Dynamic Zipper Merge for Work Zones: Safety and Operational Effects

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Dynamic Zipper Merge for Work Zones: Safety and Operational Effects

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16. Abstract: Traffic crashes and associated delays are a major concern in rural freeway work zones, particularly when lane closures result in queueing that can surprise motorists. The present study explored the safety and operational benefits of using dynamic zipper merge (DZM) systems to encourage orderly merging at 2:1 lane closures when traffic is heavy (the systems were configured to revert to conventional merging when traffic was light). Safety data for ten DZM sites comprising nearly 3600 days of construction were compared with six conventional merge (CM) sites comprising 210 days of construction. A two-step process was used to derive a crash modification factor (CMF) for the DZM treatment. First, the work zone crash rates (measured in crashes per million vehicle-miles traveled) were compared to baseline crash rates for each project site, resulting in significantly different rate ratios (RRs) of 2.58 [95% C.I. 2.02, 3.13] for conventional merge (CM) sites and 1.43 [0.93, 1.94] for DZM sites. Crashes involving deer and other animals were excluded from these rate ratios. Second, the two rate ratios were compared to compute the CMF for the DZM treatment (compared to CM). The resulting CMF was 0.56 [0.43, 0.71], corresponding to a crash reduction factor (CRF) of 44% [29%, 57%]. DZM systems appeared to be effective at reducing crashes during congested hours and—based on limited evidence—to decrease the proportion of rear-end crashes. Likewise, the findings indicate that the strongest operational benefit of the DZM lies in improved travel-time index (TTI), not in increasing or preserving average speeds. Across all sites and time periods, DZM consistently limited the growth of TTI relative to CM, suggesting better preservation of predictable and stable traffic conditions during construction.			
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EXECUTIVE SUMMARY

Traffic crashes and associated delays are a major concern in rural freeway work zones, particularly when lane closures result in queueing that can surprise motorists. The present study explored the safety and operational benefits of using dynamic zipper merge (DZM) systems to encourage orderly merging at 2:1 lane closures when traffic is heavy (the systems were configured to revert to conventional merging when traffic was light). DZM systems include sensors that detect congestion based on real time changes in speed or traffic density. When congestion (or impending congestion) is detected, changeable message signs are activated to encourage drivers to use both lanes up to the merge point and then merge cooperatively, with vehicles from the left and right lanes alternating as they enter the single-lane section. The system turns off this signage when the congestion clears, allowing vehicles to merge as they ordinarily would.

Originally, DZM systems were used mainly in urban areas with closely spaced interchanges, with the goal of shortening work zone queues to prevent slow traffic from blocking upstream exits. Previous research on these systems identified other benefits such as increased throughput, improved safety, and reduced gasoline/diesel consumption. This led to their application to rural freeway work zones, but no prior study has quantified DZM safety benefits in the rural context.

For this study of rural freeway work zones in North Carolina, safety data for ten DZM sites comprising nearly 3600 days of construction were compared with six conventional merge (CM) sites comprising 210 days of construction. Five of the CM sites were used in subsequent analysis. The sixth site (a project on northbound I-95 near Selma) was removed from the analysis because it was found to be an extreme outlier, with a during-construction crash rate more than 11 times the pre-construction rate (compared to about 2.6 times for other CM sites).

Two types of statistical outputs were produced by the study, one comparing crash rates during construction with the pre-construction (baseline) condition, and another comparing the DZM safety performance to the performance when CM arrangements were in use. For clarity, in the remainder of this document these are referred to as Rate Ratios (RRs) and Crash *Modification* Factors (CMF), respectively. In both cases, a smaller number is more desirable, with a value of 0 indicating complete elimination of all crashes. Some practitioners prefer to think in terms of a Crash *Reduction* Factor (CRF), which is usually expressed as a percentage. Since the CMF and CRF are mathematically related as shown below, a high CRF is desirable, with a value of 100% (or 1.00) indicating complete elimination of all crashes:

$$CRF = 1 - CMF$$

A two-step process was used to derive a CMF for the DZM treatment. First, the work zone crash rates (crashes per million vehicle-miles traveled) were compared to baseline crash rates for each project site. Baseline crash rates were computed using data from year(s) preceding the construction project, further limited to the project area and (to minimize seasonal effects) the months of the year when construction occurred. Since DZM systems are not expected to have any effect on animal crashes, crashes involving deer or other animals were excluded from the analysis and crash rate computations.

The RRs indicate that during construction, the crash rate for DZM sites was **1.43** times the baseline rate [95% confidence interval 0.93 to 1.94]. The RR for CM sites was notably higher at **2.58** [2.02, 3.13], indicating less desirable safety performance. The non-overlapping confidence intervals indicate the results were statistically significant.

In the next step of the analytical process, the two rate ratios were divided to compute the CMF for the DZM treatment (compared to CM). The resulting CMF was **0.56** [0.43, 0.71], corresponding to a crash reduction factor (CRF) of **44%** [29%, 57%]. Thus, the project team concludes with high confidence that DZM systems were effective at reducing crashes in North Carolina rural freeway work zones.

The project team also attempted to explore the effects of DZM on crash severity and crash type. Due to small sample sizes, only limited information could be gleaned from this analysis. The data were insufficient to draw conclusions about the effect of DZM on crash severity. With moderate confidence, the team concludes that DZM was effective in reducing rear-end crashes in the work zones. Analysis of temporal crash patterns indicates with moderate confidence that DZM systems appeared to be effective at reducing crashes during congested hours.

The study findings can be applied to predict the number of crashes in future North Carolina rural freeway work zones based on prior (non-construction) crash history. The process is as follows:

1. Extract the site's crash history data from the state crash database (e.g., TEAAS) for the month(s) of interest. Crash data from multiple years should be used to avoid sample size issues.
2. Separate the result into animal crashes (e.g., crashes involving deer) and non-animal crashes.
3. If CM will be used during construction, multiply the number of non-animal crashes by 2.58. If DZM will be used, multiply by 1.43.
4. Add the number of animal crashes from Step 2 to the estimated number of non-animal crashes from Step 3.
5. Adjust the sum in proportion to the expected construction duration. For example, if the initial crash count covered 90 days and the expected duration is 75 days, multiply by 75/90 = 0.83.

Speed and travel time data were collected from the same study sites utilizing ClearGuide, which provides various historical operational data over several years in as low as five-minute bins for detailed analysis of average travel patterns. Note that in order to obtain an accurate comparison of lane closure treatments, along with obvious variables needing to match (e.g., 2:1 lane closures only on freeways, seasons, etc.), traffic volumes needed to be similar between the two treatment types. As such, all sites with fewer than 15,000 ADT and those with higher than 20,000 AADT were excluded from comparison. DZM sites averaged a lower ADT in comparison to CM sites, with some CM sites significantly higher than any of the DZM sites, which could skew the results disproportionally in favor of the DZM treatment.

While the findings of the operational analysis are more modest than the safety analysis, they indicate that the strongest operational benefit of the DZM lies in improved travel-time index, not in increasing or preserving average speeds. This study found that when comparing speeds prior to a 2:1 lane closure to after the lane closure is in place, speed reductions were larger for CM sites than for DZM sites. Comparison of travel time index (TTI) between CM and DZM sites was more pronounced, as TTI was reduced more at CM sites versus DZM across nearly all analysis periods, including overall, for weekdays and weekends, and during the PM peak period, which is where DZM performed the best. Across all sites and time periods, DZM consistently limited the growth of travel time index (TTI) relative to CM, suggesting better preservation of predictable and stable traffic conditions during construction.

Finally, a Work Zone Evaluation Tool was developed to assist NCDOT staff in efficiently and accurately predicting how and where to implement the DZM system. This tool is user-friendly and based on North Carolina data. Standard traffic inputs like K- and D-factors (peaking and directionality), along with seasonality and day-of-week adjustments, are incorporated to provide results that closely reflect expected traffic conditions across a wide array of NC sites. This tool can help NCDOT staff predict expected queue length based on merge type, month, day-of-week, or even time-of-day. This can help NCDOT staff determine whether to implement a continuous closure, a weekend or weekday closure, or a nighttime closure. It can even assist users in determining if a 3-month closure should happen in a specific season.

As a result of these findings, the research team recommends continued use of the DZM system and even expansion across more work zones, particularly in eastern North Carolina, as western and central NC have seen a disproportionate number of DZM lane closures in comparison to eastern NC. The safety benefits of the DZM in comparison to the CM are substantial, and with the operational improvements of traffic flow at DZM sites, cost is the primary prohibiting factor. As such, the research team also recommends a cost-benefit analysis be conducted between CM and DZM implementations, as DZM systems are generally much more expensive than CM systems, but the potential cost savings due to fewer crashes and shorter travel times could outweigh the implementation costs in many cases.

Likewise, the research team recommends further research into expansion of DZM implementation, including in broader lane configurations (for instance, a 3:2 or 3:1 lane closure). This would likely require an initial microsimulation study, noting appropriate measures of effectiveness (MOEs) like expected queue length and travel time, as well as throughput and downstream headways, which appear to differ between CM and DZM sites. Real-world implementation would follow, and close attention would need to be paid to surrogate safety measures like rapid deceleration rates and conflicts or near-misses, as several years of crash data will need to accumulate to provide statistically meaningful results following implementation of broader DZM lane closures. A safety analysis of available crash data would follow once an adequate sample size is achieved.

Any expansion of the DZM system to more than 2:1 lane closures, as well as cost-benefit analysis, could then be added to the Work Zone Evaluation Tool to assist NCDOT employees and contracted service providers in better determining when and where to choose the DZM over the CM.

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Chapter 1. Introduction

1.1. Background

Lane closures are often required for construction work zones on freeways or other high-speed limited-access roadways. Speeds decrease as the traffic demand approaches the capacity of the lane(s) that remain open. This initially results in a moving queue of vehicles upstream of the closure. Further demand increases can trigger traffic flow breakdown, resulting in unstable (stop-and-go) traffic and a standing queue beginning quite far upstream of the bottleneck.

Both moving and standing queues present considerable traffic safety hazards due to the potential for inattentive or unsuspecting drivers to collide with vehicles slowed or stopped at the back of the queue. Rear-end collision risk is magnified when visibility is hampered by darkness, atmospheric conditions such as fog or smoke, or the presence of a sharp horizontal or vertical curve. The crashes can further reduce the available capacity, amplifying queueing and traffic delays and potentially resulting in secondary crashes.

Moving traffic queues are associated with the transition from stable to unstable traffic flow (Kerner 2009). Numerous empirical studies have shown that the traffic capacity is considerably higher prior to the onset of unstable flow, and slow to recover after the breakdown to unstable flow. Therefore, transportation agencies have sought solutions to delay or avoid the onset of unstable flow. Zipper merging (also called zip merge) is one such technique.

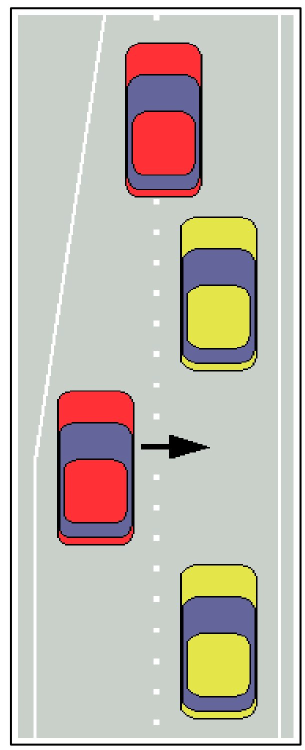


Figure 1. Zipper Merge

In a zipper merge, signage and sometimes public outreach are provided to persuade drivers to take turns entering the lane closure: one vehicle from the left lane, one from the right lane, and so forth—like the meshing of the teeth in a clothing zipper (Figure 1).

Under congested conditions, zipper merging has been shown to delay flow breakdown, reduce the overall length of the moving queue approaching the bottleneck, and reduce fuel consumption and emissions. In addition, public opinion surveys suggest road users feel zipper merging is more equitable in the sense that queue jumping is reduced or eliminated by encouraging vehicles to use all open lanes upstream of the merge point.

Zipper merge signage does not appear to be meaningful to drivers if traffic is light. Therefore, a number of agencies and vendors have explored dynamic zipper merge (DZM) systems that only activate zipper merge messaging when heavy traffic is detected. To accomplish this, DZM systems include sensors that measure the traffic speed, flow rate, or lane occupancy. The control algorithms used in these systems change the messages displayed on portable changeable message signs (PCMS) based on the observed conditions. This flexibility helps manage temporal traffic demand changes, such as rush hour versus off-peak times, ordinary traffic vs holidays, or configuration differences during various construction phases.

In principle, DZM systems should result in fewer traffic crashes and better travel times compared to conventional traffic control, where drivers tend to merge well upstream of the closure. Nevertheless, few studies have empirically evaluated the traffic safety outcomes of DZM use. To address this knowledge gap, the North Carolina Department of Transportation (NCDOT) commissioned the research team to evaluate potential operational benefits and safety outcomes and develop a CMF for DZM systems.

1.2. Problem Statement

Work zone lane closures on freeways and other high-speed limited-access facilities can degrade traffic operations and safety. They reduce capacity significantly as vehicles merge to a reduced number of lanes, causing long travel times, queueing, and even road rage.

Conventionally, traffic signs are placed upstream of the work zone to show a lane drop ahead, and drivers are advised to merge early. In general, early merging is considered beneficial for traffic safety by reducing the frequency of aggressive merging. Nevertheless, this system is inefficient when the demand is high since significant road space remains unused upstream of the work zone *(Nemeth and Rouphail, 1982; McCoy and Pesti, 2001)*. In some cases, the resulting queues can block exit ramps, resulting in even greater queuing, delay, and crash risk.

Another approach, named the Zipper Merge, guides drivers so that they merge later at the choke point where vehicles in adjacent lanes take turns. This approach is more effective in promoting traffic efficiency by fully utilizing the spaces of the current lane and the target lane; however, the zipper merge system appeared to be ineffective in low-demand conditions *(Beacher et al., 2005; Kurker et al., 2014)*. Figure 2 presents a graphic illustration of the early merge and the zipper merge approaches.

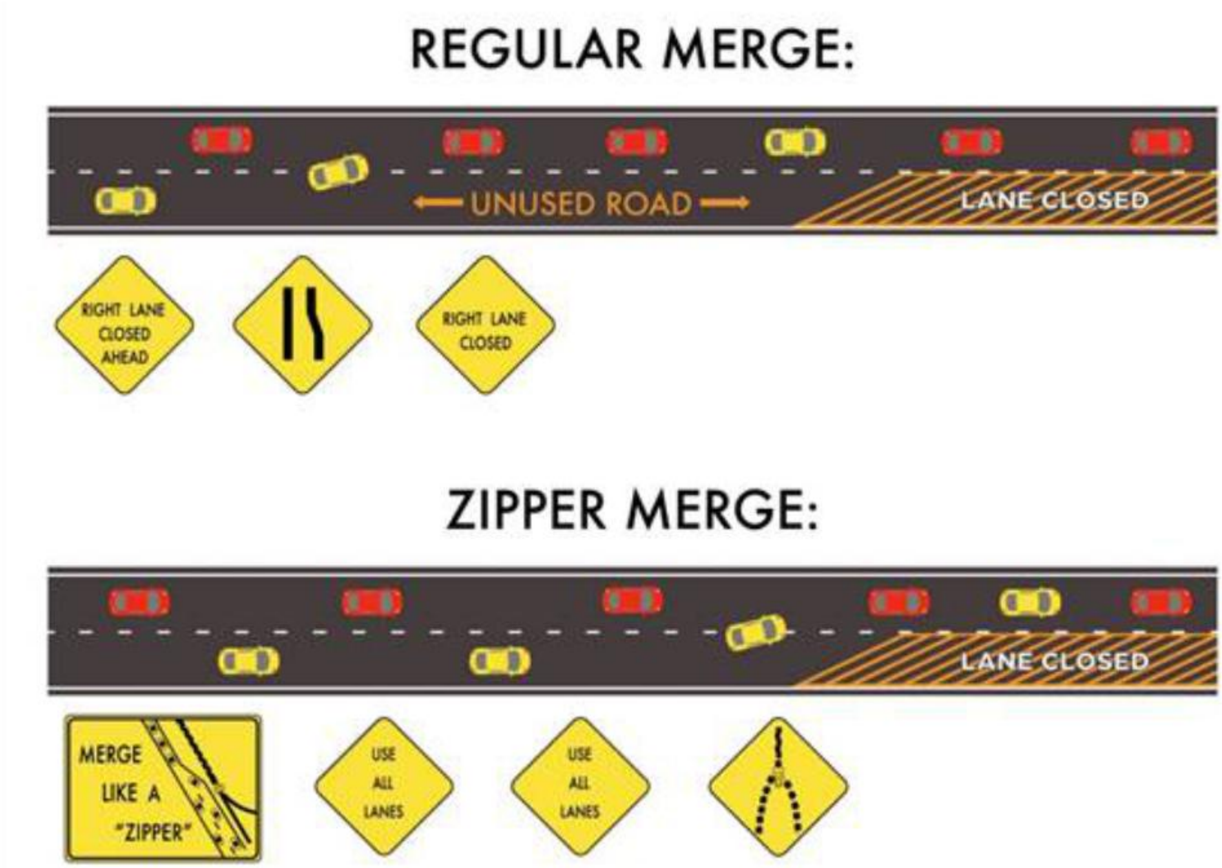


Figure 2. Regular Early Merge versus Zipper Merge

These issues motivated researchers to integrate the advantages of both strategies by developing a modified version of zipper merge system called the dynamic zipper merge, which leverages information on traffic conditions from upstream sensors and changes the merging technique through portable changeable message signs to accommodate changes in traffic volume *(McCoy and Pesti, 2001; Kang et al., 2006; Grillo et al.,* *2008; Weaver et al., 2019)*. Specifically, the DZM is a form of merge control designed to mitigate the potential hazards of lane closures by customizing the merge environment to suit the current level of traffic. When traffic is light, early merge signs encourage drivers to merge into the open lane prior to queue formation. When traffic is heavy, zipper merge signs encourage drivers to remain in the closed lane for as long as possible.

1.3. Objectives

This research will help the NCDOT to better understand the application and potential safety and operational benefits of the DZM system compared to the early merge system for different scenarios. In addition, the findings could help reduce the temporal spans of lane closures on interstates. Specifically, this research will result in findings supporting recommendations regarding the appropriate implementation of the DZM based on expected traffic conditions – namely, traffic volumes, truck percentages, and construction traffic control.

1.4. Scope of the Study

This research focused primarily on two-to-one lane closures, as these are the only types of DZM closures currently being implemented in North Carolina. Likewise, the focus of this study was on freeway work zones, with no other roadway classifications being taken into consideration because of the NCDOT's current practice on DZM implementation. While this limits the reach of the results of this study to only freeway two-to-one lane drops, it allowed for a concentrated effort with more reliable results for these scenarios.

Chapter 2. Literature Review

Merging behavior in freeway work zones plays a critical role in maintaining traffic efficiency and safety. Conventional merge operations in work zones often experience issues such as early lane changes, uneven lane usage, and increased turbulence as drivers respond to lane closures. To mitigate these challenges, researchers have investigated the zipper merge concept, initially implemented as static zipper merges, which use fixed signage to encourage late merging and alternating entry at the taper. More recently, dynamic zipper merge systems, which adjust merge instructions in real time based on traffic demand and speed conditions, have been widely implemented. The literature underscores the need to understand how these merging strategies interact with driver behavior in work zones to improve traffic flow and reduce conflicts.

2.1. Static Zipper Merge

The application of the zipper merge system at work zones dates to 1998. Between 1998 and 2002, the Netherlands, UK, and Germany applied this technique to reduce queue length upstream of lane-closure-related work zones *(USDOT, 2009; Harb et al., 2010; FHWA, 2012)*. Researchers endeavored to compare the effectiveness of the zipper and early merge system using data from these case studies. The measures of effectiveness (MOEs) used in this regard include lane utilization, work zone throughput, queue length, and travel time.

McCoy et al. 1999 assessed the Pennsylvania Department of Transportation's late merge system using field-collected traffic flow and driver behavior data from a two-to-one lane closure work zone. The results indicated that the late merge strategy reduced forced merges by approximately 75% and increased capacity by about 10% compared with the standard lane merge. These benefits were most pronounced under heavily congested conditions. The study further emphasized that the effectiveness of the late merge strategy is highly dependent on the implementation of appropriate signage to reshape driver expectations. The Texas Transportation Institute *(Walters and Cooner, 2001)* further investigated the operational benefits of the late merge strategy in a three-to-two lane closure scenario. Their comparative analysis showed that late merge delayed the onset of congestion at the merge point by approximately 14 minutes and reduced the maximum queue length by about 23%.

Beacher et al. (2005) evaluated static late merge strategies through a study that was conducted on a two-to-one lane closure in Virginia. The late merge strategy was evaluated by comparing its effectiveness with that of traditional plans for work zone lane closures. Measures of effectiveness included distribution of traffic across the travel lanes, travel time, and throughput at the lane closure. Results showed that throughput increased, but the increase was not statistically significant. Likewise, time in queue decreased, but the decrease was not statistically significant. These results were much less dramatic than those of other studies conducted in Pennsylvania and Texas. Possible reasons for this disparity include different driver populations, road types, vehicle mixes, and site-specific characteristics. The Virginia site was not on a limited-access highway as originally desired, but rather on an arterial road with multiple access points on the approaches to the work zone. In addition, the Virginia site had traffic signals within the queuing area, presenting opportunities for disturbance to traffic flow. These factors made evaluating the effectiveness of the late merge more difficult than if the site had been on a limited-access highway. Despite limited improvements in throughput and time in queue, more drivers were in the closed lane, a desired response to the late merge signs.

A similar outcome was seen at the Carroll Cropper Bridge work zone on I-275 in Kentucky and the Taylor Southgate Bridge on KY-9, where the zipper merge protocol was implemented after running the early merge protocol for several months *(Lammers et al., 2017)*. No statistically significant differences were found between the early and zipper merge treatments regarding queue length and crash frequency for the I-275 case study. The Taylor Southgate Bridge zipper merge's positive impact on traffic flow, reduced backups, and construction impact was more qualitative due to no early merge comparison. While neither case study offers definitive evidence that the zipper merge is significantly more effective than the early merge, these case studies modestly endorse the zipper merge, recommending its ongoing implementation in other work zone projects.

In Minnesota, the implementation of a late merge procedure on numerous expansive construction projects by the Minnesota Department of Transportation (MnDOT) has yielded favorable outcomes *(MnDOT, 2008)*. MnDOT observed that the utilization of variable message signs to transition between the conventional merge approach and the late merge strategy was not universally imperative. Notably, enhanced travel times within construction zones were achieved by employing signs instructing drivers to utilize both lanes during backups. Drivers demonstrated adept recognition of backup occurrences and adeptly utilized both lanes, effecting a zipper merge at the designated merge point. MnDOT emphasized that this approach mitigated the speed differentials between merging lanes, thereby enhancing the safety and ease of the merging process. Additionally, it resulted in a noteworthy reduction of approximately 40% in the length of backups. Furthermore, the alignment of the speeds of both lanes contributed to a reduction in driver frustration. It is noteworthy that despite the zipper merge fostering a safer merging environment and diminishing the length of backups, it did not lead to a reduction in travel time through the construction zone in this particular instance.

Vaughan et al. (2018) evaluated three work zones' operational and safety aspects before and after a zipper merge was implemented. Zipper merge was tried at three sites in central and eastern North Carolina: a rural arterial two-to-one lane drop, a suburban freeway three-to-two lane drop, and a rural freeway two-to-one temporary lane drop within a work zone. Treatments tested included zipper merge signs, wider dotted white lane lines, and elongated route shields. Lane usage showed minimal impact, with a maximum five percent increase in ending lane traffic, potentially due to a sign misunderstanding. Travel times generally slightly decreased, sometimes with unexplained increases, possibly due to external factors. The work zone site, using DZM, saw a significant improvement with a one-minute travel time decrease, equivalent to an 11 mph speed increase. Notably, the zipper merge enhanced safety by reducing shoulder usage for merging. Wide dotted lines at the freeway site led to smoother merging patterns, minimizing interactions between entering and exiting vehicles. Elongated route shields showed no major crash change after pavement marking installation. In general, the research showed a clear safety improvement by the zipper merge system, as fewer vehicles entered the shoulder to merge after the zipper merge was implemented. Specifically, the DZM performed the best overall when compared to the other two static setups.

2.2. Dynamic Zipper Merge

The static zipper merge system was proven able to save travel time and increase throughput when traffic flow is high; while at low-flow and high-speed conditions, drivers found it difficult to merge right upstream of the lane closure since they reach that point at high speed. To address this dilemma, *McCoy and Pesti (2001)* introduced the concept of a dynamic zipper merge system, which leverages real-time traffic flow data and dynamically switches the system between early and zipper merge techniques. Zipper merge gets activated once the upstream traffic speed drops below a pre-specified threshold or the occupancy and/or the traffic flow exceeds a pre-specified threshold. Soon after the introduction of the DZM concept, several public agencies implemented this system. For example, the Kansas and Minnesota Departments of Transportation used speed and volume-based thresholds to activate the DZM at several work zones between 2003 and 2004 *(Meyer, 2004; MnDOT, 2004)*. The Maryland Department of Transportation used an occupancy-based threshold to activate the DZM at four work zones in 2003 *(Kang et al., 2006)*. Michigan DOT used a speed threshold of 35-45 mph for a two-lane work zone on I-94 to trigger the dynamic merge system *(Datta et al., 2007)*. In most cases, this treatment was deployed at two-to-one lane closures, but a few involved three-to-two lane closures *(Walter et al., 2001; Meyer, 2004; MnDOT, 2004)*. With the implementation of the the DZM system, a number of research efforts have been conducted to investigate its effectiveness.

McCoy and Pesti (2001) pointed out that conventional traffic control plans for lane closures of rural Interstate highways normally work well as long as congestion does not develop. However, when the traffic demand exceeds the capacity of the work zone, queues may extend back past the advance warning signs, often surprising approaching traffic and increasing the crash potential. Also, smooth and orderly merging operations may be lost as some drivers remain in the closed lane attempting to squeeze into the open lane at the head of the queue, while other drivers try to prevent drivers in the closed lane from passing them by straddling the centerline or traveling slowly in tandem with another vehicle in the closed lane. These maneuvers tend to reduce the capacity of the merging operation and increase the crash potential and road rage among drivers. The research examined the advantages and disadvantages of the early merge and late merge control strategies, and proposed a new concept named the dynamic late merge, which features the integration of the late merge and conventional lane closure merge control on the basis of real-time measurements of traffic conditions in advance of the lane closure.

Harb et al. (2010) conducted a study evaluating three different merging systems implemented at the same three-to-two lane drop work zone for six days each. The research wanted to determine which merging strategy (i.e., traditional, dynamic early, or dynamic late) was optimal. The work zone they studied was rural, geographically and environmentally similar across its length, and had no on/off ramps over the duration of the work zone. Results showed that under lower volumes (less than 1,500 vphpl), the dynamic early merge was the optimal merging strategy. Under higher volumes (1,500-2,000 vphpl), the dynamic late merge was optimal. For volumes higher than 2,000 vphpl, no clear conclusion could be drawn due to data availability.

Meyer (2004) evaluated the Kansas construction area late merge (CALM) system, which comprised 5 VMS, 4 RTMS, 2 microwave traffic sensors, and a laptop-based system control center for monitoring traffic and accordingly adapting messages and modes (early merge, late merge, incident) based on downstream conditions. System operational switched from one mode to another by speed thresholds, which were determined based on prior research combined with site characteristics. Results showed that when the system was in late merge operation, lane distributions were statistically different than when in early merge operation, but the difference was small. An entrance ramp near the merge appeared to have a very strong effect on driver lane choice, influencing drivers to merge left, even when the system instructed them to hold their lanes. Dynamic late merge operation led to slightly different lane distributions than early merge, while the research highlighted the importance of site characteristics in deploying dynamic systems and designing configurations.

The Minnesota Department of Transportation *(MnDOT, 2004)* assessed its dynamic traffic control strategy, the Dynamic Late Merge System (DLMS), for lane closures in work zones. DLMS utilizes Changeable Message Signs (CMS) and a Remote Traffic Microwave Sensor (RTMS) to guide drivers when congestion forms. An evaluation report on a 2003 deployment of DLMS on US 10 was followed by the 2004 assessment at three locations around the Minneapolis-St. Paul area. From field data, it was found that the DLMS improves the overall driving conditions upstream of construction lane closures; vehicles were visually observed utilizing the majority of both lanes during congested periods. This pattern of lane use utilization resulted in a queue of nearly minimum length.

In Maryland, *Kang et al. (2006)* evaluated the operational efficiency of a dynamic late merge (DLM) system for highway work zones in terms of the input–output analysis, work zone throughput, volume distribution, and resulting queue length. Results revealed that a properly deployed DLM system can indeed outperform the CM control with respect to the total work zone throughputs. Such a system, however, may result in excessive traffic conflicts (crashes, forced merges, lane straddles, lane blocking, stop and go, etc.) if not properly integrated with existing static warning signs for work zone operations. The research also presented suggestions and guidelines developed from field observations and analysis results for potential improvement of the DLM performance, such as selection of an optimal set of control thresholds, estimation of maximum queue length, and separation of the portable changeable message signs from conventional merging and warning signs.

In Michigan, a dynamic late lane merge system (DLLMS) was implemented on three freeway segments in southern Michigan during the 2006 construction season. Each work zone segment involved a lane closure from two-to-one lane. Based on the travel time characteristics, queue, merge locations, and throughput, the effectiveness of the DLLMS was evaluated by the Wayne State University Transportation Research Group *(Datta et al., 2007)*. Before data were not available, so a conventional work zone merge system located on EB I-94 was used as a control site for the WB I-94 test site. When comparing the I-94 control and test sites, it was found that the presence of the DLLMS improved the flow of traffic (including time, speed, and number of stops) and increased the percentage of merging vehicles that merged at the taper. However, there was no statistically significant difference in traffic crash experience between the test and control sites. Another research effort by *Grillo et al. (2018)* also found that the peak period delay and speed of a work zone with the DZM on I-94 in Michigan were significantly better than those at a similar work zone with the early merge system. The total travel time savings by the dynamic zipper system were 9,550 person-hours. The results of the statistical and benefit-cost analysis of their experiments suggested that dynamic late merge systems could be deployed at locations where highways experience moderate to heavy congestion, prior to construction work zones.

The North Carolina Department of Transportation implemented the DZM system for several work zones over the past several years *(Beaver, 2020)*. For example, the slab replacement work on I-77 in Yadkin and Surry Counties and the I-40 pavement rehabilitation work in Davie County near Winston Salem in 2019 had a DZM. The devices deployed include message boards every mile for six miles, speed sensors every half mile, and signs updated every 60 seconds. The NCDOT collected probe-based travel time data and collision reports associated with the I-77 work zone before and after the DZM was implemented. The main lesson learned from these applications was that the DZM significantly reduced travel time and queues. Regarding safety performance, DZM reduced the total crash rate from 14 to 5 crashes per month compared with the conventional merge, and eliminated fatal and injury crashes (from 3 crashes per month to 0).

2.3. Human Factors

When dealing with vehicle merges at lane closure points in freeway work zones, human factors considerations become crucial to ensure the safety and efficiency of the merging process. Several research efforts have been made to investigate driver merge behavior at freeway work zones under different lane configurations and merge control strategies.

Spery et al. (2009) investigated the impacts of dynamic messaging on driver merge behavior at freeway work zones with late merge lane closure patterns. Based on a limited dataset collected at Interstate 80 in western Iowa, it was found that driver merging behavior did not indicate a statistically significant change in merging behavior or overall benefit when the dynamic message signs were activated. Moreover, the research did not identify a correlation between driver merging behavior and vehicle volumes, speeds, or classification.

Idewu and Wolshon (2010) investigated the impacts of joint merge on merging speed at construction zones, where the joint merge design was defined as an alternating merge pattern in the lane reduction area. Specifically, the joint merge employs a two-sided taper that simultaneously reduces both approach lanes into one, removing lane priority, and both lanes are responsible for safely completing a merge; thus it is expected to result in a smoother entry into the transition zone. Based on a field study conducted in Louisiana, the research found that although the overall merging speeds were similar to the CM, drivers displayed heightened caution, possibly due to the joint merge's balanced lane volume at the transition zone entrance.

Hallmark et al. (2011) identified driving maneuvers that were most detrimental to work zone safety and operations based on data collected at freeway work zones for six days. The maneuvers mainly included forced and late merges, lane straddling and queue jumping (moving from the open lane to the closing lane and back again). They also noted that queue jumping usually leads to a forced and/or late merge. Additionally, other drivers will sometimes straddle lanes or otherwise try to block queue jumpers. The team suggested the late merge, work zone information boards, and longitudinal and transverse rumble strips as methods of mitigating the observed dangerous driving maneuvers.

He et al. (2015) developed a logistic regression model to identify factors that influence drivers' lane-changing behavior at freeway work zones. In general, it was found that vehicle type, original lane average speed, and target lane volume made a significant contribution to lane changes in the work zone. Specifically, lane changes increased as traffic flow increased, indicating that drivers were more disposed to seek the higher speed lane in heavy flow condition than free flow condition. The majority of late-merging drivers were willing to overtake the slow-moving vehicles and merge back. Some other aggressive drivers kept a higher speed driving in the closing lane and merged at the closing point.

Weaver et al. (2019) employed a driving simulator to assess the independent effects of traffic volume and dynamic merge messaging on merge location and traffic throughput at work zones with a DZM. A total of 120 licensed drivers from the greater Washington, DC metropolitan area participated in the experiment. Results show that across both light and heavy traffic conditions, participants in the early merge condition merged into the open lane earlier than participants in the late merge condition. Moreover, it was found that when traffic was heavy, participants within the late merge condition cleared the advance warning area sooner than those in the early merge condition. Findings from this study support using traffic volume-based signing to increase roadway safety and efficiency during a lane closure.

Galbraith (2021) pointed out that the effectiveness of zipper merge can be reduced if drivers choose not to comply with the zipper merging rule or tend to be more accustomed to early merging. Through a literature review, the research identified seven behavioral science concepts to leverage in zipper merge communications including instructions, information, social norms, appeals to reason, emotional appeals, humor, and activators. Specifically, it was found that the use of emotional appeals, such as appeals to generosity and commiseration, can be effective in influencing public attitudes and behavior towards zipper merges; humor can make messages more memorable and increase receptiveness to the message; mnemonics and other memory activators can help drivers remember what a zipper merge is and how to do it; messages that affirm the desirable behavior can mitigate the tendency for individuals to increase consumption when informed that they use less electricity than their neighbors.

2.4. Simulation Modeling

In addition to the field data-based work zone performance assessment approach, a well-calibrated microsimulation tool will be considered to create different demand scenarios and test the suitability of various work zone merge strategies and lane closure durations to accommodate different traffic flow scenarios. Several studies applied simulation models such as VISSIM to evaluate different lane merge strategies. Some of these studies are briefly reviewed here.

A study conducted by *Beacher et. al. (2004)* evaluated the late merge work zone traffic control strategy consisting of a simulation study using VISSIM as well as a field study on the static late merge in a 2:1 work zone lane drop. While the simulated late merge increased throughputs and decreased travel time in each configuration, the improvements were only statistically significant across scenarios in a 3:1 configuration.

Further, lane configurations of 3:2 and 2:1 only saw a significant increase in throughput with higher heavy vehicle percentages.

Pesti et al. (2008) tested ten different lane configurations and lane closure scenarios for congested freeways to verify the effectiveness of dynamic late merge via VISSIM. Simulation results indicated that dynamic late merge may not work for all types of lane configurations, as only three of the ten scenarios showed positive benefits.

Wei et al. (2008) examined three lane closure scenarios at a work-zone bottleneck to evaluate the effect of a dynamic merge metering strategy at work zones. Based on the threshold volumes at merge, the cycle time of the merge metering signal was tested using VISSIM for three different cycle lengths. The average reductions in delay were reported as 21.3 % using fixed merge metering and 20 % using continuous merge metering.

Yang et al. (2009) studied a new lane-based signalized merge system for freeway work zone operations using a calibrated VISSIM model. The experimental results suggested that under heavily congested conditions, the lane-based signalized merge strategy outperformed the conventional early and late merge strategies in terms of operational efficiency and safety.

Radwan et al. (2011) evaluated the dynamic lane merge in work zones with variable speed limits. The research used VISSIM to model a two lane to one lane work zone to evaluate the use of a variable speed limit in the presence of a dynamic merge scenario. Of all the scenarios tested, the late dynamic lane merge coupled with the variable speed limit provided the greatest throughput; however, there was no statistically significant difference from the use of a normal dynamic merge with variable message boards.

Ge and Yang (2020) proposed a method for determining the length of freeway warning zone using VISSIM microsimulation modeling and surrogate safety assessment model (SSAM). A linear regression model was established to analyze the relationship between warning zone length and safety performance in terms of simulated traffic conflicts. Results showed that travel time and delay increased slowly with the increase of warning zone length; traffic conflicts decreased with the increase of warning zone length. Note that when the warning zone length is 2200m, the number of traffic conflicts, delay, and safety evaluation index were the minimum, indicating that the safety performance is the best.

Shen and Cummings (2022) compared the performance of SUMO and PTV VISSIM microscopic simulators for both zipper and early merge scenarios. Results showed the two simulators were generally equivalent in computational resource demand but produced delay estimates that were not consistent with one another. Moreover, SUMO produced more variability than PTV VISSIM, which may be an advantage when representing human behavior uncertainty that is highly variable.

Zhao et al. (2022) developed a comprehensive guideline for calibrating and validating a VISSIM microsimulation model that can emulate traffic conditions and their impacts on a freeway work zone equipped with automatic queue detection systems. Specifically, the methodology included (1) developing the base work zone model, (2) replicating the automatic queue detection warning messages, (3) calibrating the key simulation parameters using three types of data, and (4) validating the resulting simulation model using segment travel times. Another research effort *(Haque et al., 2023)* proposed an automatic microsimulation calibration methodology for identifying parameters that can match the distribution or the mean value of observed traffic data at highway work zones. Results showed that a two-lane work zone microsimulation model calibrated using the empirical distributions of traffic measures could replicate the corresponding distributions at the 5% significance level. However, if the model was calibrated using the mean value of traffic measures, it could not replicate empirical distributions.

2.5. Summary

The literature review shows that several studies attempted to evaluate different lane merge strategies in order to improve the operational and safety performance of freeway work zones operating under various lane configurations and merge strategies. In general, the following measures of effectiveness were employed for performance assessment: volume at the merge area, lane distribution, speed distribution, and traffic conflicts in the merge area.

A few studies showed some statistically significant benefits of the zipper merge system over the conventional early merge system, but the overall results were mixed. For instance, some studies found that the zipper merge system improved the average number of stops and total throughput, while the crash frequency was higher at the treatment sites. For the DZM system at work zones, although there is a lack of concrete, statistics-based proof, previous research efforts generally concluded that this merging system performs better than the traditional early merge system and static-based zipper merge systems when traffic demand is near capacity. A summary of the performance of existing freeway work zone merge systems is presented below in Table 1.

Table 1. Comparison of various freeway work zone merge strategies

Merge Strategy	Operational Performance	Safety Performance	Limitations
Conventional MUTCD Merge	No significant problem when the upstream volume is lower than work zone capacity	Potential rear-end collision when the queue extends beyond warning sign	Insufficient during high-volume periods
Early Merge	Travel time increase due to the long queue under high upstream traffic demand	Merge can be completed smoothly before approaching the merging point	Insufficient during high-volume periods
Static Zipper Merge	Reduced delay and travel time due to increased throughputs under congested traffic conditions	Potential right-of-way conflict at merge point	Potential safety issues under low-volume and high-speed conditions
Dynamic Zipper Merge	Sufficient to accommodate low- and high-demand conditions; changeable merge point based on real-time traffic information	Decreased potential for sideswipe and rear-end crashes	Threshold volume and speed need to be evaluated accurately; Relatively higher operational and maintenance costs

Moreover, a few studies used microsimulation tools to estimate the operational benefits for different lane closure and demand scenarios. For microsimulation-based research, the biggest challenge was the proper calibration of driver lane change behavior for different treatments. The common finding of these studies was that both the static and dynamic zipper merges work better than the conventional early merge system for most work zones when the traffic volume is high. While numerous studies, using both field observations and simulation models, revealed positive effects of the DZM, far fewer studies were able to find the statistical significance of these benefits. Also, the effectiveness change for different scenarios of lane closures and traffic demand levels is still unknown. Finally, the dynamic zipper merging system may have the potential of reducing the duration of work zones involving lane closures on interstates. Currently, lane closures during daytime operations are not permitted on many interstates in North Carolina since the impact during a high-demand period can be severe. However, if a work zone can reasonably handle the increased demand in daytimes with the DZM, the time span of the work zone could be reduced substantially due to the ability to leave the work zone in operation for longer periods of time.

In summary, effective traffic management in work zones is a critical aspect of modern road infrastructure, where the seamless flow of vehicles while ensuring driver safety is of paramount importance. Lane merging, in particular, plays a pivotal role in achieving these objectives. As drivers navigate lane reductions caused by construction or other factors, their choices and behaviors significantly influence traffic flow and congestion levels. Understanding the human factors involved in lane merging is essential for devising efficient traffic control strategies. In this regard, the DZM might be applicable to work zones with different types of lane closures, but the optimal setup of the devices (e.g., portable message signs and detectors) is likely to be different for three-to-one (or two) lane closures compared to two-to-one.

Chapter 3. Site Selection

Site selection was challenging for this retrospective comparison of the safety and operational performance of DZM and CM work zones. As with most observational transportation studies, the treatment and control corridors exhibit heterogeneities that cannot be controlled readily. These included grade, curvature, interchange complexity, and traffic volume.

Several DZM corridors traversed mountainous terrain with sustained grades, tight curvature, and complex geometry. Others were located in North Carolina's Piedmont (foothills) region; these are comparatively straighter corridors and have fewer steep grades. All CM corridors were located in the Piedmont or Coastal Plain and are generally linear with fewer vertical and horizontal alignment changes than the mountainous DZM locations. The DZM corridors also exhibited greater geographic overlap, meaning they were often on the same stretch of interstate and in the same general vicinity, albeit at differing times, whereas CM corridors were more spatially distinct. Across both corridor types, interchange density varies substantially, with some sites—particularly near population centers or regional connectors—featuring closely spaced access points that increase traffic turbulence independent of work zone treatment. These differences were artifacts of prior decisions about where to use DZM.

Several DZM deployments occurred in locations with inherently complex merge and diverge conditions, including high-volume entrance ramps, short acceleration lengths, or closely spaced merges that motivated the use of active traffic management strategies. Across the study sites, DZM corridors generally exhibited a moderate number of nearby interchange ramp terminal intersections, typically ranging from 1 to 5 per corridor, with an average of 0.21 roadway interchanges per mile. CM corridors showed a wider spread, ranging from 1 to 7, with an average of 0.28 roadway interchanges per mile. This suggests that while DZM and CM sites had comparable interchange densities, CM sites included a few corridors with higher intersection complexity.

Differences in interchange spacing, merge and diverge complexity, traffic composition, and the availability of parallel routes reflect underlying network design and regional context rather than experimental control. Some corridors offer parallel arterials that allow demand redistribution, while others function as the sole high-capacity route, concentrating traffic on the primary facility. This was apparent in the study sites for this research, as the DZM sites were typically in the mountainous western region of the state, where available routes are more limited due to terrain, reducing or even eliminating route choice. Likewise, several CM sites were located in the coastal plains of eastern North Carolina, where adjacent and parallel routes are more prevalent, as denoted by the slightly higher interchange density for CM sites.

The aforementioned characteristics were not explicitly quantified but are inherent to real-world deployments and may influence congestion formation and crash mechanisms independent of treatment type. As with most observational transportation studies, results should therefore be interpreted as comparative performance under realistic operating conditions, with observed differences reflecting both treatment effects and contextual factors; consistency across diverse settings supports the external validity of the findings.

Because of these variables, along with the availability of multiple DZM study sites during the data collection process, the research team determined it would be best to capture video footage of traffic behavior across the four available DZMs. Likewise, other study methods, like modeling the DZM in microsimulation or conducting a driver simulator study, have been utilized more extensively than field study of DZM corridors, meaning the availability of field sites presented a unique opportunity to capture live traffic data leading into the merge area and downstream of this choke point. This was viewed as a chance to better reflect real-world traffic behavior at a DZM.

3.1. Dynamic Zipper Merge Sites

As shown in

Table 2, ten corridors where the DZM was used during road construction were identified by the NCDOT and found to be suitable for the study. These all represent locations where the DZM had been used prior to the start of the study for 2:1 freeway lane closures (two lanes upstream merging into one downstream lane). All sites are situated in the western part of the state, and were situated in the Piedmont (foothills) or mountainous terrain regions.

Two of the locations, Cataloochee and North Pacolet, each had both directions of travel instrumented for field data collection as a part of this study. These data were to be used for the operational data analysis (Chapter 6) and calibration of the work zone evaluation tool (Chapter 7). Note that I-26 WB in North Pacolet is not included in the table below because the majority of traffic observed was across the South Carolina state line as it entered North Carolina, meaning crash data and ClearGuide data were unavailable for that site. Likewise, I-40 EB in Pigeon River is not included below because much of the upstream traffic was across the Tennessee state line.

Table 2. Dynamic zipper merge sites

Nickname	Hwy	Direc-tion	Location	County	Terrain Type	Construction			Est. Daily Traffic Volume**	Est. Truck Percentage (%)***
						Start*	End*	Days		
Jonesville 2	I-77	NB	Exit 79 to mile 83.4	Yadkin	Piedmont	05/12/19	06/21/22	755	15,700	18.1
Jonesville 2	I-77	SB	Exit 79 to mile 83.4	Yadkin	Piedmont	07/08/19	06/21/22	653	15,800	18.1
Cataloochee	I-40	EB	Mile 20	Haywood	Mountain	11/02/23	06/25/24	237	12,000	23.5
Cataloochee	I-40	WB	Mile 20	Haywood	Mountain	11/01/23	06/22/24	235	10,000	23.5
North Pacolet	I-26	EB	Columbus	Polk	Mountain	03/18/24	05/21/24	28	16,500	15.8
Pigeon River	I-40	WB	Mile 7	Haywood	Mountain	11/14/21	05/19/22	187	11,200	25.9
Redland	I-40	EB	Mile 180	Davie	Piedmont	04/26/22	05/20/22	25	19,000	11.8
Redland	I-40	WB	Mile 180	Davie	Piedmont	04/04/22	04/26/22	23	18,700	11.8
Hunting Creek	I-40	EB	Iredell Line to 0.5 mi E US 601	Iredell	Piedmont	04/22/19	11/18/21	826	17,800	11.8
Hunting Creek	I-40	WB	Iredell Line to 0.5 mi E US 601	Iredell	Piedmont	02/21/20	12/10/21	624	17,300	11.8

* Begin and end dates are the earliest and latest dates with construction-related congestion identifiable in the ClearGuide data. Due to intermittent lane closure/construction activity, the total number of construction-affected dates was often less than the calendar duration of the project. Non-construction days are excluded from the crash totals and traffic volume estimates.

** Estimated directional average daily traffic for days with construction.

*** Provided by the NCDOT Traffic Survey Group (total of single unit and multi-unit trucks).

3.2. Conventional Merge Sites

As shown in

Table 3, six corridors where the CM was used during road construction were selected by the project team based on a list of dozens of historical candidate freeway work zone locations. To satisfy the study inclusion criteria, each location was required to be a freeway corridor with 2:1 lane closures and periodic moderate to heavy congestion. ITRE staff utilized the DriveNC Traveler Information Management System (TIMS) to conduct an initial high-level filter based on 1) freeways and 2) 2:1 lane closures. The resulting work zone candidate sites were then examined using ClearGuide travel speed data to identify periodic congestion.

Through filtering for lane configuration matches and recurring congestion, the candidate site list dwindled. Likewise, because work zones within the last several years expected to experience moderate to heavy congestion in western NC were all selected for DZM implementation, the CM sites are primarily located in central and eastern North Carolina in the Piedmont and Coastal Plains terrains. While this can potentially influence the comparison results due to factors like available route choice, topography and climate differences, the team felt that a comparison of crash and operational data across actual sites was more beneficial than a simulation study. The research team was also confident in the ability to control for many of the confounding variables in the comparison of safety or operational data. Lastly, the need presented by the NCDOT included specificities of available site data of existing or previous sites, indicating a desire to compare these data between DZM and CM sites. As such, the six CM sites described in Table 3 were deemed most similar to the available DZM sites and thereby utilized in this comparison.

During analysis, the site on northbound I-95 near Selma was found to be an extreme outlier, with a crash rate during construction more than 11 times the pre-construction rate. In comparison, the crash rate ratios for other CM sites ranged from 1.67 to 3.74. Therefore, while the Selma site is included in this discussion for completeness, it was ultimately removed from the statistical data used to compute the overall rate ratios and crash modification factor.

Table 3. Conventional merge sites

Nickname	Hwy	Direc-tion	Location	County	Terrain Type	Construction			Est. Daily Traffic Volume**	Est. Truck Percentage (%)***
						Start*	End*	Days		
Rocky Mount	I-95	NB	Mile 132-138	Nash	Coastal	04/03/23	05/08/23	10	28,500	15.9
Heathsville	I-95	NB	Mile 151-165	Halifax	Coastal	04/11/23	04/25/23	9	30,900	18.4
Selma***	I-95	NB	Mile 97-98	Johnston	Piedmont	05/15/23	11/09/23	17	22,900	16.3
Jonesville 1	I-77	NB	Mile 78.4	Yadkin	Piedmont	03/26/19	05/11/19	42	17,400	18.1
Hunting Creek CM1*****	I-40	WB	Mile 170	Davie	Piedmont	06/03/19	08/28/19	82	18,000	11.8
Hunting Creek CM2*****	I-40	WB	Mile 170	Davie	Piedmont	10/15/19	12/09/19	50	18,800	11.8

* Begin and end dates are the earliest and latest dates with construction-related congestion identifiable in the ClearGuide data. Due to intermittent lane closure/construction activity, the total number of construction-affected dates was often less than the calendar duration of the project. Non-construction days are excluded from the crash totals and traffic volume estimates.

** Estimated directional average daily traffic for days with construction.

*** Provided by the NCDOT Traffic Survey Group (total of single unit and multi-unit trucks).

**** Selma construction crash rates were an outlier; site removed from final results.

***** I-40 WB in Hunting Creek had two sites that were differentiated due to distinct temporal and spatial limits; Hunting Creek CM1 ends in the same location that Hunting Creek CM2 starts, with there also being 48 days between the two ending and starting dates.

Chapter 4. Data Collection

The geographical scope of the data download was limited to the state of North Carolina, as the focus of this study was to investigate the impact of DZM work zones within the state.

4.1. Crash Records

The crash data used in this study were obtained from the NCDOT's Traffic Engineering Accident Analysis System (TEAAS). TEAAS is a crash record database that contains all reported crashes each year within the state of North Carolina, including information such as crash location, severity, mode of collision, and contributing circumstances based on law enforcement reports.

The data were downloaded for January 2017 to December 2023, encompassing a seven-year period. A targeted search was conducted within TEAAS to ensure that all relevant work zone-related crashes were captured. The search was narrowed to include only specific incident types directly related to work zones, such as construction, night-time construction, weekend construction, and maintenance activities. In addition to a preliminary review of crash data for the requested work zone and upstream sections, the NCDOT Safety Evaluation Group provided crash details for vehicle travel direction to support a directional crash analysis.

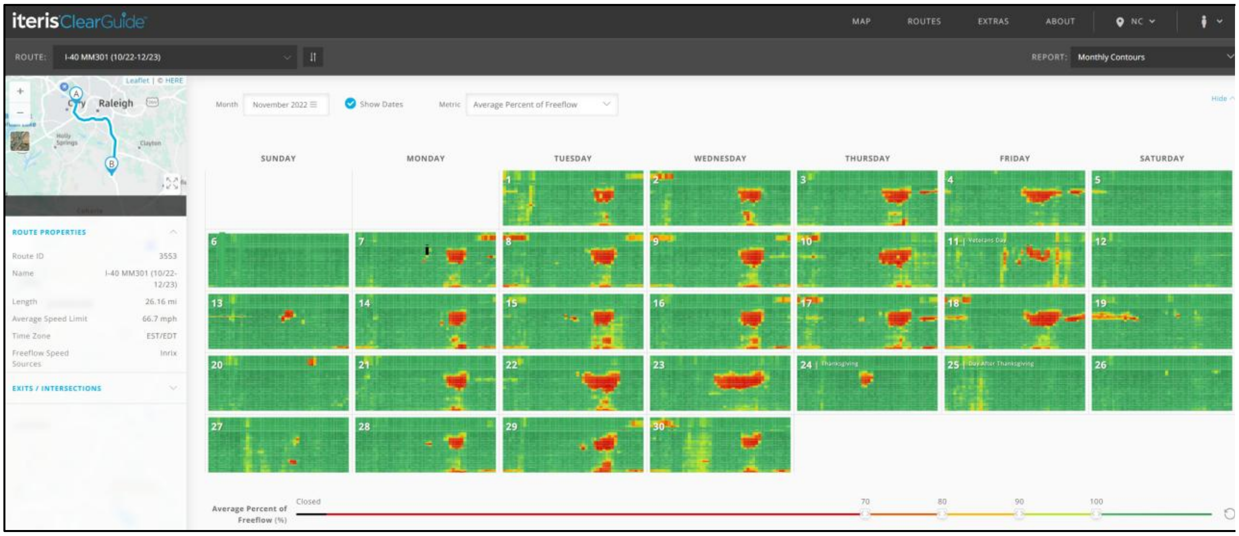
Crashes that were deemed relevant to this research included mainline crashes within the study area (i.e., within the work zone itself or within the 10-mile section upstream of each work zone). The NCDOT Safety Evaluation Group provided all crash data to the research team including, but not limited to, the following metadata of most interest:

- Location to ensure the crash occurred within the mainline
- Date to ensure the crash occurred within the study period before or during a work zone
- Time of day, which was cross-referenced to congestion data available in ClearGuide to determine if the crash occurred while traffic was congested (more detailed discussion directly below in Chapter 4.2)
- Crash type, as the research team expected rear-end and sideswipe, same direction crashes to be those most affected by the work zone merge type, while also considering other crashes
- Crash severity, included to potentially observe any trends pertinent to CMF development
- Travel direction of vehicles involved, which helped the research team reliably "place" a crash within the appropriate work zone, as each work zone was direction-specific

4.2. Traffic Speed Data

For each selected work zone, the research team used the ClearGuide platform to analyze traffic speed data and determine the maximum queue length throughout the construction period. ClearGuide compiles field-collected speed data in 5-minute intervals and visualizes it as a percentage of free-flow speed. The x-axis for each day represents time from 12:00:00 AM to 11:59:59 PM. The y-axis represents space from the beginning of the study corridor, which always starts at the bottom of the diagram (unless the user flips the view to be top-down), to the end of the corridor at the top of the diagram. In the plots, dark green indicates traffic moving at or above free-flow speed, light green represents traffic moving at 90-100% of free-flow speed, light orange represents 80-90% of free-flow speed, dark orange indicates 70-80% of free-flow speed, and red indicates traffic falling below 70% of free-flow speed.

To estimate maximum back-of-queue lengths, ClearGuide routes were created for each work zone, extending approximately 20 miles upstream and 20 miles downstream from the work zone lane drop point. The research team then manually reviewed the monthly contour plots of average speeds for each route to identify recurring upstream congestion. Figure 3 provides example monthly contour plots for freeway work zones in urban (Figure 3(a)) and rural/suburban (Figure 3(b)) settings.



(a)

(b)

Figure 3. Freeway work zone speed monthly contours: (a) I-40 Mile Marker 301; (b) I-40 Mile Marker 174

For work zones with recurring congestion, the team first selected freeway work zones that had the highest annual average daily traffic volumes (AADTs), then documented the lengths (in miles) of the five longest queues observed during the construction period. Queue lengths were measured by selecting the most congested days, identifying the merge point and the back of the queue within ClearGuide (i.e., the red area), and calculating the distance based on the platform's documented mile markers. The longest of the five observed queues was designated as the maximum queue length for each site. The research team determined that nearly all work zone queues were less than 10 miles across all DZM and CM sites. Consequently, the subsequent traffic safety analysis focused on the 10-mile upstream segment of each work zone.

4.3. Traffic Volume Data

Since the project involves work zones with varying traffic volumes, construction durations, and closure lengths, the expected crash counts vary widely from site to site. Additionally, some of the construction projects included in the study experienced substantial traffic volume fluctuations during the COVID-19 pandemic (2020-2021). Therefore, the raw crash counts were normalized to crashes per million vehicle-miles traveled (VMT). VMT is the product of the (directional) traffic volume at a site (e.g., vehicles per day) multiplied by the length of the site in miles.

The NCDOT Traffic Count Data System (TCDS) is North Carolina's primary repository of traffic count data. These records include short-duration (e.g., 48 hour) counts from tens of thousands of sites across the state, along with continuous counts (24 hours per day, 365 days per year) for about three dozen sites equipped with automatic traffic recorders (ATRs).

One work zone corresponded to an ATR location, allowing its monthly average daily traffic volume (MADT) to be obtained directly from TCDS. For the remaining sites, it was necessary to estimate MADTs by combining data from short-duration counts with information from nearby ATR stations. MADTs were then factored to estimate the daily volumes by day of week.

To assure accurate VMT estimates, the volume estimation process was designed to be responsive to fluctuations resulting from COVID-related changes in travel activity, as well as ordinary seasonal variations (Figure 4).

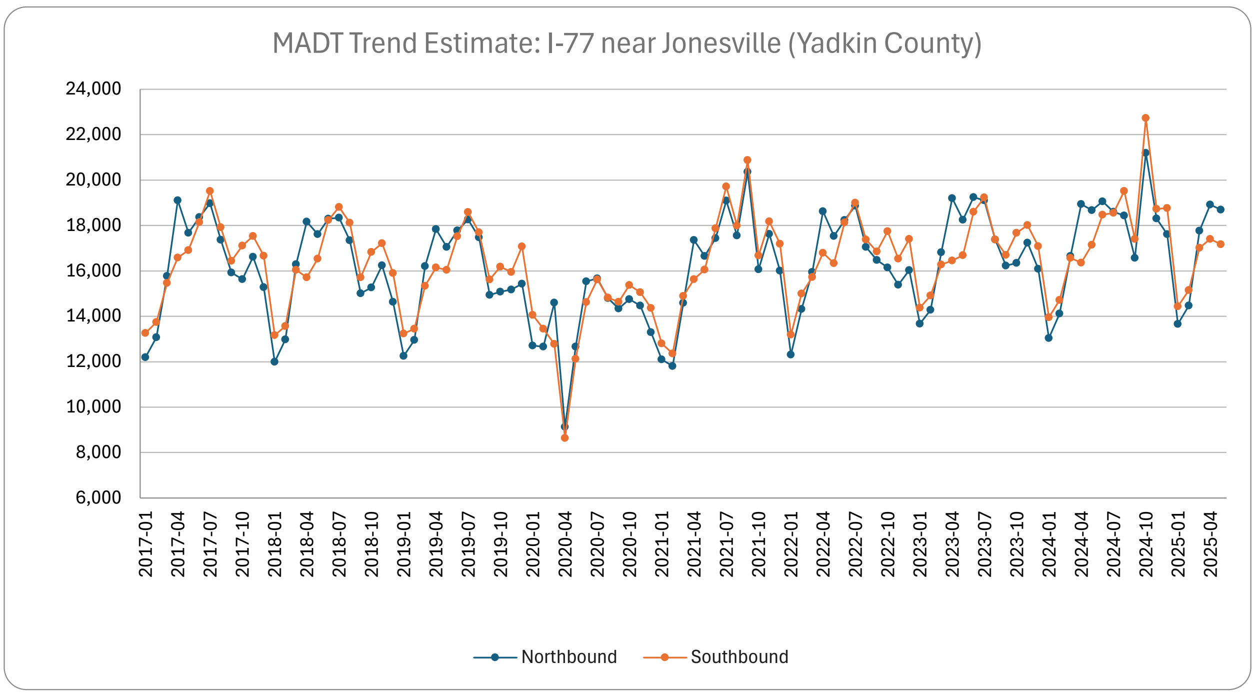


Figure 4. The traffic volume estimation process was designed to be responsive to seasonal fluctuations and travel demand effects of the COVID-19 pandemic.

Figure 5 shows an example of the MADT estimation process. At this site, only limited local data were available from the TCDS. These included non-directional annual average daily traffic volumes for 2017 and 2019, along with a directional count for part of May 2023. To generate robust MADT estimates, these data were combined with information from two nearby ATR stations. This process involved using an optimization algorithm to minimize differences between the observed counts and the computed estimates for the corresponding time periods. The resulting weighting factors were then applied to the ATR data to produce estimates of the MADT for each month from January 2017 (shown) to May 2025 (omitted from the figure for brevity).

The second step in the volume estimation process was to break down the MADT values by day of the week, as illustrated in Figure 6. For freeways, North Carolina has six sets of seasonal factors (SFs), with each factor representing a different region or corridor. The MADTs computed in the previous step were multiplied by the SFs corresponding to the site's Seasonal Factor Group as designated in TCDS. Generally, this resulted in 3073 daily volume estimates for each site, corresponding to each day from January 1, 2017 to May 31, 2025. This ensured that the volumes used to compute VMT for the crash rates corresponded to the actual dates when lane closures were present, as determined from the ClearGuide data.

Monthly Average Daily Traffic (MADT) Log

Nickname:	**Jonesville**
Location ID:	0990000083
County:	Yadkin
Location:	I-77
Type:	ESTIMATED

Targets	Year	NB	SB	Total
0990000083	2017			35,237
0990000083	2019			31,942
0990000354	2023-05	16,519	14,680	31,199

Estimates	NB	SB	Total
2017			32,940
2019			31,942
2023-05	18,246	16,685	

Site	Site Number	Weight
ATR 1	0490000002	0.051
ATR 2	0860000001	1.069

G_D			3.87
			0.00
	4.25	5.23	

Date Code	Month Name	Northbound	Southbound	Total
2017-01	January	12,189	13,258	25,446
2017-02	February	13,076	13,740	26,816
2017-03	March	15,769	15,466	31,234
2017-04	April	19,107	16,579	35,686
2017-05	May	17,671	16,906	34,577
2017-06	June	18,363	18,139	36,502
2017-07	July	18,979	19,519	38,498
2017-08	August	17,372	17,926	35,298
2017-09	September	15,930	16,446	32,376
2017-10	October	15,633	17,107	32,740
2017-11	November	16,617	17,538	34,156
2017-12	December	15,279	16,669	31,947
2018-01	January	11,999	13,171	25,170
2018-02	February	12,976	13,565	26,541
2018-03	March	16,293	16,048	32,340
2018-04	April	18,171	15,715	33,886
2018-05	May	17,615	16,537	34,152
2018-06	June	18,293	18,240	36,533
2018-07	July	18,348	18,814	37,162
2018-08	August	17,350	18,120	35,470
2018-09	September	15,006	15,715	30,722
2018-10	October	15,267	16,833	32,100
2018-11	November	16,240	17,216	33,456
2018-12	December	14,637	15,905	30,542
2019-01	January	12,250	13,237	25,487
2019-02	February	12,953	13,447	26,399
2019-03	March	16,201	15,343	31,544
2019-04	April	17,840	16,152	33,992
2019-05	May	17,046	16,047	33,093
2019-06	June	17,778	17,522	35,299
2019-07	July	18,259	18,592	36,851
2019-08	August	17,474	17,694	35,168
2019-09	September	14,945	15,620	30,565
2019-10	October	15,084	16,189	31,273
2019-11	November	15,173	15,952	31,125
2019-12	December	15,434	17,074	32,508

Figure 5. Example of monthly average daily traffic (MADT) estimation.

Nickname:	Jonesville							
Location ID:	0990000083							
County:	Yadkin							
Location:	I-77							
Type:	ESTIMATED							
Factor Group:	14							
					Raw Vol		**Adj Vol**	
Month	**Day**	**Date**	**DOW**	**Factor**	**NB**	**SB**	**NB**	**SB**
2017-01	01	1/1/2017	1	0.9816	**12,189**	**13,258**	11,964	13,013
2017-01	02	1/2/2017	2	1.0781	12,189	13,258	13,140	14,293
2017-01	03	1/3/2017	3	1.0868	12,189	13,258	13,247	14,409
2017-01	04	1/4/2017	4	1.0478	12,189	13,258	12,771	13,891
2017-01	05	1/5/2017	5	0.9654	12,189	13,258	11,767	12,799
2017-01	06	1/6/2017	6	0.8642	12,189	13,258	10,533	11,457
2017-01	07	1/7/2017	7	0.9762	12,189	13,258	11,898	12,942
2017-01	08	1/8/2017	1	0.9816	12,189	13,258	11,964	13,013
2017-01	09	1/9/2017	2	1.0781	12,189	13,258	13,140	14,293
2017-01	10	1/10/2017	3	1.0868	12,189	13,258	13,247	14,409
2017-01	11	1/11/2017	4	1.0478	12,189	13,258	12,771	13,891
2017-01	12	1/12/2017	5	0.9654	12,189	13,258	11,767	12,799
2017-01	13	1/13/2017	6	0.8642	12,189	13,258	10,533	11,457
2017-01	14	1/14/2017	7	0.9762	12,189	13,258	11,898	12,942
2017-01	15	1/15/2017	1	0.9816	12,189	13,258	11,964	13,013
2017-01	16	1/16/2017	2	1.0781	12,189	13,258	13,140	14,293
2017-01	17	1/17/2017	3	1.0868	12,189	13,258	13,247	14,409
2017-01	18	1/18/2017	4	1.0478	12,189	13,258	12,771	13,891
2017-01	19	1/19/2017	5	0.9654	12,189	13,258	11,767	12,799
2017-01	20	1/20/2017	6	0.8642	12,189	13,258	10,533	11,457
2017-01	21	1/21/2017	7	0.9762	12,189	13,258	11,898	12,942
2017-01	22	1/22/2017	1	0.9816	12,189	13,258	11,964	13,013
2017-01	23	1/23/2017	2	1.0781	12,189	13,258	13,140	14,293
2017-01	24	1/24/2017	3	1.0868	12,189	13,258	13,247	14,409
2017-01	25	1/25/2017	4	1.0478	12,189	13,258	12,771	13,891
2017-01	26	1/26/2017	5	0.9654	12,189	13,258	11,767	12,799
2017-01	27	1/27/2017	6	0.8642	12,189	13,258	10,533	11,457
2017-01	28	1/28/2017	7	0.9762	12,189	13,258	11,898	12,942
2017-01	29	1/29/2017	1	0.9816	12,189	13,258	11,964	13,013
2017-01	30	1/30/2017	2	1.0781	12,189	13,258	13,140	14,293
2017-01	31	1/31/2017	3	1.0868	12,189	13,258	13,247	14,409

Figure 6. Estimation of daily traffic volumes by day of week.

4.4. Operational Field Data

4.4.1. Site Availability

A total of four sites (two locations, each with two directions) were instrumented for the operational evaluation. Sites were selected to provide ideal geometric conditions (e.g., standard lane widths, representative grades, and horizontal curvature) and traffic conditions (e.g., typical AADT levels and heavy-vehicle percentages) so that data could be used to calibrate *Highway Capacity Manual* (HCM) procedures to North Carolina–specific conditions. In addition, the study sought to develop capacity estimates for DZM applications, which required observing driver behavior under both congested traffic and uncongested traffic.

At each site, portable video cameras were deployed to capture traffic operations upstream, through, and downstream from the active work zone lane closure. Across all sites, cameras were positioned such that:

- Location 1 captured throughput and headways downstream of the lane drop.
- Location 2 captured lane utilization and merging behavior at the taper/merge area.
- Additional upstream cameras documented lane utilization, queue formation, and progression along the corridor.

Although the number of cameras and their exact spacing varied by site, the functional layout of the observation locations was standardized to allow comparison across locations.

4.4.1.1. Cataloochee – Westbound (I-40, Pigeon River Bridge Replacement)

The westbound observation area was located on I-40 just west of Asheville, near the ascent into the Great Smoky Mountains and adjacent to the Pigeon River bridge construction (Figure 7). Data were collected April 22–May 4, 2024. Weather conditions were mostly clear.

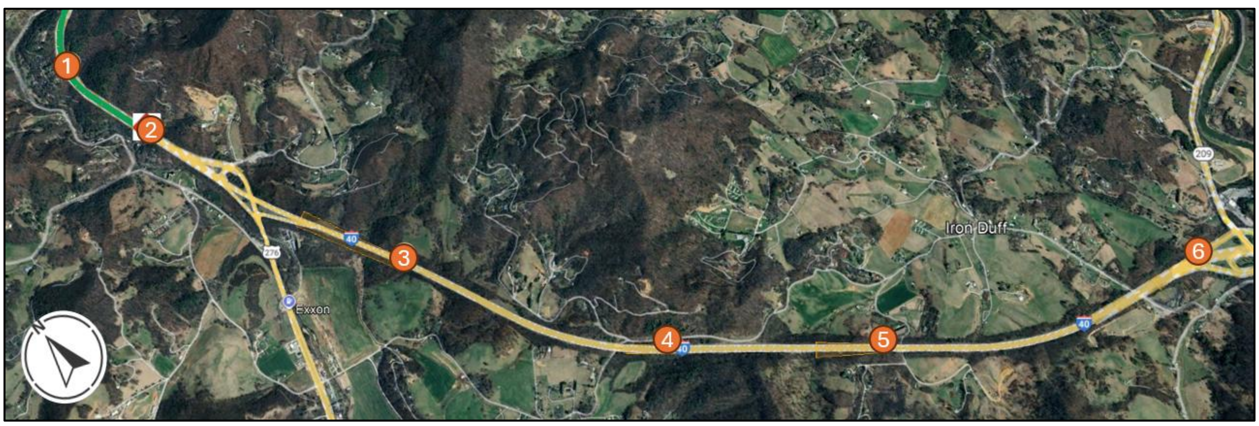


Figure 7. Camera installations along westbound I-40 in Cataloochee, NC

In total, six cameras were deployed across approximately five miles. This westbound site experienced the most severe and consistent queuing of all study locations due to a mix of daily commuter travel and heavy tourist volumes heading toward Tennessee. The DZM system was active for much of the day.

4.4.1.2. Cataloochee – Eastbound (I-40, Mountain Descent to Asheville)

The eastbound direction was located just west of Asheville, where I-40 transitions from steep, curving terrain into flatter, straighter highway approaching the city (Figure 8). Data were collected over the same April 22–May 4, 2024 period, with mostly clear weather.

Figure 8. Camera installations along eastbound I-40 in Cataloochee, NC

In total, five cameras were used for this direction. Compared to the westbound approach, congestion was lighter but still regular, influenced by the mountainous alignment and driver behavior on the downgrade.

4.4.1.3. North Pacolet – Eastbound (I-26, Columbus, NC – Bridge Repair)

The eastbound observation area was located on I-26 near Columbus, NC, beginning just north of the US-74 interchange, where the freeway reduced from three to two lanes before narrowing again to a single lane in the work zone (Figure 9). Data were collected March 18–21 and April 15–19, 2024. Weather conditions were mostly clear.

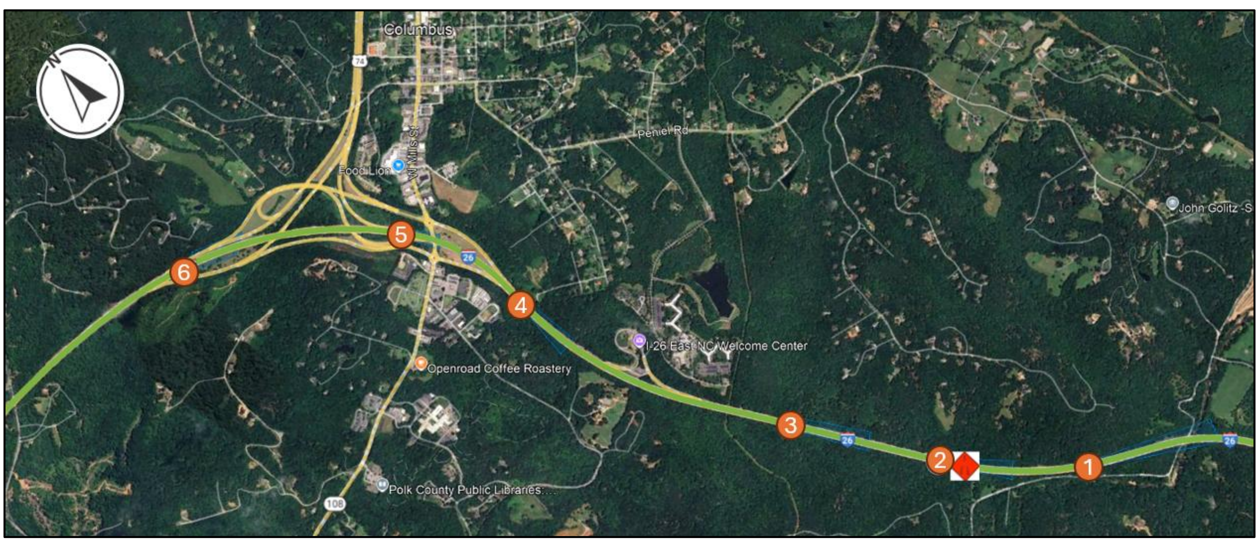


Figure 9. Camera installations along eastbound I-26 in North Pacolet, NC

A key challenge at this site was conflicting traffic control signage. DZM changeable message signs (CMS) instructed drivers to stay in both lanes until the taper and merge late. However, static roadside signs remained in place throughout the study period, indicating an early merge, with some even misidentifying which lane was closed. This led to several observable behaviors:

- The geometry created two lane-drop sections in quick succession
    - From three lanes to two at the interchange with US-74.
    - From two lanes to one at the work zone taper.

- Drivers made multiple unnecessary lane changes in the upstream approach as they attempted to reconcile the contradictory messages.
- Some drivers merged very early, creating long stretches of underutilized pavement in the closing lane.
- Other drivers, observing the CMS, remained in the closing lane longer but often swerved suddenly to merge late when confronted with static signage or slower early-merging traffic.
- The result was a chaotic and inconsistent merge pattern, with turbulence in speeds and utilization across the corridor.

In total, six cameras were deployed across approximately three miles.

4.4.1.4. North Pacolet – Westbound (I-26, Columbus, NC – Bridge Repair)

The westbound observation area was also located near Columbus, NC, with the study corridor extending into South Carolina (Figure 10). Terrain was hilly with moderate grades and curves. Data were collected during the same March–April 2024 periods as the eastbound side.

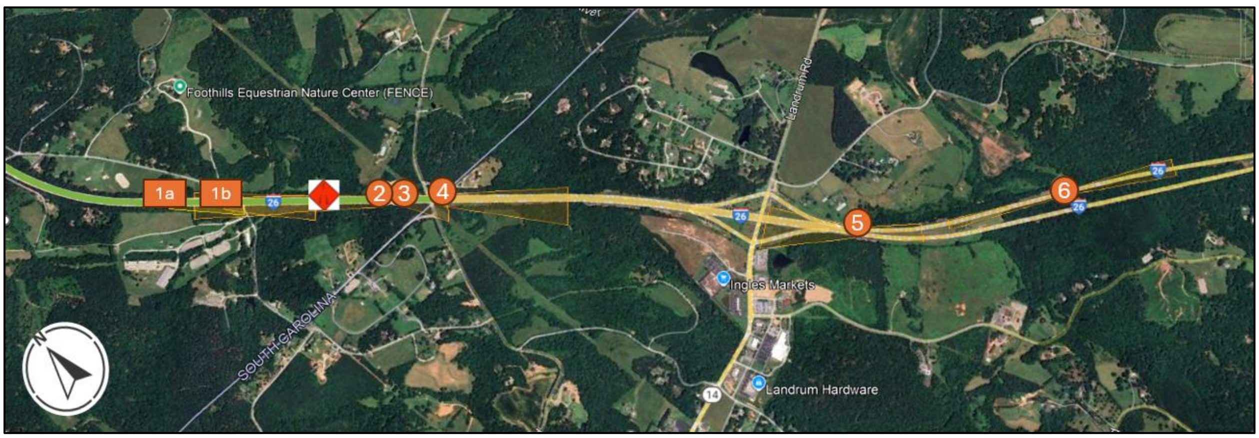


Figure 10. Camera installations along westbound I-26 in North Pacolet, NC

As with the eastbound direction, conflicting signage created significant driver confusion. The DZM system directed motorists to continue using both lanes until the taper, but static early-merge signs remained posted and often conflicted with the CMS messages. Observed driver responses included:

- Erratic lane changes well upstream of the closure, with some drivers switching back and forth multiple times.
- Reduced trust in CMS messages, as many drivers appeared to follow the static signs instead, leading to long single-lane queues upstream.
- Aggressive late merges, where drivers who followed the DZM guidance encountered drivers who had already merged early, resulting in sharp braking, hesitations, and occasional near-conflict situations.
- Overall, the merge area was marked by greater turbulence and hesitation compared to sites without conflicting signage.
- Additional cameras: upstream coverage extended across ~3 miles, though spacing was less uniform due to infrastructure limitations and limited mounting locations.

In total, seven cameras were deployed in this direction. Congestion was lighter than at Cataloochee, but the signage issues substantially reduced the clarity and usefulness of the dataset.

4.4.2. Data Collection

To evaluate the operational impacts of conventional and dynamic zipper merges, detailed field data were required on traffic performance at active work zone sites. The research team designed and implemented a data collection program that captured lane utilization, headways, and queuing behavior under real-world conditions. These data would later be used to develop the work zone evaluation tool described in Chapter Chapter 7. The subsections that follow describe the instrumentation deployed at selected sites, the procedures used to measure headways, and the methods applied to document lane-by-lane utilization during periods of congestion.

4.4.2.1. Instrumentation

Field data were collected in Western North Carolina along two highway corridors where four dynamic zipper merges were active – one in each direction on both corridors. These included the Cataloochee site (I-40 near mile marker 20) and North Pacolet site (I-26 near Columbus, NC, near the South Carolina border). Data collection for all four sites occurred during the spring of 2024, a period chosen to maximize the likelihood of consistent construction activity while minimizing the potential for weather-related disruptions.

At each DZM location, between five and seven cameras were installed. The first two cameras served consistent functions across all sites:

- Location 1: downstream of the lane drop to capture headways and throughput.
- Location 2: at the merge taper to observe lane utilization and merging behavior.

The remaining three to five upstream cameras documented lane utilization, queue formation, and traffic progression along the corridor. Because camera installations relied on available roadside infrastructure – often limited in mountainous terrain – equipment placement was carefully planned. Each camera operated daily from 6:00 a.m. to 9:00 p.m., except when interrupted by battery failures. This time period was selected to maximize battery life, as congestion is less common outside of this time frame and the image is more difficult to discern in the dark. To capture driver response to work zone messaging, at least one camera was positioned upstream of the furthest CMS. A typical camera installation and battery box is illustrated in Figure 11.

Figure 11. Example camera installation

4.4.2.2. Headways

Headway data were collected to estimate pre-breakdown and post-breakdown capacities. A camera positioned upstream of the 2:1 lane drop was used to identify the exact moment when the CMS transitioned from conventional merge messaging to zipper merge messaging. This transition consistently occurred after five minutes of sustained low speeds at the choke point, as shown in Figure 12.

Conventional merge alternating "Left Lane Closed" and a right arrow	Zipper merge alternating "Use Both Lanes" and "To Merge Point"

Figure 12. Portable changeable message sign displays prior to, and after, spillback at the choke point.

Based on the vendor specifications and the NCDOT's implementation practices, the research team identified the moment that speeds first dropped below the DZM preset threshold as five minutes prior to zipper merge activation. Pre-breakdown capacity was therefore defined as the five-minute period immediately before spillback began (ten minutes before zipper merge activation). Post-breakdown capacity was assumed to stabilize after approximately two hours of sustained queuing.

Examples of traffic conditions before and after DZM activation are provided in Figure 13. Pre-breakdown headways were captured from 0–5 minutes prior to spillback (Figure 13A and B) , while post-breakdown headways were captured after more than two hours of queueing with the DZM active (Figure 13D). These images illustrate typical traffic states upstream of the 2:1 lane drop, but do not represent the exact camera location used for headway measurement.

A) Pre breakdown (t = - 5 minutes)

B) Congestion start time (t = 0 minutes)

C) DZM start time (t = +5 minutes)

D) DZM (t = 2+ hours)

Figure 13. Examples of traffic patterns during all phases of dynamic zipper merge implementation

To calculate pre- and post-breakdown capacity, headways were obtained from a downstream camera at Location 1, approximately one-half mile beyond the lane drop (Figure 14). A time-stamp macro with distinct keystrokes for passenger cars and trucks recorded the exact time (to the nearest 0.1 second) that each vehicle crossed a fixed point on the roadway. The data were then cleaned by removing outliers with headways greater than five seconds.

Figure 14. Location ½ mile downstream of 2:1 lane drop utilized for collecting headways.

4.4.2.3. Lane Utilization

As part of the tool development, the research team estimated lane-by-lane queue lengths at zipper merge sites once traffic began to back up. These queue lengths were later used to estimate lane split for DZM sites during tool development. Lane-by-lane volumes were collected from upstream video camera views, as illustrated in Figure 13A-D. The analysis period began after queue spillback had occurred for a minimum of 5 minutes, as shown in Figure 13C and D. Similar to the headway analysis, a time-stamp macro was employed, with different keystrokes used to classify each vehicle by lane (left or right) and by type (passenger car or heavy vehicle).

Chapter 5. Safety

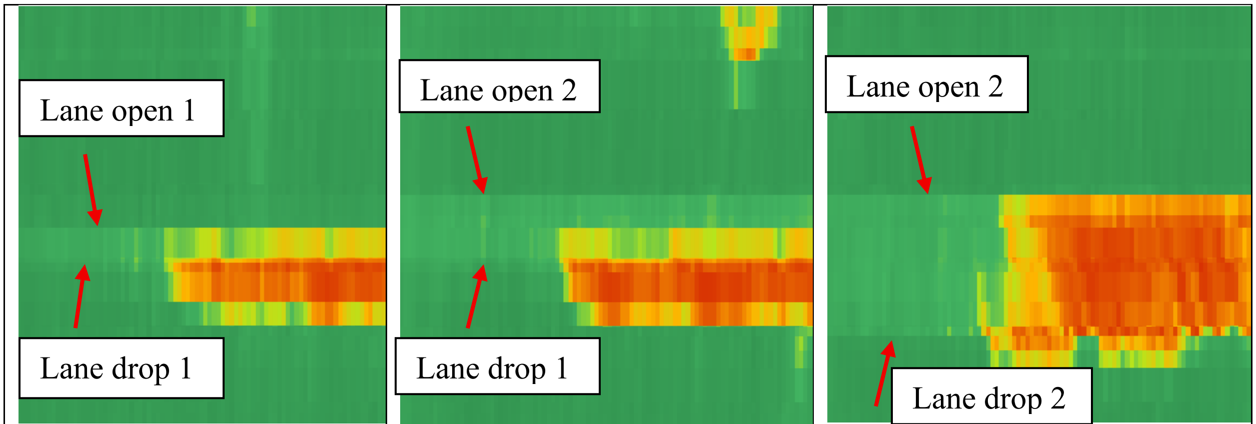
An in-depth analysis was conducted to compare the safety performance of the DZM and CM arrangements, compute risk ratios for each condition relative to a pre-construction baseline, and establish a crash modification factor that quantifies the safety benefits of DZM relative to CM. The analysis required numerous data inputs including traffic speeds, traffic volumes, and crash counts under multiple operational conditions. Publicly available car-top camera images from Bing Maps, Google Earth, and Google Maps were used to confirm construction activity. Results indicate DZM offers statistically significant safety benefits relative to CM.

5.1. Speed Data

ClearGuide was utilized to capture probe data across all DZM and CM sites. Specifically, vehicle speed and the percent free-flow speed were used to determine queueing and travel times. ClearGuide provides contour maps of corridors that help visualize traffic patterns leading up to and through a work zone. These contour maps were useful in identifying the maximum queue lengths mentioned above, but they also helped with verifying lane closures and openings, as well as ongoing congestion, or lack thereof, each day at each site.

ClearGuide speed contour maps were useful in identifying lane closures and openings to verify street view and aerial imagery available publicly. Likewise, these contour maps were also used to identify precisely when lane closures were implemented, shifted, and removed due to work zone project needs, as available imagery does not encompass the entirety of work zone durations, but is merely a moment in time within the duration of the work zone. Figure 15 below shows three images of the same work zone with varying starting and ending locations, with the direction of travel being from bottom to top and time chronologically from left to right. Lane drop X indicates where the lane drop started (went from two lanes to one) for each date. Similarly, lane open X indicates where the lane drop ended (went from one lane to two) for each date.

Images A and B have the same starting location (lane drop 1 in the figure), but different ending locations (lane open 1 in the image A and lane open 2 in image B). Likewise, images B and C have differing starting locations (lane drop 1 in image B and lane drop 2 in image C), but the same ending location (lane open 2). It was common for sites to have several different lane drop starting locations, with sites typically having one to two, and up to three different starting points. Likewise, work zones typically had one to two differing lane opening locations, but some had as many as four. One site, Hunting Creek DZM on I-40 WB, had three different starting lane drops and four different ending lane openings, resulting in a combination of nine different work zone lane drop configurations. These lane shifts varied not only in location, but also in time, as the lane drops could last as little as three days and as many as eight months at a time. Each of these configurations for each site was found through ClearGuide contour map inspection.



a) Aug 1, 2021 (lane drop 1, lane open 1)	b) Aug 15, 2021 (lane drop 1, lane open 2)	c) Sept 12, 2021 (lane drop 2, lane open 2)

Figure 15. Hunting Creek DZM EB work zone beginning and end locations

An explanation of how ClearGuide congestion data was integrated with crash data to filter crashes based on congestion follows.

5.2. Geospatial Analysis

To generate vector geometries representing each study site, precise starting and ending locations for each work zone were first established using publicly available high-resolution aerial imagery. Contractual project start dates, descriptions referencing nearby mile markers, and ClearGuide congestion data were used to constrain and verify the imagery-based locations and to confirm that the Work Zones were active. As a result, each site had highly variable starting and ending locations with date restrictions based on Clear Guide congestion. All of these “Active Work Zone” space-time links were converted to vector geometry using ArcGIS Pro and Python scripting.

“Upstream” traces were also established to capture congestion and crash activity before entering the Active Work Zone. To determine a suitable length for the Upstream trace, a corridor-length sensitivity analysis was conducted. The analysis assessed the stability of crash representation and congestion coupling at various scales: beyond 10 miles, 10-mile, 8-mile, and 5-mile segments. Results indicated that the 10-mile corridor threshold minimized variance in crash density while preserving the spatial composition and distribution of crashes, and was therefore selected for all subsequent Upstream analyses. The Upstream traces were converted to vector geometry using ArcGIS Pro and Python scripting.

To capture crash events associated with each corridor, the finalized 10-mile geometries were buffered by 100 feet on both sides to approximate the spatial extent of the roadway and its immediate roadside environment. The buffered corridors were then used to clip NCDOT-cleaned crash data, isolating only crashes spatially coinciding with each corridor. Direction of travel was validated using the Unit Travel Direction attribute in the NCDOT-provided crash dataset. When necessary, the crash reports were also reviewed to ensure that crashes were assigned to the appropriate directional corridor. Finally, the crashes were constrained by the Active Work Zone date ranges, as determined by ClearGuide congestion review. As a result of this Python-automated filtering, vehicle crashes that were spatially, directionally, and temporally consistent with the Active Work Zones and 10-mile Upstream stretches were captured. These crashes were combined to calculate the Total Crash Rate.

To integrate congestion dynamics, ClearGuide data were incorporated representing real-time and historical link performance metrics. Each ClearGuide link contained attributes describing the *average percent of free* *flow* speed, recorded at 15-minute intervals across variable temporal coverage (ranging from several months to multiple years). Using a custom Python script, the tabular link data were converted into spatial geometries aligned with the NCDOT routes while retaining all original temporal and speed attributes.

Crash records were then correlated in both space and time with the ClearGuide link dataset. For each crash, the ClearGuide link, which was within 40 ft and within 15 minutes of that crash, was spatially joined to the crash. Congestion was defined as an *average percent of free flow* less than or equal to 70%, which is consistent with the ClearGuide definition of congestion. When tabular link data were not available for extraction, the congestion information within the ClearGuide web application interface was manually verified. As a result of this analysis, congested vehicle crashes for each Work Zone and Upstream trace were captured. These crashes were used to calculate the Congested Crash Rate.

As noted above, lane closure locations can change over the duration of a construction project. For each corridor, crashes occurring in roadway segments upstream of the lane closure location(s) were obtained, including data 10 miles upstream of the furthest upstream closure. During analysis, each closure location was identified using the ClearGuide (Inrix) speed data. To assure uniformity in the analysis, all crashes in the 10-mile segment upstream of the closure were included in the determination of crash counts and crash rates corresponding to that stage of construction. Thus, the analysis reflects changes in crash rates in queues upstream of the closures with and without the DZM treatment.

Originally, crashes within the work area of each work zone were not expected to be included in the safety analysis. However, in the process of gathering saturated flow rates for use in the tool development as a part of this project, the research team noted that the saturation flow rates varied between DZM and CM lane drops. As such, the research team noted that the differing saturation flow rates could affect the operations and safety within the work zone, and thereby decided to include crashes within the work zone in the analysis and comparison between DZM and CM sites (Figure 16).

In all, this geospatial analysis enabled a consistent, data-driven classification of crash events relative to congestion intensity, facilitating subsequent analyses of corridor stability, safety performance, and congestion–crash coupling.

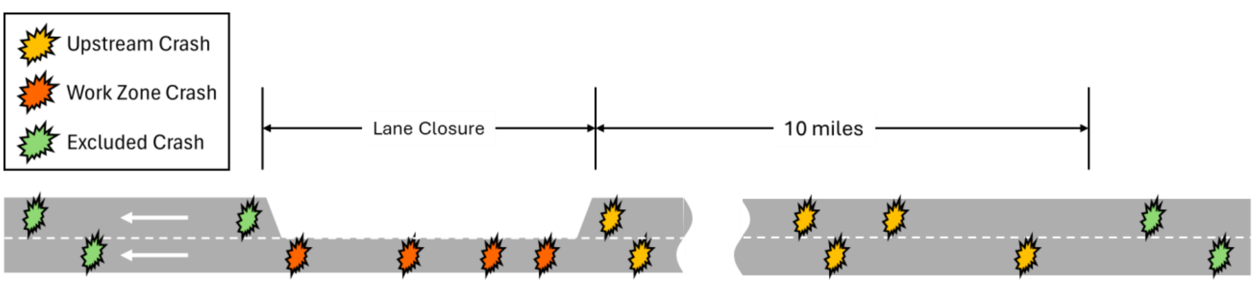


Figure 16. Definitions of Upstream and Work Zone Crashes

5.3. Extracting Hazard Ratios from Risk Records

Although the terms risk and hazard are often used interchangeably in daily conversation, in the context of safety analysis, their meanings are distinct. Risk, R, represents the probability of an adverse event. It is typically modeled as the product of hazard × exposure, where hazard, H, is the presence and severity situation with the potential to cause harm. Exposure, E, represents the extent to which people and property are exposed to that hazard:

$$R = H \times E$$

For instance, injuries and property damage caused by flooding are a *risk*, a river with the potential to flood is a *hazard,* and the number of people who live in the floodplain is a measure of *exposure.*

For a longitudinal roadway hazard such as a work zone, exposure is a function of both traffic volume and the length of the hazardous area. For example, a two-mile work zone has twice as much exposure as a one-mile work zone. Similarly, if traffic volumes increase by 25%, exposure is assumed to increase by the same proportion. In both cases, linearity is usually assumed for simplicity.

The crash reports obtained from the North Carolina TEAAS database represent the observed *risk* over the duration of each construction project. In contrast, the desired output from this project is a CMF representing the ratio of *hazard* with the DZM to hazard under a CM. Since the lengths and traffic volumes vary in each of the DZM and CM corridors, it is necessary to account for *exposure* variations when computing the CMFs from the risk data.

To standardize the comparisons, raw crash counts during each construction period were converted to crashes per million vehicle-miles traveled. The mileage component of this calculation was determined based on the length of each work zone, nominally measured from the ROAD WORK AHEAD SIGN at the upstream end of the work zone to THE END ROAD WORK SIGN at its downstream end.

To compute the crashes/million VMT metric, the project team first identified the dates when lane closures were likely to be present based on the ClearGuide travel speed data. All crashes that occurred on these specific dates were included in the computations. Additionally, the team computed the percentages of crashes that occurred during congested hours.

As discussed in more detail in a subsequent section, in one case, the traffic volumes for the VMT calculation could be obtained directly from ATR data archived in the North Carolina TCDS. In the remaining cases, volumes for the construction periods were estimated by combining data from upstream/downstream ATRs with TCDS data for ordinary (non-construction) time periods.

5.4. Safety Results

As shown in Table 4 and Table 5, the process for deriving a crash modification factor (CMF) for the DZM treatment began with converting the raw crash counts for each site to crashes per million vehicle-miles traveled (VMT). This conversion helps assure comparability across locations with widely varying traffic characteristics and work zone durations. Next, the work zone crash rates were compared to the baseline (pre-construction) crash rates for each project site. Baseline rates were computed using data from year(s) preceding the construction project, further limited to the project area and (to minimize seasonal effects) the months of the year when construction occurred. *Crashes involving deer and other animals were excluded from these computations.*

The work zone start and end points were determined from speeds reported in the ClearGuide data (although it cannot be established with certainty in this post-hoc analysis, this likely corresponds to the segment from the beginning of the lane closure taper to the END ROAD WORK sign). This allowed the computations to be stratified as follows:

- **Upstream:** Crashes per million VMT in the 10 miles upstream of the lane closure.
- **Work Zone:** Crashes million VMT in the work zone itself, i.e., the area from the upstream end of the lane closure to the point where traffic speeds returned to normal.
- **Total:** Crashes per million VMT for the entire site, i.e., the combination of the 10 miles upstream and the work zone itself.

Results were computed for individual sites, and for the aggregations of all available data for DZM sites and for CM sites. These aggregations were computed by summing the total crash counts and total VMT for all locations in each treatment category, which in effect provides more weight for sites with long construction durations. The CM site on I-95 near Selma was excluded from the aggregations because its during-construction crash rate was dramatically higher than the other locations (the reasons for this undesirable safety performance are not known to the project team).

The resulting rate ratios (RRs) were as follows:

- **DZM Sites:** During construction, the crash rate ratio for DZM sites was **1.43** times the baseline rate [95% confidence interval 0.93, 1.94].
- **CM Sites:** During construction, the crash rate for CM sites was noticeably higher at **2.58** times the baseline rate [95% C.I. 2.02, 3.13], indicating less desirable safety performance compared to the DZM arrangements.

The confidence intervals for these rate ratios are non-overlapping, indicating that the differences in DZM and CM safety performance were statistically significant.

For future analysis, the project team recommends the use of the weighted rate ratios presented in bold text above. Nevertheless, for purposes of comparison Table 4 and Table 5 also include the minimum, maximum, median, and unweighted mean (average) rate ratios, computed by giving equal weight to all sites in each treatment category.

As shown in Table 6, the project team explored two approaches for computing a crash modification factor to represent the safety performance difference between DZM and CM sites:

- **Method 1** (blue shaded cells) directly computes the ratio of crashes per million vehicle-miles traveled (VMT) during construction by dividing the aggregated crash rate for DZM sites by the aggregated crash rate for CM sites. The resulting CMF was 0.63 [0.50, 0.79], which corresponds to a crash reduction factor (CRF) of 37% [21%, 50%].
- **Method 2** (orange shaded cells) takes the more rigorous approach of dividing the Rate Ratios presented in Table 4 and Table 5. That is to say, it is a "ratio of ratios" that considers the increase in crashes associated with DZM sites (compared to the pre-construction baseline) and divides it by the increase in crashes associated with CM sites (compared to baseline). The resulting CMF was **0.56** [0.43, 0.71], which corresponds to a CRF of **44%** [29%, 57%]. This value is recommended for use in safety analyses.

Thus, the project team concludes with high confidence that DZM systems were effective at reducing crashes in North Carolina rural freeway work zones, compared to CM arrangements. Although the results of Method 1 and Method 2 differ, the confidence intervals shown in Table 6 overlap, indicating that CMF computations performed using the two methods are not statistically different. The confidence intervals also overlap when the results are stratified by area type (upstream vs. work zone).

Exact confidence intervals cannot be computed for ratios. Therefore, confidence intervals were estimated based on the total counts of crash events observed in each treatment category, using the lognormal rate ratio method described in Section 6.7.1 of the *Cochrane Handbook for Systematic Reviews of Interventions* (Cochrane Collaboration 2026) and the assumption that the data are normally distributed. For Method 2, event counts for the confidence interval were taken as the averages of the crash counts during the construction and baseline periods.

Table 4. Crash Counts and Rate Ratios (RRs) for DZM Sites.

Dynamic Zipper Merge Sites	Dir	Time Period	Days	Crash Count			Crashes Per 1,000,000 VMT*			Crash Rate Ratio (RR)**		
				Upstream	Work Zone	Total	Upstream	Work Zone	Total	Upstream	Work Zone	Combined
I-77 Jonesville 2	NB	Before Constr	502			89			0.770			
		During Constr	755	105	70	175	0.887	1.705	1.098	1.15	2.21	**1.43**
I-77 Jonesville 2	SB	Before Constr	369			64			0.844			
		During Constr	653	109	43	152	1.057	1.503	1.154	1.25	1.78	**1.37**
I-40 Cataloochee	EB	Before Constr	474			50			0.745			
		During Constr	237	38	10	48	1.341	2.305	1.469	1.80	3.10	**1.97**
I-40 Cataloochee	WB	Before Constr	470			47			0.678			
		During Constr	235	45	31	76	1.913	6.069	2.654	2.82	8.95	**3.91**
I-26 North Pacolet	EB	Before Constr	84			10			0.569			
		During Constr	28	7	0	7	1.519	0.000	1.232	2.67	0.00	**2.16**
I-40 Pigeon River	WB	Before Constr	374			30			0.641			
		During Constr	187	24	4	28	1.141	1.262	1.157	1.78	1.97	**1.80**
I-40 Redland	EB	Before Constr	75			18			1.118			
		During Constr	25	5	8	13	1.052	5.340	2.079	0.94	4.77	**1.86**
I-40 Redland	WB	Before Constr	46			8			0.995			
		During Constr	23	6	1	7	1.391	1.304	1.378	1.40	1.31	**1.39**
I-40 Hunting Creek	EB	Before Constr	546			94			0.664			
		During Constr	826	102	87	189	0.693	1.328	0.889	1.04	2.00	**1.34**
I-40 Hunting Creek	WB	Before Constr	403			92			0.879			
		During Constr	624	83	58	141	0.768	1.056	0.865	0.87	1.20	**0.98**
All DZM Sites Combined		Before Constr	3343			502			0.758			
		During Constr	3593	524	312	836	0.930	1.514	1.087	1.23	2.00	**1.43**
Summary Statistics		**Before Construction**	Minimum						0.569			
Number of Sites	10		Maximum						1.118			
			Median						0.757			
			Mean						0.790			
			Standard Deviation						0.171			
			Margin of Error (95% Confidence)						0.106			
			95% Confidence Interval (Raw)						[0.685, 0.896]			
			95% Confidence Interval (Adjusted)***						[0.652, 0.863]			
		During Construction	Minimum				0.693	0.000	0.865	0.87	0.00	**0.98**
			Maximum				1.913	6.069	2.654	2.82	8.95	**3.91**
			Median				1.099	1.415	1.194	1.33	1.98	**1.61**
			Mean				1.176	2.187	1.398	1.57	2.73	**1.82**
			Standard Deviation				0.372	1.948	0.560	0.69	2.52	**0.82**
			Margin of Error (95% Confidence)				0.231	1.208	0.347	0.43	1.56	**0.51**
			95% Confidence Interval (Raw)				[0.945, 1.407]	[0.980, 3.395]	[1.050, 1.745]	[1.14, 2.00]	[1.17, 4.29]	**[1.32, 2.33]**
			95% Confidence Interval (Adjusted)***				[0.700, 1.161]	[0.306, 2.721]	[0.739, 1.434]	[0.80, 1.66]	[0.44, 3.56]	**[0.93, 1.94]**

* VMT: Vehicle-Miles Traveled ** Rate Ratio = Crash Rate During Construction ÷ Crash Rate Before Construction *** Adjusted confidence intervals are centered on the All DZM Sites Combined value

Table 5. Crash Counts and Rate Ratios (RRs) for CM sites.

Conventional Merge Sites	**Dir**	**Time Period**	**Days**	**Crash Count**			**Crashes Per 1,000,000 VMT***			**Crash Rate Ratio (RR)**		
				Upstream	**Work Zone**	**Total**	**Upstream**	**Work Zone**	**Total**	**Upstream**	**Work Zone**	**Combined**
I-95 Rocky Mount	NB	Before Constr	72	9	1	10			**0.420**			
		During Constr	10	4	0	4	1.406	0.000	**1.159**	3.35	0.00	**2.76**
I-95 Heathsville	NB	Before Constr	30	4	1	5			**0.468**			
		During Constr	9	4	2	6	1.439	3.095	**1.751**	3.07	6.62	**3.74**
I-77 Jonesville 1	NB	Before Constr	47	2	5	7			**0.632**			
		During Constr	42	12	8	20	1.639	3.896	**2.133**	2.59	6.16	**3.37**
I-40 Hunting Creek CM 1	WB	Before Constr	47	8	3	11			**0.884**			
		During Constr	82	24	9	33	1.627	1.920	**1.698**	1.84	2.17	**1.92**
I-40 Hunting Creek CM 2	WB	Before Constr	74	18	1	19			**0.980**			
		During Constr	50	4	17	21	0.426	4.910	**1.634**	0.43	5.01	**1.67**
I-95 Selma (Outlier)	NB	Before Constr	358	38	1	39			**0.419**			
Excluded from Summary Stats		During Constr	17	13	8	21	3.338	12.211	**4.615**	7.97	29.14	**11.02**
All CM Sites Combined			628	79	12	91			**0.534**			
			210	61	44	105	1.488	3.634	**1.978**	2.79	6.81	**3.71**
All CM Sites Except Selma			270	41	11	52			**0.672**			
			193	48	36	84	1.294	3.143	**1.730**	1.93	4.68	**2.58**
Summary Statistics		**Before Construction**	**Minimum**						0.420			
Number of Sites	5		Maximum						0.980			
Excluding I-95 Selma			Median						0.632			
			Mean						0.677			
			Standard Deviation						0.248			
			Margin of Error (95% Confidence)						0.218			
			95% Confidence Interval (Raw)						[0.459, 0.894]			
			95% Confidence Interval (Adjusted)**						[0.454, 0.889]			
		During Construction	Minimum				0.426	0.000	1.159	0.43	0.00	**1.67**
			Maximum				1.639	4.910	2.133	3.35	6.62	**3.74**
			Median				1.439	3.095	1.698	2.59	5.01	**2.76**
			Mean				1.307	2.764	1.675	2.26	3.99	**2.69**
			Standard Deviation				0.504	1.894	0.348	1.17	2.82	**0.90**
			Margin of Error (95% Confidence)				0.312	1.174	0.216	0.72	1.75	**0.56**
			95% Confidence Interval				[0.995, 1.620]	[1.591, 3.938]	[1.459, 1.891]	[1.53, 2.98]	[2.24, 5.74]	**[2.14, 3.25]**
			95% Confidence Interval (Adjusted)**				[0.982, 1.607]	[1.969, 4.317]	[1.515, 1.946]	[1.20, 2.65]	[2.93, 6.43]	**[2.02, 3.13]**

* VMT: Vehicle-Miles Traveled
** Rate Ratio = Crash Rate During Construction ÷ Crash Rate Before Construction
*** Adjusted confidence intervals are centered on the All DZM Sites Combined values

Table 6. Crash Modification Factors: DZM / Conventional Merge Sites.

Method 1: Ratio of Crashes per Million Vehicle-Miles Traveled (VMT) During Construction				
All Sites Except I-95 Selma		**Upstream**	**Work Zone**	**Combined**
	Crash Modification Factor (CMF)	0.72	0.48	**0.63**
	95% Confidence Interval	[0.53, 0.97]	[0.34, 0.68]	**[0.50, 0.79]**
	Crash Reduction Factor (CRF)	28%	52%	**37%**
	95% Confidence Interval	[3%, 47%]	[32%, 66%]	**[21%, 50%]**

Method 2: Ratio of Rate of Increase in Crashes During Construction				
All Sites Except I-95 Selma		**Upstream**	**Work Zone**	**Combined**
	Crash Modification Factor (CMF)	0.64	0.43	**0.56**
	95% Confidence Interval	[0.47, 0.87]	[0.28, 0.65]	**[0.43, 0.71]**
	Crash Reduction Factor (CRF)	36%	57%	**44%**
	95% Confidence Interval	[13%, 53%]	[35%, 72%]	**[29%, 57%]**

Table 7. Changes in Crash Severity and Crash Type (animal crashes excluded).

	Crash Severity			**Crash Type**					
	Fatalities + Serious Injuries			**Rear-End Crashes**			**Same-Direction Sideswipes**		
Time Period	**Before Constr**	**During Constr**	**Change**	**Before Constr**	**During Constr**	**Change**	**Before Constr**	**During Constr**	**Change**
All DZM Sites Combined	+5%	+4%	-1%	+20%	+44%	+24%	+17%	+18%	<1%
All CM Sites Excl. Selma	+9%	+5%	-5%	+19%	+60%	+41%	+15%	+7%	-8%
I-95 Selma	+5%	+10%	+5%	+16%	+43%	+27%	+32%	+38%	+6%

As shown in Table 4, pre-construction crash rates for the DZM sites ranged from 0.693 to 1.913 crashes per million vehicle-miles traveled. Similarly, Table 5 indicates the pre-construction crash rates for CM sites ranged from 0.426 to 1.639. These rates exclude animal crashes. In comparison, North Carolina's 2020-2024 average crash rates (including animals) were 0.790 for all rural Interstate highways, 1.345 for all urban Interstates, and 1.137 for Interstates overall (NCDOT 2025).

The rate ratio findings can be applied to predict the number of crashes in future North Carolina rural freeway work zones based on prior (non-construction) crash history. The process is as follows:

1. Extract the site's crash history data from the state crash database (e.g., TEAAS) for the month(s) of interest. Crash data from multiple years should be used to avoid sample size issues.
2. Separate the result into animal crashes (e.g., crashes involving deer) and non-animal crashes.
3. If CM will be used during construction, multiply the number of non-animal crashes by 2.58. If DZM will be used, multiply by 1.43.
4. Add the number of animal crashes from Step 2 to the estimated number of non-animal crashes from Step 3.
5. Adjust the sum in proportion to the expected construction duration. For example, if the initial crash count covered 90 days and the expected duration is 75 days, multiply by 75/90 = 0.83.

As shown in Table 7, the project team also attempted to explore the effects of DZM on crash severity and crash type. Due to small sample sizes, only limited information could be gleaned from this analysis. The data were insufficient to draw conclusions about the effect of DZM on crash severity. With moderate confidence, the team concludes that DZM was effective in reducing rear-end crashes in the work zones.

As noted earlier, the DZM systems were configured to operate as conventional merges when traffic volumes were below activation thresholds established by the NCDOT.

Table 8 explores how this affected the proportion of crashes that occurred during congested hours. As shown in the table, DZM sites experienced a lower overall percentage of crashes during congested hours (49%) compared to CM sites (57%).

The team concludes with moderate confidence that the DZM systems were effective in reducing crashes during the hours when they were operating in dynamic zipper mode. Stated differently, the majority of crashes at DZM sites occurred while the DZM systems were operating in "conventional" mode. Conversely, the majority of crashes at conventional sites occurred during congested hours, when DZM mode would have been activated if they had been so equipped. These benefits were particularly notable in the work zone lane closure areas, but less pronounced upstream in the approaches.

By reducing peak-hour crashes, DZM systems appear to have mobility and air quality co-benefits. These likely include fewer incident-related traffic delays during peak travel hours. For gasoline and diesel vehicles (but not electric vehicles), these reductions in stop-and-go traffic at incident sites are likely to result in fewer vehicle emissions and lower fuel consumption per mile driven. (The situation for electric vehicles differs due to energy recovery associated with regenerative braking, as well as aerodynamic drag reductions associated with lower speed).

Table 8. Percentages of crashes during congested hours.

DZM Sites	**Percentage of Crashes During Congested Hours**		
	Upstream	**Work Zone**	**Total**
I-77 Jonesville 2 NB	50%	54%	52%
I-77 Jonesville 2 SB	67%	56%	44%
I-40 Cataloochee EB	37%	50%	40%
I-40 Cataloochee WB	22%	10%	17%
I-26 North Pacolet EB	29%	Ø	29%
I-40 Pigeon River WB	71%	75%	71%
I-40 Redland DZM EB	40%	100%	77%
I-40 Redland DZM WB	100%	0%	86%
I-40 Hunting Creek DZM EB	41%	45%	43%
I-40 Hunting Creek DZM WB	35%	67%	48%
All DZM Sites Combined	**47%**	**51%**	**49%**
Conventional Sites	**Percent of Crashes During Congested Hours**		
	Upstream	**Work Zone**	**Total**
I-95 Rocky Mount NB	50%	Ø	50%
I-95 Heathsville NB	25%	0%	17%
I-95 Selma NB	38%	88%	57%
I-77 Jonesville 1 NB	83%	63%	75%
I-40 Hunting Creek CM 1 WB	58%	89%	67%
I-40 Hunting Creek CM 2 WB	25%	41%	38%
All CM Sites Combined	**54%**	**61%**	**57%**

Ø Indicates there were no crashes for this condition, so a percentage cannot be calculated.

Chapter 6. Operations

6.1. Operations Methodology

The operational performance of freeway work zones is a critical factor in balancing mobility, safety, and public tolerance during construction activities. Lane closures reduce effective roadway capacity and, if unmanaged, can result in long delays, growing queues, and driver frustration. These operational breakdowns not only hinder mobility but also heighten crash risk and can extend the duration of traffic impacts and project staging. DZM strategies have been developed to address these issues by dynamically adjusting merge control in response to traffic conditions. By better utilizing available lanes and delaying the onset of flow breakdown, DZM systems hold the potential to preserve traffic efficiency and improve user experience.

For the purposes of this study, operations are evaluated through three primary measures: speed, and travel time index. These metrics are especially valuable because they can be consistently and comprehensively obtained from probe data providers, ensuring scalable assessment across numerous work zones. Average speed provides an intuitive indicator of congestion severity and the overall pace of movement through the work zone. Travel time index adds another critical dimension by highlighting the predictability of travel.

Focusing on these three measures allows for a rigorous, data-driven evaluation of operational impacts that is both scalable and meaningful to practitioners. Together, they capture the efficiency, severity, and consistency of traffic operations in work zones. Improvements in average travel time and speed demonstrate mobility gains, while enhanced TTI underscores that these gains are dependable across different traffic conditions. By tying operational performance to these key outcomes, agencies can more clearly assess the effectiveness of dynamic zipper merges, quantify benefits relative to conventional merge strategies, and make informed decisions about future deployments.

6.1.1. Speed

Speed is an intuitive and widely used operational measure that complements travel time by providing a direct indication of congestion severity. In ClearGuide, average speed is calculated as the mean of probe vehicle observations for each 15-minute aggregation period. For this study, both average speeds and free-flow speeds (representing expected conditions under uncongested volumes) were obtained for each route segment. Comparing the observed average speed with the free-flow benchmark highlights the degree of performance degradation in work zones. This allows for a clearer understanding of whether DZM treatments help sustain more stable flow conditions compared to conventional merging practices. Since speed is easier to interpret than travel time for many practitioners and stakeholders, it serves as an accessible measure of operational effectiveness.

6.1.2. Travel Time Index

While average speed describes typical operating conditions, TTI defined as the ratio of average travel time to free-flow travel time captures the variability that drivers experience across different days and time periods. The TTI was derived directly from ClearGuide's route reports using 15-minute resolution data. A higher TTI indicates that travel times deviate more significantly from free-flow conditions, signaling highly congested operations. From an agency perspective, improving travel time index in work zones demonstrates that mobility benefits are not only realized under average conditions but are also consistent across recurring traffic states. Comparing TTI values between DZM and CM sites provides insight into whether dynamic merging contributes to more dependable operations.

6.1.3. Methodological Framework for Comparisons

In evaluating the operational impacts of each work zone type, the analysis was structured as a before-and-after study at each site. For both DZM and CM locations, operational measures were first compared to their respective baseline (before-work-zone) conditions. The differences observed within each site type were then compared across groups to isolate the effects attributable to the merge strategy rather than site-specific characteristics. To further ensure comparability, sites were selected such that their Average Daily Traffic (ADT) values during construction were in the same general range. This combination of before-and-after analysis and careful site selection allows for an apple-to-apple comparison of operational performance between DZM and conventional work zones.

6.2. Operational Analysis

This section presents the evaluation of DZM and CM treatments across multiple operational performance measures. The analysis begins with a comparison of traffic volumes at the selected sites to ensure the groups are broadly comparable. It then examines site-specific case studies to illustrate how speeds and travel time index changed before and during work zone operations. Building on these site-level insights, aggregated comparisons are provided to evaluate differences between the DZM and the CM across all sites, with statistical testing applied to assess whether observed differences are significant. Together, these analyses provide a comprehensive picture of the operational impacts of the two merge strategies.

6.2.1. Treatments and Comparison Groups

The study included two groups of work zone sites: those implementing DZM treatments and those operating under CM configurations. The estimated AADT during construction for all sites in both groups is shown in Figure 17. As the figure illustrates, there is considerable variation in traffic volume across sites, with some locations carrying very high AADT volumes and others carrying much lower volumes. Because the objective of this analysis is to compare operational performance across treatments under comparable demand conditions, it was necessary to remove extreme outliers to ensure an apples-to-apples comparison.

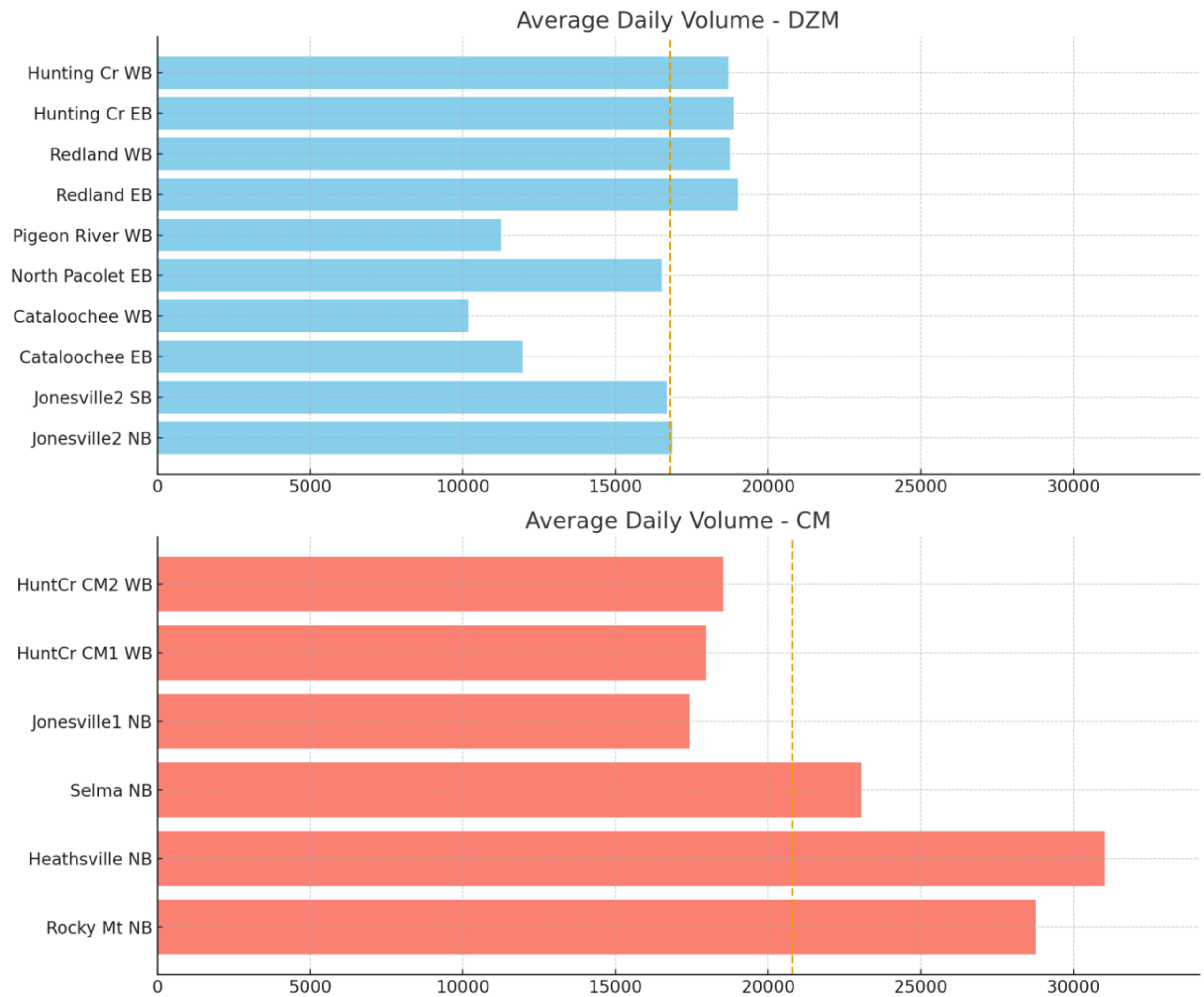


Figure 17. Estimated ADT for a) Dynamic Zipper Merge Sites and b) Conventional Merge Sites. The yellow dashed line shows the median value for each group.

To ensure that DZM and CM sites are compared under similar demand conditions, all sites were initially grouped into three ADT-based volume buckets: <15,000 ADT, 15,000–20,000 ADT, and >20,000 ADT. This stratification was necessary because speed, delay, and TTI vary strongly with traffic volume, and combining sites across substantially different volume ranges would produce biased treatment effects. After assigning sites to these buckets, it became clear that the <15,000 and >20,000 ranges were not represented in both treatment groups. Because a balanced comparison requires DZM and CM sites to coexist within the same demand bucket, all sites falling outside the 15,000–20,000 ADT range were removed. As a result, the 15,000–20,000 ADT bucket serves as the sole comparison group, and all operational metrics—speed change, TTI change, and statistical analyses—are evaluated within this consistent and comparable demand range. The updated sites are shown in Figure 18.

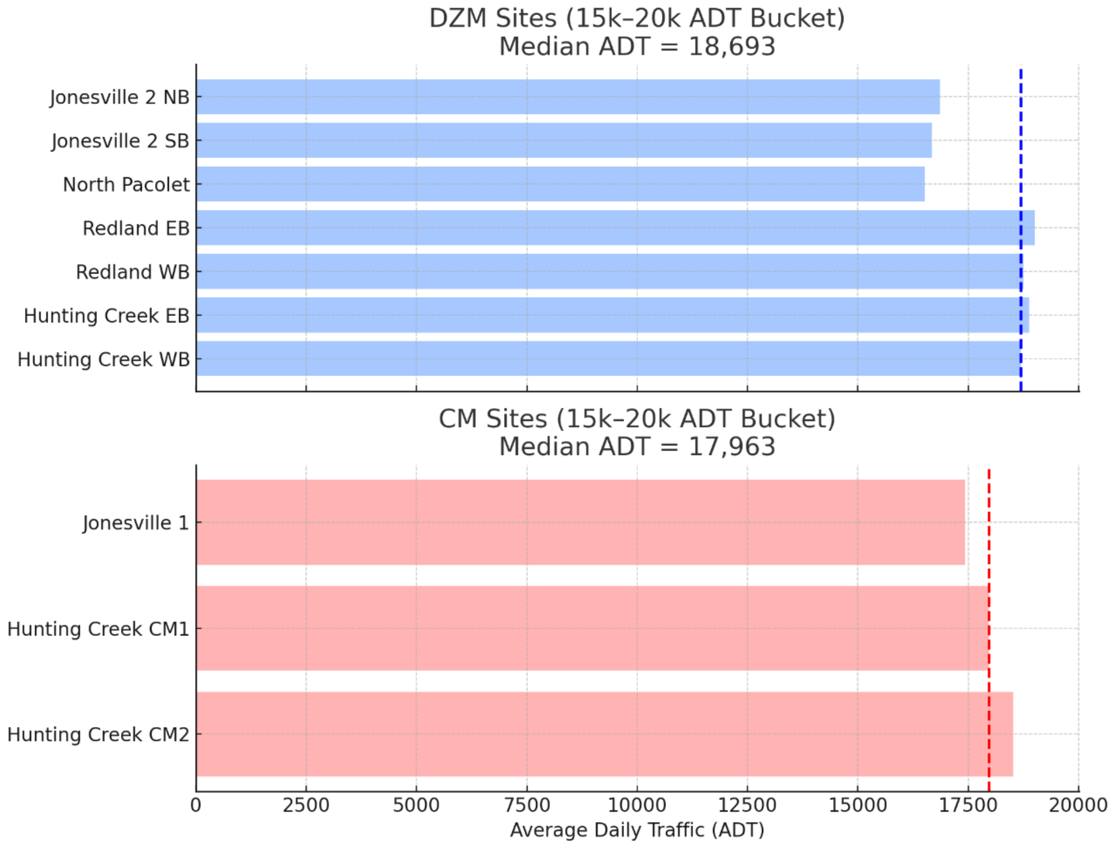


Figure 18. ADT for DZM (top) and CM (bottom) sites within the 15k–20k bucket. Bars show individual site ADT, with dashed lines marking group medians.

After the stratification, the resulting datasets for DZM and CM contained sites with ADT levels that are much more comparable in scale. A Mann–Whitney U test was conducted to evaluate whether the DZM and CM sites within the 15,000–20,000 ADT bucket are statistically comparable in terms of traffic demand. The results show no significant difference between the two groups ($U = 12.0$, $p = 0.83$), indicating that their ADT distributions are highly similar. This confirms that the bucket is well balanced and that differences observed later in operational performance measures—such as speed or TTI—are unlikely to be driven by differences in traffic volume.

6.2.2. Speed

Speed is a critical measure of operational performance in work zones because it provides a direct and intuitive indicator of congestion severity. While travel time reflects overall delay, speed highlights the immediate impact of lane closures and merge strategies on driver experience. Sustaining higher speeds through work zones not only improves mobility but also reduces the likelihood of long queues and secondary crashes. Accordingly, speed serves as an important lens for assessing the effectiveness of the DZM compared to CM treatments.

Figure 19 presents the aggregated average speed profiles for all DZM sites, comparing conditions before the work zone and during the DZM deployment. In the before period, speeds remain stable and close to free-flow levels throughout most of the day across all days of the week. During the work-zone period, however, the combined DZM sites show noticeable reductions in speed during the late morning and afternoon hours, with the most pronounced effects occurring around the PM peak. Despite these localized slowdowns, speeds outside the highest-demand periods remain relatively stable, indicating that, on average, DZM sites maintain more consistent flow for a large portion of the day.

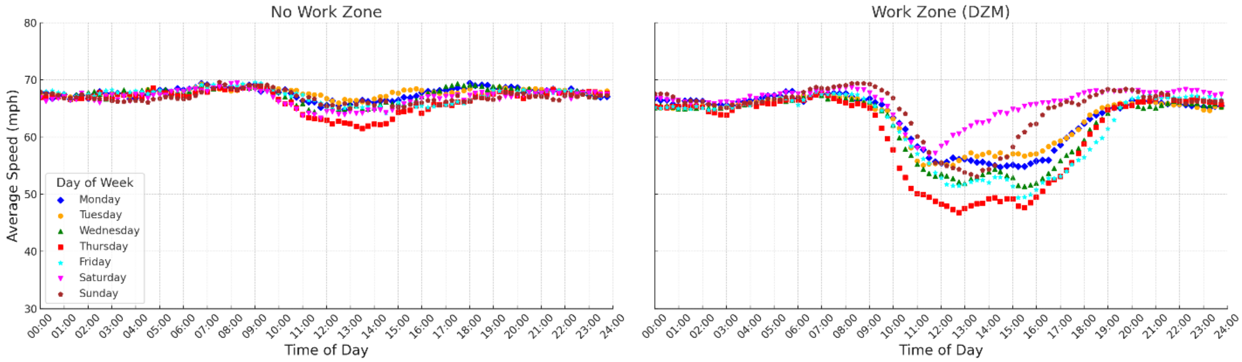


Figure 19. Average 15-minute speed profiles by time of day for DZM sites, comparing No Work Zone and Work Zone periods across all weekdays.

Figure 20 shows the aggregated average speed profiles for all CM sites, comparing the before-work-zone period to the work-zone period. Similar to the DZM group, speeds in the before period remain stable and close to free-flow levels across all days of the week. However, during the CM period, the combined sites exhibit substantial and sustained speed reductions, particularly from the late morning through the afternoon hours. These declines are deeper and persist longer than those observed at DZM sites, with several weekdays showing pronounced midday and PM-peak slowdowns. The pattern indicates that, on average, CM work zones experience more severe and more prolonged speed degradation, suggesting that CM treatments are less effective at maintaining throughput under higher-demand conditions. Similar off-peak stability observed for DZM sites is also present at CM sites; however, CM sites experience larger and more sustained speed reductions during the late morning through PM peak periods compared to DZM.

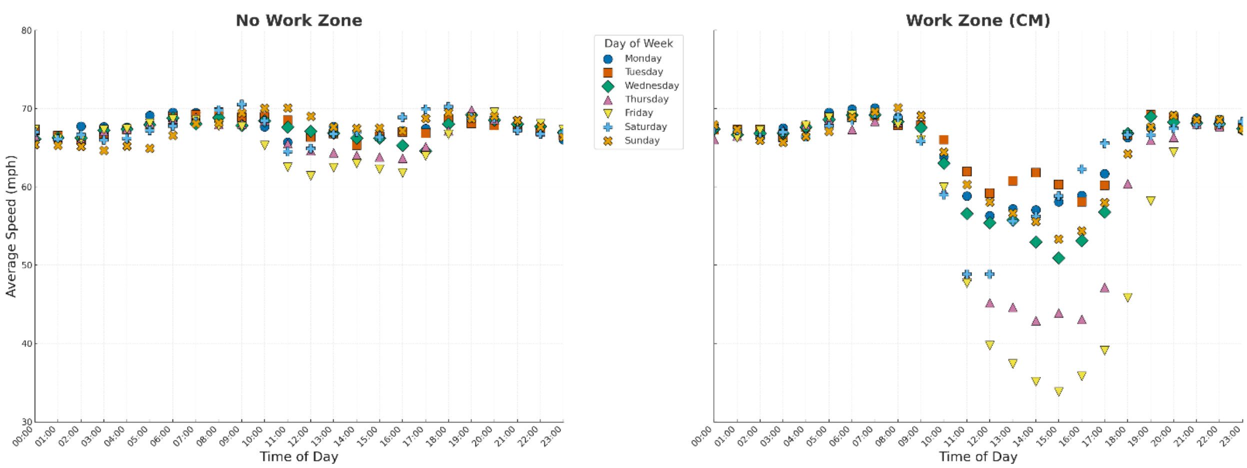


Figure 20. Average 15-minute speed profiles by time of day for CM sites, comparing No Work Zone and Work Zone periods across all weekdays.

Figure 21 summarizes the average speed percent change for DZM and CM sites across multiple time periods. The results show that both treatments experience speed reductions, but the relative patterns vary by period. Overall, the sites exhibit almost identical drops. On weekdays, the reductions are similar, with DZM showing a slightly larger decline. On weekends, however, CM sites experience a noticeably steeper reduction, while DZM sites show a more moderate drop. During the AM peak, speed reductions are minimal for both treatments. In contrast, the PM peak shows the most pronounced decline for both groups, with CM sites experiencing the largest loss, while DZM sites retain higher relative speeds. Overall, the aggregated results indicate that speed impacts vary by period, with CM sites showing larger reductions during weekends and PM peak, whereas weekday and AM-peak differences between treatments are small.

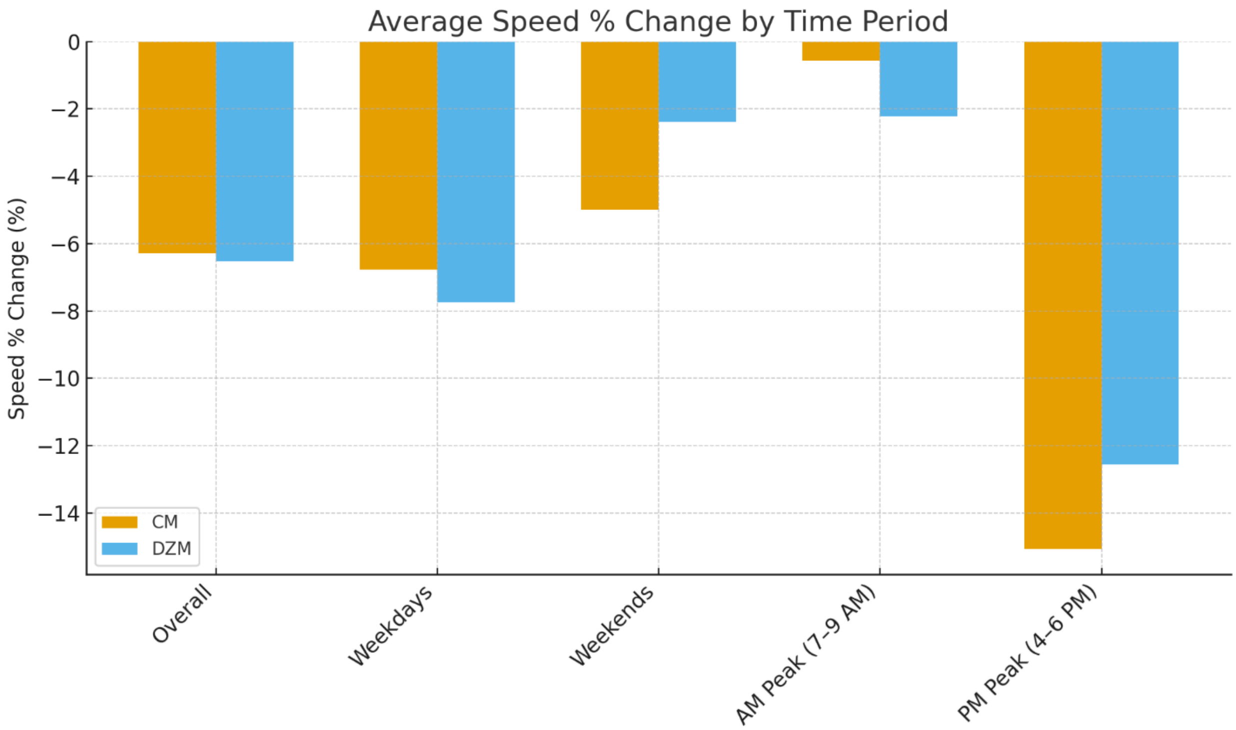


Figure 21. Average speed percent difference by time period, comparing DZM and CM sites.

To evaluate differences in speed performance between the CM and DZM programs, a before–and–after change analysis was conducted using all available raw 15-minute observations. For each treatment and time period, a change value (Δ) was computed by subtracting the mean Before-period speed from every 15-minute After-period speed measurement. This produced two distributions—ΔCM and ΔDZM—that represent how speeds shifted from the Before to After period for each treatment.

Because traffic data are non-normal and the sample sizes are large and unbalanced, the Mann–Whitney U test was used to compare the Δ distributions across the two programs. This non-parametric test does not assume normality and is well-suited for high-volume transportation datasets. Tests were performed for the Overall period, Weekdays, Weekends, AM Peak, and PM Peak, with all time-of-day classifications based on local time.

Results of the statistical tests are summarized in Table 9. Both programs experienced reductions in speed from before to after in most periods. In the Overall and Weekday periods, differences between CM and DZM were statistically significant, but the magnitudes—typically less than one mph—are small and not operationally meaningful. During AM Peak, CM showed a slight improvement while DZM declined, resulting in a statistically significant, but practically negligible difference in favor of CM. During PM Peak, both programs experienced substantial reductions, with CM exhibiting a larger decline. Weekend differences were not statistically significant.

Table 9. Results of Mann–Whitney U Δ-Speed Test (CM vs DZM)

Period	ΔCM (mph)	ΔDZM (mph)	p-value	Interpretation
Overall	−4.227	−4.381	0.0000	Statistically significant; small practical difference
Weekdays	−4.540	−5.212	0.0000	Statistically significant; DZM decreased slightly more
Weekends	−3.367	−1.592	0.966	No significant difference
AM Peak	+0.186	−1.448	0.0000	CM improved; DZM declined
PM Peak	−12.251	−8.686	0.0126	CM declined more than DZM

In summary, although several periods show statistically detectable differences between CM and DZM, most differences are modest in magnitude and should be interpreted with consideration of their practical impacts. The most meaningful period-level findings occur during the AM Peak—where CM performs relatively better—and the PM Peak—where CM shows a more pronounced decline.

6.2.3. Travel Time Index

As mentioned above, travel time index is an important measure for assessing the impact of DZM compared to CM treatments. To explore this, probe vehicle data were downloaded for representative DZM and CM sites, and developed TTI heatmaps to visualize conditions before and during the work zone periods. These heatmaps provide an intuitive way to assess how work zones affect recurring congestion, with lower TTI values (closer to 1.0) representing near-free-flow travel and higher values indicating more delay and nigh recurring congestion **.** The following two figures show example sites for each treatment.

Figure 22 presents TTI heatmaps comparing aggregate conditions across all sites during periods with No Work Zone activity and during DZM work zone operations. Under No Work Zone conditions, TTI remains consistently low throughout the week, with only minor increases appearing around midday and early afternoon on select weekdays. In contrast, the DZM heatmap shows a clear pattern of elevated TTI across multiple days, with the most pronounced increases occurring during the midday and PM hours, especially on Fridays. Additional pockets of higher TTI extend into weekend afternoons, indicating that work zone effects influence recurring congestion even outside traditional weekday peaks. Overall, the aggregated DZM conditions exhibit higher and more widespread TTI increases, concentrated in midday and PM periods when demand is stronger, rather than uniform impacts across the entire day.

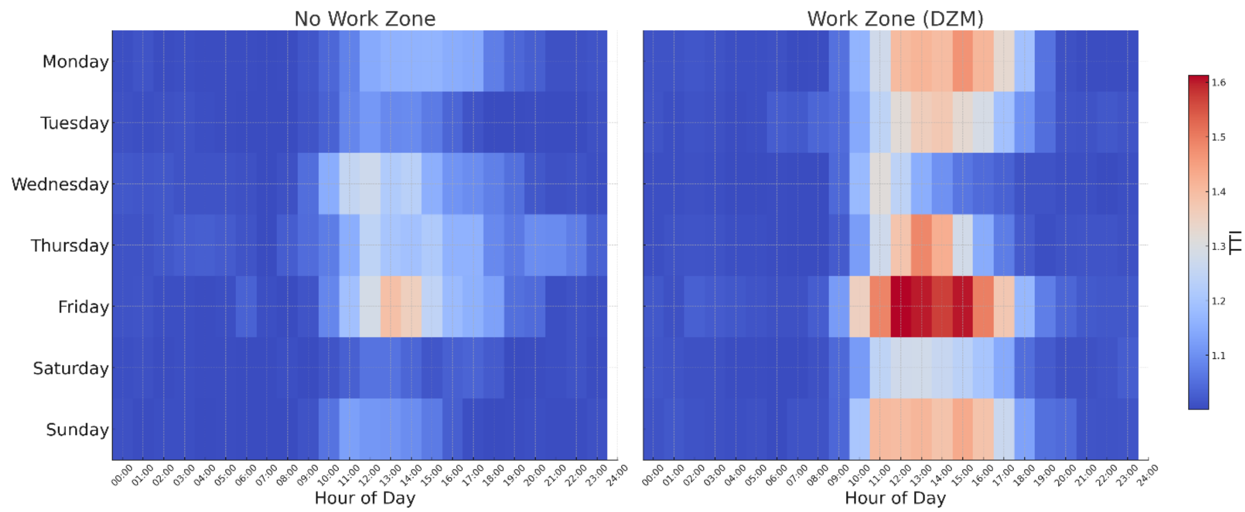


Figure 22. Hourly average Travel Time Index (TTI) heatmaps for DZM sites comparing No Work Zone and Work Zone conditions across all weekdays.

Figure 23 presents TTI heatmaps comparing aggregate conditions across all CM sites under No Work Zone conditions and during CM work zone operations. The No Work Zone heatmap shows consistently low TTI values throughout the week, with only minor increases appearing around the midday period on certain weekdays. In contrast, the CM work zone heatmap exhibits substantially higher and more widespread TTI increases, particularly during the midday and afternoon hours from Wednesday through Friday. The most intense TTI degradation occurs on Friday, where the levels rise sharply and persist over a longer portion of the day. This pattern indicates that, when aggregated across all CM locations, conventional work zone configurations are associated with broader and more sustained impacts on recurring congestion, especially during high-demand midday and PM periods.

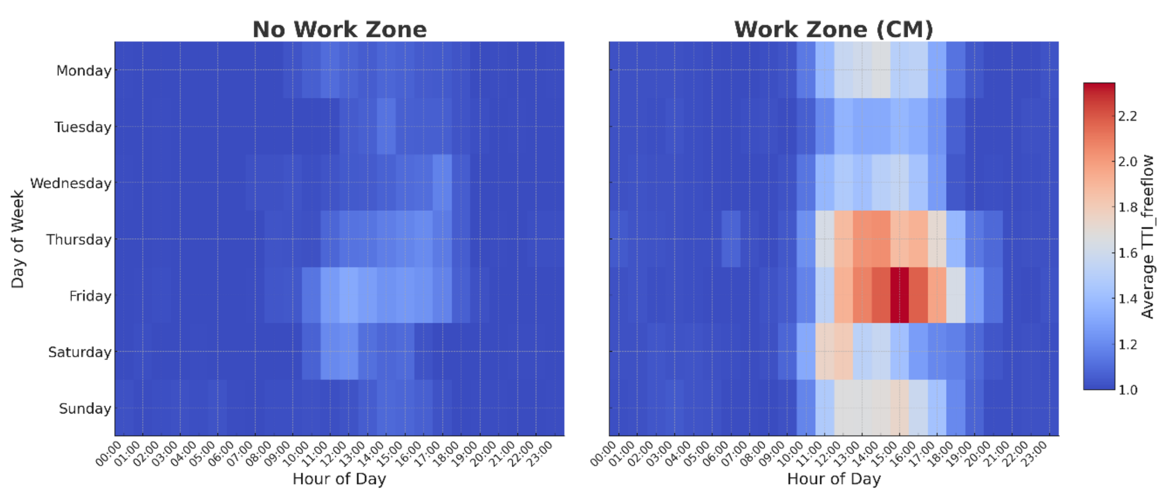


Figure 23. Hourly average Travel Time Index (TTI) heatmaps for CM sites comparing No Work Zone and Work Zone conditions across all weekdays.

Figure 24 compares the average TTI percent change for the CM and DZM treatments across five time periods: Overall, Weekdays, Weekends, AM Peak, and PM Peak. Across all periods, CM exhibits noticeably higher TTI increases than DZM. The differences are especially pronounced during the PM Peak period, where CM shows more than double the percent increase observed at DZM sites. Weekday and

Weekend periods show a similar pattern, with CM displaying substantially larger TTI increases than DZM. Even during the AM Peak, where overall changes are small for both treatments, CM still shows a slightly higher increase. Taken together, the figure indicates that DZM consistently outperforms CM in terms of limiting TTI growth, with the most meaningful advantages occurring during midday and PM peak travel periods.

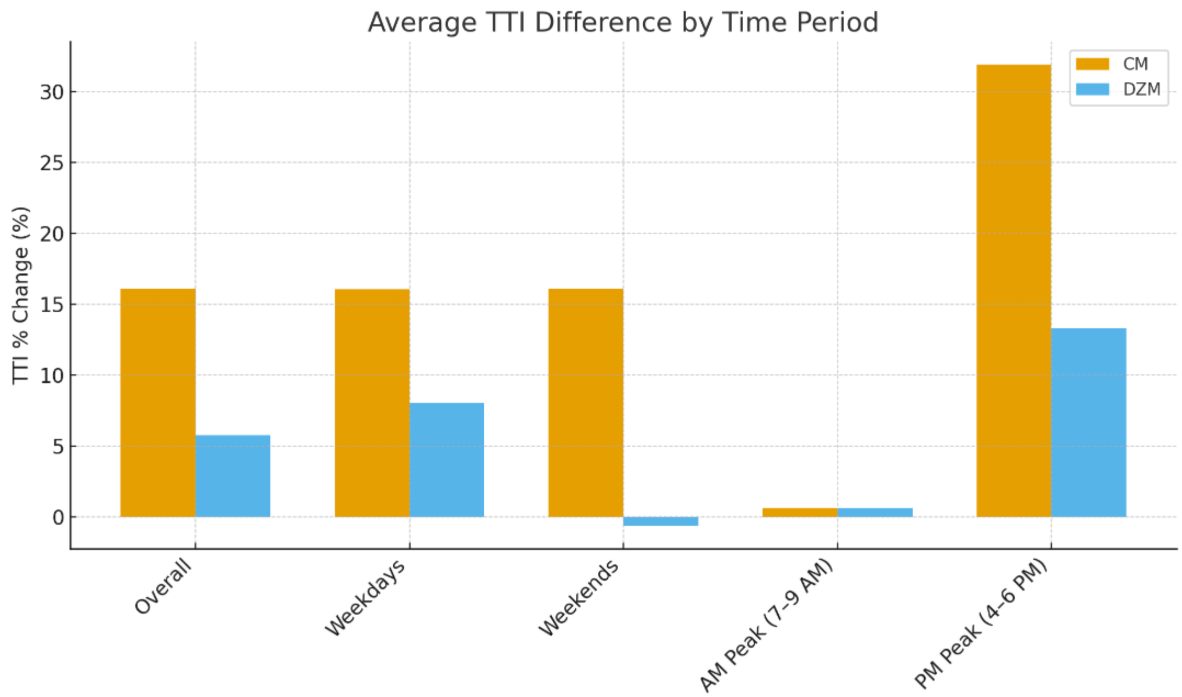


Figure 24. Comparison of TTI % between Dynamic Zipper and Conventional Merge by time periods

To evaluate changes in travel-time index between the CM and DZM programs, a before–and–after analysis was performed using all available 15-minute TTI observations. For each program and time period, a change value (Δ) was calculated by subtracting the mean Before-period TTI from each 15-minute After-period TTI value. This produced two distributions—ΔCM and ΔDZM—that describe how TTI shifted from the Before to After period for each program across all recorded time intervals.

Because TTI data are non-normal and the dataset contains large and unbalanced sample sizes, the Mann–Whitney U test was used to compare the CM and DZM Δ distributions. This non-parametric test is appropriate for traffic measures such as TTI, which often exhibit skewness and heavy tails. The analysis was conducted for Overall, Weekday, Weekend, AM Peak, and PM Peak periods based on local-time classifications.

A summary of the results is provided in Table 10. In nearly all periods, TTI increased (worsened) from Before to After for both programs. However, CM generally experienced a larger increase in TTI relative to DZM, indicating a greater degradation in travel-time reliability. The differences between ΔCM and ΔDZM were statistically significant in every period. Although the magnitudes vary, the PM Peak period shows the most meaningful difference, with CM experiencing a substantially larger TTI increase. During AM Peak, both programs experienced minimal changes, and while the statistical test shows significance due to sample size, the practical difference is small.

Table 10. Results of Mann–Whitney U Δ-TTI Test (CM vs DZM)

Period	**ΔCM (TTI)**	**ΔDZM (TTI)**	**p-value**	**Interpretation**
Overall	+0.1670	+0.0611	0.0000	CM TTIworsened more
Weekdays	+0.1673	+0.0843	0.0000	Statistically significant; CM worsened more
Weekends	+0.1656	−0.0070	0.0000	CM worsened; DZM improved slightly
AM Peak	+0.00142	+0.00579	0.0000	Both nearly unchanged; small practical diff
PM Peak	+0.4206	+0.1532	0.0000	CM worsened much more than DZM

Overall, the TTI analysis indicates that conditions worsened for both programs, but CM consistently exhibited a larger increase in TTI across all periods. These results suggest that, relative to DZM, the CM program experienced greater deterioration in conditions in the after period, with the most notable effects occurring during the PM Peak and Weekend periods.

Chapter 7. Work Zone Evaluation Tool

This chapter presented a configurable evaluation tool that was developed to compare the operational effects of conventional and dynamic zipper merges in work zones. The tool was built on the most recent procedures from the *Highway Capacity Manual (HCM)* and was designed to assist analysts in assessing work zone performance by incorporating observed and estimated traffic demand, work zone capacity, and queue formation (HCM, 2022). Seasonal and directional factors were also included, allowing scenario-based decision making to identify the conditions under which various merge strategies provided the greatest benefit.

In practice, the tool allows practitioners to explore and answer questions such as:

- Go/no-go guidance: Under what roadway and traffic conditions should dynamic zipper merges be implemented instead of conventional merging?
- Activation thresholds: When should DZMs be activated to maximize effectiveness?
- Queue planning: How long would queues be, and where should CMS signs or other traffic control devices be placed?
- Motivations and benefits: What advantages did dynamic zipper merges provide over conventional merging at specific demand levels?
- Capacity: What did observed headways suggest about pre- and post-breakdown capacities?
- Queue metrics: How could queue length and growth be measured consistently across sites?
- Performance by conditions: How did queue growth vary by merge type, traffic demand, and heavy-vehicle percentage?

7.1. Traffic Demand

A critical input to the Work Zone Evaluation Tool was traffic demand, which was derived from AADT and converted into peak-hour flow rates suitable for HCM-based capacity evaluation. Adjustments were applied to account for seasonal variation and day-of-week patterns.

7.1.1. AADT to Peak Hour Volume

Peak-hour volumes were estimated using two key factors:

- K-Factor: The K-factor represented the proportion of daily traffic occurring during the peak hour. Five K-factor groupings were used based on North Carolina-specific data (Searcy et al, 2018), noted below, and visualized in Figure 26.
    1. Two minor peaks
    2. One minor and one major peak
    3. Two major peaks
    4. Three peaks
    5. Tourist area peak patterns

- D-Factor: The D-factor reflected directional distribution. Analysts defined this factor using field data or informed estimates. Recommended values typically ranged between 0.5 and 0.7 (corresponding to 50–70% in the peak direction). For estimation, the D-factor was applied only during morning (5:00–9:00 a.m.) and afternoon (2:00–7:00 p.m.) periods. Outside these hours, traffic was assumed to operate at a balanced 50% directional split (D = 0.5).

7.1.2. Hourly Flow Conversion

Peak-hour volumes were further refined through the following adjustments:

- Peak Hour Factor (PHF): Accounted for flow concentration within the peak hour by adjusting for uneven 15-minute subintervals.
- Heavy Vehicle Adjustment: Converted mixed traffic into passenger car equivalents (PCEs) based on the proportions of single-unit trucks (SUTs) and tractor-trailers (TTs). Single-use trucks are described as shorter, rigid-frame trucks such as delivery vehicles. Tractor-trailers are longer combination vehicles with a higher impact on capacity.

Lookup tables, such as those available from the NCDOT's Traffic Survey Group, were used to select representative heavy-vehicle splits. Three ratio options for SUTs and TTs were provided:

- SUT (50%) / TT (50%)
- SUT (70%) / TT (30%)
- SUT (30%) / TT (70%)

Applying these adjustments produced standardized peak-hour demand in passenger cars per hour per lane (pcphpl), which served as the input for all capacity comparisons.

These adjustments provide passenger cars per hour per lane (pcphpl), the required input for capacity comparison.

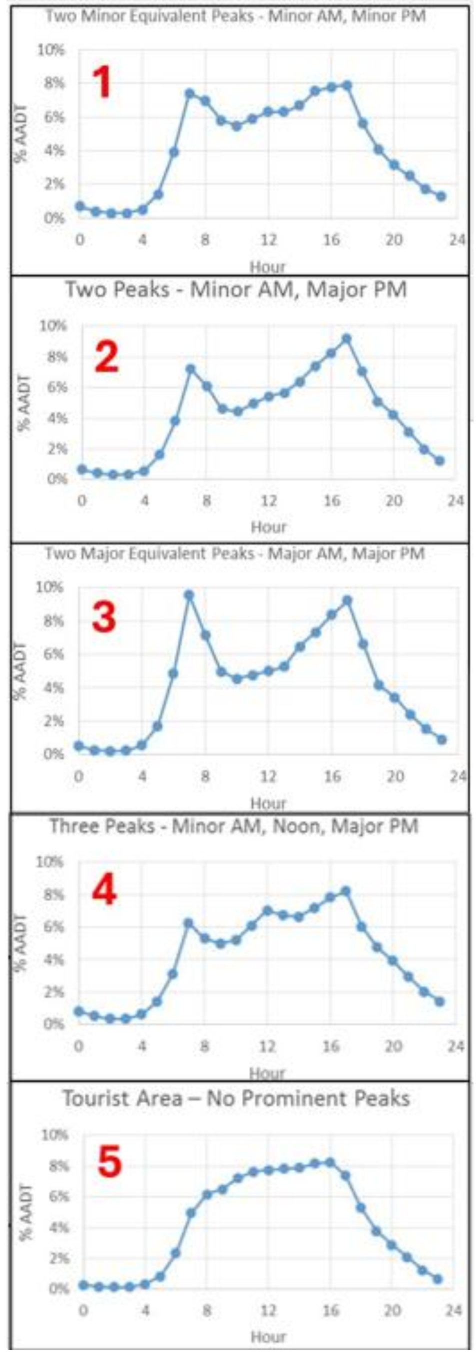


Figure 25. "Peaking" options for estimating traffic across the full 24-hour day (Search et al., 2018)

7.1.3. Seasonal and Daily Adjustments

The tool incorporated 12 seasonal factor groups provided by the NCDOT's Traffic Survey Group (six for interstate and six for non-interstate facilities) (Poslusny, 2025). This allowed analysts to evaluate monthly variation, yielding 13 time periods (12 months plus an "average month" option).

Day-of-week adjustments were also included, enabling analysis for an average day or for any of the seven individual days (Sunday through Saturday). Combined, these provided eight day-type options.

Seasonal and day-of-week factor groups are regularly updated by the Transportation Data Management System (TDMS) of the Transportation Mobility and Safety Division (TDMS). As data is updated by the TDMS, it can be populated into the "Mthly & Daily Factors" sheet of the tool.

7.2. Estimating Capacity and Queue Length

Accurate estimation of capacity and queue length is critical for evaluating work zone performance and comparing merge strategies. Capacity determines the maximum sustainable flow through the bottleneck under both uncongested and congested conditions, while queue length quantifies the extent of traffic spillback once demand exceeds this capacity. Together, these measures provide the foundation for assessing operational efficiency, user delay, and safety risk. The Work Zone Evaluation Tool incorporated *Highway Capacity Manual* (HCM) procedures for conventional merges and supplemented them with field-based adjustments for dynamic zipper merges, ensuring that estimates reflected both national guidance and North Carolina–specific operating conditions.

7.2.1. Capacity Estimation

7.2.1.1. Conventional Merge (HCM Procedure)

Post-breakdown capacity, or the Queue Discharge Rate (QDR), was estimated using the HCM formula (HCM 2022), page :

$$QDR = 2{,}093 - (154 \times LCSI) - (194 \times f_{BR}) - (179 \times f_{AT}) + (9 \times f_{LAT}) - (59 \times f_{DN})$$ **Equation 1**

where:

- LCSI = merge strategy (assumed 2:1 lane drop = 2.0)
- f_{BR} = barrier type (hard = 0, soft = 1
- f_{AT} = area type (urban/suburban = 0, rural = 1)
- f_{LAT} = lateral distance to barrier (nearest 0.5ft)
- f_{DN} = day/night factor (day = 0, night = 1)

Once the post-breakdown capacity is computed, *pre-breakdown capacity*, c_{wz}, for the CM can be estimated. Pre-breakdown capacity reflects the flow rate before breakdown occurs. It can be calculated using the following equation (HCM 2022):

$$c_{WZ} = \frac{QDR}{1-\alpha_{WZ}}$$ **Equation 2**

where α_{wz} is the capacity drop, typically ranging from 10–15%. For conventional work zone sites, the HCM recommends a default value of 13.4% when site-specific data are unavailable.

7.2.1.2. Dynamic Zipper Merge (Field Estimated)

The research team was specifically tasked with developing a procedure that could evaluate both conventional and DZM sites. While the HCM provides a structured approach for conventional work zone capacity analysis, it does not include a method for analyzing zipper merges and has not been calibrated to North Carolina–specific conditions. To address this gap, the Work Zone Evaluation Tool incorporated field data collected at a representative zipper merge site on I-40 westbound near mile marker 20.

This location was selected for several reasons. First, it was a rural interstate corridor along a major route, which reflected the most common applications of zipper merges within North Carolina. Second, the lane-drop area contained little to no grade, reducing the influence of geometric factors. Third, the work zone used a hard-barrier design, which, according to HCM guidance, provides the highest potential capacity. Finally, although the site carried a relatively high percentage of heavy trucks, traffic streams frequently contained platoons of passenger cars between heavy vehicles. These conditions allowed the research team to isolate and measure passenger car headways under near-ideal conditions in the single downstream lane of the DZM.

At this site, saturation headways were measured between passenger cars in queues of five or more vehicles, following the data collection approach described in Section Chapter 1. A time-stamp macro was used to record vehicle arrival times, and outliers with headways greater than five seconds were removed. Average and median headways were then calculated for both pre-breakdown and post-breakdown periods, as illustrated in Table 11. Using these values, capacity was estimated from the fundamental traffic flow relationship:

$$c = \frac{3600}{\bar{h}} \qquad \textbf{Equation 3}$$

where,

- c = capacity (veh/h/ln)
- $\bar{h}$ = average saturation headway (sec/veh)

Table 11. Estimates of capacity for pre- and post-breakdown based on headways

Measure	Pre-Breakdown		Post-Breakdown		% Capacity Reduction
	Headway (s)	Capacity (pcphpl)	Headway (s)	Capacity (pcphpl)	
Average	1.98	1,822	2.33	1,643	-9.80%
Median	1.80	2,000	1.93	1,865	-6.75

The average headways collected during pre-breakdown and post-breakdown conditions produced corresponding capacity estimates. Because dominant outliers had already been removed, the average values were adopted as the basis for determining pre- and post-breakdown capacities at the zipper merge site.

From these estimates, the capacity drop for dynamic zipper merges, α_{wz_DZM} (capacity drop) was calculated by comparing the post-breakdown and pre-breakdown capacities. The results indicated a reduction of 9.8%, which was notably lower than the HCM default of 13.4% for conventional work zones. This finding suggested that dynamic zipper merges improved capacity by approximately 3% to 4% relative to conventional merges.

7.2.1.3. Model Calibration

The team then used the same data collected for Section 4.4 to develop an NC-specific calibration factor for *pre-breakdown* capacity calculated from the HCM procedure. To do this, the team first had to estimate the *post-breakdown capacity,* QDR, for a CM using Equation 1 and the I-40 site characteristics noted below.

- merge strategy (LCSI): hard barrier = 2.0;
- barrier type (f_{BR}): hard barrier = 0;
- area type (f_{AT}): rural = 1;
- lateral distance to barrier (f_{BR}): 1.0 ft; and
- day or night factor (f_{DN}): day = 0.

$$QDR = 2{,}093 - (154 \times LCSI) - (194 \times f_{BR}) - (179 \times f_{AT}) + (9 \times f_{LAT}) - (59 \times f_{DN})$$

$$QDR = 2{,}093 - (154 \times 2.0) - (194 \times 0) - (179 \times 1) + (9 \times 1.0) - (59 \times 0)$$

$$QDR = 1{,}615 \ pcphpl$$

Next, the *pre-breakdown* capacity for a standard work zone is estimated using the default capacity reduction, α_{wz}, of 13.4%.

$$c_{WZ} = \frac{QDR}{1 - \alpha_{WZ}} = \frac{1{,}615}{1 - 0.134} = 1{,}865 \ pcphpl$$

The calibration factor, CF, is then computed using the *HCM estimated* pre-breakdown capacity (1,865 pcphpl) and the *field estimated* pre-breakdown capacity (1,822 pcphpl) in Table 11.

$$CF = \frac{c_{Field}}{c_{HCM}} = \frac{1{,}822}{1{,}865} = 0.977$$

Because this value was close to 1.0, the HCM procedure was assumed to reasonably replicate North Carolina work zone capacities.

7.2.2. Comparing Flow and Capacity

To determine when queues were present, hourly demand was compared against pre- and post-breakdown capacities for day and night conditions. Nighttime capacities were reduced by 59 pcphpl to reflect the day/night factor. For consistency, nighttime was defined as 25 minutes after sunset to 25 minutes before sunrise (civil twilight).

The comparison logic follows these steps:

1. Compare hourly demand to pre-breakdown capacity
   - If demand ≤ pre-breakdown capacity → no queue forms
   - If demand > pre-breakdown capacity → queue forms
2. Use post-breakdown capacity while queue exists
   - If demand + remaining queue from previous period > post-breakdown capacity → continue using post-breakdown capacity
   - If demand + remaining queue from previous period ≤ post-breakdown capacity → revert back to using pre-breakdown capacity

7.2.3. Queue Length Estimation

Queue length was primarily influenced by three factors: the type of merge strategy employed (conventional versus DZM), the density of vehicles within the queue (i.e., jam density), and temporal variations in traffic volumes by season and day. Once queues were present, their length was estimated as the number of passenger cars that exceeded the post-breakdown capacity of the work zone. Jam density was then applied to convert these excess passenger cars per hour per lane (pcphpl) into physical distance.

Based on HCM guidance, jam density values typically ranged from 150 to 250 passenger cars per mile per lane. In cases where field-validated values were not available, the HCM recommended a default jam density of 220 vehicles per mile. The queue length in miles was therefore calculated as the ratio of excess demand to jam density. It is important to note that the resulting queue length represented the number of vehicles if they were all stacked into a single lane.

After the total back-of-queue length was estimated, it was distributed across the open and closed lanes upstream of the taper according to lane distribution factors developed for conventional and zipper merge conditions. The subsections below describe the estimation procedures for each merge type.

7.2.3.1. Conventional Merge

Under CM conditions, drivers tended to abandon the closing lane earlier as queues lengthened, producing increasingly unbalanced lane use near the taper. This early-merge pattern was documented in several field studies, including recent pooled-fund evaluations in Missouri and Michigan, as well as earlier research by McCoy and Pesti (2002) and MnDOT (2004). These studies consistently showed that long queues at uncontrolled lane drops concentrated the majority of traffic in the open lane, with the closing lane carrying only a small share near the taper.

To capture this relationship, the tool applied a method originally developed by McCoy and Pesti. The basic premise of this method was that as the standing queue increased, the proportion of traffic remaining in the closing lane decreased proportionally. The procedure is straightforward and starts by utilizing the excess demand, “N” in pcphpl, for each hour that cannot be processed using the post-breakdown capacity. The proportion of vehicles in the open (P_o) and closed (P_c) lanes is then calculated as follows, with the procedure consisting of two steps:

1. Back-of-queue distance. The number of excess vehicles, N, measured in pcphpl for each hour that could not be processed under post-breakdown capacity, was converted to distance using jam density. Because both upstream lanes were assumed to be filled at jam density (k_j), the back-of-queue length was estimated as:

$$L_{mi} = \frac{N}{k_j} \qquad \textbf{Equation 4}$$

2. Lane distribution at the taper. The distribution of vehicles between the open and closed lanes at the taper was then estimated using an empirical relationship:

$$P_{open} = min\ (0.95,\ 0.82 + 0.06\ x\ L_{mi}) \qquad \textbf{Equation 5}$$

$$P_{closed} = 1 - P_{open} \qquad \textbf{Equation 6}$$

   where P_{open} is the proportion of flow in the open lane and P_{closed} is the proportion in the closed lane. This relationship reflected the observed tendency for longer queues to yield stronger open-lane dominance. By definition, the share of vehicles in the closed lane could not fall below 5 percent.

A graphical representation of the estimated lane distribution across the open and closed lanes is provided in Figure 26.

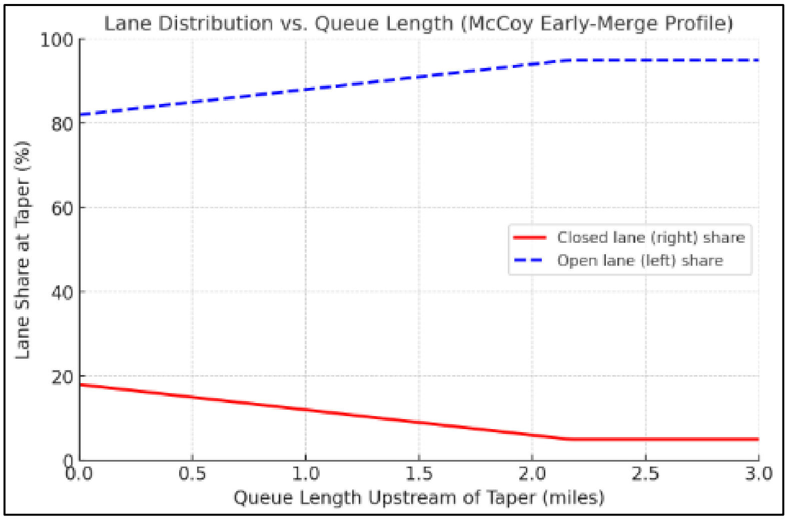


Figure 26. Lane distribution across open and closed lanes for work zones utilizing a conventional merge (Pesti et. al., 2002).

7.2.3.2. Dynamic Zipper Merge

Queue lengths for zipper merge sites followed a different approach because the lane distribution could not be inferred directly from queue length in the same way as conventional sites. Instead, lane-by-lane distributions were derived from observed video-based traffic counts at cameras positioned upstream of the choke point during work zone related congestion – meaning congestion directly related to the work zone and lane drop presence and not due to a downstream crash. Vehicle counts were tabulated by lane (open versus closed) and vehicle class (passenger car versus truck). To standardize the analysis, trucks were converted into passenger car equivalents using a factor of 2.5.

The processed counts were then aggregated to provide total demand in pcphpl for the open and closed lanes as shown in Table 12. Across three observed zipper merge events, the overall average distribution was 62 percent in the open lane and 38 percent in the closed lane.

Table 12. Distribution of traffic across open and closed lanes of a 2:1 zipper merge

DZM	Left (Closed) Lane				Right (Open) Lane				Distribution	
Activation	Cars	Trucks	Trucks_PCE	Total	Cars	Trucks	Trucks_PCE	Total	Left	Right
1	1353	269	673	2026	835	986	2465	3300	38%	62%
2	816	54	135	951	470	663	1658	2128	31%	69%
3	1337	481	1203	2540	583	1250	3125	3708	41%	59%
			Overall:	**5516**				**9136**	**38%**	**62%**

Because of the camera setup used in this study, it was not possible to quantify how lane distribution varied with queue length at DZM sites, as was done for conventional merges. Instead, the observed aggregate distributions were applied directly in the tool to estimate lane-by-lane queue lengths for zipper merge conditions.

7.3. Comparison of Work Zone Facility Types

With capacity and queue estimates available for both conventional and dynamic zipper merge installations, the Work Zone Evaluation Tool provided multiple ways to compare the two facility types. This section describes the evaluation options, visual outputs, and decision-support features of the tool.

7.3.1. Evaluation Options

The tool enables systematic comparison of conventional and dynamic zipper merge configurations across a rich set of scenarios. In total, each scenario considers the following options for analysis:

- Two directions of travel (e.g., eastbound versus westbound)
- Two merge types (conventional versus dynamic)
- Thirteen time periods (12 months plus an "average month" option)
- Eight day-type periods (7 days plus an "average day" option)

This structure resulted in 416 potential evaluation combinations, giving analysts flexibility to investigate a wide range of site-specific and temporal conditions.

7.3.2. Visual Tools and Filters

The tool incorporated a worksheet titled *WZ Graphs* to provide visual outputs of the results. This feature displayed the maximum queue length for each merge type, broken down by lane (open versus closed) and by month of occurrence. Figure 27 provides an example of the graphical output.

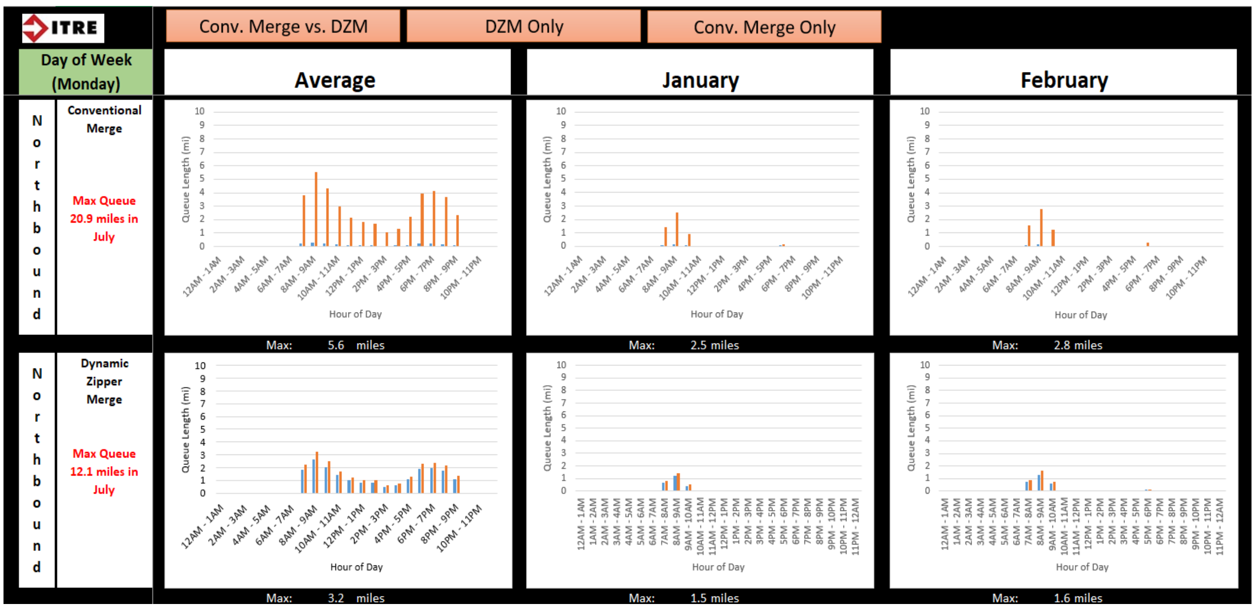


Figure 27. Example graphics from tool. Note: Only one direction shown. In addition, results for March through December are not provided due to space constraints.

Interactive buttons allow analysts to filter results by 1) merge strategy (conventional versus zipper merge) and direction of travel (eastbound or westbound). This filtering system enables quick comparisons across merge strategies and directions while highlighting seasonal and directional variability.

7.3.3. Decision Support

Beyond visualization, the tool was designed to guide decision-making regarding the implementation of work zone merge strategies. Key questions addressed by the tool include:

- Is a DZM needed based on the presence and severity of anticipated queues?
- Which months or days of the week provide better operating conditions to minimize queuing?
- Are there times of day or days of the week when merging operations should be avoided altogether?

- Where should signage for zipper merge installations be placed based on anticipated construction dates, traffic patterns, and backs of queue?

By answering these questions, the tool offers a flexible, data-driven framework for proactive planning and strategic deployment of merge strategies. In addition, it established a platform that can be expanded to include additional facility types in the future, such as divided arterials.

Chapter 8. Findings and Conclusions

The study set out to evaluate whether dynamic zipper merge systems improve safety and traffic operations compared to conventional early-merge strategies during 2:1 freeway work-zone lane closures in North Carolina. Its objectives were to quantify safety outcomes – including crash modification factors – assess operational impacts such as speed, queueing, and travel-time index, and develop recommendations for when and where the DZM should be implemented based on traffic demand, truck percentages, and work-zone characteristics. Because the NCDOT had been increasingly deploying DZM systems but lacked comprehensive empirical evidence from real-world sites, the project focused on comparing performance across a range of existing and historical work zones. The scope was intentionally limited to freeway 2:1 lane drops, the configuration where the DZM was actually in use, ensuring reliability of comparisons across sites and usefulness to the NCDOT per current DZM implementation.

The literature review highlighted decades of research on early merge, static zipper merge, and dynamic zipper merge strategies, including studies from the central, eastern, and southern United States and Europe. While results varied across settings, prior work generally found that zipper-merge concepts delay breakdown, shorten queues, reduce lane-changing conflicts, and improve perceived fairness – especially under high-demand conditions. However, inconsistencies across driver populations and roadway types, as well as limited statistical evidence for the DZM, motivated the need for more robust field evaluation.

Methodologically, the research used a multi-source empirical dataset, including seven years of crash records from TEAAS, speed and congestion profiles from ClearGuide, estimated directional volumes and VMT derived from ATR-supported adjustments, and field-collected video capturing headways, merging behavior, lane utilization, and queue progression at four North Carolina DZM sites. Ten DZM sites and five CM sites were compared using crash rates per million VMT along with operational metrics, providing one of the most comprehensive observational evaluations of the DZM to date. Beyond that, a Work Zone Evaluation Tool was created based on these findings to assist the NCDOT with determining where and how to best implement the DZM.

8.1. Safety: Key Findings

As discussed in more detail in Section 5.4, the project team concludes with high confidence that compared to conventional merge arrangements, the DZM systems were effective in reducing crashes, both in the upstream approach areas and in the work zone closure areas. Pooling the data from all locations, DZM sites experienced **44%** fewer crashes per million vehicle-miles travelled compared to CM sites [95% confidence interval 29% to 57%]. This crash reduction factor (CRF) of 0.44 corresponds to a CMF of **0.56** [0.43, 0.71]. This value is recommended for use in computing the economic benefits of the DZM in North Carolina.

Compared to the pre-construction baseline crash rates, both DZM and CM arrangements resulted in crash rate increases during construction. Nevertheless, the DZM sites experienced considerably smaller increases. Specifically, the crash rate ratio (RR) for DZM sites was **1.43** [0.93, 1.94] times the baseline rate, while the overall crash rate at CM sites was **2.58** [2.02, 3.13] times the baseline rate. These differences are statistically significant. The findings can be applied to predict the number of crashes in future North Carolina rural freeway work zones based on prior (non-construction) crash history. The process is as follows:

1. Extract the site's crash history data from the state crash database (e.g., TEAAS) for the month(s) of interest. Crash data from multiple years should be used to avoid sample size issues.
2. Separate the result into animal crashes (e.g., crashes involving deer) and non-animal crashes.
3. If CM will be used during construction, multiply the number of non-animal crashes by 2.58. If DZM will be used, multiply by 1.43.
4. Add the number of animal crashes from Step 2 to the estimated number of non-animal crashes from Step 3.

5. Adjust the sum in proportion to the expected construction duration. For example, if the initial crash count covered 90 days and the expected duration is 75 days, multiply by 75/90 = 0.83.

The available data were not sufficient to determine whether the DZM systems influenced overall crash severity. Nevertheless, the team concluded with moderate certainty that the DZM system reduced rear-end collisions. Another notable benefit of the DZM systems was an apparent reduction in crashes during congested hours compared to the CM sites. This suggests co-benefits for reductions in incident-related road user delays and (for gasoline and diesel vehicles) corresponding reductions in engine emissions associated with stop-and-go traffic at incident sites.

8.2. Operations: Key Findings

The operational analysis relied on high-resolution 15-minute probe data and a consistent before–and–after evaluation framework to quantify changes in speed and travel-time reliability (TTI). By aggregating data across all qualified sites in the 15,000–20,000 ADT range and applying non-parametric statistical tests, the study provides a robust and scalable assessment of how each merge strategy affects mobility during construction.

Across the full set of operational measures, travel-time reliability emerged as the clearest differentiator between the two treatments. Both the heatmap visualizations and the aggregated TTI percent-change results show that CM work zones experience more widespread and more intense reliability degradation during construction. DZM sites, while not immune to delays, exhibit smaller and more localized increases in TTI, with materially lower percent increases across all major time periods. The before–and–after Δ-TTI statistical tests reinforce this pattern: CM shows significantly larger reliability deterioration than DZM in every time period, with especially large differences during the PM peak and weekends. These results demonstrate that the DZM strategy provides a consistent and measurable advantage in preserving reliability under work-zone conditions.

Speed impacts were more balanced between the two treatments. Both DZM and CM sites experienced notable speed reductions during construction, particularly in the PM peak period. The directional patterns differ by time period: CM shows larger reductions during weekends and PM peaks, while DZM sites exhibit slightly larger weekday reductions. However, the before–and–after Δ-speed tests indicate that the magnitude of these differences is generally small, often less than 1 mph in practical terms, even when statistically detectable. The operational implication is that the DZM treatment does not produce large or systematic improvements in absolute speeds, but it also does not perform worse than CM. Rather, speed impacts appear to be driven primarily by demand and typical congestion patterns rather than merge strategy alone.

Taken together, the findings indicate that the strongest operational benefit of the DZM lies in improved travel-time reliability, not in increasing or preserving average speeds. Across all sites and time periods, DZM consistently limits the growth of TTI relative to CM, suggesting better preservation of predictable and stable traffic conditions during construction. For the NCDOT, this provides clear evidence that DZM is a promising work-zone strategy where reliability and user experience are key performance objectives. Future deployments may find the greatest benefit in corridors with recurring midday and PM-peak congestion, where the reliability advantages of DZM were most pronounced in this analysis.

8.3. Study Limitations

This study focused on the only current configuration of the DZM system in North Carolina, which is the two-to-one lane closure. The study carefully examined the potential safety and operational benefits of this system. However, any inference into a different type of lane closure, like three-to-two or three-to-one, is theoretical due to the unavailability of these types of sites currently and will need further exploration. Also, while the research team was able to find several CM sites for comparison, these were still very limited. This was somewhat expected, however, as the NCDOT has effectively implemented a practice of utilizing the DZM where traffic volumes, and thereby congestion, are expected to be high. This meant a low availability of sites with significant queueing to which DZM sites could be compared. Likewise, the research team inquired with the NCDOT early in the project timeline about the possibility of implementing a CM that would later be converted to a DZM, which would allow for a true before-and-after study, but this was understandably rejected because of the known safety benefits of the DZM at highly congested corridors.

Chapter 9. Recommendations

The research conducted in this study provided a foundation for evaluating conventional merge and dynamic zipper merge operations in North Carolina. The research team recommends that the NCDOT continue to implement the DZM at high-volume 2:1 lane reductions, primarily because of the safety benefits – a worthy priority of the NCDOT – but also because of the operational benefits. Likewise, the research team recommends further implementation of the DZM for work zones in all parts of North Carolina where appropriate per these findings.

The context for this recommendation is that DZM has historically been utilized in the western portion of the state, along with some in central North Carolina. Eastern North Carolina has scarcely seen the DZM, but could greatly benefit from its implementation when the arrangement is cost-effective (consider the safety performance of the I-95 CM sites included in this study).

While the safety benefits of DZM are clear, cost is still a consideration. DZM setup cost is considerably more than implementing a CM, and DZM deployment could be impractical for short-duration projects. Therefore, a cost-benefit analysis of DZM versus CM would greatly serve the NCDOT.

A benefit/cost procedure can be used to identify appropriate thresholds for cost-effective DZM deployment, given variables such as traffic volume, baseline crash rate, and anticipated construction duration. In general, the benefit/cost ratio can be expected to be greatest at sites with high traffic volumes, high baseline crash rates, and long project durations. B/C ratios will also be affected by the cost of the DZM systems, which will likely differ for contractor-supplied systems, equipment rental, and direct ownership by NCDOT—and could also differ based on the DZM technical specifications.

While the findings advanced current understanding and produced a practical evaluation tool, several areas were identified where additional research would strengthen the knowledge base and expand the tool's applicability.

- **Standardize Lane Distribution Assumptions.** For consistency across projects, the NCDOT should establish standard lane distribution factors for conventional merges (using the McCoy and Pesti method) and for dynamic zipper merges (using field-observed values). These defaults can then be applied in preliminary analysis, with the option for refinement through site-specific data collection.
- **Integrate Seasonal and Directional Factors.** Work zone planning should formally incorporate seasonal variation, directional distribution, and heavy-vehicle adjustments in estimating traffic demand, ensuring that closure schedules reflect realistic operating conditions.
- **Broaden Site Types.** This study focused primarily on rural interstate facilities. Future efforts should include urban and suburban interstate sites where traffic demand patterns, driver behavior, and roadside constraints may differ significantly. Research could also expand to evaluate other closure configurations, such as 3:2 lane drops and additional lane-reduction variations. This could begin as microsimulation studies for the sake of liability, then expand to real-world applications that would be closely monitored for surrogate safety measures like rapid deceleration rates and conflicts or near-misses. Data gathered during microsimulation, as well as any available field data, could then be used to ensure that the work zone evaluation tool can be applied consistently across the full range of work zone types managed by the NCDOT.
- **Refine Lane Distribution Models.** For conventional merges, the lane distribution model applied here was based on the McCoy and Pesti method, supported by national and pooled-fund studies. For dynamic zipper merges, more research is needed to determine how lane distribution varies with

queue length, similar to the established models for conventional merges, rather than relying only on aggregate lane counts.

- **Refine Work Zone Guidance.** Current work zone manuals and guidance documents should be updated to reflect the capacity and queue length findings presented here. This includes recognizing the lower capacity drop associated with dynamic zipper merges compared to conventional merges and incorporating these values into statewide planning assumptions.
- **Economic and User-Impact Measures.** The current study emphasized operational measures of performance, such as capacity and queue length. Future studies should incorporate delay costs, fuel consumption, emissions, and safety surrogates to provide a broader assessment of user impacts under different merge strategies. Forthcoming research needs statements could expand into this tool in lieu of older tools currently being utilized.
- **More Detailed Study of Work Zone Related Crash Rates.** Crash rates within the work zone varied substantially across both DZM and conventional sites; however, the sample sizes and available geometric and contextual detail were insufficient to isolate the specific factors driving this variation. Several operational and geometric elements are likely to influence safety performance inside the active work area, including: (1) horizontal alignment changes or lane shifts that require vehicles to deviate from standard paths; (2) nighttime versus daytime work operations, including the presence, quality, and consistency of temporary lighting; (3) the amount and positioning of construction equipment in the median or on the shoulders; (4) the frequency and location of construction vehicle entries and exits; and (5) expected back-of-queue locations relative to vertical curves and other sight distance constraints. These conditions can differ greatly across projects and over time, influencing driver workload, expectancy, and speed compliance in ways that may increase or decrease crash risk. Because these elements could not be consistently documented or quantified across all sites, the study could not conclusively attribute high or low work-zone crash rates to any single cause.

Chapter 10. Implementation Plan

The findings from this study highlighted several opportunities for the NCDOT to improve the planning and management of work zone merge strategies. Of critical importance as a part of this project was the creation of the Work Zone Evaluation Tool for helping to determine the proper placement of dynamic zipper merges across North Carolina. The following are steps the NCDOT could take to implement the findings of this research.

- **Adopt the Work Zone Evaluation Tool.** The tool developed in this study should be used by the NCDOT Work Zone Traffic Control group to evaluate site-specific conditions and determine whether conventional or dynamic zipper merges are most appropriate. Its scenario-based structure enables proactive planning based on seasonality, day of week, and directional demand.
- **Tool Enhancement and Deployment.** The Work Zone Evaluation Tool demonstrated strong potential as a decision-support platform. Future research should extend its capabilities to integrate economic performance measures and the like. Pilot testing with NCDOT field staff would also provide valuable feedback on usability and functionality. The tool is intuitive for NCDOT staff versed in this area, but holding a CLEAR webinar to share the tool's utility with NCDOT staff would be beneficial.

Likewise, the findings from this research have the potential for broader application and implementation by practitioners across the United States. As such, the research team will identify the appropriate journal(s) and conference(s) for sharing these results. Journals like ITE (Institute of Transportations Engineers) and TRR (Transportation Research Record)/TRB (Transportation Research Board) are obvious options, as well as the American Society of Highway Engineers (ASHE). Other conferences where these results could be interesting are also available, such as the National Travel Monitoring Exposition and Conference, which may find interest in some of the methods used to capture and filter traffic and crash data.

This section presents the plan for putting the project's tool and findings into practice at NCDOT. It details the final deliverables, implementation steps, and metrics that will guide successful integration into agency workflows.

Explanation of Deliverables. The final deliverables include a written report that outlines the research conducted to compare dynamic zipper merges to conventional merges in 2:1 lane drop work zones and a Work Zone Evaluation Tool for assistance to the NCDOT in determining appropriate implementation of the dynamic zipper merge treatment in long-term work zones.

Influence on NCDOT. The Work Zone Evaluation Tool will help NCDOT's Work Zone Traffic Control group to evaluate site-specific conditions and determine whether conventional or dynamic zipper merges are most appropriate. Its scenario-based structure enables proactive planning based on seasonality, day of week, and directional demand. The final report for this research provides a defensible rationale for choosing a DZM over a CM for a long-term lane closure when safety and operational benefits likely outweigh the implementation costs associated with DZM installation.

The research team recommends that the NCDOT consider funding future research into a cost-benefit analysis of the DZM to best determine when and where to implement a DZM over a CM. While the safety and operational benefits of the DZM are apparent from this final report, there is still a substantial cost associated with DZM implementation in comparison to a CM that should be considered when determining which merge method to use. Per the NCDOT, a 6-month implementation of the DZM costs approximately $200,000-225,000, whilst a one-year implementation costs approximately $350,000-400,000.

Likewise, the NCDOT should consider expanding the Work Zone Evaluation Tool via research into 3:2, 3:1, or other work zone lane drop configurations. The research team expects that this research would start with a microsimulation study to determine predicted saturation flow and lane utilization rates to add to the

Work Zone Evaluation Tool, then expanding to real-world implementation to refine operational metrics and determine potential safety benefits.

Implementation Process. The Work Zone Evaluation Tool demonstrated strong potential as a decision-support platform. Future research should extend its capabilities to integrate economic performance measures and the like. Pilot testing with NCDOT field staff would also provide valuable feedback on usability and functionality. The tool is intuitive for NCDOT staff versed in this area, but holding a CLEAR webinar to share the tool's utility with NCDOT staff would be beneficial.

The findings of a DZM-specific CMF can also be utilized by NCDOT staff to help, along with the Work Zone Evaluation Tool, determine appropriate implementation of the DZM system.

Measures of Success. This research can be used to guide the NCDOT in the implementation of dynamic zipper merges to more strategically determine the appropriate scenarios for DZM use, as well as the proper placement of signage throughout a DZM corridor. To adequately measure the success of rolling out more DZM work zones, the NCDOT could study the operational effects of the DZM in comparison to CM work zones in near real time with tools like ClearGuide, and could also conduct a review of future DZM and CM implementations in regard to their safety. This was an area of interest to the research team that simply was not possible due to the current, albeit understandable, strategies of the NCDOT in utilizing DZM work zones on high traffic corridors.

Additional Assistance. The research team will work with the Office of Strategic Initiatives and Program Support and the Work Zone Traffic Control group on training with and implementation of the Work Zone Evaluation Tool. The research team likewise hopes to work with these groups on future research into a cost-benefit analysis of dynamic zipper merges.

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