian and left turn type crashes, CMVs ran red light and failure to yield, and making left turn by CMVs as a precrash movement. The cluster includes 4.3 percent of the KAB CMV-involved work zone crashes. Some of the most significant work zone crash contributing factors are failing to yield, improper driving behavior such as running a red light, and driving at improper speed in the work zone. Similarly, the crash narrative analysis found that the primary influencing factors for the crashes included in Cluster 4 were failure to yield, construction vehicle ingress/egress, turning, stationary intrusions, and worker/equipment encroachment. Construction vehicles were involved in 63 percent of the crashes in this cluster.

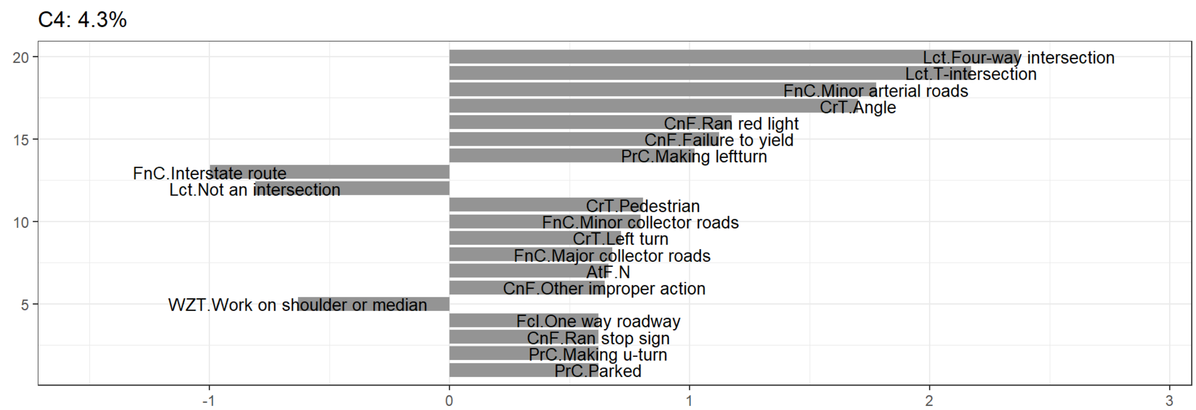


Figure 24. Intersection Crashes on Minor Arterial and Collector Roadways with Driving Related Contributing Factors.

Figure 25 shows the correlated factors based on the data in Cluster 4. More crashes occurred in urban areas than in rural areas, but all occurred the most on non-freeways. In urban areas on non-freeways, sideswipe-passing, parked vehicle, and pedestrian crashes had the same frequency, and they all mostly happened in the activity area. Sideswipe passing and pedestrian crashes were primarily associated with lane closures. In rural areas on non-freeways, angle and rear-end crashes had the same frequency and mostly happened in the activity area. The angle crashes occurred with the same frequency for lane closures and lane shifts/crossovers, while the rear-end crashes occurred with the same frequency for lane closures and intermittent or moving work. Most of the cases in both rural and urban areas happened in daylight conditions.

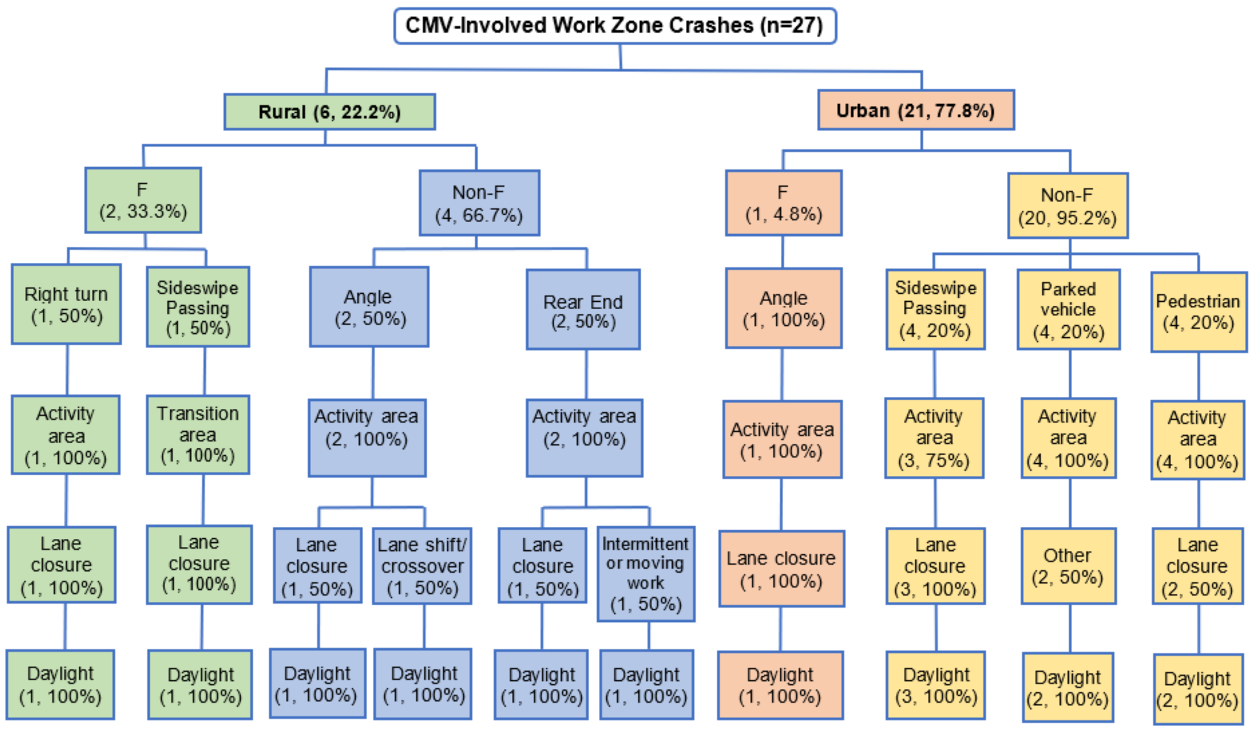


Figure 25. Nested Logit Tree Diagram for CMV-Involved Work Zone Crashes (Cluster 4).

Cluster 5, Vehicle Turning-Related Crashes at Intersections

Custer 5 includes 3.2 percent of the KAB CMV-involved work zone crashes (see Figure 26). In this cluster, both left turn crash and precrash contribution of CMVs by making a left turn have the strongest associations. Following these two, the precrash contribution of CMVs by making a right turn and right turn crashes have higher associations compared to other categories. T-intersection as a crash location has higher association compared to other types of locations. The association also includes failure to yield, ran stop sign, and improper turn by CMVs. These crashes occurred mostly on arterial roads and major collector roads. Similarly, the crash narrative analysis found that the primary influencing factors for the crashes included in Cluster 5 were turning and failure to yield. Construction vehicles were involved in four of the crashes in this cluster, including one that occurred as a construction vehicle was leaving the workspace. Improper driving movements, such as making an improper turn or failing to yield, increases the likelihood of ending up in crashes in work zones.

Figure 27 shows the correlated factors based on the data in Cluster 5. Most of the crashes in this cluster occurred in rural areas on non-freeways. In rural areas, the most common crash type was left turn, and the most frequent location of crashes was the activity area. The most frequent type of work zone was a daytime lane closure. In urban areas, most of the crashes also occurred on non-freeways. Left turn and right turn crashes had the same frequency. For left turn crashes, the activity area was the most frequent location of crashes with a variety of daytime work zone types. For the right turn crashes, the activity area and transition area had the same frequency.

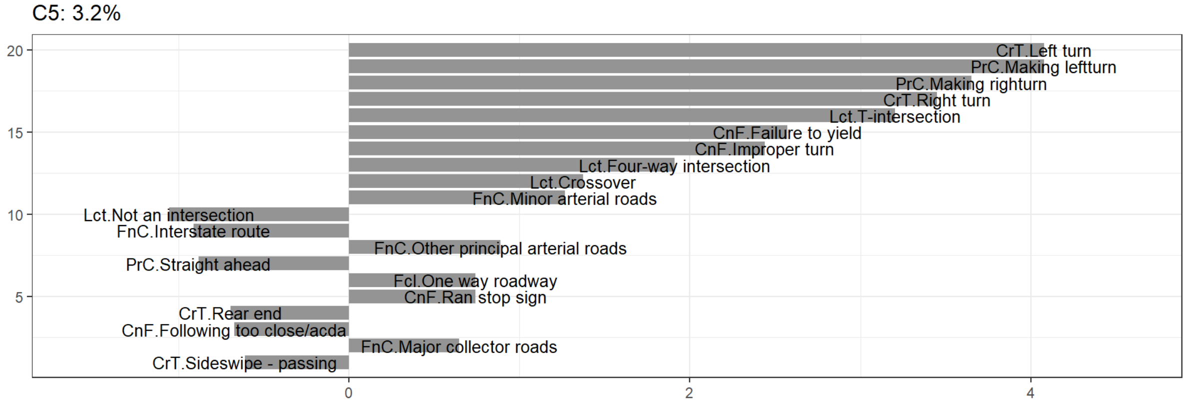


Figure 26. Turning-Related Crashes at Intersections on Arterial and Major Collector Roads.

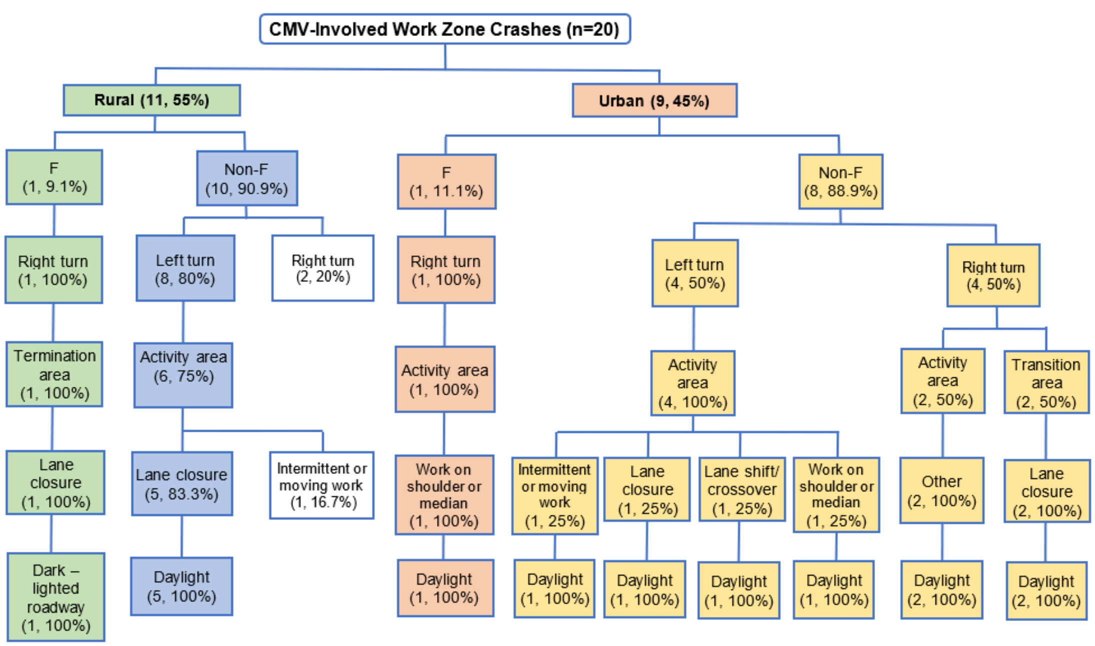


Figure 27. Nested Logit Tree Diagram for CMV-Involved Work Zone Crashes (Cluster 5).

Cluster 6, Backing-Related Crashes at Curved Locations

Cluster 6 includes only 0.8 percent of the KAB CMV-involved work zone crashes. In Figure 28, backing type crashes had the strongest association among other categories (i.e., the longest bar on the positive side). The categories of precrash contribution of backing and improper backing also have higher association compared to others. The other categories in this association are sand, mud, dirt, oil, and gravel as roadway surface condition, off ramp as crash location, straight grade roadway alignment, and dawn/dusk as lighting condition. The crash narrative analysis found that the primary influencing factors for the crashes included in Cluster 6 were wrong-way maneuver, turning, stationary intrusion, and CMV operator error. Three of the crashes in this cluster involved a construction vehicle.

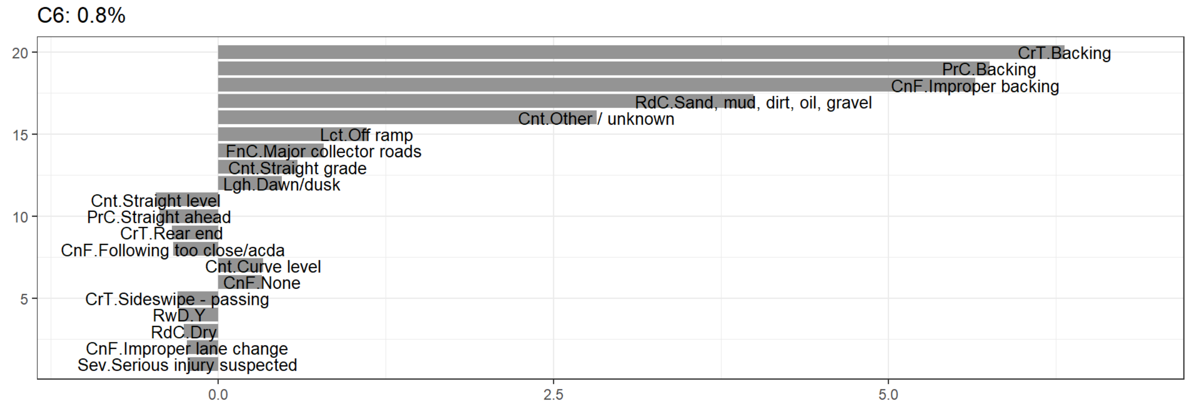


Figure 28. Backing-Related Crashes on Major Collector Roads.

Figure 29 shows the correlated factors based on the data in Cluster 6. The most common crashes in this cluster occurred in urban areas on freeways in the activity area with either a lane closure or work on the shoulder or median. Only one crash happened on a non-freeway in an urban area in the activity area during a daytime lane closure. The one crash in a rural area occurred on a non-freeway in the activity area during daytime intermittent or moving work.

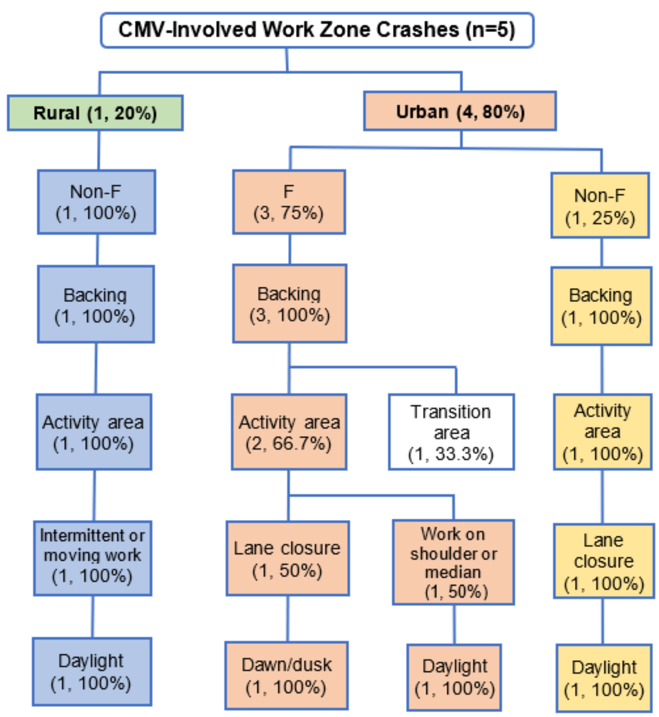


Figure 29. Nested Logit Tree Diagram for CMV-Involved Work Zone Crashes (Cluster 6).

APPENDIX C: FIELD STUDIES

In Phase 1, the research team identified and reviewed potential projects and data sources for use in the field studies. In Phase 2, the research team developed a detailed experimental plan for the field studies based on the Phase 1 findings and conducted field studies to observe the operational and safety impacts of construction access points. This appendix is divided into the following sub-sections:

- Potential projects.
- Potential data sources.
  - Vehicle probe-based data sources.
  - Exploratory analysis.
- Data collection.
- Data reduction.
  - Gate design and measurements.
  - Construction vehicle ingress/egress paths.
  - PET methodology.
  - Speed data.
  - Lane change counts.
  - Volume counts.
- Results.
  - Construction vehicle entering the workspace.
  - Construction vehicles exiting the workspace.

POTENTIAL PROJECTS

In Phase 1, ODOT personnel provided the research team with TIMS (*55*) database information downloaded on February 27, 2023. It included over 29,500 projects. The research team used database queries to identify interstate (I) projects let by ODOT beginning no later than the end of August 2023 and finishing no earlier than the end of December 2023. Work types were limited to:

- Adding through lanes.
- Interchange expansions.
- Interchange safety improvements.
- Major roadway rehabilitation.

The search produced 14 candidate projects. Two of the project plan sets were not readily available online since they were design build projects. The research team downloaded and reviewed plan sets for the remaining 12 standard build projects to determine if ODOT's construction access point standard construction drawing (MT-103.10) was included. Seven of the 12 projects were found to use the construction access point standard construction drawing (see Table 55). Researchers reviewed plans for several additional projects on limited access facilities (i.e., other non-interstate freeways). However, none were shown to use the construction access point standard.

ODOT also provided a bid item search from 2019 to 2023 for Item 829E00100, which identified projects using Supplemental Specification 829 *Work Zone Egress Warning System* (WZEWS). The results included five projects, three of which were scheduled to end by June 1, 2023, which would preclude them from use for this research project. The remaining two projects are shown in Table 55.

Table 55. ODOT Projects Using Standard Construction Drawing MT-103.10.

PID	County	Roadway	Begin Date	End Date	WZEWS
93006	Muskingum	I-70	7/6/2021	10/31/2027	Yes
95639	Franklin	I-70	7/18/2022	6/15/2025	No
106002	Summit	I-77	7/1/2021	8/30/2024	No
107375	Montgomery	I-75	9/7/2022	7/30/2025	No
107376	Montgomery	I-75	4/3/2023	7/31/2026	No
107630	Madison/Pickaway	I-71	3/1/2023	10/1/2026	Yes
108482	Cuyahoga	I-480	1/1/2023	7/31/2024	No

PID = Project identification number.

POTENTIAL DATA SOURCES

In Phase 1, the research team followed a two-step methodology to identify potential data sources that could be used to characterize traffic operations in work zones at a microscopic level. First, the research team worked with ODOT staff to explore transportation data sources and services available. Second, the research team reviewed technical reports, journal articles, and conference proceedings to identify other relevant data sources used by the research community.

The following sections discuss readily available vehicle probe-based data sources and an exploratory analysis the research team conducted to assess the feasibility of using such data sources to investigate the impacts of CMVs entering and exiting work zone access points. Additionally, the research team evaluated Wejo connected vehicle data, but they became unavailable before the field studies were conducted.

Vehicle Probe-Based Data Sources

Vehicle probe-based data refer to a data collection method in which sensors mounted on vehicles are used to collect information about the vehicle itself and the surrounding environment. Examples of vehicle probe-based data include GPS, speed, hard braking, acceleration, temperature, tire pressure, and heading.

The research team explored the vehicle probe-based transportation datasets and data services that are currently available for ODOT. These are the National Performance Management Research Data Set (NPMRDS), INRIX, and Drivewyze®. In Phase 1, the research team reviewed each potential data source and identified opportunities and limitations of their use in field studies.

National Performance Management Research Data Set

NPMRDS is a vehicle probe-based dataset acquired from INRIX by FHWA for the National Highway System (NHS), which includes interstates, freeways, and other major roads. This dataset consists of field-observed travel time and speed data collected anonymously from passenger and commercial connected vehicles and smartphone users (*56*). Table 56 summarizes NPMRDS relevant information for this project.

Table 56. NPMRDS.

Data source	INRIX
Data services for ODOT	NPMRDS Analytics
Variables	Speed and travel time
Spatial aggregation	Traffic Message Channel (TMC) linear reference system
Temporal aggregation	5-minute, 15-minute, or 1-hour increments
Opportunities	A platform to monitor performance of the NHS, identify where improvements or mitigation strategies might be needed, and measure the effect of any change to the transportation system such as traffic incidents.
Limitations	TMC links are about half a mile to a mile long in urban/suburban areas and five to 10 miles long in rural areas. This spatial resolution is low for monitoring traffic operations at work zones. Moreover, the 5-minute temporal aggregation does not provide sufficient level of detail to monitor the events of commercial vehicles entering/exiting the work zone.

INRIX

INRIX is a vehicle probe-based dataset collected from over 400 distinct sources of probe data from 300 million real-time vehicles and devices around the world. These include anonymous GPS-based data from a variety of vehicle types (i.e., commercial fleet, delivery, and passenger vehicles), smartphone users, and other market-specific sources of real-time traffic information (e.g., construction and road closures, real-time incidents, sporting and entertainment events, weather forecasts, school schedules, etc.) (*57*). Table 57 summarizes INRIX relevant information for this project.

Table 57. INRIX.

Data source	INRIX
Data services for ODOT	RITIS, INRIX IQ
Variables	Speed and travel time
Spatial aggregation	INIRIX XD
Temporal aggregation	Real-time, 1-minute, 10-minute, 15-minute, or 1-hour increments
Opportunities	RITIS and INRIX IQ are a collection of web-based tools to analyze and visualize vehicle probe-based data, create reports, and download raw data for analyzing in the user's computer. These platforms can monitor travel time, speed, dangerous slowdown alerts, congestion levels, and travel time reliability along work zones. In informal conversations with INRIX, it was mentioned that data could be aggregated into smaller segments upon request.
Limitations	INRIX XD are a maximum of 1,600 meters in length (approx. 1 mile). This spatial resolution is low for monitoring traffic operations at work zones. INRIX dangerous slowdown alerts are only provided in real time (i.e., historical data cannot be retrieved).

Drivewyze®

Drivewyze® is a data services company that provides in-cab messaging warnings of "sudden slowdown ahead" and "congestion ahead" to CMV drivers via their electronic logging devices (ELDs), smartphones, or tablets in real time (*58*). Drivewyze® gathers the information required to create the alerts from INRIX real-time dangerous slowdown, queues, and road closure information (*59*). Table 58 summarizes Drivewyze® relevant information for this project.

Table 58. Drivewyze®.

Data source	INRIX
Data services for ODOT	Drivewyze® CMV Traffic Alert Dashboard
Variables	Number and location of congestion and dangerous slowdown alerts sent to CMVs.
Spatial aggregation	INIRIX XD
Temporal aggregation	Real-time, minute, day, week, month, quarter, and year
Opportunities	Currently, ODOT is subscribed to the Drivewyze® CMV Traffic Alert Dashboard that provides the number and location of congestion and slowdown alerts sent to CMVs in real time. Historical data are also available for post event analysis. This platform allows ODOT to quantify the number of congestion and slowdown alerts sent to CMVs in work zones.
Limitations	Drivewyze® is also subjected to the limitations associated to the use of INRIX XD linear reference system. INRIX XD are a maximum of 1,600 meters in length. This spatial resolution is low for monitoring traffic operations at work zones.

Exploratory Analysis

In Phase 2, the research team evaluated the feasibility of using the INRIX Real-Time Traffic Flow Data Application Programming Interface and Drivewyze® Tableau Dashboard to investigate the impacts of CMVs entering and exiting work zone access points.

The INIRIX Real-Time Traffic Flow Data provided speed and incident data (i.e., safety alerts and dangerous slowdowns) for each 300 ft segment every 1 minute with 3-minute latency:

- Speed: Traffic speed was expressed in miles per hour.
- Safety alerts: Incidents happening on roadways that may slow the traffic. These were classified into crashes and hazards, events, construction, and congestion alerts. Moreover, INRIX reported incident descriptive information with severity ranging from 0 (lowest severity) to 4 (highest severity).
- Dangerous slowdowns: A slowdown occurred when there was a difference in speed of more than 35 mph between one segment and the following one. Slowdown severity was also reported. It ranged from 3 (moderate) to 5 (severe).

Drivewyze® incident data contained congestion and slowdown alerts sent to CMV drivers in real time via their ELDs, smartphones, or tablets.

Figure 30 presents the approach followed for two work zones using the construction access point standard construction drawing. The research team developed a piece of software to automatically collected speeds, incidents, and slowdowns from INRIX every 5 minutes for 300 ft roadway segments. Drivewyze® data were directly downloaded from its dashboard. Data collected were stored in a database (see Box 1 in Figure 30). Next, the research team processed and fused the database (see Box 2 in Figure 30). The result was a set of daily speed profiles with speed data for each 5-minute interval.

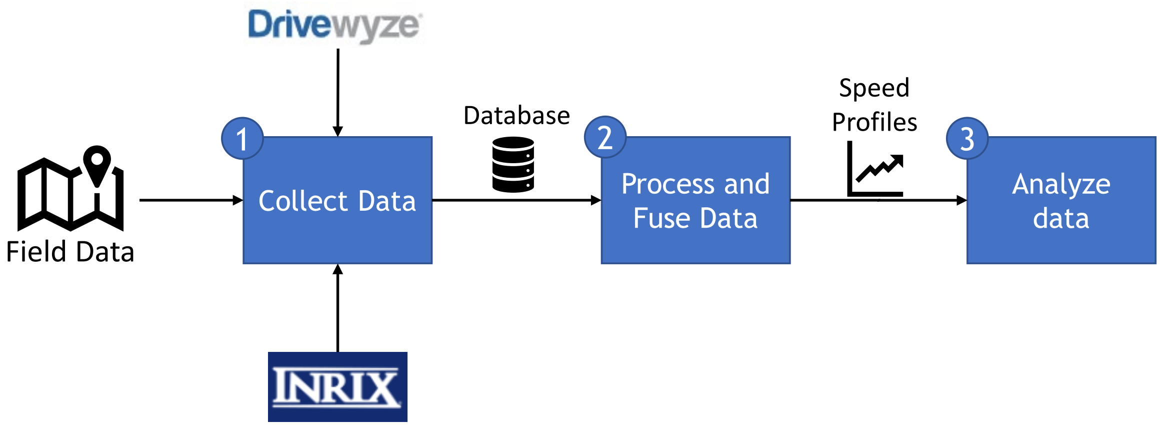


Figure 30. Vehicle Probe-Based Data Source Exploratory Analysis Approach.

Once speed profiles were generated, the researchers started the analysis to identify impacts on traffic flow that CMVs might cause when entering or exiting the work zone at dedicated access points (i.e., gates). Specifically, researchers examined speed profiles at the segments where gates were located and the surrounding segments. In the cases where congestion was generated at the gate segment, researchers checked the videos gathered at the field, and observed the number of CMVs exiting/entering the access point as well as incident data from INRIX and Drivewyze® to confirm whether the congestion was due to a CMV entering or exiting the gate. The results of the exploratory analysis showed that these data sources were not granular enough to detect and measure the impacts on traffic when CMVs entered or exited a workspace access point. Therefore, the research team used more traditional methods of data collection for the field studies.

DATA COLLECTION

In Phase 2, the research team selected three projects (PID 107630, PID 107375, and PID 107376) for the field studies. Table 59 contains information about each project, and Figure 31 is a map showing their locations. PID 107630 was located southwest of Columbus on I-71 in a rural area. The other two projects were located on I-75 in Dayton in urban areas.

Table 59. Field Study Sites.

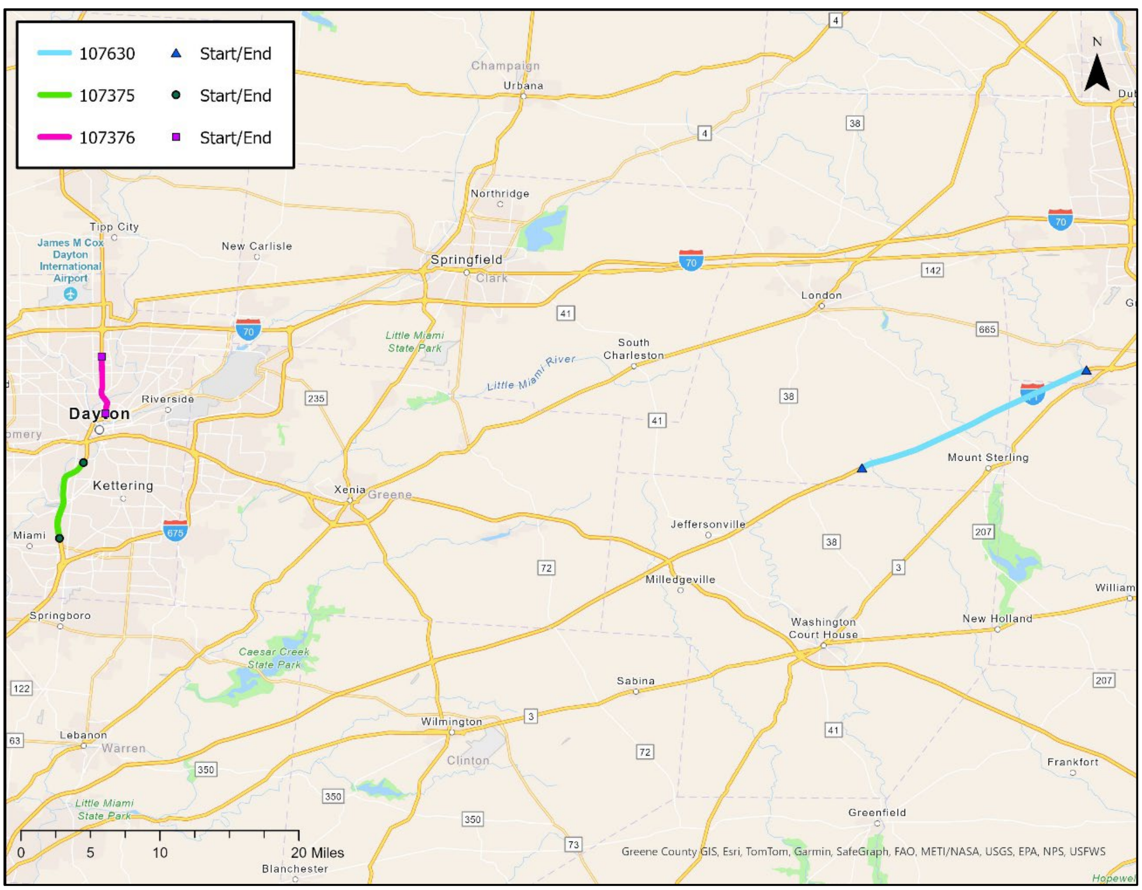
PID	Roadway	Project Length (miles)	Average AADT (2023)	Project Type
107630	I-71	14.3	46,083	Major reconstruction
107375	I-75	6	117,352	Major reconstruction
107376	I-75	4.2	106,681	Major reconstruction

AADT = Annual average daily traffic from the ODOT Traffic Monitoring Management System.

The research team collected data in October 2023. Data collection included physical measurements of the workspace access points, speed profiles of construction vehicles using the workspace access point, spot speed measurements of the vehicles in the open travel lanes, GPS mapping of the work zones, documentation of various site characteristics, and video data from cameras mounted on two portable trailers that recorded CMVs entering and exiting the workspace access points and the vehicles in the open travel lanes. The two camera trailers were dedicated as 6176 and 6178 and were moved around as needed to capture workspace access points where CMVs were regularly entering or exiting the workspace.

The research team collected data at PID 107630 from October 2 to October 21. However, researchers were only onsite to move the portable trailers from October 2 to October 6 and again from October 16 to October 21. The research team collected data at PID 107353 and PID 107376 from October 16 to October 21.

Figure 32 contains a summary of the total hours of video data recorded for each project. In total, the research team collected approximately 606 hours (25 days) of video data across all the sites, with most video data recorded at PID 107630 due to that project's extensive use of many workspace access points designed to meet the standard construction drawing.



Map Source: Greene County GIS, Esri, TomTom, Garmin, SafeGraph, FAO, METI/NASA, USGS, EPA, NPS, USFWS.

Figure 31. Map of Field Study Sites.

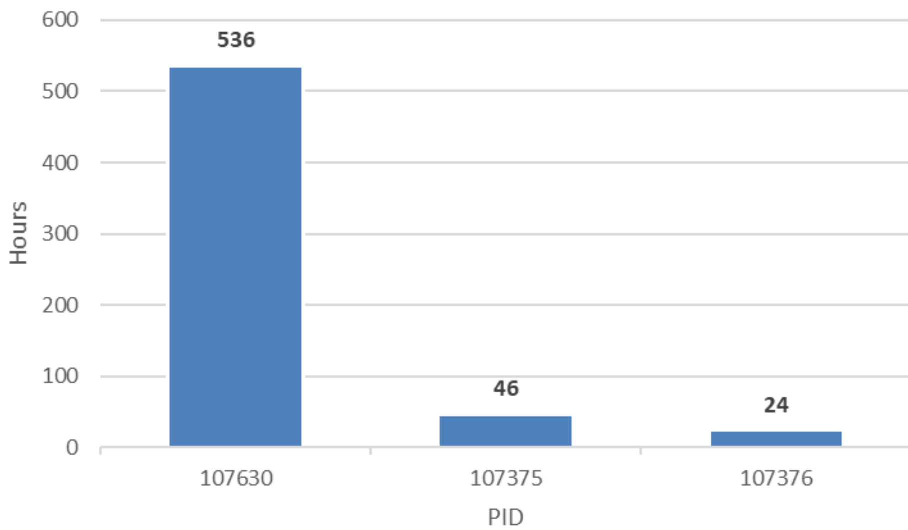


Figure 32. Hours of Video Collected for Each Project.

DATA REDUCTION

After data collection was completed, the research team extracted and downloaded the video into 1-hour video files. Since the activity of interest (i.e., CMVs entering or exiting the workspace access point) is a relatively quick event and the research team was not continually onsite at PID 107630 to reposition the portable camera trailers, the research team first reviewed the videos to determine which 1-hour files contained useful data. If a video file contained at least one CMV entering or exiting the workspace, then that video file was considered for further data processing and analysis. Post-reduction, the research team retained 107 hours, 14 minutes, and 8 seconds of video data from camera 6178, and 36 hours, 41 minutes, and 42 seconds of video data from camera 6176 for a total post-reduction video time of 143 hours, 55 minutes, and 50 seconds.

During the initial video review, the research team also collected additional information about each video file, such as the time of day, the primary and secondary types of vehicles using the workspace access point, the number of CMVs that used the workspace access point, how each CMV entered or exited the workspace access point (i.e., travel path), whether the CMV was full or empty, the camera position, the weather conditions, and the workspace access point number (if applicable). The research team also assessed the video's viewpoint to determine whether additional metrics (e.g., volume counts, lane change counts, last-minute lane change counts, and PET measurements) could be confidently analyzed.

In total, 1,304 CMVs were recorded entering or exiting the workspace across all sites, with 1,271 of those coming at PID 107630 (see Table 60). Furthermore, dividing the number of CMVs observed entering or exiting the workspace by the number of recorded video hours generated a rate that provided the research team with insight into how active each project was during the data collection period (see Figure 33).

Table 60. Number of CMVs Using the Workspace Access Point for Each Project.

PID	Number of CMVs
107630	1271
107375	16
107376	17
Total	1304

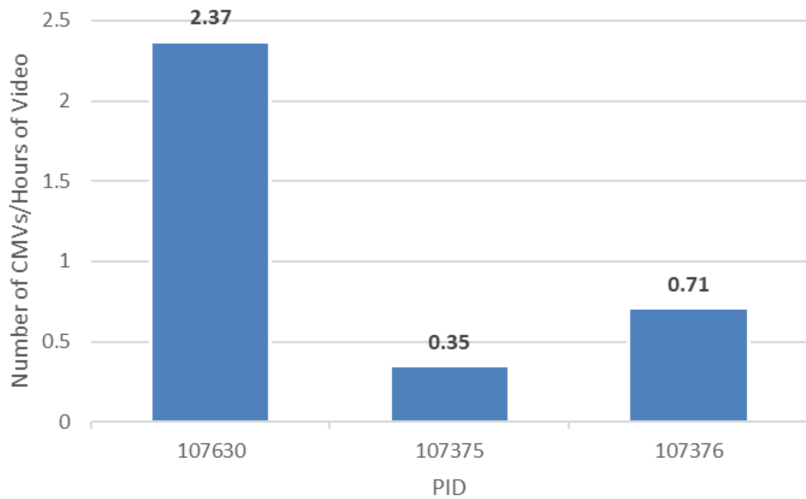


Figure 33. Number of CMVs per Hours of Recorded Video for Each Project.

Gate Design and Measurements

Figure 34 contains an excerpt from the ODOT Construction Access Points standard construction drawing (MT-103.10). This standard provides a dedicated lane outside the travel lanes for construction vehicles to decelerate and accelerate. For work zone ingress, construction vehicles should enter the dedicated lane as soon as possible, decelerate, and turn into Opening A. For work zone egress, construction vehicles exit through Opening B, accelerate in the dedicated lane, and merge into the open travel lanes. The deceleration area is 650 ft long, while the acceleration area is 790 feet long.

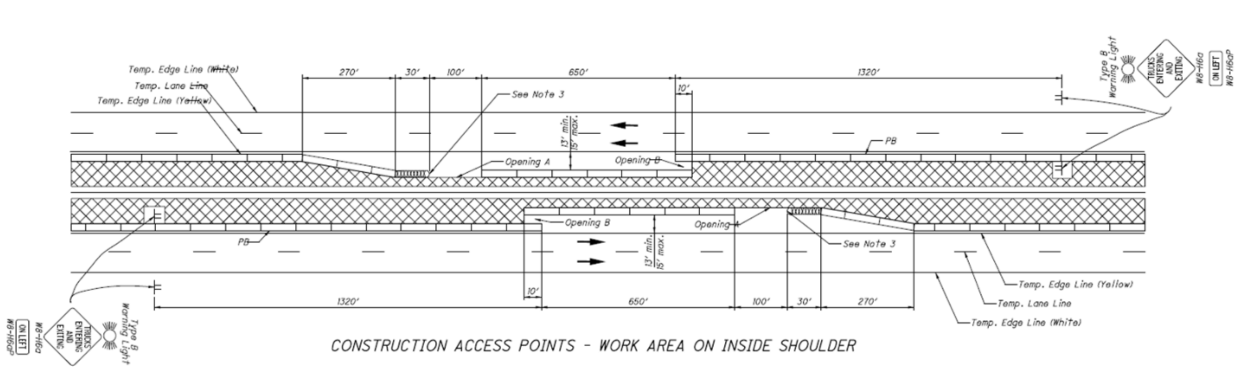


Figure 34. Excerpt from ODOT Standard Construction Drawing MT-103.10.

Table 61 contains a summary of the workspace access point characteristics at the three projects. Most of the workspace access points at PID 107630 were designed based on the ODOT standard construction drawing. The contractor also used a temporary turnaround so cement trucks could more easily make a U-turn and access the opposite direction of travel and slip configurations at the beginning and end of the project for entering and exiting the workspace. PID 107375 also utilized a slip entry configuration for access to the workspace. Slip configurations are single points of access for either entering or exiting the workspace that utilized paved shoulders at the beginning or end of the project to provide an area for construction vehicles to decelerate or accelerate. PID 107376 utilized the ODOT standard construction drawing; however, construction vehicles used Opening B to both enter and exit the workspace.

Table 61. Field Study Workspace Access Point Characteristics.

PID	Access Point Number	Access Point Design	Width of Opening B (ft)	Barrier Overlap at Opening B (ft)	Tangent Length (ft)	Length of Opening A (ft)	Crash Cushion (ft)	Termination Taper (ft)
107630	1	Slip entry	N/A	N/A	N/A	N/A	N/A	N/A
107630	2	SCD	15.5	7	588	127.5	34	264
107630	New 2	SCD	15.5	-2	648	80	34	252
107630	3	SCD	15	9.5	600	112.5	34	264
107630	4	SCD	15.5	0	612	117.5	34	264
107630	5	SCD	15.5	9	648	120	34	264
107630	6	SCD	15.5	-2	648	82.5	34	252
107630	7	SCD	15.5	2	648	85	34	264
107630	8	SCD	15	5	648	87.5	34	264
107630	9	SCD	16	6	648	90	34	264
107630	10	SCD	16	2.5	648	95	34	276
107630	11	SCD	15	0	660	90	34	264
107630	12	SCD	16	7	648	85	34	264
107630	13	SCD	15	0	648	87.5	34	264
107630	14	Slip exit	N/A	N/A	N/A	N/A	N/A	N/A
107630	15	Median U-turn	N/A	N/A	N/A	N/A	N/A	N/A
107375	16	Slip entry	N/A	N/A	N/A	N/A	N/A	N/A
107376	17	SCD		13	744	200	34	60

N/A = not applicable; SCD = standard construction drawing (MT-103.10).

Most of the workspace access points implemented at the field study sites followed the standard construction drawing quite well. The biggest deviations were for the barrier overlap at Opening B (ranged from −2 to 9.5 ft) and length of Opening A (ranged from 80 ft to 200 ft).

Construction Vehicle Ingress/Egress Paths

While reviewing the videos for post processing, the research team noticed that the construction vehicles were utilizing the dedicated lane in a variety of ways to access the workspace. So, the research team documented the construction vehicles' paths for each entry and exit and then organized them into 10 categories. Three of the categories (Type 1, Type 2, and Type 3) applied to construction vehicles entering the workspace (ingress), and six of the categories (Types 4, Type 5, Type 6, Type 7, Type 8, and Type 9) related to construction vehicles exiting the workspace (egress). The research team created the remaining category for all the maneuvers that did not fit into the other nine categories. Figure 35 shows the construction vehicle paths for Types 1—9.

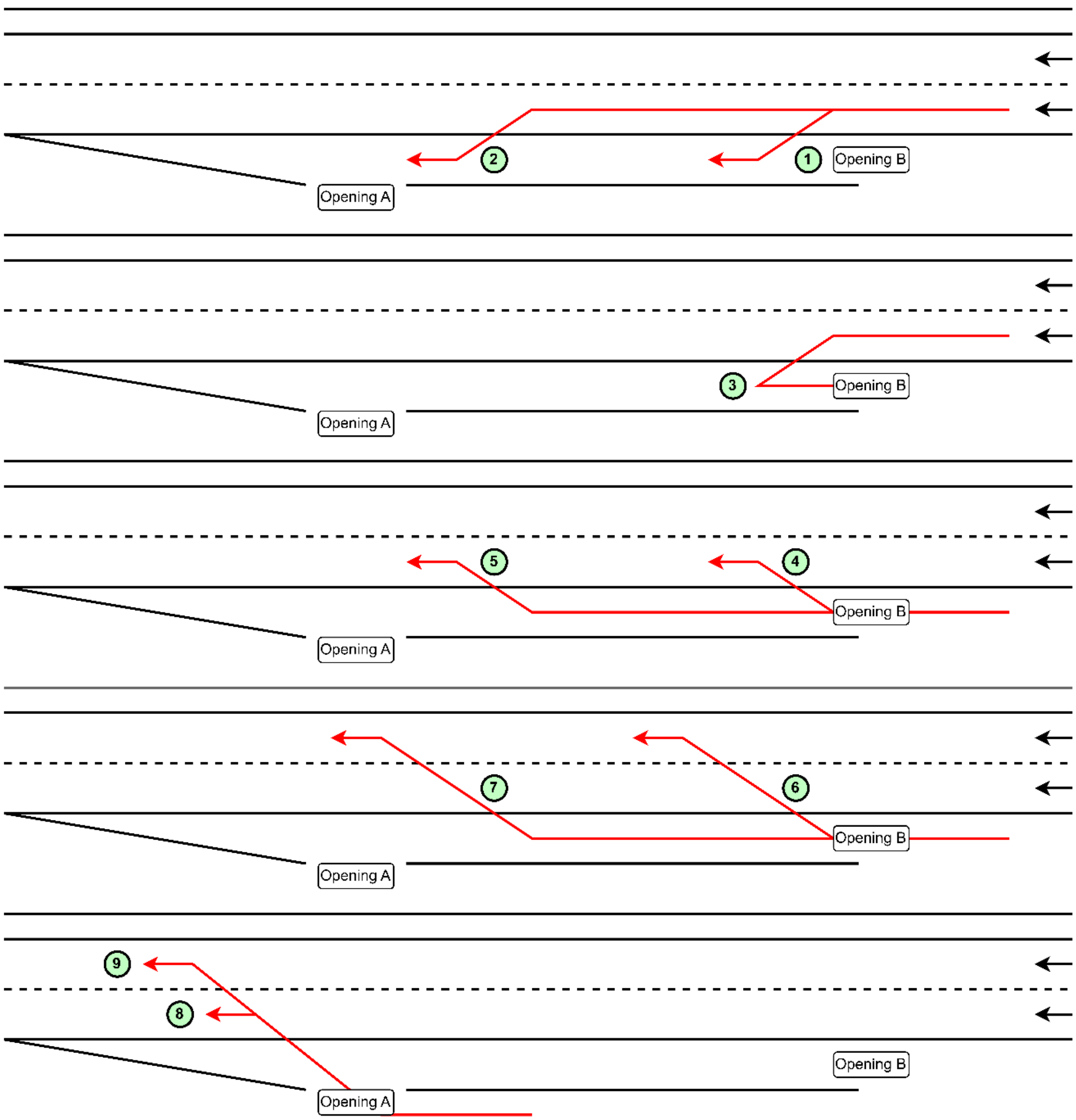


Figure 35. Work Zone Ingress and Egress Types.

Type 1 entrances included construction vehicles approaching a workspace access point from the adjacent travel lane and almost immediately entering the dedicated lane (i.e., before the midpoint of the dedicated lane). For this entry type, some construction vehicle drivers would begin slowing down in the main lanes of travel before entering the dedicated lane. Other construction vehicle drivers would enter the dedicated lane at higher speeds and then use the dedicated lane to decelerate. Figure 36 shows an example of a construction vehicle almost immediately entering the dedicated lane.

Figure 36. Example of a Type 1 Entrance.

Type 2 entrances included construction vehicles approaching a workspace access point from the adjacent travel lane and entering the dedicated lane after the midpoint of the dedicated lane. For this entry type, some construction vehicle drivers remained fully in the travel lane until past the midpoint of the dedicated lane. Other construction vehicle drivers would slowly change lanes such that they did not fully enter the dedicated lane until past the midpoint. Figure 37 shows an example of a construction vehicle entering the dedicated lane past the midpoint.

Type 3 entrances included construction vehicles approaching a workspace access point from the adjacent travel lane, entering the dedicated lane, coming to a complete stop in the dedicated lane, and then reversing in the dedicated lane to enter the workspace via Opening B. The research team observed this maneuver being used the most by cement trucks at PID 107630 and PID 107376. At PID 107630, a bridge was being built between two workspace access points, and the cement pump truck was most easily accessible from the exit of the nearest workspace access point. At PID 107376, this maneuver was the only type of entrance that could be executed due to how the workspace access point was installed. Figure 38 shows an example of a cement truck completing a Type 3 maneuver.

Figure 37. Example of a Type 2 Entrance.

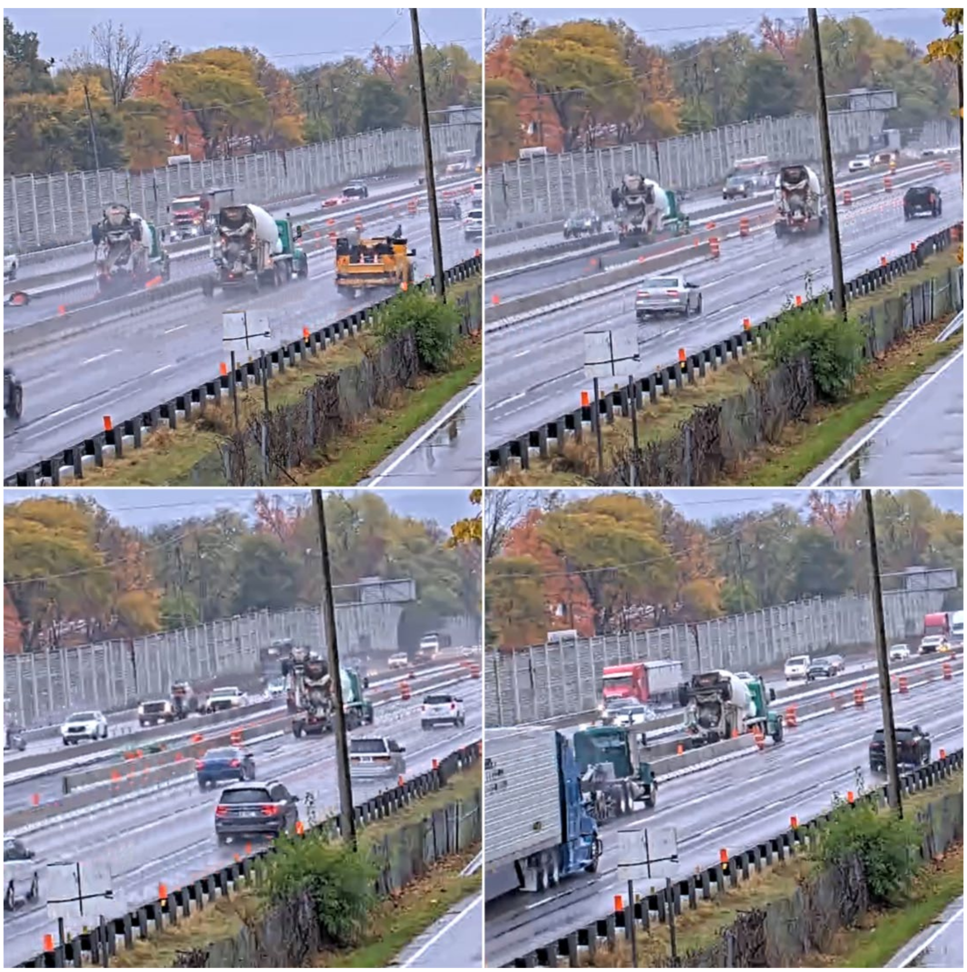


Figure 38. Example of a Type 3 Entrance.

Type 4 exits included construction vehicles approaching the workspace exit and almost immediately entering the adjacent (inside) travel lane (i.e., before the midpoint of the dedicated lane) rather than using the full length of the dedicated lane to accelerate. For this exit type, construction vehicle drivers typically approached the workspace exit point, stopped at the exit point, and then waited for a gap in the main lane traffic before accelerating and merging. Figure 39 shows an example of a construction vehicle almost immediately entering the adjacent travel lane.

Figure 39. Example of a Type 4 Exit.

Type 5 exits included construction vehicles approaching the workspace exit, using the dedicated lane to accelerate, and then merging into the adjacent travel lane after the midpoint of the dedicated lane. Even though the construction vehicle driver used the dedicated lane to accelerate, in some instances drivers would still arrive at the workspace exit, stop at the exit point, and wait for a gap in the main lane traffic. Figure 40 shows an example of a construction vehicle exiting the dedicated lane past the midpoint.

Type 6 exits were like Type 4 exits except that the construction vehicles immediately crossed the adjacent (inside) travel lane and merged into the outside lane. For this type of exit, construction vehicle drivers were especially prone to stopping at the workspace exit and waiting for a gap in the main lane traffic. Figure 41 shows an example of a construction vehicle almost immediately entering the outside travel lane.

Figure 40. Example of a Type 5 Exit.

Figure 41. Example of a Type 6 Exit.

Type 7 exits were like Type 5 exits except after accelerating in the dedicated lane the construction vehicles crossed the adjacent (inside) travel lane and merged into the outside lane. For this type of exit, construction vehicle drivers also typically came to stop at the workspace exit and waited for a gap in the main lane traffic. Occasionally, a construction vehicle driver would stop further into the dedicated lane instead of the workspace exit point (Opening B). Figure 42 shows an example of a construction vehicle exiting the dedicated lane past the midpoint and crossing over into the outside travel lane.

Figure 42. Example of a Type 7 Exit.

Type 8 exits included construction vehicles exiting the workspace from Opening A and immediately entering the adjacent (inside) travel lane. Most construction vehicle drivers completing this maneuver arrived at the workspace entry, stopped, waited for a gap in the main lane traffic, and then merged into the inside lane. In some instances, another construction vehicle would be arriving, so that driver would have to stop in the dedicated lane and wait for the exiting construction vehicle to move (potentially blocking the line of sight of the exiting construction vehicle). Figure 43 shows an example of a construction vehicle exiting through Opening A and the conflict with another construction vehicle.

Figure 43. Example of a Type 8 Exit.

Type 9 exits were like Type 8 exits except that the construction vehicles immediately crossed the adjacent (inside) travel lane and merged into the outside lane. This type of maneuver was also observed once and involved an asphalt paver. The paver may have been too large to use Opening B. A shadow vehicle with a truck-mounted attenuator did exit the workspace using Opening B behind the asphalt paver to block main lane traffic while the asphalt paver crossed the travel lanes. Figure 44 shows the asphalt paver exiting through Opening A and the shadow vehicle exiting through Opening B.

Type 10 maneuvers primarily included construction vehicle entrance and exit paths that that were unique or did not involve the standard construction vehicle access point design. One such instance involved a construction vehicle entering the roadway via an entrance ramp, pulling off and stopping on the right shoulder of the ramp, waiting for a gap in the main lane traffic, and then crossing both travel lanes and entering Opening A of the workspace access point (see Figure 45). Another example included a temporary turnaround that was built in the work zone so that cement trucks did not have to drive miles down in the road to U-turn and access the opposite direction of travel (see Figure 46). The last example included the use of a wide left shoulder that was closed, allowing construction vehicles to decelerate and enter the workspace (see Figure 47).

Figure 44. Example of a Type 9 Exit.

Figure 45. Example of Type 10 Exit—Entrance Ramp.

Figure 46. Example of Type 10—U-turn.

Figure 47. Example of Type 10—Existing Shoulder.

Table 62 shows the number of construction vehicles completing each ingress/egress path type. Type 1 was the most represented entrance type, while Type 5 was the most represented exit type, which indicates that construction vehicle drivers were typically using the workspace access point design as intended. All the maneuver types were captured at PID 107630. Conversely, PID 107375 only included Type 10 maneuvers, and PID 107376 only included Type 3 and Type 4 paths. Due to the small number of construction vehicles entering/exiting the workspace at PID 107375 and PID 107376 and the use of unconventional vehicle paths, the research team decided to focus on PID 107630 for the remainder of the data analysis.

Table 62. Percent Distribution of Entrance and Exit Types per Project.

PID	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8	Type 9	Type 10	Total
107630	35%	11%	6%	11%	25%	4%	3%	2%	< 1%	1%	98%
107375	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%
107376	0%	0%	1%	< 1%	0%	0%	0%	0%	0%	0%	1%
Total	35%	11%	7%	11%	25%	4%	3%	2%	< 1%	2%	100%

PET Methodology

The research team adapted and modified the PET methodology (*60*, *61*) to use as a surrogate safety measure to assess construction vehicle merging and diverging behaviors. Traditionally, a simple equation is used to calculate the time gap between one vehicle leaving and another vehicle entering a dedicated conflict area. This time gap can help determine how close one vehicle is to colliding with another. Lower PET times are considered "riskier" or less safe than a higher PET time. While the dedicated conflict area can vary, the PET calculation essentially remains unchanged and looks like the following in its most basic form:

$$PET = t_2 - t_1$$

Where:

- PET = post encroachment time.
- t_1 = time first vehicle leaves potential conflict point.
- t_2 = time second vehicle arrives at potential conflict point.

The concept of PET has been applied to many different settings and a variety of scenarios, but at its core it is applied when there is a situation in which one vehicle passes an arbitrary point at t_1 and another vehicle passes through that same point at t_2. For example, a single lane scenario would involve two vehicles traveling in the same lane, one in front of the other, with no lane changes made and uniform velocity. An invasion line, or conflict area, could be drawn perpendicular to the lanes, and a PET time could be calculated based on the times in which the first vehicle's rear end last touched the invasion line and when the second vehicle's front end first touched the invasion line. This concept is most commonly applied to intersections with multiple potential points of conflict.

Since this project involves vehicles changing lanes and non-uniform velocity amongst all vehicles, the traditional PET methodology needed to be altered. Qi et al. (*61*) conducted a study that calculated PETs for vehicles in lane change scenarios with one vehicle traveling in one lane at a constant velocity and another vehicle in an adjacent lane traveling at a constant velocity and changing lanes in front of the first vehicle. In a lane change scenario, imagine that one vehicle is traveling in lane A at constant velocity and another vehicle is traveling in lane B at constant velocity. The vehicle in lane B wants to change lanes into lane A and get ahead of the vehicle in lane A. Under this scenario, the invasion line would be drawn perpendicularly to the lanes at the point where the front of the vehicle in lane B first begins to cross into lane A. At this point, the vehicle that is changing lanes is now in the path of the vehicle that did not change lanes, so there is a potential conflict.

Once the invasion line is set, then t_1 can be measured when the rear of the vehicle that changed lanes finishes crossing through the invasion line completely. Next, t_2 is measured when the front of the vehicle that is still in lane A first begins to touch the invasion line. Once t_1 and t_2 are found, then the previous formula can be used and the PET can be calculated.

For this project, the research team used a similar methodology to calculate the PETs of the construction vehicles entering and exiting the workspace via access points designed according to the ODOT standard construction drawing at PID 107630. The research team began by reviewing videos that contained construction vehicles using an access point to determine if the camera angle was suitable for accurately capturing the time measurements needed to calculate the PET. Once the research team confirmed the viability of each video, every instance of a construction vehicle entering and exiting the workspace was manually reviewed to obtain the needed time measurements. The research team calculated one to four PETs for each construction vehicle dependent upon whether it was entering or exiting and whether it was in the inside or outside lane. All the construction vehicles entering the workspace (Types 1, 2, and 3) were traveling in the inside lane and thus had one PET calculated between them and the following vehicle (i.e., $PET_{Enter,Following}$). For construction vehicles exiting the workspace, the research team computed PETs for the vehicles in the inside lane in front of (leading) and behind (following) the construction vehicle. So, every exiting construction vehicle had two inside lane PET values (i.e., $IPET_{Exit,Following}$ and $IPET_{Exit,Leading}$). If the construction vehicle moved directly into the outside lane (Types 6, 7, and 9), then the research team calculated two additional PET values (i.e., $OPET_{Exit,Following}$ and $OPET_{Exit,Leading}$).

For construction vehicles entering the workspace (Types 1—3), the research team drew the invasion line (red line in Figure 48) perpendicular to the main lanes as soon as the vehicle’s rear bumper was fully in the dedicated lane (yellow line in Figure 48). The research team recorded the time at which that happened as t_{R1}. With the invasion line drawn, the video was played until the front bumper of the next vehicle in the same lane touched the invasion line (see Figure 49). The research team recorded the time at which that happened as t_{F2}. With the time values in hand, t_{R1} was subtracted from t_{F2} to calculate the $PET_{Enter,Following}$ time between the construction vehicle and the following vehicle.

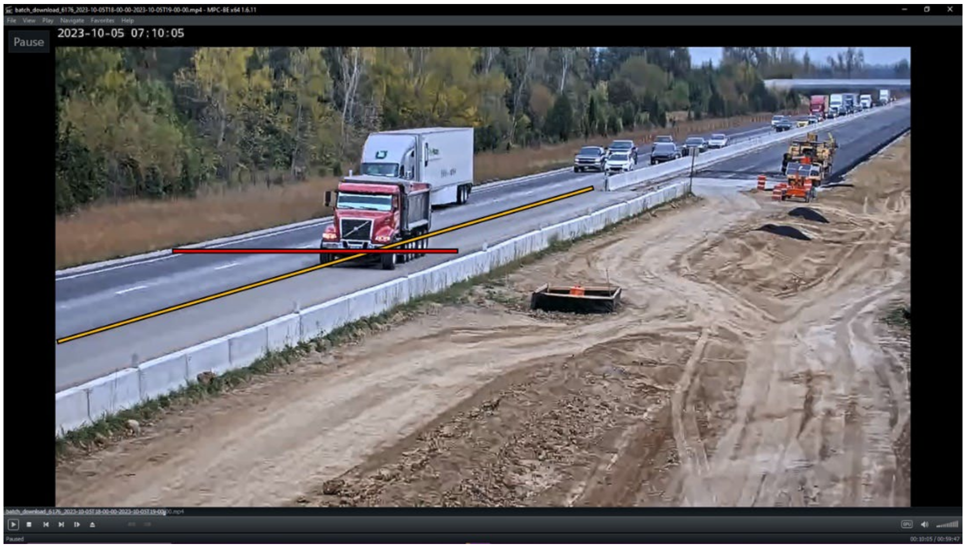


Figure 48. Video Frame Showing the Invasion Line and t_{R1} for a Construction Vehicle Entering the Workspace Access Point.

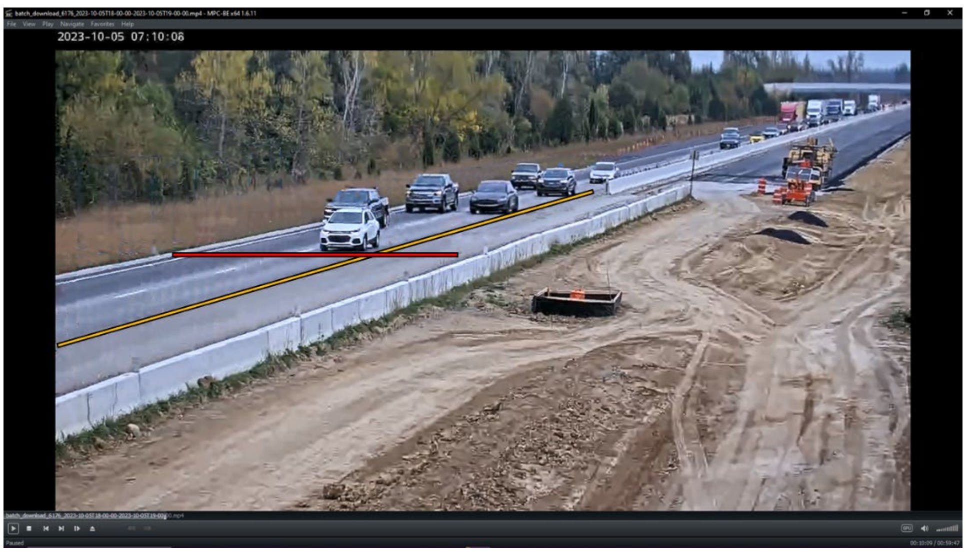


Figure 49. Video Frame Showing the Invasion Line and t_{F2} for a Construction Vehicle Entering the Workspace Access Point.

For the construction vehicles exiting the work zone (Types 4—9), the process was similar but with additional steps. Since the construction vehicle was exiting the workspace access point, the establishment of the invasion line occurred at t_0, when the construction vehicle's front left corner first began to enter the inside travel lane (see Figure 50). t_{R1} was then recorded when the rear end of the construction vehicle finished crossing the invasion line (see Figure 51). Next, the video was played until the front bumper of the next vehicle touched the invasion line, and that time was recorded as t_{F2} (see Figure 52). Finally, the video was rewound until the rear end of the leading vehicle crossed the invasion line, and that time was recorded as t_{R2} (see Figure 53). With all the times recorded, the research team subtracted t_{R1} from t_{F2} to calculate $IPET_{Exit,Following}$ and took the absolute value of the difference between t_0 and

t_{R2} to calculate $IPET_{Exit,Leading}$. If the construction vehicles exited the workspace access point and immediately crossed over into the outside lane (Types 6, 7, and 9), then the research team computed a second set of PETs for the leading and following vehicles relative to the construction vehicle exiting the inside lane (i.e., $OPET_{Exit,Following}$ and $OPET_{Exit,Leading}$).

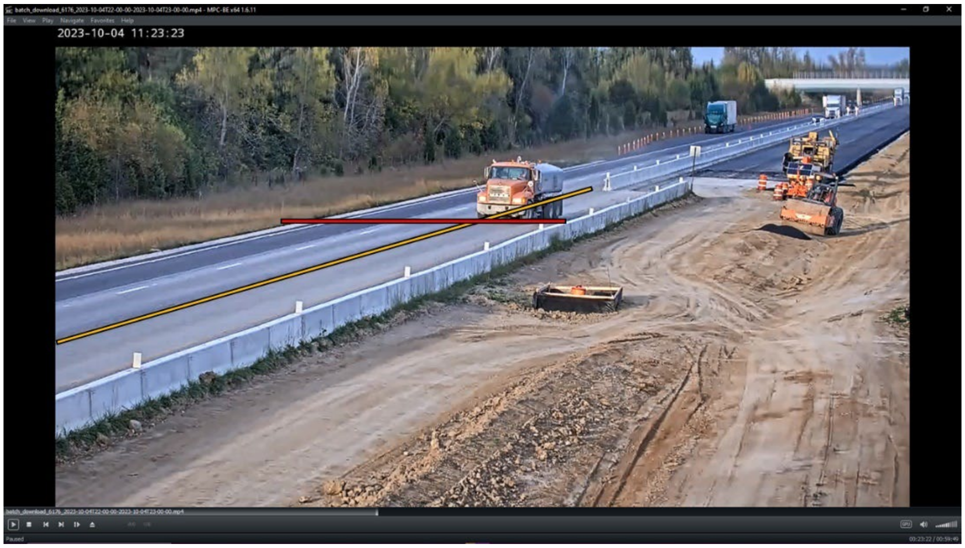


Figure 50. Video Frame Showing the Invasion Line and t_0 for a Construction Vehicle Exiting the Workspace Access Point.

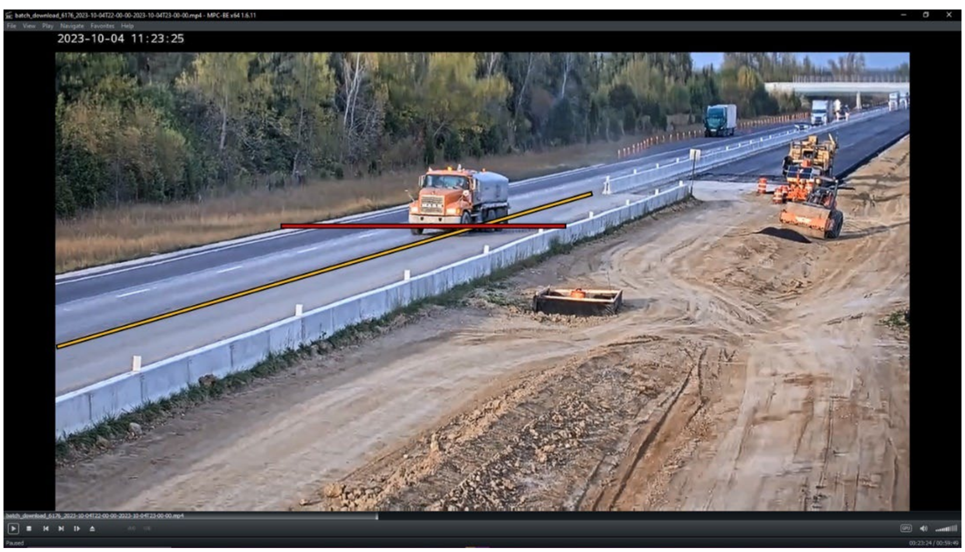


Figure 51. Video Frame Showing the Invasion Line and t_{R1} for a Construction Vehicle Exiting the Workspace Access Point.

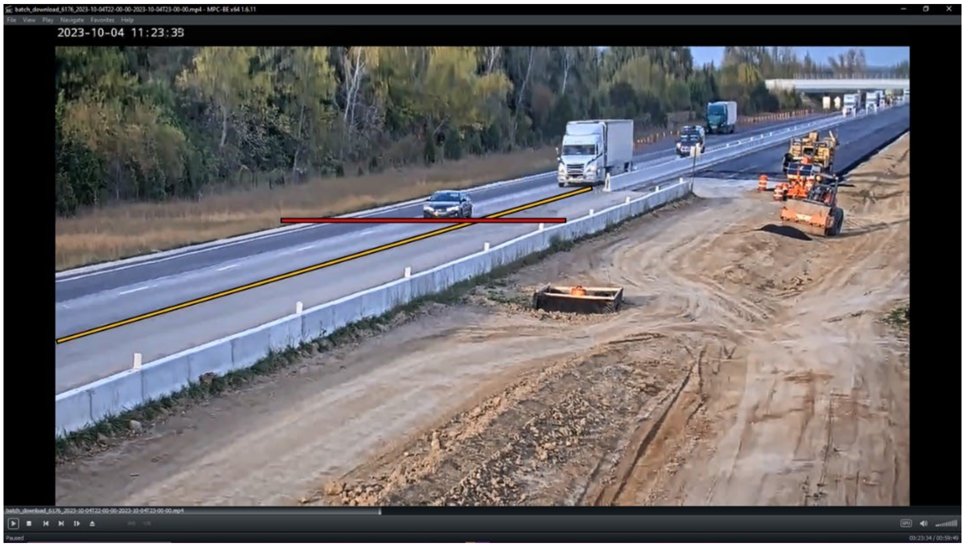


Figure 52. Video Frame Showing the Invasion Line and t_{F2} for a Construction Vehicle Exiting the Workspace Access Point.

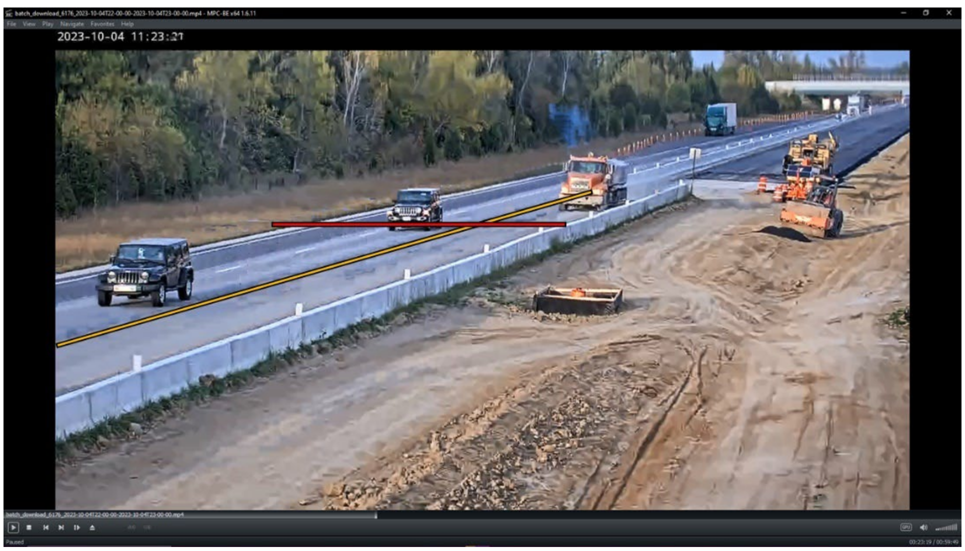


Figure 53. Video Frame Showing the Invasion Line and t_{R2} for a Construction Vehicle Exiting the Workspace Access Point.

In total, the research team attempted to compute PETs for 549 construction vehicles but could only accurately do so for 357 construction vehicles (resulting in 535 PETs). Issues impacting accuracy included camera angle, camera focus, and camera frame rate (10 fps). In some cases, the camera angle provided a sufficient view to obtain measurements for construction vehicles entering the workspace but not exiting the workspace or vice versa. On occasion the video would go in and out of focus, making it difficult to obtain accurate measurements. Also, in some cases the following vehicle was another construction vehicle.

Figure 54 shows the 535 PET values. The PET values are not plotted against anything specific on the X axis. Instead, they are simply plotted in the order that they were calculated and shown to give an idea as to the range of PET values that existed after the initial data reduction. While reviewing these data, the research team noticed the large range of PET values (i.e., from less than 1 second to just over 50 seconds). A review of the longer PETs revealed that most were due to the next following vehicle changing lanes prior to the invasion line. In those cases, that vehicle was not used in the computation. Instead, the subsequent following vehicle in the same lane as the construction vehicle was used to compute the PET value. The research team computed descriptive statics for each PET group and determined that the highest average plus one standard deviation yielded a threshold of 22 seconds. The final PET dataset used for analysis contained 352 construction vehicles and 507 PETs (see Table 63).

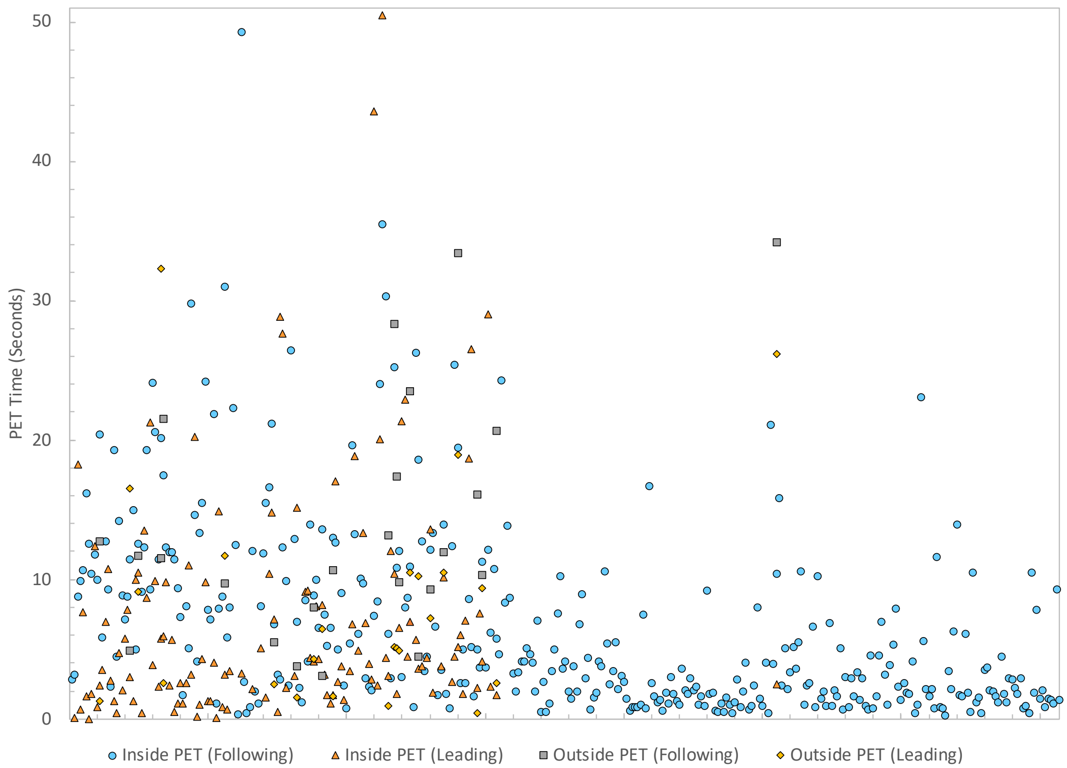


Figure 54. PET Values after Initial Data Reduction.

Table 63. Final PET Dataset.

PET Group	Sample Size
$PET_{Enter,Following}$	223
$IPET_{Exit,Following}$	119
$IPET_{Exit,Leading}$	123
$OPET_{Exit,Following}$	20
$OPET_{Exit,Leading}$	22
Total	507

Speed Data

At PID 107630, the research team used light detection and ranging (LIDAR) equipment to collect spot speed data at access points 2, 4, 5, and 6 to assess the operating characteristics of the travel lanes. The research team separated the data into passenger vehicles and CMVs and calculated the average speed for each group of vehicles and overall.

The research team also used the LIDAR equipment to capture continuous speeds and corresponding distances of construction vehicles entering and exiting the workspace at access points 2, 3, and 5. Using these data, the research team created speed deceleration profiles for loaded dump trucks and speed acceleration profiles for loaded and unloaded dump trucks and lowboy trailers. The LIDAR equipment did not register speeds below 10 mph.

Lane Change Counts

The research team reviewed approximately 72 hours of video collected at PID 107630 to count lane changes occurring in the immediate vicinity of a construction vehicle entering or exiting the workspace (i.e., behind or adjacent to the construction vehicle). The research team used the FHWA vehicle classification scheme F report (*62*), which includes 13 different vehicle types, but grouped them into four categories, as shown in Table 64. Lane change movement was simply determined by whether a lane change was made from the outside (right) lane to the inside (left) lane or the inside (left) lane to the outside (right) lane.

Table 64. Vehicle Type Classification for Lane Change Counts.

Description	Code	FHWA Class
Passenger cars and pickups (may have trailers)	PC	1, 2, 3
Buses (any size)	BU	4
Singley unit trucks (straight chassis)	SU	5, 6, 7
Heavy trucks (articulated/swivel point)	HT	8, 9, 10, 11, 12, 13

As mentioned previously, the research team measured the lane change counts only when a construction vehicle was entering or exiting the workspace. The construction vehicles themselves were not included in the lane change counts. Depending on the camera angle, the video may have been suitable to count lane changes only for construction vehicles exiting the workspace, only for construction vehicles entering the workspace, or both.

To make lane change counts easier and more consistent across team members, each camera angle had a set perimeter defined within the frame of the video in which lane changes were counted. This perimeter took the form of a green transparent box that was determined based on the area of influence of the construction vehicles entering or exiting the workspace (see Figure 55). Once a construction vehicle entered the dedicated lane completely (shown as a red line in Figure 55) or exited the green box, then lane change counts were concluded for that construction vehicle. For CMVs exiting the work zone, the lane change counts began once a construction vehicle hit an orange line that was overlaid on the frame of the video (see Figure 55). The research team initially conducted lane change counts for 778 construction vehicles but limited the analysis to the 352 construction vehicles with PETs.

Figure 55. Example of Video Overlays Used for Lane Change Counts.

While normal lane changes were counted for each construction vehicle, last-minute lane changes were also counted separately using a similar methodology. Last-minute lane changes were defined as lane changes that occurred directly behind a construction vehicle and influenced the calculation of PET in a negative way. Last-minute lane changes were included in the normal lane change counts, but also separated out to assess whether any specific construction vehicle maneuver led to more or less last-minute lane changes.

Volume Counts

The research team collected lane level volume counts for the first 15 minutes of each hour of video that was used to measure PET and/or observe lane changes and then multiplied the 15-minute counts by four to get an approximate hourly volume. The research team counted and classified each vehicle according to Table 64. A simple red line overlay was used to identify the location of the volume counts (see Figure 56). The location of the volume counts (i.e., red line) was determined separately for each video prior to data reduction since the camera angle changed throughout the data collection period.

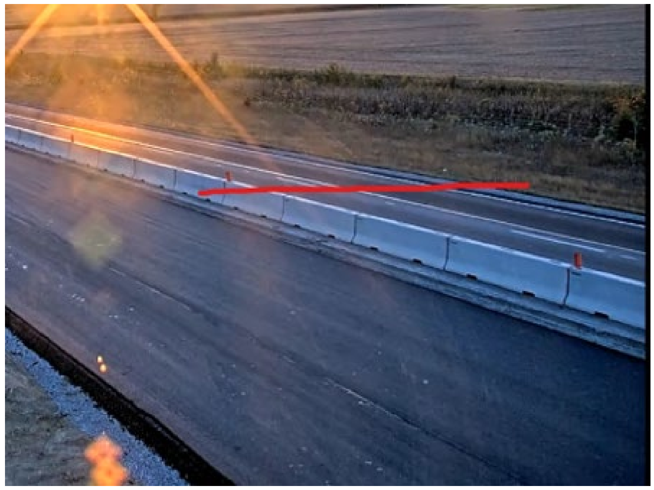


Figure 56. Example of a Red Volume Count Line.

RESULTS

The results section is divided into two sections. The findings from construction vehicles entering the workspace are discussed first, followed by the findings from construction vehicles exiting the workspace.

Construction Vehicles Entering the Workspace

Table 65 contains a summary of the $PET_{Enter,Following}$ findings for the 223 construction vehicles entering the workspace (Types 1—3, see Figure 35). The average $PET_{Enter,Following}$ was 3.31 seconds, with a standard deviation of 3.33 seconds, and ranged from 0.26 second to 21.11 seconds. For all the entry path types combined, the research team computed the 15th percentile, 50th percentile, and 85th percentile values and used them to define threshold values for the level of traffic conflict (0.86, 2.04, and 5.97 seconds, respectively) (*61*). The research team used these thresholds to divide the PET values into four conflict levels: serious conflict, general conflict, slight conflict, and potential conflict. Table 66 shows the percent of the $PET_{Enter,Following}$ values in each conflict level. Table 67 contains the lane change findings for construction vehicles entering the workspace.

The intended construction vehicle path (i.e., Type 1) resulted in the smallest average $PET_{Enter,Following}$ value (2.92 seconds) and the highest percentage of serious conflicts (14 percent). For this entry type, the research team observed that most construction vehicle drivers would begin slowing down in the travel lanes before entering the dedicated lane. These unexpected slowdowns in the inside lane resulted in 140 vehicles moving from the inside lane to outside lane (76 percent), with 41 percent of those being last-minute lane changes (see Table 67).

Figure 57 shows the deceleration profiles of 30 fully loaded dump trucks slowing down in the inside travel lane upstream of the workspace access point. The deceleration profile of each truck ended when the dump truck's right rear tire crossed the inside edge line (i.e., the truck was fully in the dedicated lane), even though the trucks continued to decelerate in the dedicated lane. This figure shows that most of the dump trucks began decelerating in the inside travel lane between 800 and 1200 ft upstream of Opening A (i.e., 400 to 800 ft before entering the dedicated lane). The average beginning truck speed was 55 mph, with a range from 41 to 62 mph, and the average ending truck speed was 43 mph, with a range of 29 to 59 mph. In comparison, the average speed of the vehicles in the travel lanes was 66 mph even though the posted speed limit was 60 mph. The average truck reduced its speed by 13 mph in the inside lane before entering the dedicated lane. These findings illustrate the speed differential between construction vehicles and other traffic in the inside lane as the construction vehicles were slowing down to enter the workspace. For reference, the Type 1 maneuvers were observed when traffic volumes ranged from 1000 to 1700 vph.

Table 65. $PET_{Enter,Following}$ Findings for Construction Vehicles Entering the Workspace.

Entry Path Type	Sample Size	Percent of Sample	Average $PET_{Enter,Following}$ (seconds)	Standard Deviation (seconds)	Minimum Value (seconds)	Maximum Value (seconds)
1	180	81%	2.92	2.87	0.41	16.70
2	25	11%	4.55	5.03	0.26	21.11
3	18	8%	5.51	3.64	1.72	13.88
Total	223	100%	3.31	3.33	0.26	21.11

Table 66. Percent of $PET_{Enter,Following}$ Values by Safety Level for Construction Vehicles Entering the Workspace.

Entry Path Type	Serious Conflict 0-0.86 (seconds)	General Conflict 0.86-2.04 (seconds)	Slight Conflict 2.04-5.97 (seconds)	Potential Conflict 5.97-∞ (seconds)
1	14%	30%	28%	9%
2	1%	4%	3%	3%
3	0%	1%	4%	3%
Total	15%	35%	35%	15%

Table 67. Lane Change Findings for Construction Vehicles Entering the Workspace.

Entry Path Type	Number of CMVs	Number of Lane Changes	Percent Changed from Inside to Outside	Percent Changed from Outside to Inside	Percent Last-Minute Lane Changes	Average Number of Lane Changes Per CMV
1	167	185	76%	24%	41%	1.1
2	20	28	79%	21%	46%	1.4
3	12	6	100%	0%	100%	0.5
Total	199	219	77%	23%	43%	1.1

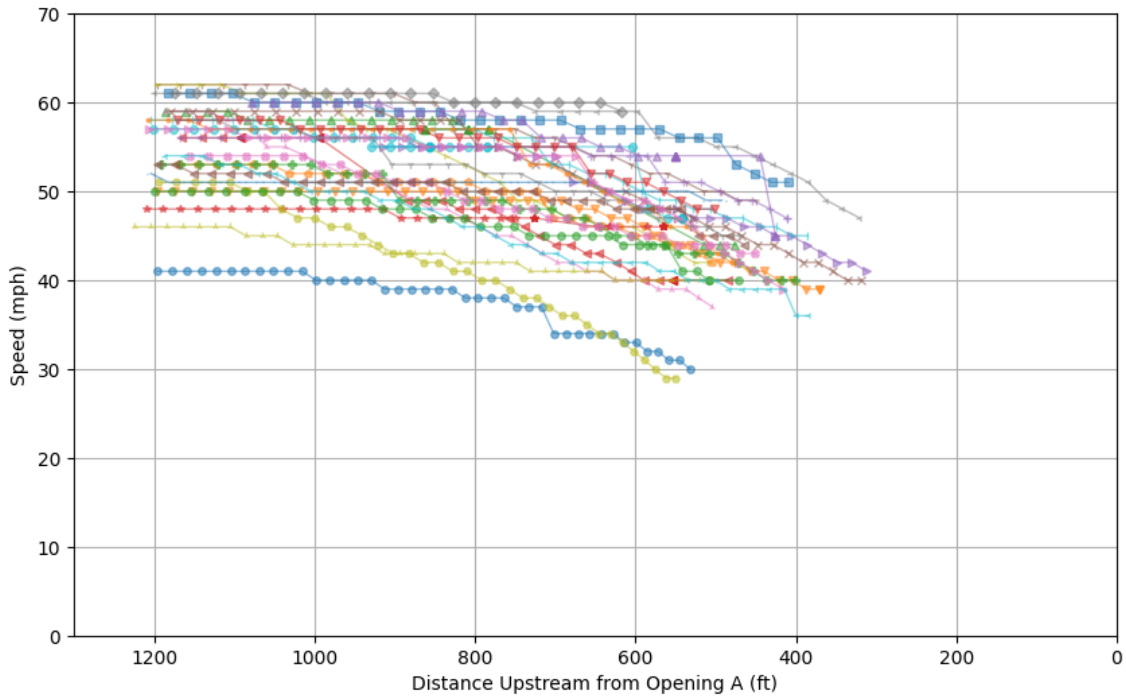


Figure 57. Deceleration Profiles of Loaded Dump Trucks.

When construction vehicles remained in the travel lane and entered the dedicated lane further downstream (Type 2), the average $PET_{Enter,Following}$ was longer and resulted in less serious conflicts. However, the average number of lane changes per construction vehicle, the percent of lane changes from the inside to the outside lane, and the percent of last-minute lane changes were like Type 1. These findings imply that the construction vehicle drivers may have chosen this path when there was not a vehicle immediately behind them. This could also be attributed to the smaller sample size and slightly lower traffic volumes (i.e., approximately 1000 to 1600 vph).

For the Type 3 entrances, the $PET_{Enter,Following}$ was the longest (5.51 seconds on average). However, this maneuver was only observed when the traffic on the main lanes was much lower (i.e., approximately 250 to 1000 vph).

Construction Vehicles Exiting the Workspace

Table 68 contains a summary of the $IPET_{Exit,Leading}$ findings for 122 of the 128 construction vehicles exiting the workspace (Types 4—7, see Figure 35), and Table 69 contains a summary of the $IPET_{Exit,Following}$ findings for 118 of the 128 construction vehicles exiting the workspace (Types 4—7). The research team did not include Types 8—9 because of their small sample size. The $IPET_{Exit,Leading}$ average was 5.57 seconds, with a standard deviation of 5.12 seconds, and ranged from 0.01 second to 21.35 seconds. The $IPET_{Exit,Following}$ average was 9.64 seconds, with a standard deviation of 4.95 seconds, and ranged from 1.07 seconds to 21.88 seconds.

The research team also calculated descriptive statistics for the gap each construction vehicle took in the inside lane (i.e., time between the leading and following vehicles) (see Table 70). The average gap was 15.20 seconds, with a standard deviation of 5.23 seconds, and ranged from 1.15 seconds to 36.02 seconds.

Table 68. $IPET_{Exit,Leading}$ Findings for Construction Vehicles Exiting the Workspace.

Exit Path Type	Sample Size	Percent of Sample	Average $IPET_{Exit,Leading}$ (seconds)	Standard Deviation (seconds)	Minimum Value (seconds)	Maximum Value (seconds)
4	26	21%	8.07	5.77	1.28	21.35
5	72	59%	4.93	5.17	0.01	21.26
6	19	16%	5.66	3.49	1.68	15.12
7	5	4%	6.24	5.43	1.66	13.60
Total	122	100%	5.77	5.12	0.01	21.35

Table 69. $IPET_{Exit,Following}$ Findings for Construction Vehicles Exiting the Workspace.

Exit Path Type	Sample Size	Percent of Sample	Average $IPET_{Exit,Following}$ (seconds)	Standard Deviation (seconds)	Minimum Value (seconds)	Maximum Value (seconds)
4	25	21%	8.86	4.35	2.88	19.32
5	71	60%	9.13	5.04	1.07	21.88
6	17	14%	11.97	4.72	5.00	20.12
7	5	4%	12.85	5.07	6.13	20.41
Total	118	100%	9.64	4.95	1.07	21.88

Table 70. Inside Lane Gap Findings for Construction Vehicles Exiting the Workspace.

Exit Path Type	Sample Size	Percent of Sample	Average Gap (seconds)	Standard Deviation (seconds)	Minimum Value (seconds)	Maximum Value (seconds)
4	25	22%	16.54	8.57	3.28	34.81
5	67	59%	13.84	8.37	1.15	36.02
6	17	15%	17.50	5.92	7.20	25.89
7	5	4%	19.09	6.93	9.17	25.73
Total	114	100%	15.20	5.23	1.15	36.02

The research team computed the 15^{th} percentile, 50^{th} percentile and 85^{th} percentile values for the $IPET_{Exit,Leading}$, $IPET_{Exit,Following}$, and inside lane gap separately and used them to define threshold values for the level of traffic conflict for each metric. Table 71, Table 72, and Table 73 show the percent of the $IPET_{Exit,Leading}$, $IPET_{Exit,Following}$, and inside lane gap values in each conflict level, respectively. Table 74 contains the lane change findings for construction vehicles exiting the workspace.

Table 71. Percent of $IPET_{Exit,Leading}$ Values by Safety Level for Construction Vehicles Exiting the Workspace.

Exit Path Type	Serious Conflict 0-1.29 (seconds)	General Conflict 1.29-3.95 (seconds)	Slight Conflict 3.95-10.47 (seconds)	Potential Conflict 10.47-∞ (seconds)
4	< 1%	6%	10%	4%
5	15%	20%	15%	9%
6	0%	6%	9%	< 1%
7	0%	2%	0%	2%
Total	16%	34%	34%	16%

Table 72. Percent of $IPET_{Exit,Following}$ Values by Safety Level for Construction Vehicles Exiting the Workspace.

Exit Path Type	Serious Conflict 0-4.30 (seconds)	General Conflict 4.30-9.06 (seconds)	Slight Conflict 9.06-14.04 (seconds)	Potential Conflict 14.04-∞ (seconds)
4	3%	10%	5%	3%
5	12%	20%	20%	8%
6	0%	4%	7%	3%
7	0%	< 1%	3%	< 1%
Total	15%	35%	35%	15%

Table 73. Percent of Inside Lane Gap Values by Safety Level for Construction Vehicles Exiting the Workspace.

Exit Path Type	Serious Conflict 0-7.41 (seconds)	General Conflict 7.41-13.84 (seconds)	Slight Conflict 13.84-24.20 (seconds)	Potential Conflict 24.20-∞ (seconds)
4	2%	9%	6%	5%
5	12%	22%	18%	7%
6	< 1%	4%	8%	2%
7	0%	< 1%	3%	< 1%
Total	15%	35%	35%	15%

Table 74. Lane Change Findings for Construction Vehicles Exiting the Workspace.

Exit Path Type	Number of CMVs	Number of Lane Changes	Percent Changed from Inside to Outside	Percent Changed from Outside to Inside	Percent Last-Minute Lane Changes	Average Number of Lane Changes Per CMV
4	27	30	93%	7%	23%	1.11
5	77	77	83%	17%	22%	1
6	18	8	13%	87%	100%	0.44
7	5	0	N/A	N/A	N/A	N/A
Total	127	115	81%	19%	28%	0.91

N/A—not applicable.

The intended construction vehicle path (i.e., Type 5) resulted in the smallest average $IPET_{Exit,Leading}$ value (4.93 seconds), the second smallest $IPET_{Exit,Following}$ value (9.13 seconds), and smallest inside lane gap average value (13.84 seconds). The Type 5 maneuvers also resulted in the highest percentage of serious conflicts for all three metrics (15 percent, 12 percent, and 12 percent, respectively). As mentioned previously, construction vehicle drivers typically stop at the workspace exit point (i.e., Opening B) and wait for a gap in the main lane traffic before accelerating and merging. Even though the construction vehicle drivers used most of the dedicated lane to accelerate and waited for gaps in the traffic, the potential for serious conflicts was still found.

Figure 58 and Figure 59 contain the acceleration profiles of 19 empty and 32 fully loaded dump trucks accelerating in the dedicated lane and then entering the inside travel lane, respectively. The acceleration profile of each truck ended when the dump truck's left rear tire crossed the inside edge line (i.e., the truck was fully out of the dedicated lane). Most of the profiles begin at 10 mph because the LIDAR equipment did not register speeds below 10 mph. These figures show that most of the empty dump trucks entered the inside lane more than 600 ft from Opening B, showing that they used most of the dedicated lane to accelerate. The average speed of the empty trucks when entering the inside travel lane was 42 mph, with a range of 33 to 48 mph. On average, the empty dump trucks increased their speed by 30 mph in the dedicated lane before entering the inside lane. In contrast, the fully loaded dump trucks tended to enter the inside lane more quickly (average distance was approximately 470 ft from Opening B) and at a lower speed (average speed when entering the inside travel lane was 27 mph, with a range of 17 to 34 mph). On average, the fully loaded dump trucks increased their speed by 16 mph in the dedicated lane before entering the inside lane. In comparison, the average speed of the vehicles in the travel lanes was 69 mph even though the posted speed limit was 60 mph.

Such slow-moving construction vehicles in the inside lane led to 64 vehicles moving from the inside lane to outside lane (83 percent), with 22 percent of those being last-minute lane changes (see Table 74). These findings illustrate the impact of the speed differential between construction vehicles and other traffic as the construction vehicles are exiting the workspace and entering the inside travel lane. For reference, the Type 5 maneuvers were observed when traffic volumes ranged from 900 to 1800 vph.

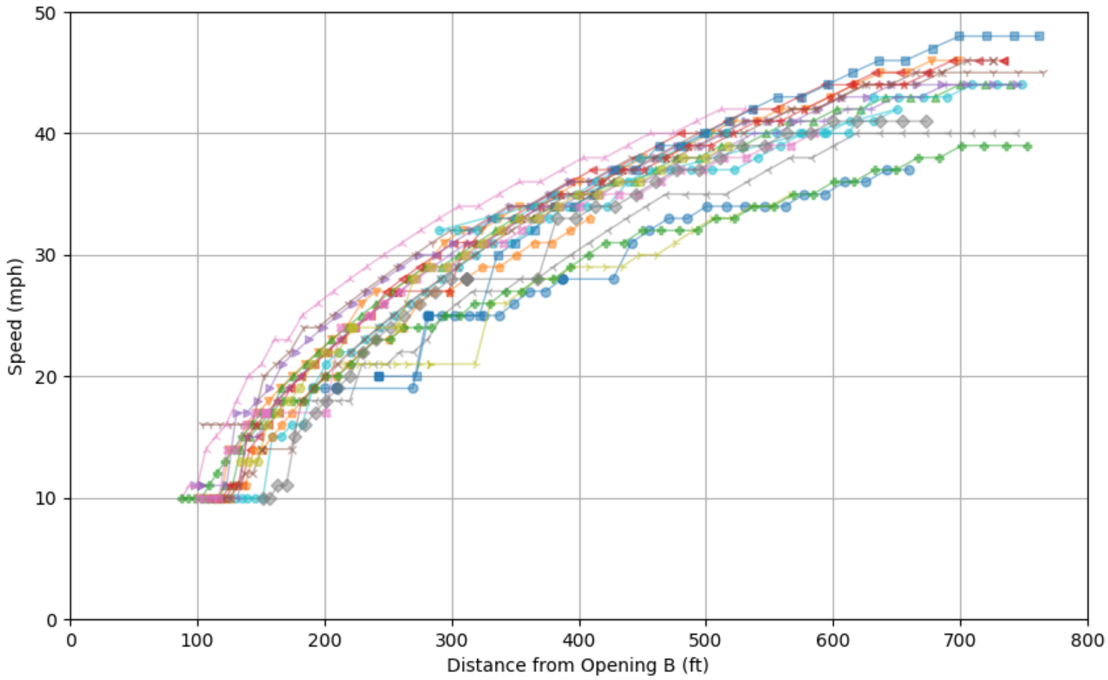


Figure 58. Acceleration Profiles of Empty Dump Trucks.

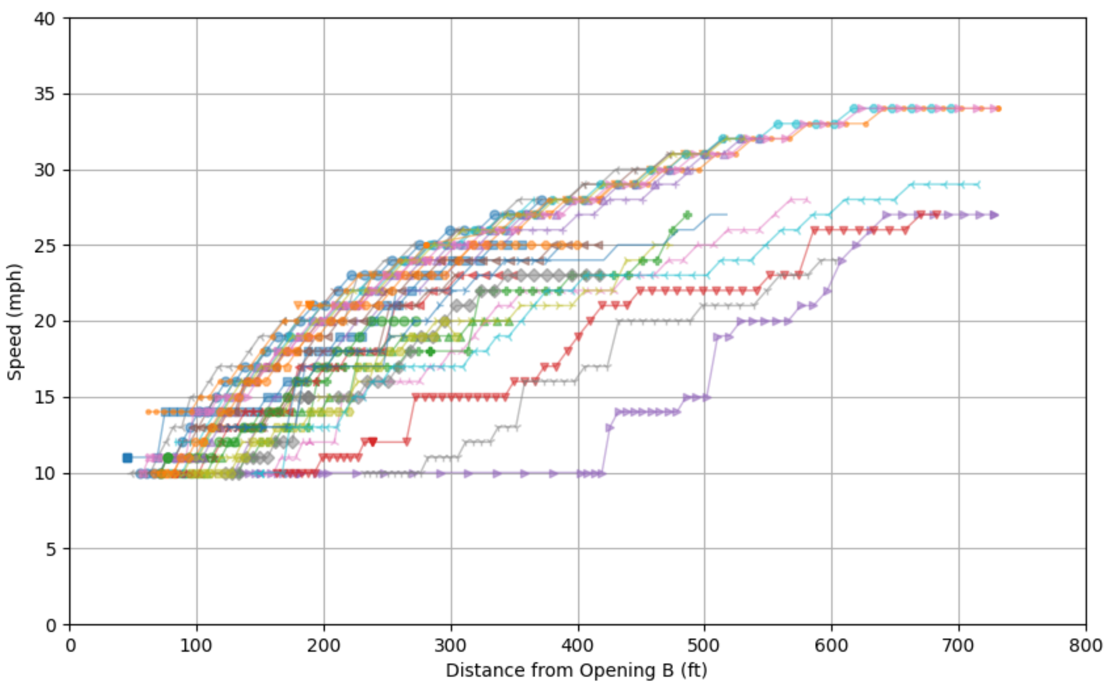


Figure 59. Acceleration Profiles of Loaded Dump Trucks.

When construction vehicles almost immediately entered the inside lane after stopping at Opening B (Type 4), the average $IPET_{Exit,Leading}$ value (8.07 seconds) was the largest, the average $IPET_{Exit,Following}$ value was the smallest (8.86 seconds), and the inside lane gap average value (13.84 seconds) was the second smallest. Even though the Type 4 path resulted in less serious conflicts across all metrics (less than 1-3 percent), the percent of lane changes from the inside to the outside lane (93 percent) and the percent of last-minute lane changes (23 percent) was higher than for Type 5 maneuvers. While construction vehicle drivers completing this maneuver left a larger gap between them and the leading vehicle, the gap between them and the following vehicle was shorter, resulting in more lane changes. For reference, the Type 4 maneuvers were observed when traffic volumes ranged from approximately 900 to 1500 vph.

For the Type 6—7 entrances, the average $IPET_{Exit,Leading}$ values were between 5.5 and 6.5 seconds and the average $IPET_{Exit,Following}$ values were the longest (around 12 seconds), leading to larger average gaps (17.50 and 19.09 seconds, respectively). For these two maneuvers, the research team also examined PETs and their corresponding gaps for the lane change from the inside lane to the outside lane (see Table 75, Table 76, Table 77, Table 78, Table 79, and Table 80). Interestingly, for the Type 7 paths, the average $OPET_{Exit,Leading}$ value (4.02 seconds) was less than the corresponding inside lane value (6.24 seconds), indicating the construction vehicle was closer to the leading vehicle in the outside lane. The opposite was found for the Type 6 paths. For both path types, the average $OPET_{Exit,Following}$ values were less than the corresponding inside lane values. For Type 6 maneuvers, this resulted in vehicles moving from the outside lane to the inside lane (87 percent) and all of those being last-minute lane changes. Overall, the average gap in the outside lane (16.84 and 15.52 seconds, respectively) was slightly smaller than the average gap in the inside lane (17.50 and 19.09, respectively). Interestingly, these maneuvers were observed when the traffic on the main lanes was higher (i.e., approximately 1100 to 1700 vph).

Table 75. $OPET_{Exit,Leading}$ Findings for Construction Vehicles Exiting the Workspace.

Exit Path Type	Sample Size	Percent of Sample	Average $OPET_{Exit,Leading}$ (seconds)	Standard Deviation (seconds)	Minimum Value (seconds)	Maximum Value (seconds)
6	17	77%	7.25	5.29	0.40	18.95
7	5	23%	4.02	3.84	0.92	9.10
Total	22	100%	6.51	5.10	0.40	18.95

Table 76. $OPET_{Exit,Following}$ Findings for Construction Vehicles Exiting the Workspace.

Exit Path Type	Sample Size	Percent of Sample	Average $OPET_{Exit,Following}$ (seconds)	Standard Deviation (seconds)	Minimum Value (seconds)	Maximum Value (seconds)
6	15	75%	10.58	6.02	3.08	21.52
7	5	25%	11.50	1.56	9.27	13.12
Total	20	100%	10.81	5.23	3.08	21.52

Table 77. Outside Lane Gap Findings for Construction Vehicles Exiting the Workspace.

Entry Path Type	Sample Size	Percent of Sample	Average Gap (seconds)	Standard Deviation (seconds)	Minimum Value (seconds)	Maximum Value (seconds)
6	14	74%	16.84	9.02	5.29	24.12
7	5	26%	15.52	3.30	12.29	20.78
Total	19	100%	16.49	7.74	5.29	24.12

Table 78. Percent of $OPET_{Exit,Leading}$ Values by Safety Level for Construction Vehicles Exiting the Workspace.

Exit Path Type	Serious Conflict 0-1.50 (seconds)	General Conflict 1.50-5.13 (seconds)	Slight Conflict 5.13-10.52 (seconds)	Potential Conflict 10.52-∞ (seconds)
6	9%	27%	23%	18%
7	9%	5%	9%	0%
Total	18%	32%	32%	18%

Table 79. Percent of $OPET_{Exit,Following}$ Values by Safety Level for Construction Vehicles Exiting the Workspace.

Exit Path Type	Serious Conflict 0-4.82 (seconds)	General Conflict 4.82-10.52 (seconds)	Slight Conflict 10.52-16.26 (seconds)	Potential Conflict 16.26-∞ (seconds)
6	15%	30%	15%	15%
7	0%	5%	20%	0%
Total	15%	35%	35%	15%

Table 80. Percent of Outside Lane Gap Values by Safety Level for Construction Vehicles Exiting the Workspace.

Exit Path Type	Serious Conflict 0-11.45 (seconds)	General Conflict 11.45-16.46 (seconds)	Slight Conflict 16.46-22.47 (seconds)	Potential Conflict 22.47-∞ (seconds)
6	16%	21%	21%	16%
7	0%	16%	11%	0%
Total	16%	37%	32%	16%

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