Improving the Effectiveness of Zipper Merge Lane Control in Freeway Work Zones

Final Report
December 2024

SWZDI
Smart Work Zone Deployment Initiative

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About the Smart Work Zone Deployment Initiative

The Smart Work Zone Deployment Initiative (SWZDI) is a transportation pooled fund that supports research investigations into better ways to improve the safety and efficiency of traffic operations and highway work in work zones. The primary objective is to promote and support research and outreach activities that focus on innovative policies, processes, tools, and products that enhance the implementation, safety, and mobility impacts of work zones.

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16. Abstract

The late merge, or "zipper" merge, has become a common strategy to increase work zone capacity by encouraging drivers to stay in their lanes until they reach a defined merge area, where they alternately merge. While the zipper merge has been shown to provide improved operational performance, there is considerable variability in driver familiarity and behavior when encountering the zipper merge. In addition to determining where and when merging should occur, agencies also determine whether lane merge control is static or dynamic. This study provides insights into the use and efficacy of various types of lane merge control strategies. The research included a literature review, a state department of transportation (DOT) survey, a road user survey, and field evaluations conducted at several freeway work zones in Michigan and Missouri. The state DOT survey found that 93% of agencies use static lane merge compared to only 40% that use dynamic lane merge, the latter of which is more widely used in urban freeways than rural freeways. Various factors are considered when deciding whether to use a dynamic lane merge, including annual average daily traffic, peak hour volumes, and duration of work. The road user surveys showed that drivers would typically merge closer to the taper under zipper merge lane control compared to early merge; however, compliance with this strategy increased significantly when a portable changeable messages sign (PCMS) was used as a supplementary device. Drivers also indicated that traffic signs with textual messages, either with or without supplementary graphical messages, were preferred over graphical-only signs. Driver merging behavior was also found to vary depending upon both the merging strategy (i.e., early versus late/zipper) and the vehicle's location with respect to the start of the taper. Interestingly, there was significant variability in respondents' perceptions of whether the zipper merge impacts traffic safety and operations. Familiarity and comfort with the zipper merge were strong determinants of driver behavior and perceptions. The results suggest that outreach campaigns may help to raise awareness of the zipper merge. The field evaluations showed that the zipper merge tended to result in better use of available capacity. However, at low volumes, drivers tend to merge earlier without any adverse impact on operations. For example, the M-53 study location (average volume of 940 vehicles/hour) had utilization rates of less than 15% on average but did not experience any substantive negative impacts on operations. The field evaluations also assessed the impact of varying the location of the PCMS within the work zone, including near the taper and one mile upstream of the taper. It is recommended from the field evaluations that if only a single PCMS is to be used, it should be positioned nearly one mile upstream of the taper displaying USE BOTH LANES/DURING BACKUPS. If an additional PCMS is available, it is recommended to be positioned within 1,000 ft upstream of the lane closure displaying MERGE HERE/TAKE TURNS.

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IMPROVING THE EFFECTIVENESS OF ZIPPER MERGE LANE CONTROL IN FREEWAY WORK ZONES

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LIST OF ABBREVIATIONS

ATSSA	American Traffic Safety Services Association
CMS	changeable message sign
DOT	department of transportation
FHWA	Federal Highway Administration
MDOT	Michigan Department of Transportation
MoDOT	Missouri Department of Transportation
MUTCD	*Manual on Uniform Traffic Control Devices*
PCMS	portable changeable message sign
SWZDI	Smart Work Zone Deployment Initiative
TAC	technical advisory committee
TMP	Transportation Management Plan

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EXECUTIVE SUMMARY

Single-lane closures are quite common in freeway work zones and require drivers to determine when and where to merge from a lane that is about to close to an adjacent open lane. This merging generally occurs between the first lane closed ahead sign and the start of the taper. Early and late merge lane control are the two most common types of lane merge control strategies used by state departments of transportation (DOTs). Prior studies have shown the benefits of using the zipper/late merge strategy over the conventional early merge strategy; however, the zipper merge relies on both cooperation and compliance among drivers, and there is significant potential to improve driver merging behavior. This project aimed to assess factors associated with work zone lane merge controls and their impacts on efficiency and safety as measured by impacts on flow rates, lane selection behavior, and driver compliance with the intent of the merge control strategy. This project provides guidance on the selection of both the type and location of work zone lane merge control based on these factors, as well as how to best communicate pertinent information to drivers to yield the intended results.

To achieve these goals, the researchers conducted a synthesis of different work zone lane merge control strategies across the United States through an extensive literature review and analysis of different work zone lane merge control schemes as a part of a nationwide state agency survey. A road user survey of drivers across the nine Smart Work Zone Deployment Initiative (SWZDI) states was also conducted to better understand road users' perceptions, familiarity, and comfort with early and zipper merge lane control. The road user survey evaluated drivers' stated preferences under various scenarios that utilize either early merge or zipper merge control, as well as their preferences concerning various signage strategies that support each method. This included supplemental portable changeable message signs (PCMS). In addition, a series of field studies was conducted to assess lane utilization behavior under zipper merge lane control in advance of single-lane closures on two-lane (per direction) freeway work zones in Michigan and Missouri. The impacts of upstream PCMS on lane utilization were also evaluated as part of these field studies.

State DOT Survey

State DOT practices for work zone lane merge control were synthesized through a review of DOT resources (e.g., typical applications, specifications, guidance, and outreach materials) and an agency survey that was developed and administered by the researchers. The survey consisted of 19 questions and was sent to the DOTs from all 50 states and the District of Columbia. Survey responses were received from 45 DOTs, including all 9 SWZDI states.

Survey results indicated that 18 of the 45 DOTs that responded to the survey use dynamic lane merge in work zones, while 42 responding DOTs noted the use of static lane merge in work zones. Eighteen of the DOTs utilize dynamic late merge, while six of those DOTs also utilize dynamic early merge. Dynamic lane merge is most often implemented on urban freeways and for two-to-one lane drops in work zones. Based on the survey results, the most frequently considered factors when determining whether to implement dynamic lane merge are annual average daily traffic (AADT), peak-hour volumes, and duration of work. Other factors mentioned in DOT guidance include queuing and encroachment on upstream intersections or interchanges.

DOTs generally provide operational requirements for dynamic lane merge systems in their standards and specifications. Agencies most often utilize speed thresholds for activation or deactivation of dynamic lane merge systems in work zones. These speed thresholds vary among DOTs in their standards or specifications, but typically range from 20 mph to 40 mph. Dynamic lane merge is sometimes implemented along with other smart work zone technologies in work zones, such as end-of-queue warning systems (14 DOTs) and traveler information systems (13 DOTs).

Some DOTs provide layouts for lane merge systems for work zones in their standard drawings or typical applications. These layouts include information such as the locations of traffic control devices and sensors, and, in some cases, messages that should be displayed on PCMS based on their location and prevailing traffic conditions.

The survey also sought information regarding challenges in the use of dynamic lane merge systems. Challenges to the implementation of dynamic lane merge in work zones include driver inattention, lack of perceived need, and the need for complementary enforcement. Those DOTs that exclusively use static lane merge cited a lack of perceived need, lack of information on benefits, lack of available guidance, and the prioritization of other work zone safety countermeasures (e.g., speed management, end of queue warning systems) as the primary reasons they do not utilize dynamic lane merge.

Feedback on the performance of lane merge control strategies in work zones was also received through the survey. DOTs generally consider queue length, delay, and speed as performance measures for dynamic lane merge in work zones. The average performance rating (1 = highly ineffective, 5 = highly effective) for dynamic lane merge in work zones by responding DOTs was 3.61 out of 5, indicating that DOTs find the use of dynamic lane merge in work zones to be moderately effective. System performance can sometimes vary depending on project location.

Road User Survey

A companion road user survey was used to provide additional insights into driver understanding and adherence to lane merge scenarios, as well as associated driver behaviors when navigating both early and late/zipper merge control strategies at single-lane closures in freeway work zones. The survey was designed and implemented through the Qualtrics platform and distributed among residents of the nine SWZDI states. The road user survey also aimed to assess the impacts of the optional installation of PCMS to supplement a standard static sign configuration. Regression models were estimated to understand drivers' preferred merging locations under various sign configurations, as well as in consideration of the behaviors of other drivers. Respondents also detailed their perceptions as to the safety and operational performance of select scenarios.

The results showed that drivers typically prefer to merge early into the open lane regardless of the lane control strategy. However, providing information more conspicuously through PCMS increased compliance, as drivers were willing to merge closer to the taper when PCMS were used in addition to static signage. Generally speaking, drivers tended to slow down and allow other vehicles to merge. However, these trends varied depending on the merging strategy (early versus late/zipper) and the location of the merging maneuver with respect to the start of the taper. Overall, respondents were more likely to continue to drive at the same speed and more effectively use the soon-to-be-closed lane when the zipper merge was in place. Regardless of the lane merge control strategy, driver behavior was generally more aggressive closer to the taper compared to further upstream.

In terms of signage alternatives, drivers generally preferred signs that conveyed information both graphically and textually, followed by signs that used only text. For instance, when conveying the information that the right lane is closed ahead, drivers preferred the textual sign (W9-2) LANE ENDS MERGE LEFT over the graphic sign (W4-2). Purely graphical signs generally showed lower preference among drivers, a result that is in contrast with some of the broader research literature (Er-hui et al. 2013, Messina 2012, Viganò and Rovida 2015).

Though some literature indicates the zipper merge has both operational and safety benefits over early merge (Franks 2014), the survey results generally showed mixed results. Only 25% of the drivers included in the survey perceived the zipper merge to be safer than early merge, and only 32% of the drivers believed the zipper merge was more effective than the early merge in reducing congestion and traffic backups. These perceptions could be due to personal experiences, such as drivers feeling as though those in the closed lane are “cutting” in front of them, or from other negative personal driving experiences. Drivers who were more familiar or more comfortable with the zipper merge strategy tended to perceive it as better than the early merge strategy from both a safety and operational perspective.

Drivers were also asked what types of media would be most effective for outreach campaigns related to the zipper merge. Nearly 42% of respondents suggested the use of TV advertisements and newspapers, 28% suggested using social media, and 14% suggested using public meetings and driver’s license handbooks for better public outreach. Older drivers preferred TV advertising and newspapers, while younger drivers preferred TV advertising, newspapers, and social media for outreach purposes. This information can be used as a basis for education and outreach campaigns by road agencies to improve work zone knowledge and behavior.

Field Evaluation Study

A series of field evaluations were performed at four freeway work zone lane closures in 2023 and 2024 to assess lane utilization behavior under zipper merge lane control and evaluate strategies aimed at improving compliance in advance of single-lane closures. The study focused on utilization of the soon-to-be-closed lane (measured as the proportion of all vehicles that were in that specific lane). One assessment was conducted in Missouri, while the three other field evaluations were carried out in Michigan. A fixed set of criteria was defined to select sites to ensure minimum variability across sites with respect to site geometry. These criteria included a stationary work zone site located on the freeway with two travel lanes in each direction, a two-to-one lane drop configuration (i.e., one lane closure on a two-lane freeway per direction), and moderate to high traffic volumes. In order to evaluate the impact of lane merge strategies on driver behavior, the I-44 Big Piney Rivers Bridge Repair project was chosen as the work zone evaluation site for the Missouri portion of the study. The list of sites chosen in Michigan included the following:

- Site-1: Eastbound (EB) I-94 in Macomb County from 23-mile road to county line road
- Site-2: Eastbound (EB) I-96 EB near Grand Rapids from Thornapple Drive SE to Whitneyville Avenue SE
- Site-3: Southbound (SB) M-53 in Macomb County from 22-mile road to M-59

In Michigan, the data were collected using a series of pole-mounted high-definition video cameras installed along the work zone to cover at least half a mile of distance upstream of the start of the taper. The location of the cameras varied across sites depending upon the availability of a suitable location to mount the cameras on the roadside, a sufficient distance away from the travel lane. At the Missouri field assessment location, radar sensors were mounted on masts attached to portable trailers at the roadside for nonintrusive traffic data collection. Two radar sensors were deployed on eastbound I-44 to track individual vehicle speeds and lane use. The key findings from the field evaluations in freeway work zones are summarized as follows:

- When an upstream PCMS was installed at the first location (nearly 4,500 ft upstream of taper), lane utilization increased significantly across all three sites. This PCMS displayed USE BOTH LANES/DURING BACKUP, and its primary purpose was to provide drivers with more effective information about the upcoming zipper merge lane control. For distances closest to the taper (which varied from 600 ft to 1,200 ft across sites), the installation of U/S PCMS increased lane utilization by 2.3% to 3.9%. Similarly, at distances 1,500 to 2,000 ft upstream of the taper, lane utilization increased the lane utilization by 3.2% to 5.1%. Further upstream (2,200 ft to 3,200 ft from taper), lane utilization increased by 4% to 5%.
- The second PCMS was installed approximately 450 ft upstream of the start of the taper. This PCMS displayed MERGE HERE/TAKE TURNS alternatively to indicate the assigned merging location to the drivers. This PCMS was also accompanied by the traditional static “merge here” arrow and “take turns” sign. Compared to the static signs-only test condition, lane utilization was still higher when two PCMS were installed; however, the results showed that the installation of a second PCMS only had a marginal effect on lane utilization.
- The results showed that for every 100 vehicles/hour increase in traffic volume, lane utilization increased by 0.25% to 0.83% across sites. The average increase in lane utilization across all sites was 0.6% for every 100 vehicles/hour. Additionally, the proportion of heavy vehicles in both the open and closed lanes significantly affected the percentage of vehicles utilizing the closed lane. A 10% increase in truck percentage in the closed lane and open lane corresponded to a 1.5% reduction and 0.6% increase in lane utilization, respectively. The effect of heavy vehicles on lane utilization was more pronounced as the traffic density increased.
- As the traffic density in the open lane increases, the proportion of vehicles using the closed lane also increases. Lane utilization increased by 1% for every 10 vehicles/mile increase in

the open lane density. Interestingly, traffic density in the closed lane was not found to significantly affect lane utilization.

Recommendations for Improving Zipper Merge Effectiveness in Freeway Work Zones

Findings from the Missouri field study support implementing the zipper merge strategy in work zones, as drivers under the static merge condition were prone to merge into the open lane earlier, resulting in a loss of available capacity. In general, the Michigan field studies showed that the zipper merge was more effective under moderate traffic volumes. Under lower volumes, vehicles tended to merge earlier without any adverse impacts on operations. This was demonstrated at the M-53 site, where mean volumes were approximately 940 vehicles/hour.

Providing information more conspicuously through PCMS increased compliance, as drivers were willing to merge closer to the taper when PCMS were used in addition to static signage. The results from companion field evaluations showed similar trends, wherein the utilization of the closed lane increased significantly when a PCMS was installed nearly one mile upstream of the taper. The survey results showed that the addition of another PCMS nearer to the start of the taper showed further improvements in closed lane utilization. However, the field study showed that the installation of a second PCMS only had a marginal effect on lane utilization. Therefore, the study recommends using one PCMS nearly a mile upstream of the taper displaying USE BOTH LANES/DURING BACKUPS. If there is an availability of another PCMS, then an additional PCMS can be placed closer to the taper displaying MERGE HERE/TAKE TURNS.

When asked about their preference for zipper merge signage (to encourage drivers to stay in the closed lane as long as possible), drivers preferred a fully textual sign RIGHT LANE CLOSED AHEAD with a plaque showing USE BOTH LANES that indicated the expected behavior. Currently, this sign is less widely used than the USE BOTH LANES DURING BACKUPS sign, which indicates the need to revisit signage guidelines during zipper merge lane control.

Another important and consistent finding was related to drivers’ familiarity and comfortability with zipper merge. With an increase in either of these metrics, both the compliance with zipper merge and the perceived benefits of zipper merge increased. Moreover, older people consistently showed lower compliance rates and poorer perceptions of zipper merge. As stated earlier, the success of zipper merge depends on driver understanding and cooperation with zipper merge signage; thus, there is a need to educate drivers about the expected behavior during zipper merge lane control. To that end, drivers were also asked which platform they think has more outreach and can educate a greater number of drivers about zipper merge. Nearly 42% of participants suggested using TV advertisements and newspapers, 28% suggested using social media, and 14% suggested using public meetings and driver’s license handbooks for better public outreach. Older drivers preferred TV advertising and newspapers, while younger drivers preferred TV advertising, newspapers, and social media for outreach purposes. This information can be used as a basis for education and outreach campaigns by road agencies to improve work zone knowledge and behavior.

1. INTRODUCTION

1.1. Background and Problem

Single-lane closures are quite common in freeway work zones and require drivers to determine when and where to merge from a lane that is about to close to an adjacent open lane. This merging generally occurs between the first lane closed ahead sign and the start of the taper. Under conventional temporary traffic control plan designs, vehicles start merging maneuvers based on available gaps, flow characteristics, the presence of heavy vehicles, and guidance from traffic control devices (Weng et al. 2015). These merging maneuvers can result in significant variability in travel speeds between vehicles in the open and soon-to-close lanes, as well as in driver decision-making as to when and where to merge. This potentially elevates the risks for some of the most common types of work zone crashes, such as rear-end and sideswipe crashes (Xie et al. 2018). In 2022, the share of rear-end crashes and speed-related crashes was found to be 21% and 34% of all work zone-related fatal crashes, respectively (FHWA 2024). Apart from a safety perspective, lane closures can lead to reduced capacity, increased delays, extremely long queues on the open lane, confusion, and queue-jumping behavior (Pesti et al. 2007, Yang et al. 2023). Therefore, selecting appropriate work zone lane merge control is crucial to work zone safety.

Various types of merging systems have been implemented to improve traffic operations and safety in lane closure scenarios. Definitions of the most common types of merging systems are provided below (ATSSA 2012, MnDOT 2015):

- **Static merging systems** use static signage to convey information to drivers regarding the merge point. The merge point does not change with traffic conditions.
- **Dynamic merging systems** allow the merging technique to vary based on traffic conditions and include dynamic early merge and dynamic late merge.
- **Early merge systems** encourage drivers to leave the closed lane well in advance of the designated merge point.
- **Late merge (also known as zipper merge) systems** encourage drivers to stay in their lane until a designated merge point. At the designated merge point, drivers alternate moving into the open lane.
- **Active zipper merge systems** utilize smart work zone technologies to inform drivers when they should use both lanes and where to merge.
- **Passive zipper merge systems** inform drivers to use both lanes if a backup is present and allow drivers to decide if there is a backup.

Under early merge lane control, drivers are encouraged to merge as soon as practical after encountering the first lane closed ahead sign (Lammers et al. 2017). Even though early merge is a conventional merging strategy used widely across the United States, it has some disadvantages. For instance, the capacity of the work zone may be reduced as traffic begins to merge into open lanes earlier under moderate to high traffic volumes, resulting in unused capacity in the closed lane (Algomaiah and Li 2022). The lost capacity in the upstream section of the closed lane can also lead to extremely long queues in the open lane. This queuing can extend beyond work zone warning signage, surprising motorists and increasing the risk of end-of-queue crashes. The unused capacity in the closed lane approaching the taper also allows the potential for queue jumping, where vehicles try to pass on the closed lane and cut in near the work zone. Queue-jumping behavior could lead to lane-changing crashes, as well as motorist anger and frustration (Pesti et al. 2007).

To overcome these issues, a late merge strategy was developed by the Pennsylvania Department of Transportation (PennDOT). Under late merge lane control, drivers are encouraged to stay in the closed lane up to the start of the taper with the help of proper signage, thereby utilizing the full capacity of the closed lane. This method is also referred to as the “zipper merge” because it involves vehicles taking turns merging at the taper (i.e., like a zipper) (Spiller et al. 2017). There are also variants of these general strategies, such as dynamic late lane merge control, which provides a flexible merging point based on the traffic demand with the help of sonic detectors or Doppler radars (Grillo et al. 2008). Under any type of lane merge control strategy, a right-of-way hierarchy develops between vehicles in the open and soon-to-be-closed lanes. A lack of knowledge and understanding of these strategies, as well as the rationale for their implementation, may lead to dissatisfaction and confusion among road users. To address this problem, various techniques have been proposed, such as the joint merge, where both lanes taper to make a single center lane, which eliminates lane priority (Idewu and Wolshon 2010). Signalized merges also deal with this problem by utilizing traffic signals at the merge point to assign priority and control the vehicle flow on both lanes (Yuan et al. 2019). However, the most widely applied strategies are the early and zipper merge strategies. The potential benefits of zipper merging include full use of the available capacity, more uniform merging at one location only, and fairness to drivers in both lanes (Spiller et al. 2017). Previous research has also found that the zipper merge decreases travel times, delays, and rear-end crashes (Ramadan and Sisiopiku 2015). The strategy can also reduce the speed differential between the vehicles of open and closed lanes, reduce congestion, queue length, and the overall backup length by 40% (MnDOT 2008).

Prior studies have shown the benefits of using the zipper/late merge strategy over the conventional early merge strategy; however, the zipper merge relies on both cooperation and compliance of drivers (Beacher et al. 2005), and there is significant potential to improve the driver merging behavior. Typically, the zipper merge uses a series of signs to direct drivers to stay in their lanes and cooperatively merge at the start of the taper (Algomaiah and Li 2022). A prior study suggested the use of portable changeable message signs (PCMS) and portable variable speed limits (VSL) to reduce the severity and frequency of crashes and to reduce the speed variance among vehicles in open and closed lanes (Ghasemzadeh and Ahmed 2019). The latest edition of the *Manual on Uniform Traffic Control Devices* (MUTCD) (U.S. DOT 2023) offers general guidance on sign placement for lane closures in work zones on limited-access freeways for conventional and zipper merge lane control. However, there is no guidance as to the placement of PCMS relative to the location of the work zone taper.

Despite the widespread use of zipper and early merge strategies, research has generally shown mixed results related to the safety and operational efficiency of these strategies based on field and simulation studies (Algomaiah and Li 2021, Gan et al. 2022, Ramadan and Sisiopiku 2015, Ramadan and Sisiopiku 2016, Saha and Sisiopiku 2020; Weng et al. 2015, Weng et al. 2018). By design, both early merge and late merge control strategies are expected to elicit different responses from drivers. Thus, it is crucial that drivers are familiar with and understand the expected behavior under both strategies.

Therefore, this study utilizes a road user survey to better understand road users' perceptions, familiarity, and comfort with early and zipper merge lane control, as well as their preferences with respect to various signage strategies that are used in support of each method, including the effect of supplemental PCMS. The results of this survey are supplemented through a series of field studies that were conducted in Michigan and Missouri, culminating in guidance as to how agencies can design, implement, and publicize merging strategies in consideration of anticipated impacts on operations and safety.

1.2. Study Objectives

The primary goal of this project is to develop guidance to aid agencies in determining how to most effectively implement lane closures in consideration of driver behavioral response and related metrics associated with traffic safety and operations. The specific objectives of this study are to:

- Conduct a synthesis of different lane merge control strategies in setting work zone merging approaches in the United States through an extensive literature review and analysis of different work zone lane merge control schemes across Smart Work Zone Deployment Initiative (SWZDI) states.
- Assess factors associated with work zone lane merge controls and their impacts on efficiency and safety as measured by impacts on flow rates, speeds, and driver compliance.
- Provide guidance as to the type and location of work zone lane merge control based on these factors, including thresholds for when different lane merge controls are appropriate, as well as how to best communicate pertinent information to drivers in order to yield the anticipated results.

The remainder of the report provides details related to the work performed to accomplish the study objectives. To that end, the remainder of this report is organized as follows:

- Chapter 2: Literature Review
- Chapter 3: State DOT Survey
- Chapter 4: Road User Survey
- Chapter 5: Michigan Field Evaluation Methodology and Results
- Chapter 6: Missouri Field Evaluation Methodology and Results
- Chapter 7: Conclusions and Recommendations

2. LITERATURE REVIEW

This chapter presents the results of the literature review for lane merge strategies in work zones. Reference materials that were compiled for the literature review included research reports, journal articles, and state department of transportation (DOT) guidelines, policies, and standards. The chapter is organized into the following sections: General Guidance and Resources (Section 2.1); State DOT Guidelines, Policies, Standards, and Outreach Materials for Dynamic Lane Merge in Work Zones (Section 2.2); and Research Studies for Lane Merge Control Strategies in Work Zones (Section 2.3). Tabular summaries of state DOT resources, including hyperlinks, are provided in Appendix A.

2.1. General Guidance and Resources

General guidance and resources for lane merge control strategies are available from sources such as the American Traffic Safety Services Association (ATSSA). ATSSA (2012) provides guidance regarding the use of dynamic lane merging strategies, including early and late merge, on topics such as conditions for implementation, signage, and sample layouts. The ATSSA guidance includes a flow chart to help decide whether to implement early or late merging based on hourly traffic volumes and other factors. The ATSSA guidance notes that dynamic merge strategies are more beneficial for work zones with traffic demands that fluctuate.

Other resources include a pooled fund study report and NCHRP synthesis on smart work zone technologies. The pooled fund study report provides a summary of resources and summarizes the benefits of dynamic merge systems (Roelofs and Brookes 2014). An NCHRP synthesis on smart work zone technologies included a survey that found that 27% of state DOTs have implemented dynamic lane merge systems, and 31% of state DOTs plan to implement dynamic lane merge systems in the future (Brown and Edara 2022). These results indicate that dynamic lane merge systems are well-established and used by state DOTs.

The latest edition of the MUTCD (U.S. DOT 2023) provides general guidelines for sign placement during lane closures in work zones for late (zipper) merge lane control strategy. Section 6N.19 of the MUTCD addresses guidance for the late merge lane control strategy, specifying that "[s]tatic Late Merge signing should consist of the STAY IN LANE TO MERGE POINT (R9-4a) sign and the MERGE HERE TAKE TURNS (W9-2a) sign." Additionally, the MUTCD includes a list of signs that can be used on PCMS at upstream and merge point locations during late merge implementation. However, the MUTCD does not provide specific guidance on the placement of PCMS in relation to the work zone taper or on the effectiveness of various messages. Figure 1 illustrates a sample layout of sign configurations for the late merge strategy according to the latest MUTCD.

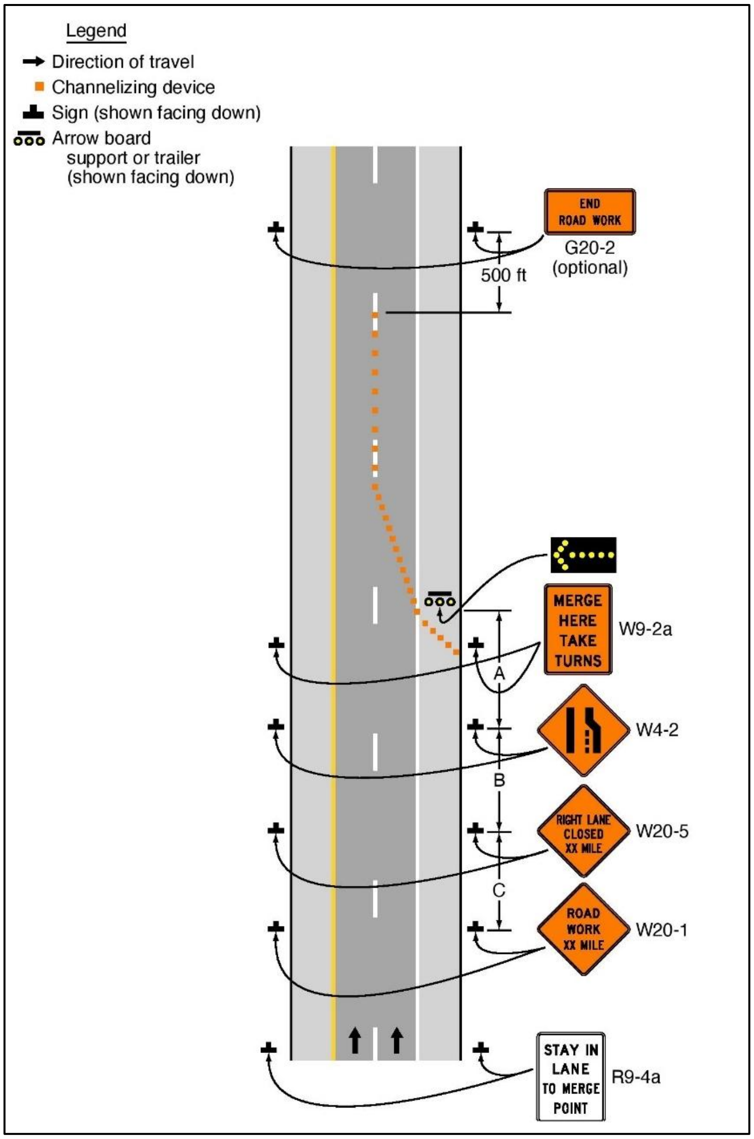


Figure 1. Sample layout for a single-lane closure with late merge from MUTCD

2.2. State DOT Guidelines, Policies, Standards, and Outreach Materials for Dynamic Lane Merge in Work Zones

This section summarizes state DOT guidelines, policies, standards, and outreach materials for dynamic lane merge in work zones. Additional information, including hyperlinks, may be found in tabular summaries in Appendix A. This section utilizes the language used by each state DOT, especially as various DOTs use the terms dynamic late merge or zipper merge, which both refer to the same type of system.

2.2.1. Guidance for Use of Dynamic Lane Merge in Work Zones

DOTs provide some guidance on the use of dynamic lane merge in work zones, such as conditions for which dynamic lane merge should be considered. Examples are provided below.

- The Indiana DOT (INDOT) allows the use of zipper merge in urban areas when there are queues for at least two hours per day for five days per week that often block intersections or ramps (INDOT 2020). The use of zipper merge also requires the approval of the district traffic engineer.
- The Missouri DOT (MoDOT), in its Engineering Policy Guide (MoDOT 2024), indicates that zipper merge should be considered for static work zones with a duration of at least two days, traffic volumes over 1500 vehicles per hour for at least two hours of the day, and estimated queue lengths that could encroach on the operation of upstream intersections or interchanges.
- The Wisconsin DOT (WisDOT) suggests that a dynamic lane merge system should be considered for a single-lane closure on a divided highway with possible moderate to heavy congestion (WisDOT 2024a). WisDOT’s guidance also provides an overview of system benefits, such as increased throughput and reduced queuing, crashes, and aggressive driving.
- PennDOT (2014) encourages consideration of the use of late merge when capacity is restricted, although field implementation of late merge in Pennsylvania has shown mixed results. Pennsylvania’s guidance indicates that the use of late merge can lead to reduced queuing, increased capacity, and less potential for road rage.
- The Minnesota DOT (MnDOT) provides an overview of active and passive zipper merge in its Traffic Engineering Manual (MnDOT 2015). Active zipper merge utilizes smart work zone technologies to inform drivers when they should use both lanes and where to merge. Passive zipper merge informs drivers to use both lanes if a backup is present and allows drivers to decide if there is a backup. MnDOT’s guidance indicates that both methods are effective, but active zipper merge results in higher compliance.

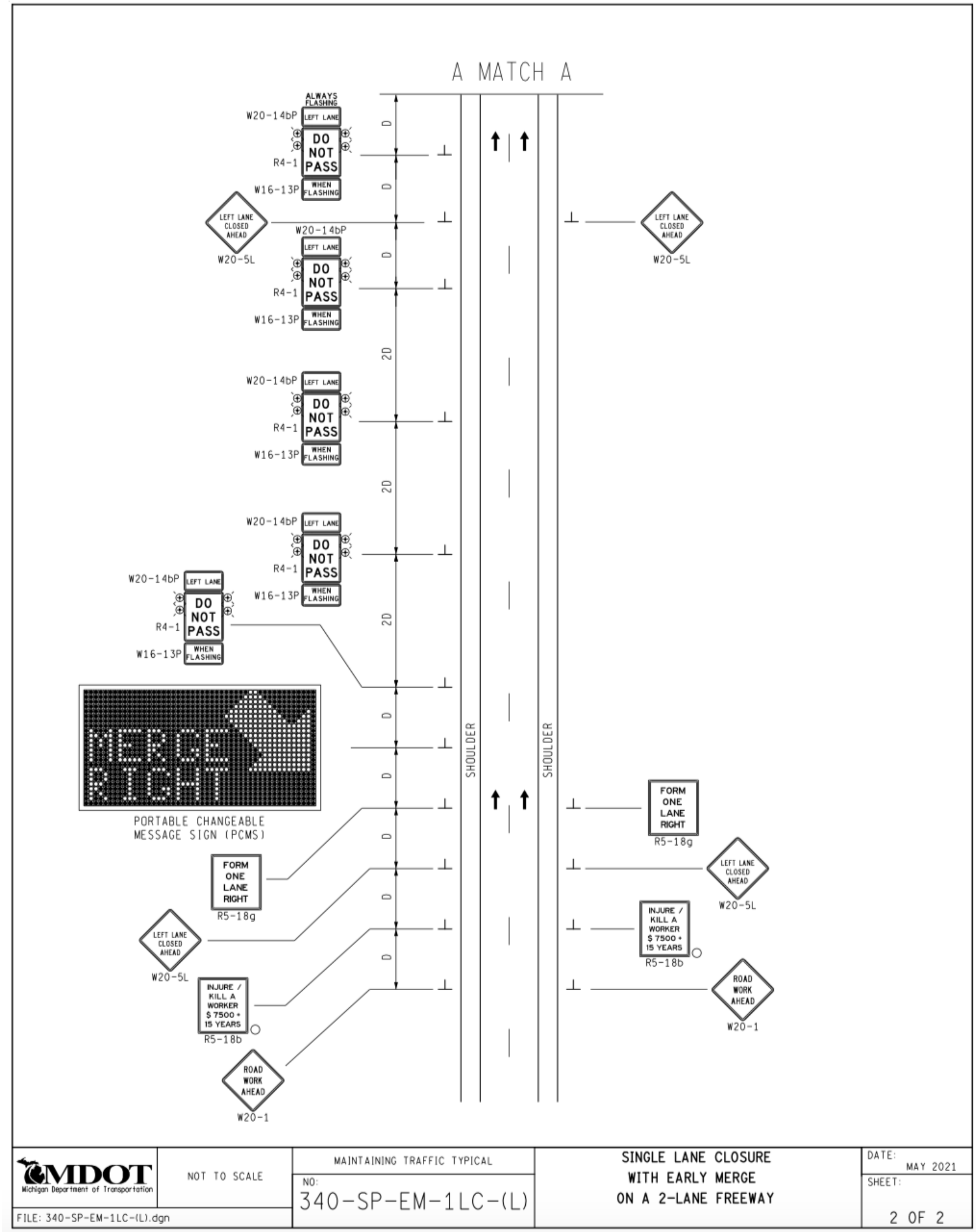
2.2.2. Layouts for Lane Merge Systems for Work Zones

Some DOTs also provide layouts for lane merge systems for work zones in their standard drawings or typical applications. These layouts include information such as locations of traffic control devices and sensors, general notes, and, in some cases, messages that should be displayed on PCMS based on location and traffic conditions. Examples of DOT standards and typical applications are highlighted below:

- Michigan DOT (MDOT) includes layouts for both early merge (see Figure 2) and late merge (MDOT 2021).
- MnDOT provides layouts for passive lane merge for a stationary work zone (see Figure 3) and active lane merge for both stationary and moving (short duration, one hour or less) work zones (see Figure 4) (MnDOT 2018, MnDOT 2024a).
- Washington State DOT (WSDOT) provides layouts for smart work zone systems for two or three lanes and queue lengths of 6 or 9 miles (WSDOT 2024b). An example is shown in

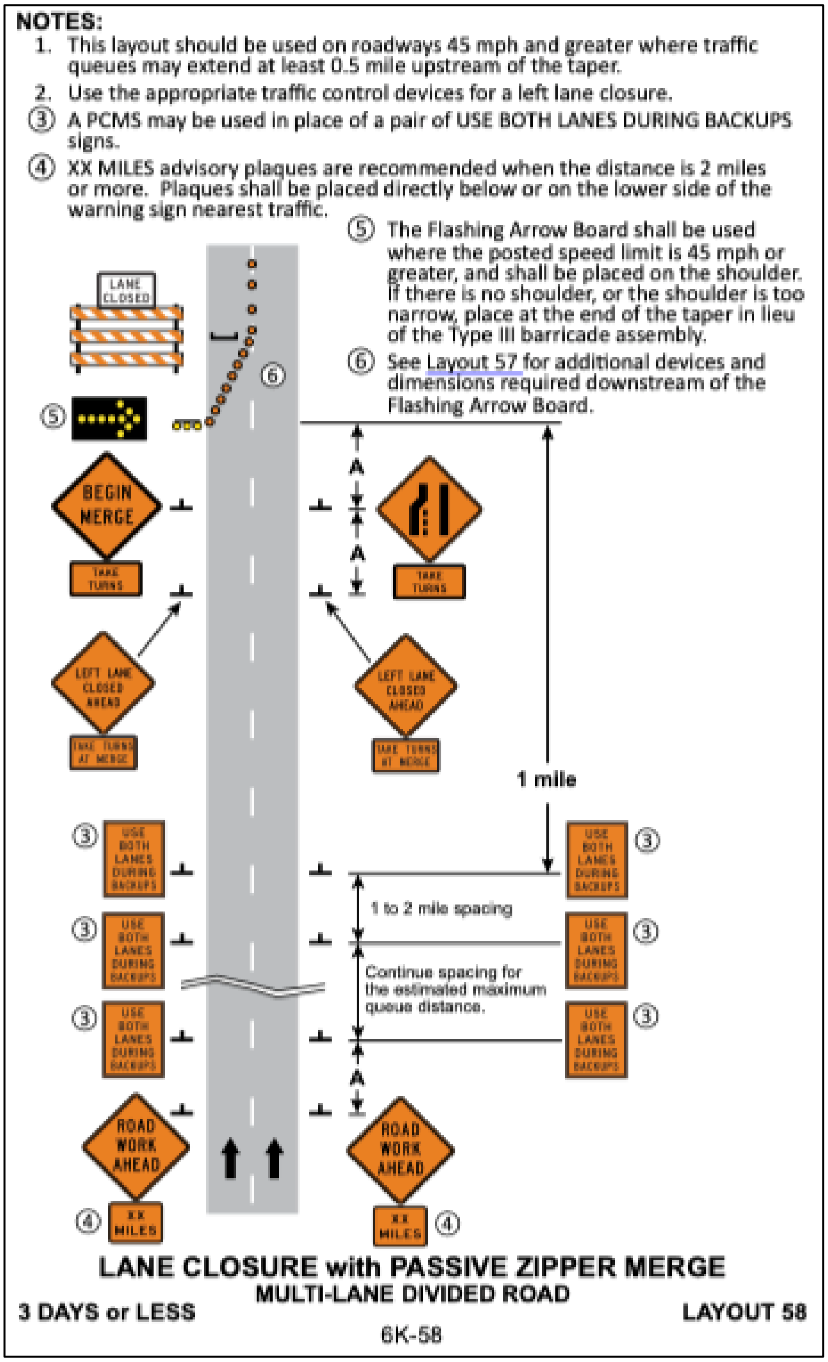
Figure 5. The layouts specify locations and messages for PCMS based on location and traffic conditions. For some conditions, the PCMS shows queue warning messages.

- Utah DOT’s (UDOT’s) layout for lane closure shows optional signs for zipper merge as specified by the project (UDOT 2024).
- INDOT (2020) provides a layout for static signs for zipper merge and allows for the use of PCMS.



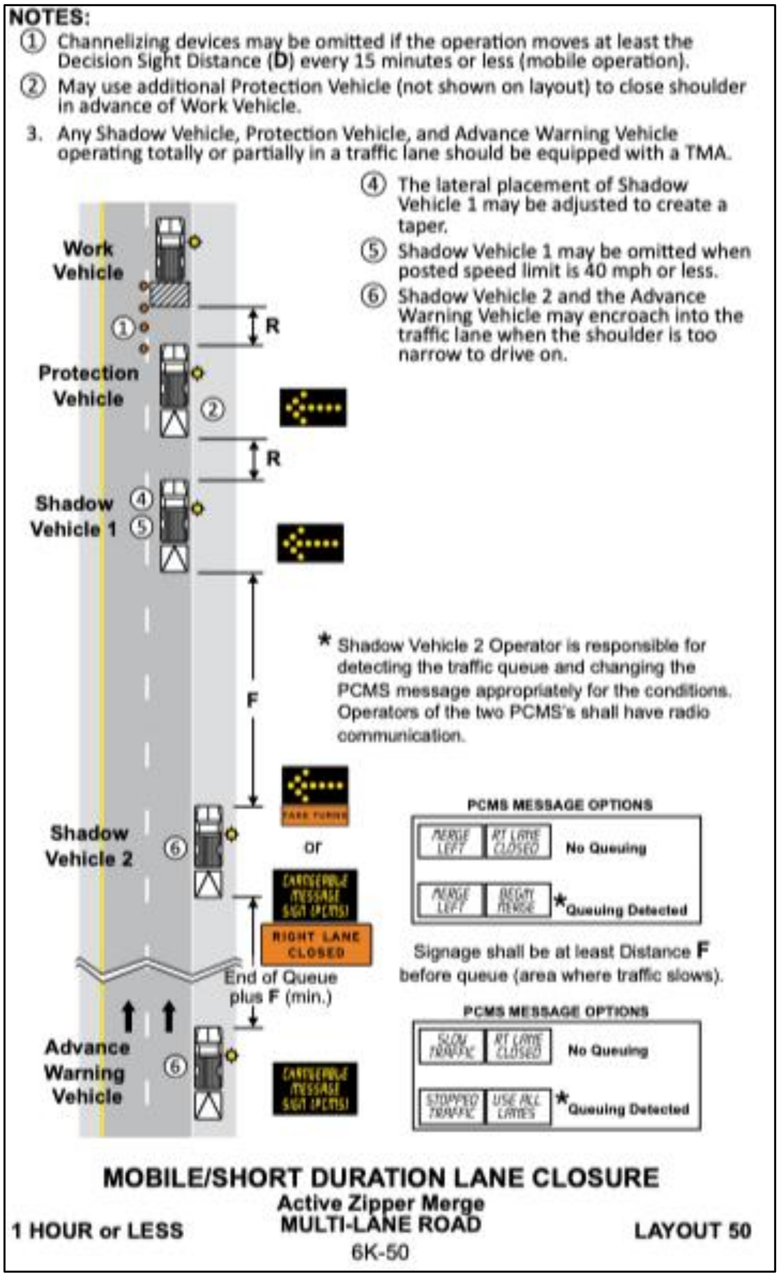
MDOT 2021

Figure 2. Layout for single-lane closure with early merge for MDOT



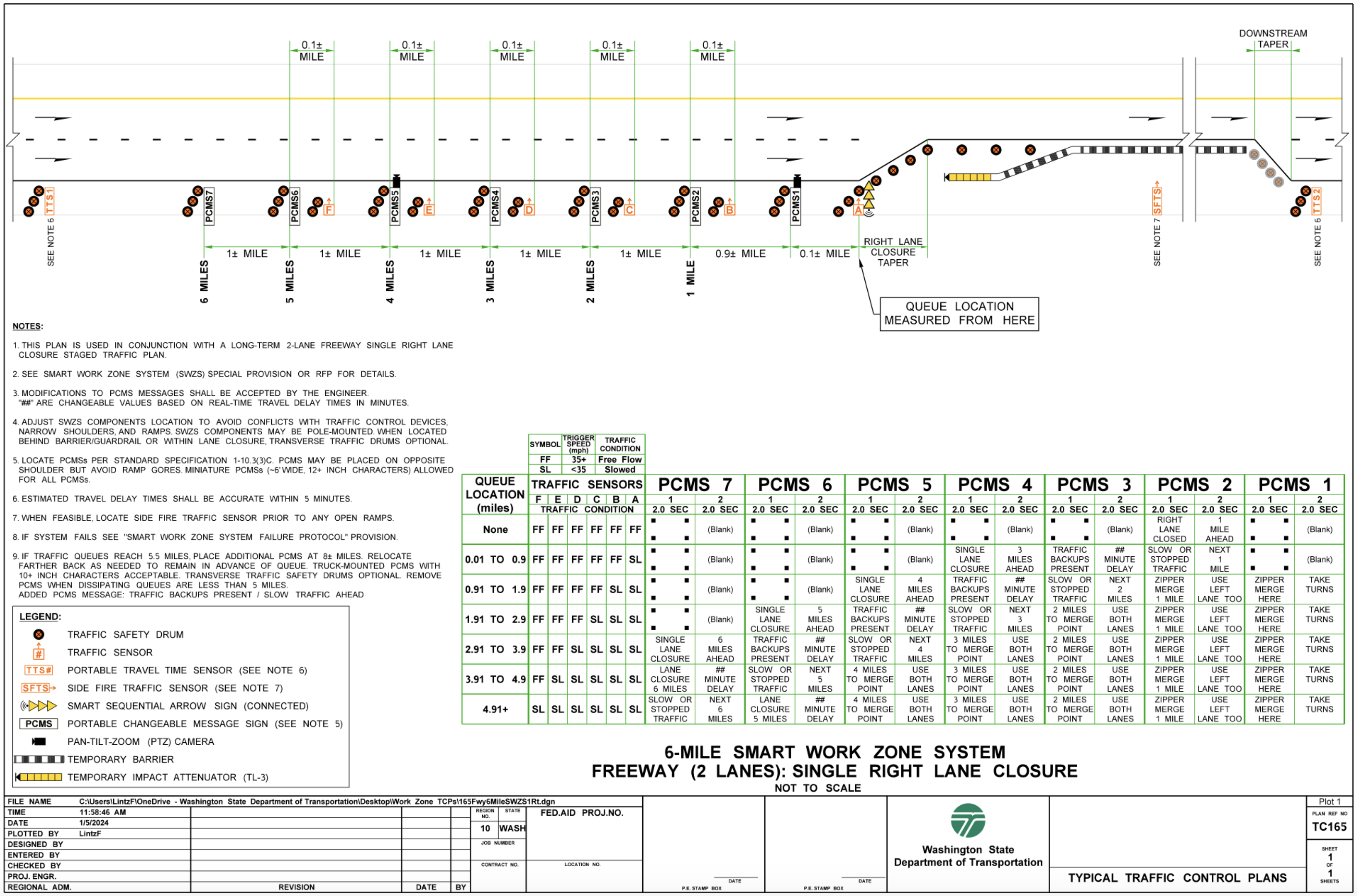
MnDOT 2018

Figure 3. Layout for lane closure with passive zipper merge on multilane highway for MnDOT



MnDOT 2018

Figure 4. Layout for active zipper merge for mobile/short duration lane closure on multilane highway for MnDOT



SYMBOL	TRIGGER SPEED (mph)	TRAFFIC CONDITION
FF	35+	Free Flow
SL	<35	Slowed

QUEUE LOCATION (miles)	F	E	D	C	B	A	PCMS 7 1 (2.0 SEC)	PCMS 7 2 (2.0 SEC)	PCMS 6 1 (2.0 SEC)	PCMS 6 2 (2.0 SEC)	PCMS 5 1 (2.0 SEC)	PCMS 5 2 (2.0 SEC)	PCMS 4 1 (2.0 SEC)	PCMS 4 2 (2.0 SEC)	PCMS 3 1 (2.0 SEC)	PCMS 3 2 (2.0 SEC)	PCMS 2 1 (2.0 SEC)	PCMS 2 2 (2.0 SEC)	PCMS 1 1 (2.0 SEC)	PCMS 1 2 (2.0 SEC)
None	FF	FF	FF	FF	FF	FF	■ ■ ■ ■	(Blank)	■ ■ ■ ■	(Blank)	■ ■ ■ ■	(Blank)	■ ■ ■ ■	(Blank)	■ ■ ■ ■	(Blank)	RIGHT LANE CLOSED	1 MILE AHEAD	■ ■ ■ ■	(Blank)
0.01 TO 0.9	FF	FF	FF	FF	FF	SL	■ ■ ■ ■	(Blank)	■ ■ ■ ■	(Blank)	■ ■ ■ ■	(Blank)	SINGLE LANE CLOSURE	3 MILES AHEAD	TRAFFIC BACKUPS PRESENT	## MINUTE DELAY	SLOW OR STOPPED TRAFFIC	NEXT 1 MILE	■ ■ ■ ■	(Blank)
0.91 TO 1.9	FF	FF	FF	FF	SL	SL	■ ■ ■ ■	(Blank)	■ ■ ■ ■	(Blank)	SINGLE LANE CLOSURE	4 MILES AHEAD	TRAFFIC BACKUPS PRESENT	## MINUTE DELAY	SLOW OR STOPPED TRAFFIC	NEXT 2 MILES	ZIPPER MERGE 1 MILE	USE LEFT LANE TOO	ZIPPER MERGE HERE	TAKE TURNS
1.91 TO 2.9	FF	FF	FF	SL	SL	SL	■ ■ ■ ■	(Blank)	SINGLE LANE CLOSURE	5 MILES AHEAD	TRAFFIC BACKUPS PRESENT	## MINUTE DELAY	SLOW OR STOPPED TRAFFIC	NEXT 3 MILES	2 MILES TO MERGE POINT	USE BOTH LANES	ZIPPER MERGE 1 MILE	USE LEFT LANE TOO	ZIPPER MERGE HERE	TAKE TURNS
2.91 TO 3.9	FF	FF	SL	SL	SL	SL	SINGLE LANE CLOSURE	6 MILES AHEAD	TRAFFIC BACKUPS PRESENT	## MINUTE DELAY	SLOW OR STOPPED TRAFFIC	NEXT 4 MILES	3 MILES TO MERGE POINT	USE BOTH LANES	2 MILES TO MERGE POINT	USE BOTH LANES	ZIPPER MERGE 1 MILE	USE LEFT LANE TOO	ZIPPER MERGE HERE	TAKE TURNS
3.91 TO 4.9	FF	SL	SL	SL	SL	SL	LANE CLOSURE 6 MILES	## MINUTE DELAY	SLOW OR STOPPED TRAFFIC	NEXT 5 MILES	4 MILES TO MERGE POINT	USE BOTH LANES	3 MILES TO MERGE POINT	USE BOTH LANES	2 MILES TO MERGE POINT	USE BOTH LANES	ZIPPER MERGE 1 MILE	USE LEFT LANE TOO	ZIPPER MERGE HERE	TAKE TURNS
4.91+	SL	SL	SL	SL	SL	SL	SLOW OR STOPPED TRAFFIC	NEXT 6 MILES	LANE CLOSURE 5 MILES	## MINUTE DELAY	4 MILES TO MERGE POINT	USE BOTH LANES	3 MILES TO MERGE POINT	USE BOTH LANES	2 MILES TO MERGE POINT	USE BOTH LANES	ZIPPER MERGE 1 MILE	USE LEFT LANE TOO	ZIPPER MERGE HERE	TAKE TURNS

WSDOT 2024b

Figure 5. Layout for zipper merge for right lane closure (two lanes) for WSDOT

2.2.3. Operational Requirements for Lane Merge Systems in Work Zones

DOTs also specify operational requirements for lane merge systems in work zones, such as travel conditions that trigger the system. These thresholds are typically based on speed and vary across DOTs. Other DOT requirements include system functionality. Example DOT operational requirements are highlighted below:

- MoDOT, in its job special provision for zipper merge, requires the system to detect traffic conditions for free-flow and congestion (MoDOT 2024). As general guidance, MoDOT indicates that detection of congested conditions can be based on speeds (typically less than 20 to 35 mph) or volumes (typically greater than 1,500 to 1,700 vehicles per hour per lane).
- The Oregon DOT (ODOT), in its standard for a smart work zone system, provides a table of messages that should be displayed on PCMS (based on queue length, PCMS location, and traffic conditions) (ODOT 2019). ODOT categorizes traffic conditions into six groups based on speed, as shown in Figure 6.
- The Tennessee DOT (TDOT) prescribes PCMS messages for its portable queue warning/dynamic late merge system based on PCMS location and traffic conditions (TDOT 2024). Messages are based on these traffic conditions: free-flow and two tiers of slow (45 mph or less or 20 mph or less). Messages with WARNING STOPPED TRAFFIC are displayed for speeds of 20 mph or less.
- WSDOT requires the smart work system to include these functions: queue detection, dynamic lane merge, and traveler information (work zone travel delay) (WSDOT 2024a). Standard drawings show the layout of traffic control devices and messages for PCMS based on queue location and traffic conditions (free-flow 35 mph or higher, slow less than 35 mph) (WSDOT 2024b). The required accuracy for estimated travel times is five minutes.
- WisDOT's guidance and standard drawings indicate that the dynamic late merge system only activates for speeds lower than 40 mph (WisDOT 2024a, WisDOT 2024b).
- The North Carolina DOT (NCDOT) provides the logic for programming the zipper merge system and requires the software to cover three functions: queue warning, driver merge instructions, and lane closure notification (NCDOT 2023a).
- UDOT (2024) requires the use of changeable message signs (CMS) (instead of static signs) for freeways with speeds of 65 mph or higher.

Symbol	Trigger Speed, V (mph)	
F	>45	Free Flow
NF	35–45	Non–Free Flow
M	25–35	Moderate/ Slowed
SG	>0–25*	Stop/ Go
S	0**	Stopped
A	>0	Any condition. Speed varies between stoppage point & taper.

ODOT 2019

Figure 6. Trigger speeds for different traffic conditions for ODOT

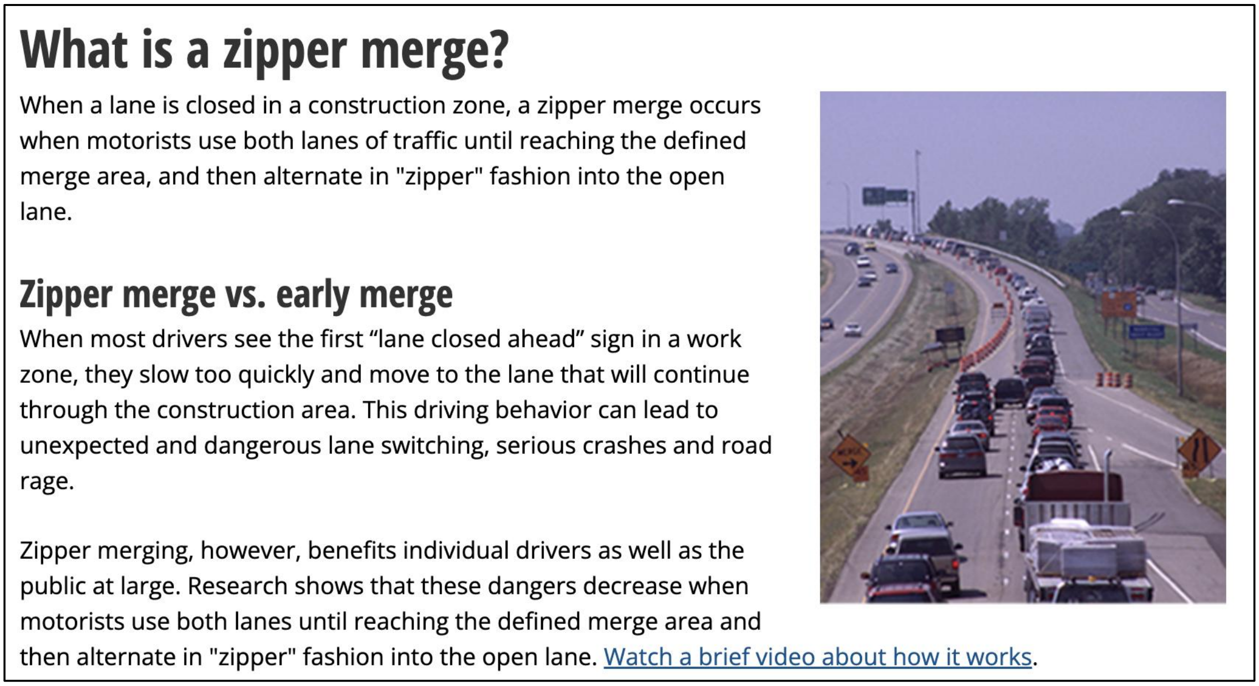
2.2.4. *Other Requirements for Lane Merge Systems in Work Zones*

State DOTs include other requirements for lane merge systems in work zones, such as approval processes, websites with travel information, materials, and measurement and payment, in special provisions and other documents. Examples of other DOT specifications are shown below:

- MoDOT's job special provision for a dynamic late merge system includes requirements for the system, smart work zone plan, materials, system manager, operational testing, and measurement and payment (MoDOT 2024). A work zone and intelligent transportation systems plan must be submitted to the engineer for approval three weeks prior to system mobilization. The contractor must host a website that provides real-time information on system components. Payment is by lump sum.
- NCDOT's special provision for a dynamic late merge system includes requirements for materials and system operations, construction methods, and measurement and payment (NCDOT 2023a). System specifications, including a security plan and protocol, must be submitted at least 10 days prior to system delivery. A website showing real-time speeds and posted messages must be maintained by the contractor. Any system malfunctions must be addressed within 24 hours. Payment is made for system deployment and relocation and for each day the system operates.
- WSDOT provides a list of vendors for the smart work zone system, which includes dynamic lane merge (WSDOT 2024a). The contractor must conduct a coordination meeting at least one week before the system is initialized. WSDOT also prescribes data requirements and a failure protocol.
- WisDOT's special provision for a dynamic late merge system includes requirements for device placement, programming, measurement, and payment. Programming (WisDOT 2024c). Vendor verification must be submitted to the engineer and Bureau of Traffic Operations 14 calendar days prior to the pre-construction meeting. A weekly summary report must be provided to the engineer. Data must be archived, and a website with real-time data (e.g., speeds, device locations, PCMS messages) is required. Payment is based on per day of operation, with deductions for each day in excess of one day for system deficiencies.

2.2.5. *Public Outreach Materials for Lane Merge Systems in Work Zones*

Several DOTs, such as Minnesota (2024b), Missouri (2022), Montana (2018), North Carolina (2023b), and Virginia (2024), provide public outreach materials (e.g., websites, videos) for lane merge systems in work zones. These outreach materials cover topics such as system benefits, how to merge properly, and pilot programs. An excerpt from MnDOT's outreach website for zipper merge is shown in Figure 7, and a screenshot from the Montana DOT's (MDT's) outreach video is shown in Figure 8. WisDOT (2024a) requires public outreach for any project that utilizes a dynamic lane merge system. When zipper merge is used, INDOT (2020) requires the district traffic engineer to notify the district media relations director and provide support for public outreach.



What is a zipper merge?

When a lane is closed in a construction zone, a zipper merge occurs when motorists use both lanes of traffic until reaching the defined merge area, and then alternate in "zipper" fashion into the open lane.

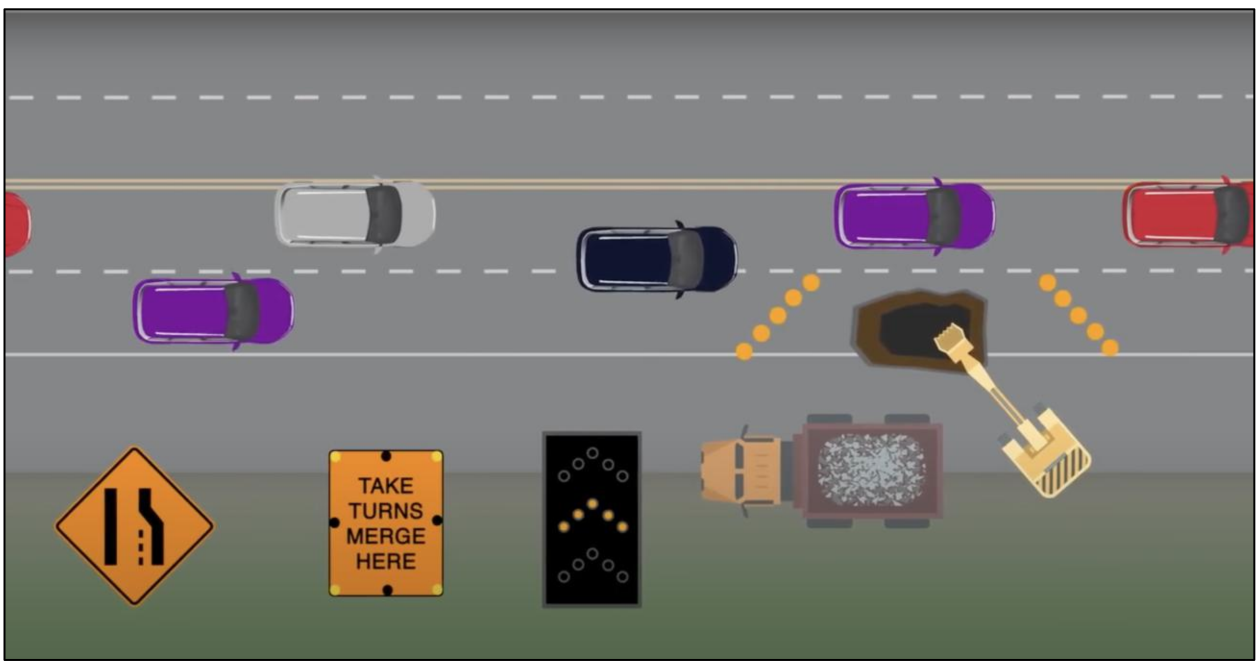
Zipper merge vs. early merge

When most drivers see the first “lane closed ahead” sign in a work zone, they slow too quickly and move to the lane that will continue through the construction area. This driving behavior can lead to unexpected and dangerous lane switching, serious crashes and road rage.

Zipper merging, however, benefits individual drivers as well as the public at large. Research shows that these dangers decrease when motorists use both lanes until reaching the defined merge area and then alternate in "zipper" fashion into the open lane. Watch a brief video about how it works.

MnDOT 2024b

Figure 7. Excerpt from MnDOT’s outreach website for zipper merge



MDT 2018

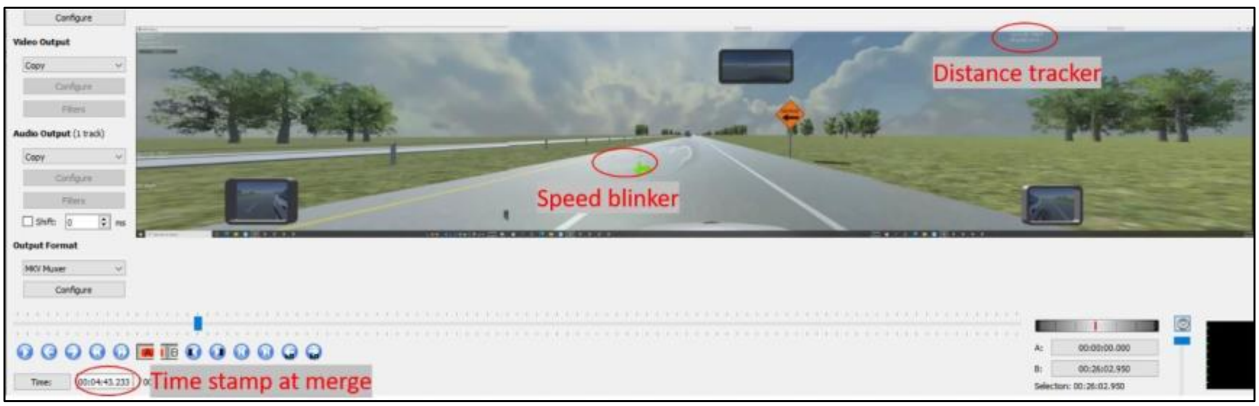
Figure 8. Screenshot from MDT outreach video for dynamic late merge

2.3. Research Studies for Lane Merge Control Strategies in Work Zones

As described in the following sections, research studies have generally shown alternative lane merge strategies to be effective in improving system performance.

2.3.1. Research Studies on Merge Configurations and Signage

Some research studies have investigated merging configurations and signage. A driving simulator study on zipper merge found that placement of the last CMS near the taper led to more desirable driver behavior (Sun et al. 2021). Figure 9 shows an example of the extraction of merging performance measures for the driving simulator. The study also found that public education was a critical component in attaining driver compliance and ensuring that the zipper merge functions properly. A survey found that 94% of respondents found an explanation of zipper merge beneficial.



Sun et al. 2021

Figure 9. Extraction of performance measures for merging in Missouri driving simulator study

A field investigation of two alternative message displays for a portable dynamic lane merge system in Rhode Island found that a display with an alternating roadwork graphic and speed limit sign on top and an alternating MERGE LEFT message and merging traffic arrows on bottom provided the best performance in encouraging zip merge behavior (Reinker et al. 2015). The field study encompassed three work zones on a three-lane freeway that was reduced to two lanes over four days.

2.3.2. Evaluation Studies for Early and Late Merge Systems in Work Zones

Field studies have generally shown that the use of early and late merge systems in work zones leads to improvements in capacity. For example, a Virginia field study of late merge (two-to-one lane closure) did not find a statistically significant increase in throughput with the late merge even though drivers merged later (Beacher et al. 2004). A field study using data from I-95 in Florida compared dynamic early merge, dynamic late merge, and a standard merge configuration

(Harb et al. 2011). Results showed that dynamic early merge was associated with higher capacity than the standard merge configuration, but the dynamic late merge did not significantly increase capacity. A field evaluation of dynamic late merge at work zones on I-94 in Michigan compared three sites with dynamic late merge to a control site (Datta et al. 2007). Findings indicated that the use of dynamic late merge led to lower travel times, higher travel speeds, and higher throughput. A field study conducted at two work zones in Kentucky found that the use of dynamic late merge helped improve traffic flow, but the researchers did not identify conclusive data showing significant improvements in operations or safety with the use of the dynamic late merge (Lammers et al. 2017).

Driving simulators and microsimulation have also been used to assess early and late merge systems in work zones. A driving simulator study conducted in the Washington, DC, area assessed the effects of traffic volume and dynamic merge messaging on merge location and throughput (Weaver et al. 2019). Study findings indicated that drivers merged farther upstream with dynamic early merge and that the dynamic late merge was associated with higher throughput for high traffic volumes.

Microsimulation studies have shown that dynamic merge strategies in work zones lead to higher throughput. An analysis of late merge using computer simulation found that throughput increased throughput across several traffic factors (e.g., percentage of heavy vehicles) for a three-to-one lane closure. However, throughput only increased for three-to-two and two-to-one lane closures when the traffic included more than 20% heavy vehicles (Beacher et al. 2004). A microsimulation study of static early merge, static late merge, and dynamic late merge by Kang et al. (2011) found that dynamic late merge and static late merge led to higher throughput than static early merge. However, static early merge was associated with less speed variation and fewer merging conflicts near the taper at low traffic volumes. A research study by Harb et al. (2012) of dynamic early merge, dynamic late merge, and a standard merge configuration using a microsimulation model found that dynamic early merge led to the highest throughputs. A microsimulation study of dynamic lane merge used in conjunction with variable speed limits found that the use of dynamic late merge with or without variable speed limits led to higher throughputs for higher traffic volumes (Radwan et al. 2011). However, the study found that all merge control strategies had comparable throughput at low and medium traffic volumes.

A survey has also been used to determine driver preferences for merging strategies in work zones. A survey of 455 drivers was conducted in Australia to compare the following merging strategies in work zones: early merge, late merge, joint lane merge, signalized merge, and Australian conventional merge (Siriwardene et al. 2024). Results indicated that drivers most preferred conventional merge and early merge and least preferred joint lane merge and signal merge. In addition, respondents believed that conventional merge, early merge, and late merge were most beneficial for helping them comprehend when and where they needed to change lanes.

The availability of safety evaluations for lane merge control strategies is somewhat limited. A safety assessment of a dynamic late merge in Kansas found three fewer crashes per week than in a similar work zone located nearby (KDOT 2016). Analysis of crash data from I-94 in Michigan did not find a statistically significant difference in crashes between sites with dynamic late merge and a control site (Datta et al. 2007).

2.3.3. Evaluation Studies for Other Types of Merge Control Strategies in Work Zones

Previous research studies have also investigated the use of other types of merge control strategies in work zones, such as cooperative systems and lane-based signal merge control systems. Examples of research studies on cooperative systems are provided below:

- The use of a New England Merge for highway work zones, which forces vehicles to cooperate and create safe gaps for merging in advance of a lane closure, was suggested by Ren et al. (2021). The New England Merge utilizes two metering zones where drivers adjust their headways and longitudinal positions (but are not allowed to change lanes) and a merging zone where drivers change lanes. Microsimulation was used to compare the New England Merge to late merge, early merge, and no control based on operational and surrogate safety measures. Results indicated that the New England Merge provided better operational and safety performance than other merge strategies.
- A study by Ren et al. (2020) investigated the use of a proposed cooperative work zone control merge strategy that assumed all vehicles are fully automated, connected, and cooperative and utilized a reinforcement learning algorithm. Microsimulation was used to compare the proposed strategy with late merge, early merge, cooperative adaptive cruise control, and no control. Results indicated that the proposed strategy outperformed other strategies for both safety and performance under congested traffic conditions.
- A simulation was used by Algomaiah and Li (2022) to investigate a merging system for work zone lane closures based on a cooperative lane merge strategy in environments with connected vehicles and connected and autonomous vehicles. Results indicated capacity increases of 17% (decentralized) and 45% (centralized) for the cooperative lane merge strategy compared to a traditional work zone merge configuration.
- A microsimulation study to investigate a late merge system with and without connected vehicles enabled was conducted by Algomaiah and Li (2021). The scenario with connected vehicles allowed cooperative merge with communication between vehicles. Results show that the late merge with connected vehicles provided better operational performance than the late merge without connected vehicles. Both late merge scenarios performed better than a traditional early merge strategy.

Simulation studies have also shown that signalized lane-based merge control strategies in work zones have the potential to improve operational performance, especially with flexible phase sequences and lengths. For example, an alternative merge control strategy using a lane-based signal merge system was developed by Mao et al. (2013) and evaluated through simulation. The system utilizes lane-based signals or variable signs to inform drivers in various lanes when they can move through the work zone in the open lane. The results indicated that the lane-based signal merge strategy led to improved operational performance compared to conventional merge, early merge, and late merge. In addition, the use of dynamic and flexible phase sequences and lengths improved system performance. A proposed signal-based lane control merge system for work zones was evaluated by Yuan et al. (2019) using microsimulation. Results showed that a system with flexible phase sequences and lengths provided better operational performance than a system with fixed cycle lengths.

2.4. Summary of Findings from Literature Review

The findings from the review of DOT resources suggest a wide range of DOT practices for dynamic lane merge, especially regarding criteria for determining when to deploy dynamic lane merge in a given work zone and speed thresholds for activating the system once deployed. DOTs also use various public outreach strategies, such as websites and videos, to educate the public about dynamic lane merge.

Prior research studies have used several methods (e.g., field evaluation, simulation, driving simulator, and driver surveys) to investigate alternative lane merge control strategies, such as early and late merge, cooperative systems, and lane-based signal merge control systems. These studies have generally found that alternative lane merge control strategies are effective at increasing throughput compared to conventional lane merge strategies. However, research on the safety performance of alternative lane merge control strategies is somewhat limited.

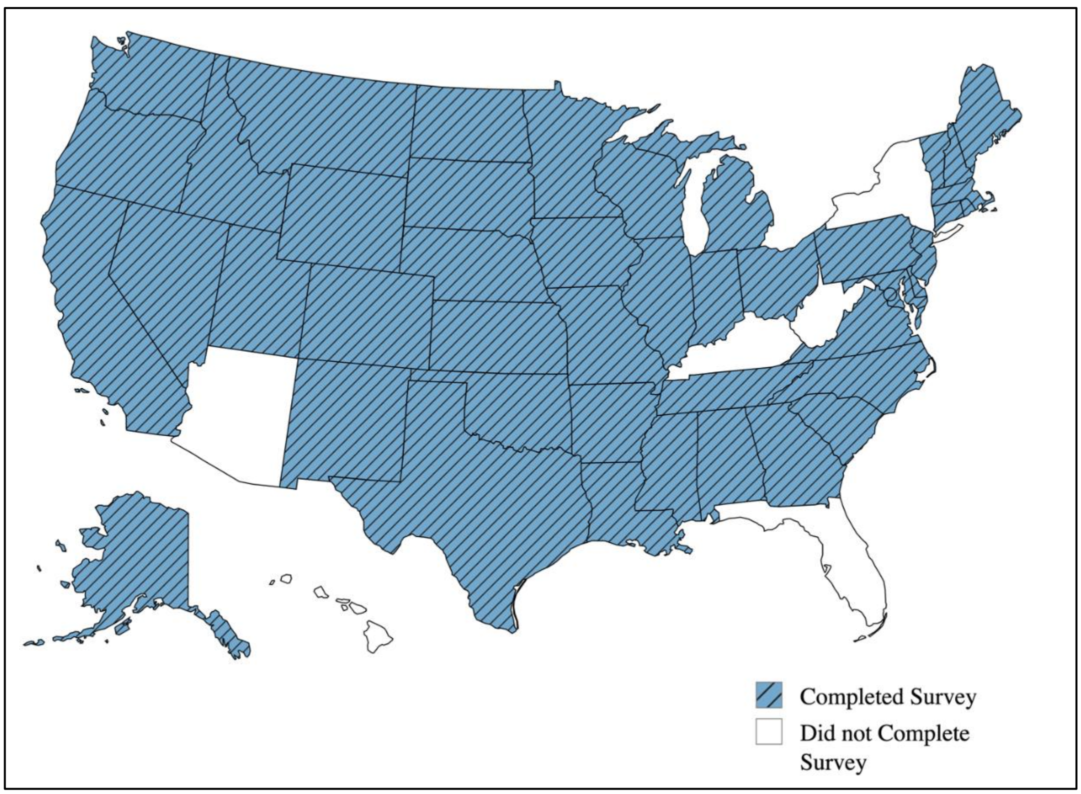
Most of the research from the past 10 years has focused on the use of simulation and driving simulators to evaluate alternative lane merge control strategies in work zones. The availability of field studies on lane merge control strategies in work zones in the past 10 years is somewhat limited. In addition, most of the research from the past five years has investigated cooperative (e.g., connected and autonomous vehicles) and signal-based work zone control merge strategies through the use of simulation. With recent trends, such as the increase in distracted driving, there is a need for additional field research on the benefits of dynamic lane merge systems and the development of guidelines for their use.

3. STATE DOT SURVEY

This chapter presents the methodology and results of the survey that was administered to DOTs within all 50 states and the District of Columbia.

3.1. Survey Methodology

The researchers developed and administered an online survey on lane merging in work zones. The survey consisted of 19 questions and was reviewed by the project technical advisory committee (TAC) before being sent to the DOTs from all 50 states and the District of Columbia via Qualtrics Survey Software (Qualtrics 2024). The survey was sent to one respondent from each DOT using a contact list developed based on information obtained from FHWA and previous surveys conducted by the researchers on work zone-related topics. Each DOT respondent received a unique survey link that could be shared within the DOT for collaboration purposes, with responses limited to one per DOT. Figure 10 shows responses were received from 45 DOTs for a response rate of 88%. The survey response rate for the SWZDI states was 100%.



Map created with mapchart.net

Figure 10. Map showing DOTs that responded to the survey on lane merge in work zones

The survey covered various topics regarding lane merge in work zones, such as the extent of use, practices and policies, performance, and implementation challenges. The survey utilized skip logic based on whether the responding DOT uses dynamic lane merge or static lane merge in work zones. Survey respondents who indicated in response to the first question that they do not use dynamic lane merge in work zones were only asked two additional questions regarding their use of static lane merge in work zones and an open-ended comment question that was shown to all survey respondents. DOTs that use dynamic lane merge in work zones were asked 17 questions. A copy of the full survey is provided in Appendix B, and the survey responses for each DOT, including comments and resources submitted, are given in Appendix C.

3.2. Survey Results

This section presents the survey results and is divided into the following subsections: Lane Merge Strategies (Question 1), Extent of Use of Dynamic Lane Merge (Questions 2, 5), Practices for Dynamic Lane Merge (Questions 4, 6, 7, 8, 9, 10, 16), Resources for Dynamic Lane Merge (Questions 3, 15), Performance of Dynamic Lane Merge (Questions 11, 12, 13, 14), Exclusive Use of Static Lane Merge (Questions 17, 18), and Other Survey Feedback (Question 19).

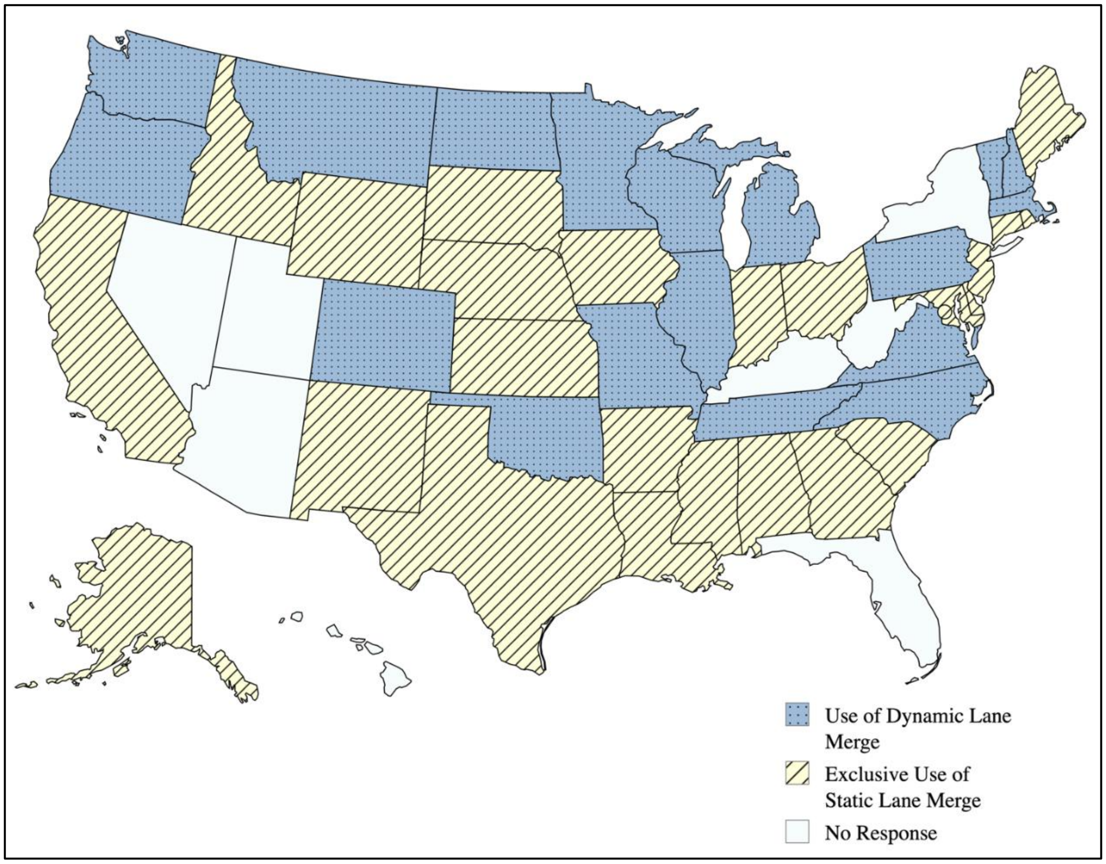
3.2.1. Lane Merge Strategies

The first survey question asked DOTs about their use of dynamic lane merge and static lane merge in work zones. As shown in Table 1, 18 of 45 responding DOTs indicated that they use dynamic lane merge in work zones, while 42 respondents indicated that they utilize static lane merge for work zones. Two respondents did not answer this question. A map showing responses by DOT is shown in Figure 11.

Table 1. Survey results for use of dynamic lane merge and static lane merge in work zones (Q1)

Lane Merge Strategy	Count
Dynamic lane merge	18
Static lane merge	42
Total Responses	**43**

Notes: Total number of respondents = 45. Respondents could select multiple answers.



Map created with mapchart.net

Figure 11. Map showing the use of dynamic lane merge in work zones by DOT

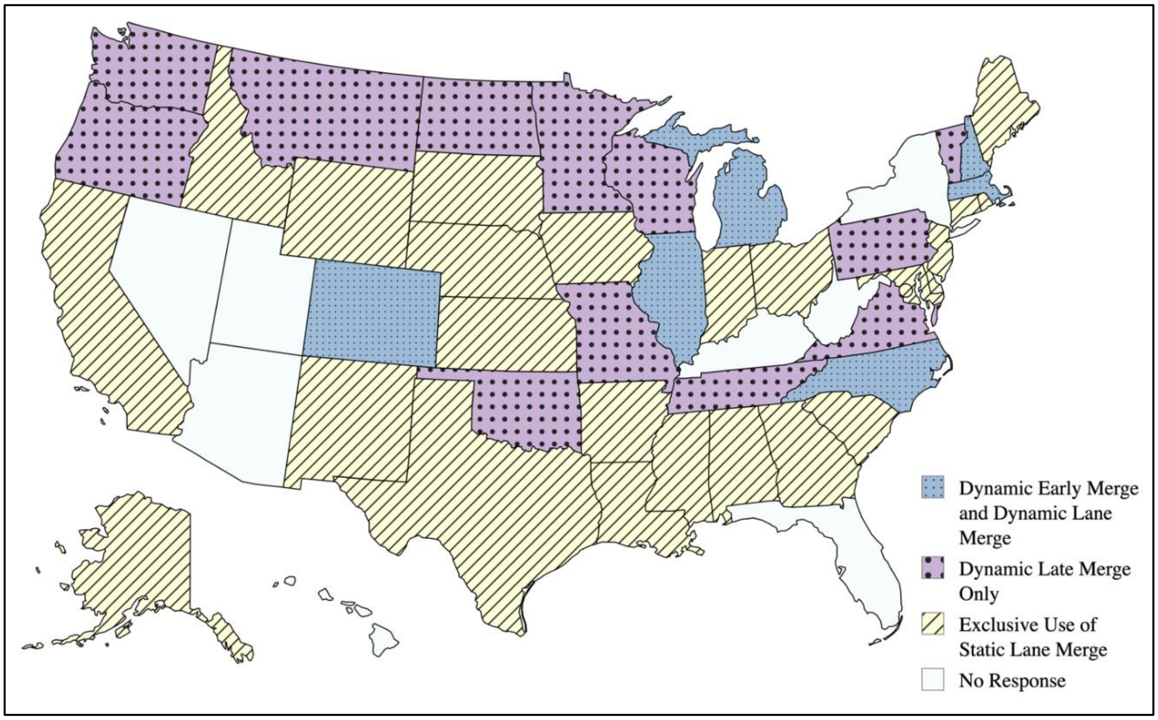
3.2.2. Extent of Use of Dynamic Lane Merge

Questions 2 through 16 of the survey were shown to the 18 DOTs, and they indicated the use of dynamic lane merge in Question 1. Question 2 asked DOTs about their use of dynamic early merge and dynamic late merge. The results, shown in Table 2, indicate that all 18 of these DOTs use dynamic late merge, while six responding DOTs also utilize dynamic early merge. A map showing the results for this question is provided in Figure 3.

Table 2. Survey results for use of dynamic early merge and dynamic late merge in work zones (Q2)

Dynamic lane merge strategy	Count
Dynamic early merge	6
Dynamic late merge	18
Total Responses	**18**

Notes: Number of respondents who viewed the question = 18. Respondents could select multiple answers.



Map created with mapchart.net

Figure 12. Map showing the use of dynamic early merge and dynamic late merge in work zones by DOT

Question 5 of the survey sought information regarding the frequency of use of dynamic lane merge in work zones for different types of facilities. The results, provided in Table 3, show that dynamic lane merge is most often implemented on urban freeways and least often implemented on rural multilane highways.

Table 3. Survey results for frequency of use of dynamic lane merge in work zones by facility type (Q5).

Facility Type	Frequently	Sometimes	Rarely	Never	Total	Average
Rural Freeways	1	9	8	0	18	2.61
Rural Multilane	0	5	8	5	18	2.00
Urban Freeways	2	12	3	1	18	2.83
Urban Multilane	1	4	8	5	18	2.06
Other	0	0	0	1	1	1.00

Notes: Number of respondents who viewed the question = 18. Average calculated based on these values: Frequently = 4, Sometimes = 3, Rarely = 2, Never = 1.

3.2.3. Practices for Dynamic Lane Merge

Multiple survey questions asked DOTs about various aspects of their practices for dynamic lane merge in work zones. Question 4 sought information regarding the types of lane drops for which dynamic lane merge is implemented. The results, provided in Table 4, indicate that 17 responding DOTs utilize dynamic lane merge for two-to-one lane drops in work zones, while eight responding DOTs implement dynamic lane merge for three-to-two lane drops. Other responses included the use of dynamic lane merge for any single-lane drop in work zones and for work zones over capacity on freeways.

Table 4. Survey results for types of lane drops used with dynamic lane merge (Q4)

Type of Lane Drop	Count
3 to 2	8
2 to 1	17
Other	2
Total Responses	**18**

Notes: Number of respondents who viewed the question = 18. Respondents could select multiple answers.

The results for Question 6, shown in Table 5, indicate that responding DOTs consider a wide range of factors when determining whether to implement dynamic lane merge in a work zone. The most frequently considered factors are annual average daily traffic (AADT), peak hour volumes, and duration of work, while stakeholder input and terrain are considered least often. Other factors noted in the text responses are interchange density and likelihood of queuing.

Table 5. Survey results for factors considered when trying to determine whether to implement dynamic lane merge in a work zone (Q6)

Factor	Frequently	Sometimes	Rarely	Never	Total	Average
AADT	11	6	1	0	18	3.56
Area Type (Urban or Rural)	7	7	2	1	17	3.18
Crash History	5	9	3	1	18	3.00
Duration of Work	9	9	0	0	18	3.50
Length of Work Zone	8	6	2	2	18	3.11
Peak Hour Volumes	12	5	1	0	18	3.61
Percent Trucks	5	6	4	2	17	2.82
Stakeholder Input	3	5	7	2	17	2.53
Terrain	4	5	6	2	17	2.65
Type of Work Activity	7	5	2	4	18	2.83
Work Zone Speed Limit	4	7	3	3	17	2.71
Worker Presence	6	6	2	3	17	2.88
Other	2	0	0	0	2	4.00

Notes: Number of respondents who viewed the question = 18. Average calculated based on these values: Frequently = 4, Sometimes = 3, Rarely = 2, Never = 1.

The results for Question 7, provided in Table 6, show that responding DOTs most often utilize speed for activation or deactivation thresholds for dynamic lane merge in work zones, followed by volume and a combination of multiple traffic measures. Three responding DOTs consider specific time periods (e.g., peak hours).

Table 6. Survey results for criteria for activation or deactivation thresholds for dynamic lane merge in work zones (Q7)

Criterion	Count
Based on specific time periods (e.g., peak hour)	3
Speed	12
Volume	6
Combination of multiple traffic measures	6
Other	1
Total Responses	**18**

Notes: Number of respondents who viewed the question = 18. Respondents could select multiple answers.

As shown in the responses to Question 8 in Table 7, responding DOTs most often utilize radar and microwave detectors to detect vehicle presence with dynamic lane merge in work zones. The use of programmed PCMS was mentioned in the other text responses.

Table 7. Survey results for types of vehicle presence detectors used with dynamic lane merge in work zones (Q8)

Type of Vehicle Presence Detector	Count
Microwave	8
Pneumatic tubes	1
Radar	14
Video	3
Other	2
None of the above	1
Total Responses	**18**

Notes: Number of respondents who viewed the question = 18. Respondents could select multiple answers.

In response to Question 9 (see results in Table 8), responding DOTs indicated that they often use dynamic lane merge in work zones in conjunction with end-of-queue warning systems (14 responding DOTs) and traveler information systems (13 responding DOTs). Two responding DOTs answered None of the above.

Table 8. Survey results for use of other smart work zone technologies with dynamic lane merge in work zones (Q9)

Smart Work Zone Technology	Count
End of queue warning system	14
Traveler information system	13
Other	1
None of the above	2
Total Responses	**18**

Note: Number of respondents who viewed the question = 18. Respondents could select multiple answers.

The results for Question 10, provided in Table 9, indicate that both measured pay items and lump sum pay items are equally utilized by DOTs as a basis of payment for dynamic lane merge in work zones. Other methods mentioned in the text responses include monthly or weekly payments with all other smart work zone systems and lump sum for deployment, per day after installation, and per move if relocation of the system is necessary. Two responding DOTs were not sure of the method used.

Table 9. Survey results for the basis of payment for dynamic lane merge in work zones (Q10)

Basis of Payment	Count
Measured pay item	7
Lump sum pay item	7
No direct payment	0
Other	4
Total	**18**

Note: Number of respondents who viewed the question = 18.

Question 16 of the survey sought information from DOTs regarding implementation challenges for dynamic lane merge in work zones. The results, shown in Table 10 indicates that the factors perceived to be the most challenging are driver inattention, lack of perceived need, and the need for enforcement. The need for a design consultant was noted in the text responses.

Table 10. Survey results for perceived challenges to implementation of dynamic lane merge in work zones (Q16)

Factor	Count
Agency understaffing	5
Availability of dynamic lane merge systems/vendors	4
Coordination with subcontractors	5
Cost	4
Driver inattention	8
Lack of agency buy-in	4
Lack of available guidance	4
Lack of contractor buy-in	3
Lack of information on benefits	4
Lack of perceived need	8
Need for enforcement	6
Other	1
None of the above	0
Total Responses	**16**

Notes: Number of respondents who viewed the question = 18. Respondents could select multiple answers.

3.2.4. Resources for Dynamic Lane Merge

Questions 3 and 15 asked DOTs about guidance, policies, and outreach materials for dynamic lane merge in work zones. In response to Question 3, 13 responding DOTs indicated that they have developed resources (e.g., policy, guidance, standards, or typical applications) for lane merge control strategies in work zones, while five responding DOTs have not developed these types of resources. Responding DOTs were also asked to provide these resources, and a tabular summary of submitted resources is provided in Appendix D.

The results for Question 15 are provided in Table 11 indicate that responding DOTs have most often developed social media sites as public outreach materials for dynamic lane merge in work zones, followed by websites, videos, flyers, and/or pamphlets, and collaborating with mass media. One DOT noted in the comments that dynamic lane merge works better in the field without project-specific media outreach.

Table 11. Survey results for types of outreach materials developed for dynamic lane merge in work zones (Q15)

Type of Outreach Material	Count
Flyer and/or pamphlet	6
Website	7
Social media site	8
Video	7
My agency uses materials from other agencies	0
My agency has not developed public outreach materials for dynamic lane merge systems	4
My agency is in the process of developing public outreach materials for dynamic lane merge systems	2
Collaborating with mass media (e.g., television, radio)	6
Other	1
Total Responses	**17**

Note: Number of respondents who viewed the question = 18. Respondents could select multiple answers.

3.2.5. Performance of Dynamic Lane Merge

The survey included four questions related to the performance of dynamic lane merge in work zones. The results for Question 11, shown in Table 12, indicate that 13 responding DOTs utilize performance measures for dynamic lane merge. Responding DOTs most often use queue length, delay, and speed as performance measures for dynamic lane merge in work zones. Safety performance measures are also incorporated, with seven responding DOTs utilizing the number of crashes.

Table 12. Survey results for performance measures for dynamic lane merge in work zones (Q11)

Performance Measure	Count
Number of crashes	7
Crash severity	3
Observed conflicts/safety	5
Driver compliance	5
Occupancy	2
Queue length	12
Speed	10
Delay	11
Other	0
My agency does not use performance measures to assess the performance of dynamic lane merge in work zones	5
Total Responses	**18**

Note: Number of respondents who viewed the question = 18. Respondents could select multiple answers.

Question 12 asked DOTs to rate the performance of dynamic lane merge systems under their jurisdiction on a scale of 1 (highly ineffective) to 5 (highly effective). The average rating was 3.61 out of 5 with a standard deviation of 0.70, indicating that responding DOTs find the use of dynamic lane merge in work zones to be moderately effective. One DOT noted in the comments that performance varies depending on project location.

Question 13 of the survey sought information regarding the factors perceived to influence the performance of dynamic lane merge in work zones. The results, provided in Table 13, show that responding DOTs generally agree that all of these factors have an effect on the performance of dynamic lane merge in work zones. The factors believed to have the greatest impact on performance are activation thresholds, traffic volumes/congestion, and the location of the merge point. Education and media coverage were noted in the text responses.

Table 13. Survey results for factors that affect the performance of dynamic lane merge in work zones (Q13)

Factor	Strongly Agree	Somewhat Agree	Neither Agree nor Disagree	Somewhat Disagree	Strongly Disagree	Total	Average
Activation Thresholds	11	4	3	0	0	18	4.44
Location of Merge Point	7	7	4	0	0	18	4.17
Percent Trucks	5	8	4	1	0	18	3.94
Presence of Positive Protection	0	5	10	2	1	18	3.06
Traffic Volumes/ Congestion	10	6	2	0	0	18	4.44
Type of Work Activity	1	5	12	0	0	18	3.39
Use of Additional Countermeasures (e.g., Enforcement)	4	8	6	0	0	18	3.89
Work Zone Duration	5	7	5	1	0	18	3.89
Work Zone Length	2	7	5	4	0	18	3.39
Work Zone Speed Limit	3	6	6	3	0	18	3.50
Worker Proximity	2	7	5	4	0	18	3.39
Other (Please describe)	2	0	0	0	0	2	5.00

Notes: Number of respondents who viewed the question = 18. Average calculated based on these values: Strongly Agree = 5, Somewhat Agree = 4, Neither Agree Nor Disagree = 3, Somewhat Disagree = 2, Strongly Disagree = 1.

In response to Question 14, one DOT (MoDOT) indicated that it had completed evaluation studies for dynamic lane merge in work zones.

3.2.6. Exclusive Use of Static Lane Merge

The survey included two questions for responding DOTs that only utilize static lane merge based on their response to Question 1 (including the two DOTs who did not answer Question 1). In response to Question 17 (see results in Table 14), DOTs cited lack of perceived need, lack of information on benefits, lack of available guidance, and the prioritization of other work zone safety countermeasures (e.g., speed management, end-of-queue warning systems) as the primary reasons they do not utilize dynamic lane merge in work zones.

Table 14. Survey results for reasons for non-use of dynamic lane merge (Q17)

Response	Count
Agency understaffing	8
Cost	4
Lack of available guidance	9
Lack of information on benefits	13
Lack of perceived need	14
Other work zone countermeasures are a higher priority (please briefly describe other countermeasures in the box below)	9
Other	6
Total Responses	**27**

Notes: Number of respondents who viewed the question = 27. Respondents could select multiple answers.

In response to Question 18, 17 of the responding DOTs that do not utilize dynamic lane merge indicated that they have developed policies, guidance, standards, or typical applications regarding the use of static lane merge strategies in work zones. A tabular summary of the resources submitted for this question is provided in Appendix C.

3.2.7. Other Survey Feedback

The final question of the survey asked DOTs to provide any other comments regarding the use of lane merge in work zones. A full list of these comments is provided in Appendix D. Some example comments are highlighted below:

- Responding DOTs highlighted the importance of dynamic traffic control, consistency, and education.
- One DOT would likely consider a dynamic lane merge if there was documentation to show that benefits exceed the cost.
- Some responding DOTs have tried dynamic lane merge on a limited number of projects. One DOT has provisions for the use of dynamic lane merge but has not yet implemented it because it has not found the right conditions to try it.

3.3. Summary of Key Survey Findings

The key findings from the survey of state DOTs are summarized as follows.

3.3.1. Key Survey Findings for Use of Lane Merge in Work Zones

- Eighteen of 45 responding DOTs (40%) indicated that they use dynamic lane merge in work zones, while 42 responding DOTs (93%) indicated that they use static lane merge in work zones. Twenty-five responding DOTs (56%) indicated that they use static lane merge exclusively in work zones.
- Eighteen responding DOTs (40%) utilize dynamic late merge, while six of those DOTs (13%) also utilize dynamic early merge.

- Dynamic lane merge (including dynamic early merge and dynamic late merge) is most often implemented on urban freeways and least often implemented on rural multilane highways.
- DOTs most often use dynamic lane merge for two-to-one lane drops in work zones.
- The most frequently considered factors when determining whether to implement dynamic lane merge in a work zone are AADT, peak hour volumes, and duration of work, while stakeholder input and terrain are considered least often.

3.3.2. Key Survey Findings for Practices for Lane Merge in Work Zones

- Responding DOTs most often utilize speed for activation or deactivation thresholds for dynamic lane merge in work zones, followed by volume and a combination of traffic measures.
- To detect vehicle presence for dynamic lane merge in work zones, responding DOTs most frequently utilize nonintrusive radar and microwave detectors.
- Dynamic lane merge is sometimes implemented along with other smart work zone technologies in work zones, most frequently with end-of-queue warning systems (14 responding DOTs) and traveler information systems (13 responding DOTs).
- Both measured pay items and lump sum pay items are equally utilized by DOTs as the basis of payment for dynamic lane merge in work zones. Other methods include monthly or weekly payments with all other smart work zone systems and lump sum for deployment, per day after installation, and per move if relocation of the system is necessary.
- Thirteen of the 18 responding DOTs that implement dynamic lane merge have developed resources (e.g., policy, guidance, standards, or typical applications) for lane merge in work zones.
- DOTs have developed various types of outreach materials for dynamic lane merge in work zones, with social media sites, websites, videos, flyers, and/or pamphlets, and collaborating with mass media is the most prevalent type of outreach material.
- Seventeen of the 27 responding DOTs that do not implement dynamic lane merge in work zones have developed policies, guidance, standards, or typical applications regarding the use of static lane merge strategies in work zones.

3.3.3. Key Survey Findings for Performance and Challenges for Lane Merge in Work Zones

- Responding DOTs most often use queue length, delay, and speed as performance measures for dynamic lane merge in work zones.
- The average performance rating (1 = highly ineffective, 5 = highly effective) for dynamic lane merge in work zones was 3.61 out of 5 with a standard deviation of 0.70, indicating that responding DOTs find the use of dynamic lane merge in work zones to be moderately effective. System performance can sometimes vary depending on project location.
- Among the responding DOTs that use dynamic lane merge, the factors perceived to be the most challenging to the implementation of dynamic lane merge in work zones are driver inattention, lack of perceived need, and the need for enforcement.
- One responding DOT (MoDOT) has completed evaluation studies for dynamic lane merge in work zones.

Responding DOTs that exclusively use static lane merge cited a lack of perceived need, lack of information on benefits, lack of available guidance, and the prioritization of other work zone safety countermeasures (e.g., speed management, end of queue warning systems) as the primary reasons they do not utilize dynamic lane merge in work zones.

4. ROAD USER SURVEY

This chapter presents the methodology and results of the road user survey that was administered to drivers in nine SWZDI states. The survey was developed strategically to gather information on drivers' preferences for various signage strategies, including the placement of PCMS to improve the efficiency of zipper merge. The following sub-sections provide details on survey development, data summary, and statistical methods used as a part of the data analyses.

4.1. Survey Design

The road user survey was designed and implemented through the Qualtrics platform and distributed among residents of the nine SWZDI states (Illinois, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, Texas, and Wisconsin) in the United States in 2024. Participation in the survey required drivers to meet specific criteria, which included a minimum age of 18 years, having a valid driving license, and residing in one of the SWZDI states. Additionally, the survey participant must have driven in the calendar year 2023 for further consideration in the study.

The survey was categorized into four sections. The first section collected general driver demographic data, including the participant's age, gender, race, type of valid driver's license (commercial or not), annual household income, highest education level, state of residence, and miles traveled in the year of the survey. The second section of the survey presented four different scenarios with varying sign configurations encountered in a freeway lane closure work zone to the participants and recorded their preferred location to merge into the open lane relative to the start of the taper. These four sign configurations were as follows:

1. Standard early merge with static signs
2. Standard zipper merge with static signs
3. Standard zipper merge with static signs along with a PCMS installed far upstream of the taper displaying USE BOTH LANES and DURING BACKUPS on alternating panels
4. Standard zipper merge with static signs along with a PCMS installed far upstream of the taper displaying USE BOTH LANES and DURING BACKUPS on alternating panels, and a downstream PCMS closer to the taper displaying MERGE HERE and TAKE TURNS on alternating panels

Figure 13 shows an example of a figure that was presented to the participants in the survey. The figure corresponds to the third scenario from above (i.e., standard zipper merge with static signs and one PCMS upstream). Similar figures with appropriate signage were also presented for the other three scenarios. In each of these scenarios, the survey respondents were told to assume they were driving in the black car in the right lane and were asked to indicate where they would prefer to merge from the lane about to close to the open lane. The available responses for these four scenarios were Section A, Section B, Section C, and Section D, with Section A being farthest (upstream) from the taper and D being closest to the taper.

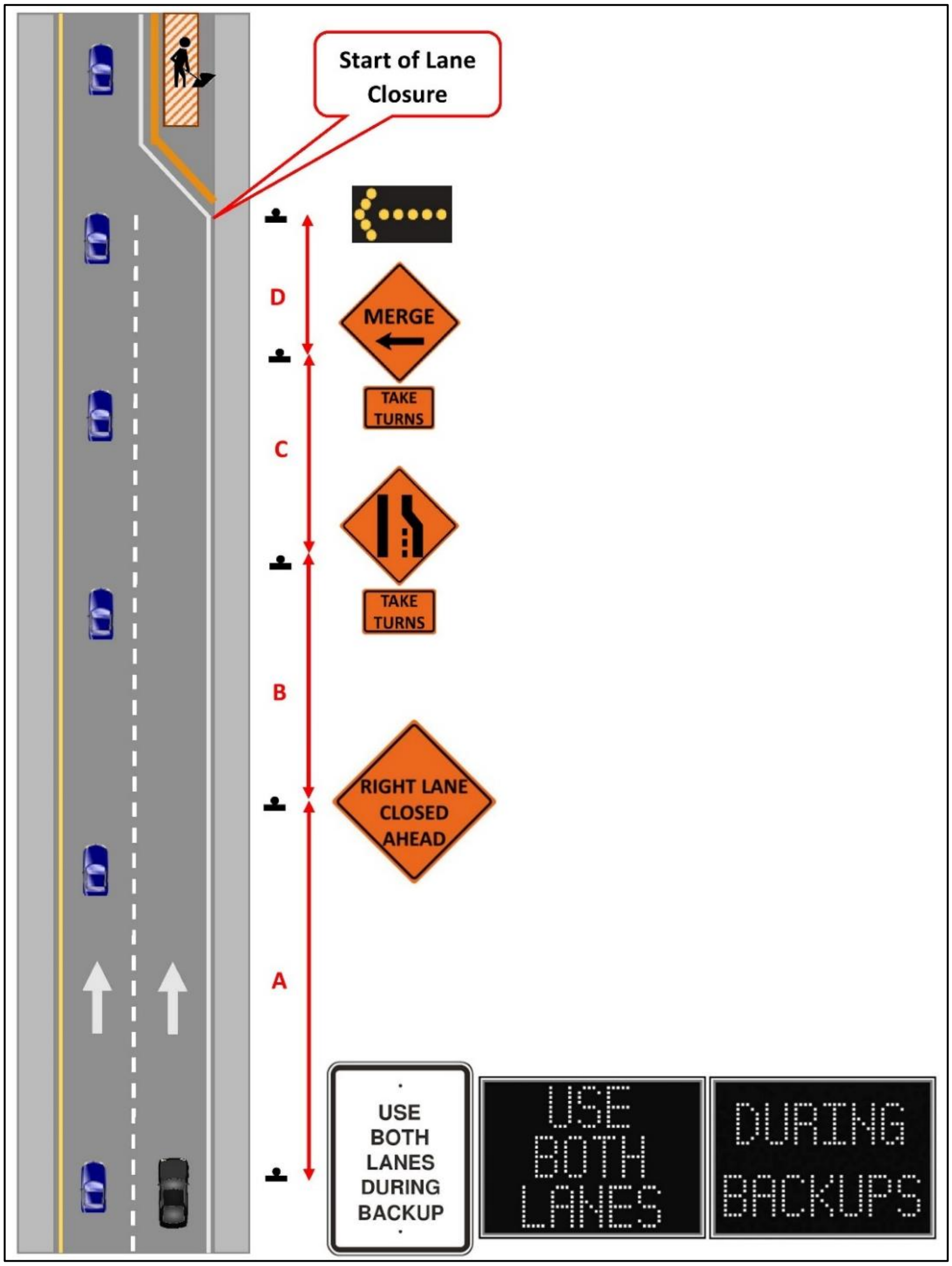


Figure 13. Driver preferred location to merge for third sign condition

The second set of questions in this section collected data on how respondents would behave if another driver attempted to merge from the closed lane into the open lane where the respondent was located. A series of questions with associated figures were included, with one example shown in Figure 14, which depicts the survey participant in a black car driving in the open lane and another driver in an orange car driving in the closed lane and attempting to merge in front of the respondent's car. The same question was asked for two different sign configurations—(1) standard early merge with static signs and (2) standard late merge with static signs—and two merging locations—(1) when both cars are in Section A and (2) when both cars are in Section D. For each of these four scenarios, four response choices were provided as given below:

1. Slow down and allow the orange vehicle to merge in front of you.
2. Continue driving at the same speed without giving any consideration to the orange vehicle.
3. Accelerate to prevent the orange vehicle from merging in front of you.
4. Other. Please specify. (Text response)

The third section of the survey recorded the participants' preferences from among a series of various signs. Each sign was intended to convey a similar message, and participants were asked to choose their preferred sign from among these alternatives. For example, the participants were shown signs W9-2 (RIGHT LANE CLOSED AHEAD, textual sign) and W4-2 (graphical right lane closed sign) and were asked to provide their opinion as to which sign better conveys the message that the right lane is closed ahead. Finally, the last section of the survey collected information about the general understanding of zipper merge among the participants, whether they feel comfortable with it, and which type of media/platform has the best potential for education and outreach about different lane merge strategies. A copy of the full road user survey is provided in Appendix B, along with the images of all the sections and subsections of the survey.

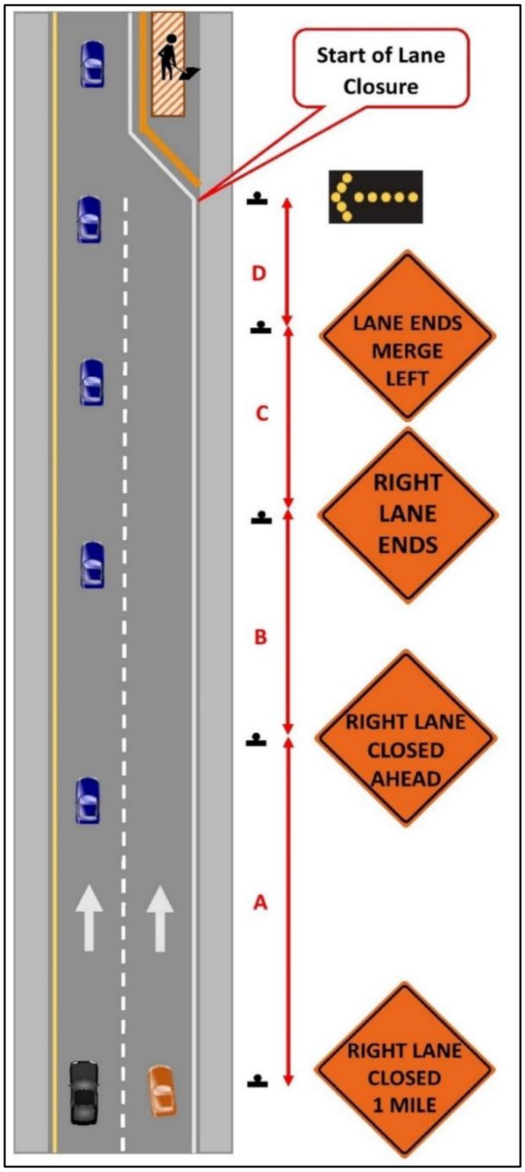


Figure 14. Driver's preferred course of action to vehicle trying to merge in the open lane

4.2. Data Summary Results

This section presents the data summary of the responses received for the road user survey. A total of 1,050 complete and valid responses were received for the survey. This section is divided into two subsections. The first subsection deals with the data summary of general information about the driver asked in the first section of the survey, and the second subsection deals with the data summary of questions asked in the survey's second, third, and fourth sections.

4.2.1. Data Summary for General Driver Information

Table 1 summarizes data describing the survey respondents, including demographics and travel-related information. The general information on drivers included nine questions, collecting data on participants' demographics, type of valid driver's license (commercial or not), annual household income, highest education level, state of residence, and miles traveled in the year of the survey. Most of the demographic variables presented in Table 15 followed a normal distribution. Nearly 52% of the respondents were 55 years or older, and 30% of the total respondents were male. Only 17% of the respondents possessed a commercial driver's license. Among the participants, 28% had an annual income between $25,000 and $49,999, around 27% had a 4-year degree, and 22% had education of high school or less. Approximately one-third of participants were from Texas, followed by Illinois and Michigan, which comprised roughly 14% of the sample.

Table 15. Data summary of demographics and travel characteristics of participants

Variable	Categories	Count	Percentage
Driver's age (years)	18–24	43	4.1
	25–34	98	9.3
	35–44	162	15.4
	45–54	194	18.5
	55–64	230	21.9
	65–74	231	22.0
	75–84	88	8.4
	85 or older	4	0.4
Driver's gender	Male	321	30.6
	Female	722	68.8
	Other	7	0.7
Driver's Race	Non-Hispanic - White	850	81.0
	Black or African American	73	7.0
	Hispanic	68	6.5
	Asian	28	2.7
	Other	24	2.3
	Prefer not to say	7	0.7
Miles traveled in 2023	4,000 or less	249	23.7
	4,001 to 8,000	242	23.1
	8,001 to 12,000	224	21.3
	12,001 to 16,000	157	15.0
	16,001 to 20,000	92	8.8
	More than 20,000	86	8.2
Income groups	Less than $10,000	36	3.4
	$10,000–$24,999	114	10.9
	$25,000–$49,999	295	28.1
	$50,000–$75,999	198	18.9
	$75,000–$99,999	156	14.9
	$100,000–$149,999	141	13.4
	More than $150,000	75	7.1
	Prefer not to say	35	3.3

Variable	Categories	Count	Percentage
Education Level	Less than high school	15	1.4
	High school graduate	222	21.1
	2-year degree	126	12.0
	4-year degree	286	27.2
	Some college	273	26.0
	Graduate or Professional degree	128	12.2
Commercial vehicle license	Yes	181	17.2
	No	869	82.8
State of residence	Texas	347	33.1
	Illinois	156	14.9
	Michigan	154	14.7
	Wisconsin	104	9.9
	Missouri	88	8.4
	Minnesota	85	8.1
	Iowa	49	4.7
	Kansas	42	4.0
	Nebraska	25	2.4

4.2.2. Data Summary of Merging-Related Questions Asked in the Survey

Subsequent sections of the road user survey included a total of 11 questions collecting data on driver's preferences on location to merge relative to merging points for different sign configurations, their responses if a vehicle in an adjacent lane is trying to merge into their lane, preferences among a series of various signs, their understanding of the zipper merge and best outreach practices the majority of population about best practices and education related to different lane merge strategies.

Figure 15 presents the data summary of the driver's preferred location for merging into the open lane under the four different signage configurations. As stated earlier, the four sign configurations are early merge static signs, the zipper merge static signs, the zipper merge static signs with upstream (U/S) PCMS, and the zipper merge static signs with upstream and downstream (D/S) PCMS. In Figure 15, section A refers to a far upstream section, and section D refers to a section closest to the work zone taper, as shown in Figure 13. The preferred merging location was closer to the taper under the zipper merge scenario than the early merge. Moreover, the addition of PCMS in combination with the standard zipper merge static signs further improved lane utilization as drivers tended to merge closer to the taper, thereby increasing the utilization of the closed lane.

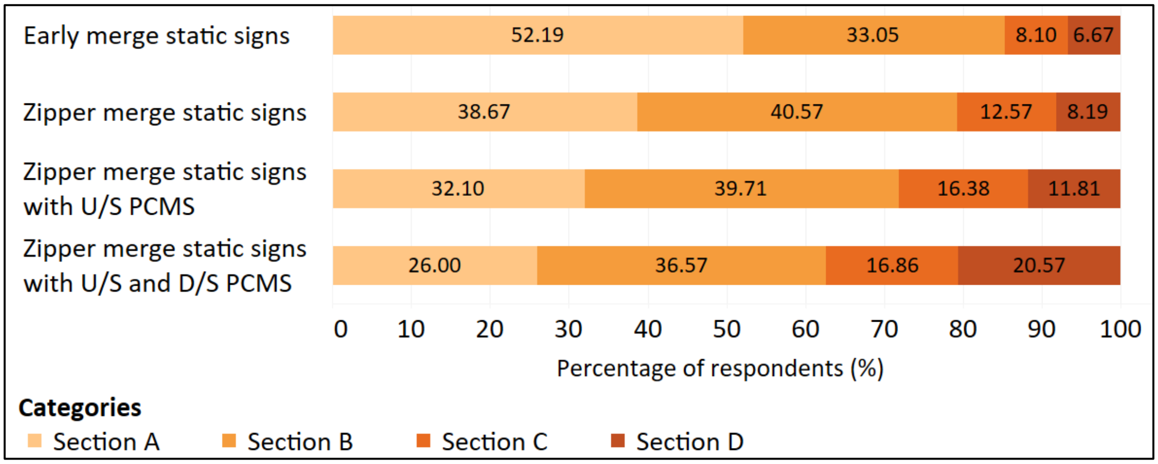


Figure 15. Drivers' preferred location for merging in the open lane

Figure 16 shows the driver's preferred course of action when they see another vehicle (referred to as the orange vehicle in the survey, as discussed previously) in the closed lane trying to merge into their open lane. This figure shows the results of two scenarios: when the merging maneuver is taking place far upstream of the taper and when the merging maneuver is taking place closer to the taper. Compared to the early merge lane control strategy, zipper merge control showed a lower inclination among respondents to allow other drivers from the closed lane to merge in front of them, particularly when the merging maneuver was assumed to occur far upstream of the taper. Nearer to the taper, the general driver response was similar under both lane merge control strategies.

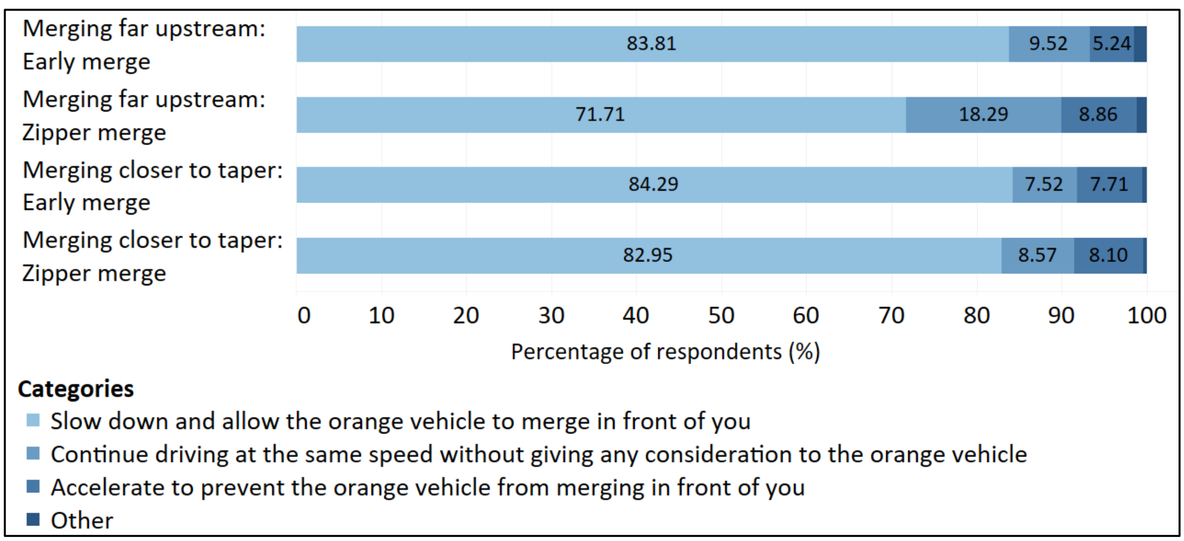


Figure 16. Drivers' preferred course of action for other drivers merging in their lane

Figure 17 shows respondent preferences among three alternative sign sequences that were used in concert with zipper merge lane control. This figure included responses to all three questions asked about preferred signs among a series of alternatives. Overall, drivers preferred signs that conveyed the intended message textually or both textually and graphically rather than the signs that conveyed the message graphically alone. For instance, when conveying the information that the right lane is closed ahead, drivers preferred the textual sign (W9-2) LANE ENDS MERGE LEFT over the graphic sign (W4-2). Similarly, drivers preferred signs that combined textual and graphical signs when indicating merging locations and behaviors over entirely textual signs, as shown in Figure 17. Lastly, when asked about their preference for zipper merge signage (to encourage drivers to stay in the closed lane as long as possible), drivers preferred an entirely textual sign that indicated the expected behavior. Currently, this sign is less widely used than the USE BOTH LANES DURING BACKUPS sign, which indicates the need to revisit signage guidelines during zipper merge lane control. A prior study conducted for the Federal Highway Administration (FHWA) reported that the USE BOTH LANES DURING BACKUPS sign did not convey the message about merging properly (Katz et al. 2023).

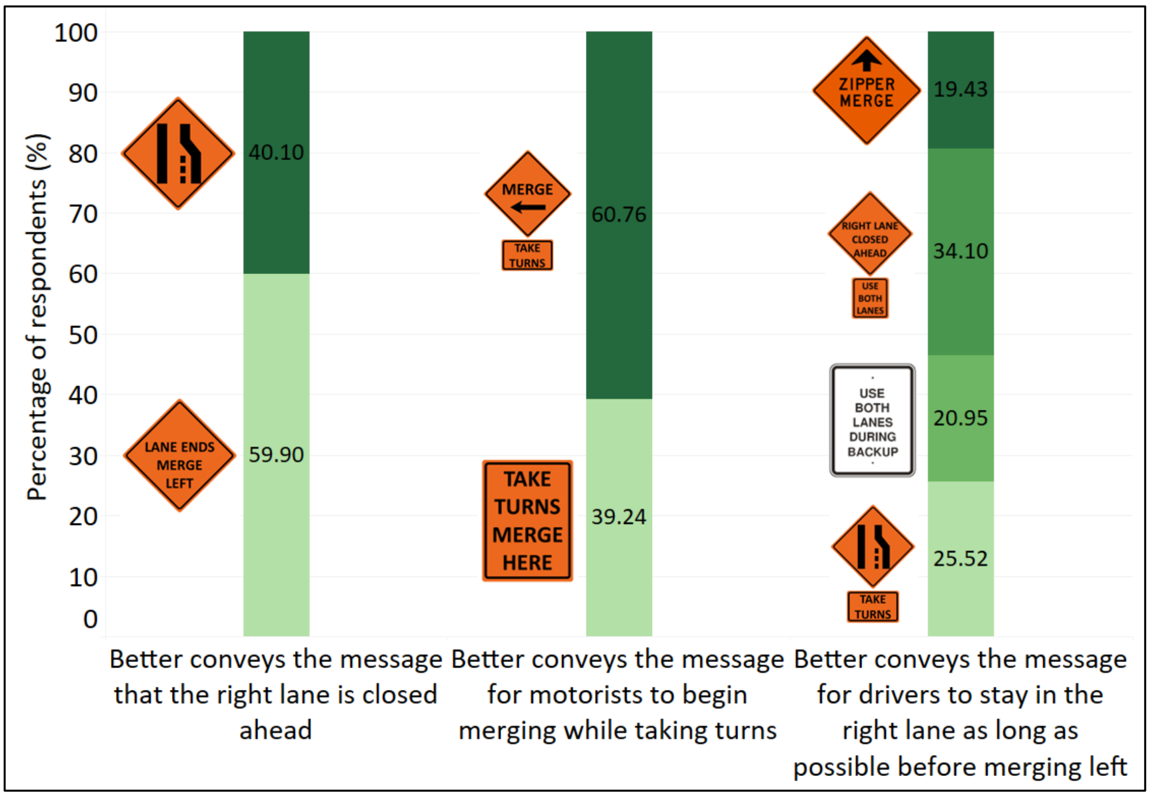


Figure 17. Drivers' perception of signs for various messages

Figure 18 presents a summary related to drivers' perceptions of the operational and safety performance of the zipper merge lane control compared to early merge lane control. Despite the extant research indicating that zipper merge has operational and safety benefits over early merge (Franks 2014), the survey results generally showed opposing trends. Only 25% of the drivers included in the survey perceived zipper merge to be better than early merge in terms of safety improvement, and only 32% of the drivers agreed that zipper merge is better than early merge in reducing congestion or backups. This could be due to various factors, including drivers feeling as though those in the closed lane are "cutting" in front of them or other issues arising from personal driving experiences.

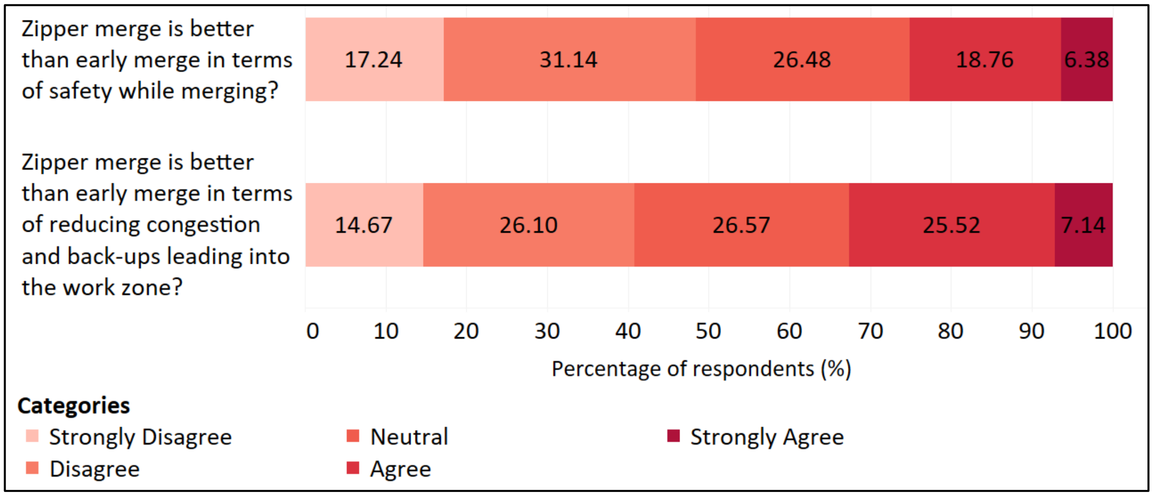


Figure 18. Drivers' perception of the suitability of zipper merge compared to early merge

Figure 19 shows the responses of driver's preferred lane merge control strategy when they were asked to merge as soon as possible and merge as late as possible. The options for these questions were early merge signing configuration and zipper merge signing configuration, both of them and none. For merging as soon as possible, half of the drivers preferred an early merge signing configuration, and nearly 25% responded to merging as soon as possible in both signing configurations. It might reflect the drivers' tendency to merge early, irrespective of signage. Maximum drivers preferred zipper merge signing configuration for merging as late as possible, closely followed by none of them option. It means drivers do not want to merge as late as possible in any signing configuration.

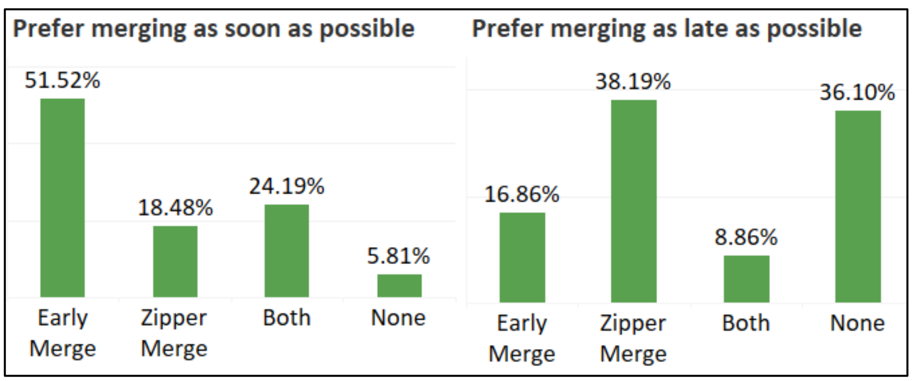


Figure 19. Driver's preferred lane merge control strategy

Table 16 presents a data summary of the question asking about the driver's familiarity with zipper merge. Nearly half of the drivers were unfamiliar with the zipper merge lane control strategy, and only one-third were familiar with the zipper merge. These results suggest a need to develop education and outreach materials to increase awareness of the zipper merge among the majority of drivers.

Table 16. Driver's familiarity with zipper merge

Answer Choice	Count	Percent Response
Yes	356	33.90 %
No	522	49.71 %
Maybe	171	16.29 %
Other	1	0.10 %
Total	1,050	100%

The comfort of drivers with different lane merge lane control strategies was also asked about in the survey. This question had two options: comfortable with zipper merge and comfortable with early merge. As shown in Table 17, more than 78% (n = 826) of drivers are comfortable driving in an early merge lane control strategy. In comparison, only 21% (n = 224) of drivers were comfortable driving in a zipper merge lane control strategy. Table 17 also shows the proportion of respondents comfortable with early or zipper mergers in different age groups. Among those comfortable with zipper merge, respondents older than 35 are more comfortable than younger respondents. This might be an artifact of the driving experience of older people, who are more comfortable with the zipper merge strategy.

Table 17. Driver's comfortability of different merging strategies

Answer Choice	Age Group	Count	Percent Response
Comfortable with early merge (n = 826)	18-24	35	4.24 %
	25-34	73	8.84 %
	35-44	115	13.92 %
	45-54	158	19.13 %
	55-64	194	23.49 %
	65-74	179	21.67 %
	75-84	68	8.23 %
	85 or older	4	0.48 %
Comfortable with zipper merge (n = 224)	18-24	8	3.57 %
	25-34	25	11.16 %
	35-44	47	20.98 %
	45-54	36	16.07 %
	55-64	36	16.07 %
	65-74	52	23.21 %
	75-84	20	8.93 %

Table 18 shows the data summary of responses to questions about practices that have better outreach to the maximum number of the public. 41.6% of respondents agreed that TV advertisements and newspapers have better outreach, followed by 29.6% agreeing with social media (including Facebook, Instagram, and Twitter). These questions also had the option to include the answer in the text, where drivers responded to other options such as DMV booklets, mailbox flyers, and clear and better signage like electric signage, and a few responded that all of the above means were better.

Table 18. Data summary of best practices to outreach more people

Answer Choice	Count	Percent Response
TV advertisements and newspapers	437	41.62 %
Social media	311	29.62 %
Public meetings of transport agencies	131	12.48 %
Radio	128	12.19 %
Other	43	4.10 %
Total	1050	100%

In order to target the drivers of a particular age group, it is required to know which platform is chosen most by drivers of different age groups. Figure 20 shows the platform choice for drivers of different age groups. Older drivers aged 55 or above are more interested in getting information about different lane merge control strategies with the help of TV advertisements and newspapers. Drivers aged 35 to 54 years preferred social media platforms, closely followed by TV advertisements and newspapers. Drivers who are younger than 35 years prefer social media as the best means to educate them about different lane merge control strategies. Public meetings and radio were only preferred by the drivers who are older than 35 years.

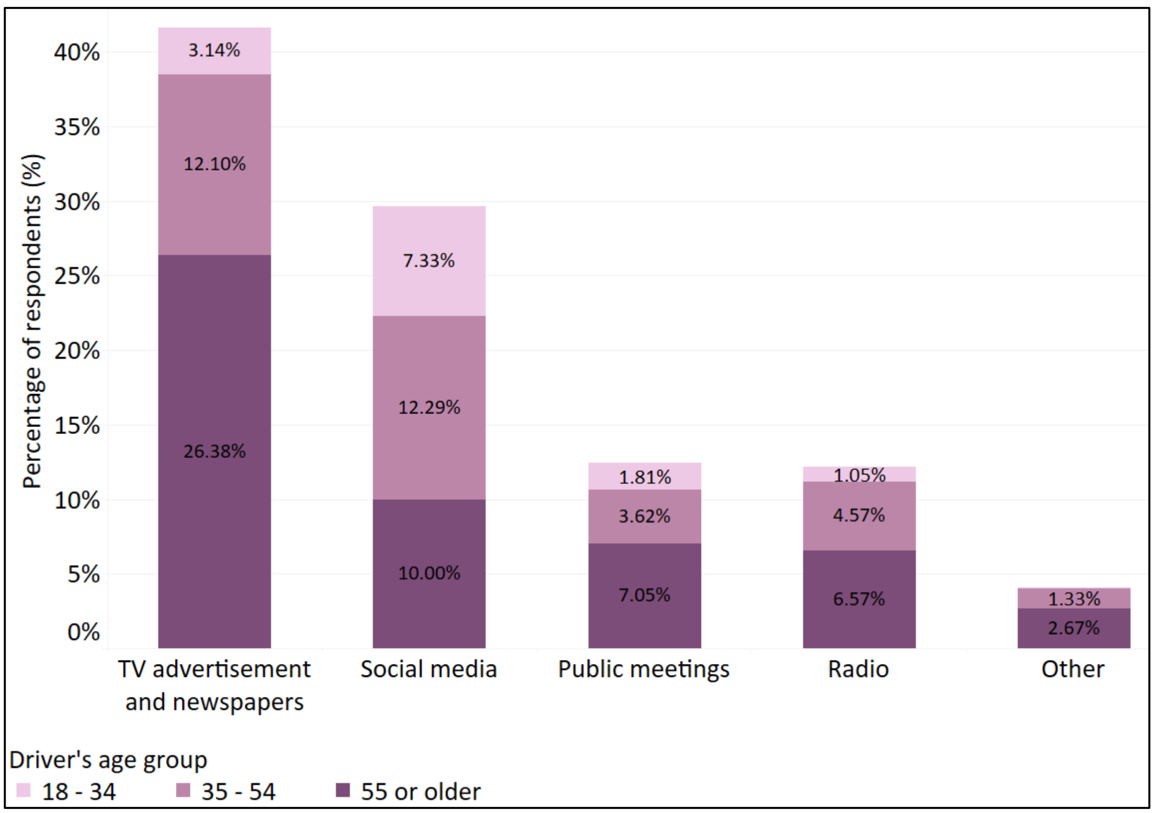


Figure 20. Data summary to better outreach the people with respect to age group

4.3. Statistical Methods

To better understand why respondents felt or stated they would behave in a certain way under various scenarios, a series of regression models were estimated to understand how these views varied within and across respondents. Depending upon the nature of responses to each research question, one of two different types of statistical methods was estimated: a multinomial logistic regression model or an ordered logit model.

4.3.1. Multinomial Logit Model

The responses to those questions examining driver decision-making during merging maneuvers were analyzed using multinomial logistic regression. In the multinomial logit model, a linear function is specified, as shown in equation 1.

$$U_{ijt} = \alpha_j + X_{it}\beta_j + \varepsilon_{ij}, \qquad (1)$$

where α_j is a constant term that is specific to the j^{th} response category (e.g., merging location, whether to allow the other driver to merge), X_{it} is a vector of explanatory variables affecting the driver's response (e.g., age, driving experience, familiarity with the zipper merge), β_j is a vector of parameters that are estimated through maximum likelihood techniques and ε_{ij} is an error term that is assumed to follow a generalized extreme value distribution. Given this function, the probability of the j^{th} response category being selected is determined as per equation 2.

$$P_{ij} = \frac{\exp^{(\alpha_j + X_{it}\beta_j)}}{\sum_{k=1}^{J} \exp^{(\alpha_k + X_{it}\beta_k)}} \ , j = 1,2,3. \qquad (2)$$

Separate models were estimated for two question types of interest. First, a multinomial logit model was estimated to analyze drivers' preferred merging locations when encountering various sign configurations. A second model was estimated to assess how drivers responded when another driver was attempting to merge into their lane. As each of these question types was asked for various scenarios of interest, correlation is expected among responses from the same individuals. To account for this correlation among the responses from the same survey respondents, a subject-specific random effect was introduced in the model, as shown below.

$$U_{ijt} = \alpha_j + v_{ij} + X_{it}\beta_j + \varepsilon_{ij}, \qquad (3)$$

where, v_{ij} represents state-specific random effects. These random effects are the same for each survey participant and are assumed to be uncorrelated and independent. Consequently, the probability of survey response i falling under j^{th} response category is given as

$$P_{ijt} = \frac{\exp^{(\alpha_j + v_{ij} + X_{it}\beta_j)}}{\sum_{k=1}^{J} \exp^{(\alpha_k + v_{ik} + X_{it}\beta_k)}} \ , j = 1,2,3,4. \qquad (4)$$

4.3.2. Ordered Logit Model

For other questions that followed a clearer ordering structure, an ordered logit model was estimated. This included questions such as the respondents' perceptions of the zipper merge (compared to the early merge) in terms of relative safety or efficiency. These responses followed a ranked structure (ranging from strongly disagree to strongly agree). Such questions were analyzed using ordered logit models. These modes are derived by defining an unobserved variable as a linear function for each observation, as shown in equation 5.

$$z = \beta X + \varepsilon, \quad (5)$$

where X is a vector of variables determining the discreet ordering for observation *n*, β is a vector of estimable parameters, and ε is a random disturbance assumed to be logistically distributed. The observed ordinal data, *y*, for each observation, is defined as shown in equation 6.

$$\begin{aligned} &y = 1 \; if \; z \le \mu_0 \\ &y = 2 \; if \; \mu_0 \le z \le \mu_1 \\ &y = \ldots \\ &y = I \; if \; z \ge \mu_{I-1}, \end{aligned} \quad (6)$$

where, μ are thresholds that define *y*, which corresponds to integer ordering, with *I* being the highest integer-ordered response. μ and β are estimated jointly, which reduces the estimation problem to determining the probability of I-specific ordered responses for each observation *n*. The ordered selection probabilities can be calculated using equation 7.

$$\begin{aligned} &P(y = 1) = \Lambda(\mu_1 - \beta X) \\ &P(y = 2) = \Lambda(\mu_2 - \beta X) - \Lambda(\mu_1 - \beta X) \\ &P(y = I) = 1 - \Lambda(\mu_{m-1} - \beta X), \end{aligned} \quad (7)$$

where, $\Lambda()$ is the cumulative logistic distribution. When estimating these models, no random effects were specified, as each row represented a unique participant with no repetition.

4.4. Results and Discussion for Statistical Models

The results of the statistical analyses are presented in the following subsections. When interpreting the model results, a positive sign for a parameter estimate means that as that variable increases, the likelihood of the specific choice/alternative of interest increases. In contrast, a negative sign means the specific choice of interest is less likely as that independent variable is increased. Odds ratios (OR) are also provided to aid in interpretation. For multinomial logit models, these indicate the change in the odds of a specific response being selected for a one-unit increase in a predictor variable. For ordered models, the OR represents the change in the odds of the response being in a specific choice category compared to its odds of being in any preceding category when a specific parameter is increased by one unit.

4.4.1. Model Results for Driver's Preferred Location to Merge

Table 19 presents the estimated mixed-effects multinomial logistic regression model for drivers' preferred location to merge relative to the taper for different signage configurations. The dependent variable had four response categories from Section A to D, with Section D being the closest to the taper and Section A being the furthest away. Section A was considered as the baseline response category.

The results showed that drivers were more likely to merge further closer to the taper during zipper merge static sign conditions compared to early merge static sign conditions. The addition of an upstream PCMS, as well as the addition of a second downstream PCMS, both increased the likelihood of drivers merging closer to the taper under a zipper merge scenario.

The driver's preferred merging location was also compared between drivers familiar with the zipper merge and those not. As expected, drivers with greater familiarity tended to merge closer to the taper. However, the odds of merging were highest in Section C among drivers familiar with the zipper merge. Similarly, drivers somewhat familiar with zipper merge were also most likely to merge in Section C. In addition to familiarity, comfort also played a role, as those respondents who were comfortable with the zipper merge were most likely to merge in the area closest to the taper.

Differences in the merging location preferences were also observed based on the driver's age. As the driver's age increased, they became increasingly less likely to merge in the area closest to the taper. The older group of drivers over 55 years were the most likely to merge in Section A, i.e., furthest away from the start of the taper. This is a possible reflection of greater caution on the part of this age group (Finn and Bragg 1986). Another factor that influenced responses was the individual's education level, which was divided into two categories based on whether the respondent had any education beyond high school. The results showed that the drivers with higher education were more likely to merge closer to the taper, with Section C being the most preferred merging location.

Table 19. Analysis results for preferred location of merging into the open lane

Merge Location	Variables	Estimate	p-value	OR
Section B	Intercept	-0.908	0.003	na
	Sign condition: Early merge static signs		Baseline	
	Zipper merge static signs	0.581	0.000	1.788
	Zipper merge static signs with U/S PCMS	0.756	0.000	2.129
	Zipper merge static signs with U/S and D/S PCMS	0.879	0.000	2.409
	Not familiar with zipper merge		Baseline	
	Familiar	0.215	0.086	1.240
	Might be familiar	0.243	0.114	1.274
	Not comfortable with zipper merge		Baseline	
	Comfortable with zipper merge	0.384	0.008	1.468
	Age group: below 25 years		Baseline	
	25-34 years	0.018	0.957	1.018
	35-55 years	-0.286	0.339	0.751
	Above 55 years	-0.028	0.923	0.972
	Education: high school or less		Baseline	
	Higher education	0.344	0.008	1.410
Section C	Intercept	-2.226	0.000	na
	Sign condition: Early merge static signs		Baseline	
	Zipper merge static signs	0.772	0.000	2.164
	Zipper merge static signs with U/S PCMS	1.318	0.000	3.737
	Zipper merge static signs with U/S and D/S PCMS	1.626	0.000	5.084
	Not familiar with zipper merge		Baseline	
	Familiar	0.795	0.000	2.214
	Might be familiar	0.444	0.029	1.559
	Not comfortable with zipper merge		Baseline	
	Comfortable with zipper merge	1.100	0.000	3.005
	Age group: below 25 years		Baseline	
	25-34 years	-0.668	0.093	0.513
	35-55 years	-0.896	0.010	0.408
	Above 55 years	-0.923	0.007	0.397
	Education: high school or less		Baseline	
	Higher education	0.449	0.010	1.567
Section D	Intercept	-2.236	0.000	na
	Sign condition: Early merge static signs		Baseline	
	Zipper merge static signs	0.674	0.002	1.961
	Zipper merge static signs with U/S PCMS	1.406	0.000	4.079
	Zipper merge static signs with U/S and D/S PCMS	2.440	0.000	11.469
	Not familiar with zipper merge		Baseline	
	Familiar	0.519	0.006	1.680
	Might be familiar	0.232	0.341	1.262
	Not comfortable with zipper merge		Baseline	
	Comfortable with zipper merge	1.720	0.000	5.585
	Age group: below 25 years		Baseline	
	25-34 years	-0.743	0.086	0.476
	35-55 years	-1.283	0.001	0.277
	Above 55 years	-1.541	0.000	0.214
	Education: high school or less		Baseline	
	Higher education	0.138	0.488	1.148

4.4.2. Model Results for the Preferred Course of Action by Drivers in the Open Lane

Table 20 presents the mixed-effects multinomial logistic regression model results for drivers' preferred course of action when a vehicle in an adjacent closed lane is trying to merge into an open lane under various scenarios. The dependent variable had three response categories: (1) continue driving at the same speed without considering the merging vehicle, (2) slow down to allow the vehicle to merge in, and (3) accelerate to prevent the vehicle from merging in front of the driver. The category of no action, i.e., continuing driving at the same speed without considering the merging vehicle, was set as the baseline. The responses with the fourth category as other (text response) were removed from the model due to a lack of specific information. As such, positive (negative) coefficients reflect those variables associated with higher (lower) likelihoods compared to this baseline category.

Table 20. Preferred course of action by drivers in the open lane

The preferred course of action	Variables	Estimate	p-value	OR
Slow down and allow the adjacent lane vehicle to merge in front of you	Intercept	2.224	0.000	na
	Merging far upstream: Early merge		Baseline	
	Merging far upstream: Zipper merge	-0.855	0.000	0.425
	Merging close to taper: Early merge	0.289	0.081	1.335
	Merging close to taper: Zipper merge	0.155	0.337	1.168
	Not familiar with zipper merge		Baseline	
	Familiar	-0.573	0.000	0.564
	Might be familiar	-0.293	0.125	0.746
	Not comfortable with zipper merge		Baseline	
	Comfortable with zipper merge	-0.307	0.047	0.735
	Age of driver	0.012	0.005	1.012
	Miles driven per thousand	0.012	0.285	1.012
	Income per thousand	-0.005	0.001	0.995
Accelerate to prevent the adjacent lane vehicle from merging in front of you	Intercept	-0.462	0.272	na
	Merging far upstream: Early merge		Baseline	
	Merging far upstream: Zipper merge	-0.083	0.703	0.920
	Merging close to taper: Early merge	0.689	0.004	1.993
	Merging close to taper: Zipper merge	0.631	0.007	1.880
	Not familiar with zipper merge		Baseline	
	Familiar	-0.592	0.003	0.553
	Might be familiar	-0.576	0.031	0.562
	Not comfortable with zipper merge		Baseline	
	Comfortable with zipper merge	-0.032	0.879	0.969
	Age of driver	-0.002	0.700	0.998
	Miles driven per thousand	0.034	0.030	1.034
	Income per thousand	-0.003	0.095	0.997

The results showed different trends based on where the merging maneuvers were taking place. When another driver in the closed lane tried to merge into the open lane far upstream of the taper, drivers in the open lane were more likely to continue driving at the same speed during zipper merge lane control (compared to early merge lane control). However, if the merging was being attempted much closer to the taper, drivers in the open lane were more likely to change their behavior and either slow down or accelerate. Interestingly, drivers were more likely to accelerate and prevent the other vehicle from merging. This was true under both early merge and late merge control strategies, with the difference being more pronounced under the early merge scenario. This reinforces concerns that drivers are averse to others “cutting” in line when they have an opportunity to merge sooner.

Drivers who were familiar with the zipper merge were more likely to continue driving at the same speed when another vehicle in the adjacent lane was trying to merge into the open lane. Similarly, drivers who indicated higher comfort with zipper merge were also more likely to continue driving at the same speed. These results suggest that drivers adapt as they gain more experience with the zipper merge. Older drivers were more likely to slow down to allow the other vehicle to merge, and, in contrast, younger drivers were more likely to accelerate to prevent the other driver from merging. This may reflect differences in driving behavior, risk perception, or experience between these groups. Other variables, such as annual mileage traveled, may have also captured the effects of experience. Drivers with higher annual mileage were more likely to show aggressive behavior and accelerate to inhibit another vehicle from merging in front of them.

4.4.3. Model Results for Drivers’ Perception of Zipper Merge

Table 21 presents the results of the ordinal logit models that assessed respondents’ perceptions of the zipper merge from a safety and operational perspective. The responses to these questions were ordinal, with responses on a five-point Likert scale ranging from strongly disagree to strongly agree.

Starting with perceptions of safety impacts, the results showed that older drivers felt the zipper merge was less safe than the traditional early merge strategy. Older drivers also felt the zipper merge was worse at reducing congestion and backups than the early merge. This could be reflective of the relative novelty of the zipper merge for this group of drivers. In contrast, drivers with higher levels of education perceived the zipper merge to be both safer and more efficient. These results suggest a need to develop education and outreach materials to increase awareness of the zipper merge among these groups of drivers.

Drivers who were more familiar or more comfortable with the zipper merge strategy tended to perceive it as better than the early merge strategy from a safety and operational perspective. This further reinforces the need for education and the fact that drivers can be expected to become more comfortable with the zipper merge as they gain more experience and knowledge of the strategy.

Table 21. Model results for driver's perception of zipper merge

Zipper merge is better than early merge in terms of safety				
Variables		Estimate	p-value	Odds Ratio
Thresholds	Strongly disagree	-2.012	0.000	na
	Disagree	-0.306	0.314	na
	Neutral	1.235	0.000	na
	Agree	3.278	0.000	na
Age group: below 25 years			Baseline	
25-34 years		-1.044	0.002	0.352
35-55 years		-1.066	0.000	0.344
Above 55 years		-1.270	0.000	0.281
Education: high school or less			Baseline	
Higher education		0.321	0.017	1.379
Not familiarity with zipper merge			Baseline	
Familiar		0.611	0.000	1.842
Might be familiar		0.315	0.046	1.370
Not comfortable with zipper merge			Baseline	
Comfortable with zipper merge		2.503	0.000	12.225
Zipper merge is better than early merge in terms of congestion and backups				
Variables		**Estimate**	**p-value**	**Odds Ratio**
Thresholds	Strongly disagree	-1.699	0.000	na
	Disagree	-0.166	0.579	na
	Neutral	1.205	0.000	na
	Agree	3.469	0.000	na
Age group: below 25 years			Baseline	
25-34 years		-0.321	0.334	0.725
35-55 years		-0.467	0.116	0.627
Above 55 years		-0.709	0.015	0.492
Education: high school or less			Baseline	
Higher education		0.202	0.130	1.224
Not familiarity with zipper merge			Baseline	
Familiar		0.935	0.000	2.546
Might be familiar		0.211	0.176	1.235
Not comfortable with zipper merge			Baseline	
Comfortable with zipper merge		1.993	0.000	7.337

5. MISSOURI FIELD EVALUATION STUDY

5.1. Study Methodology

A dynamic lane merge system field study was conducted on the representative road section (the I-44 Big Piney Rivers Bridge Repair project) in Missouri. The study methodology and results are described in the following sections.

5.1.1. Radar Sensors

In order to evaluate the impact of lane merge strategies, driver behaviors, and overall traffic flow, radar sensors were used to automatically detect and record vehicle counts, speeds, and lane usage. The radar sensors provided continuous and accurate data for a detailed analysis of traffic patterns in the work zones.

The speed sensors used were the Houston Radar SpeedLane Pro (Houston Radar 2023). The sensors function in all weather and lighting conditions and can accurately detect the lane, speed, and class of each vehicle. The sensor data can be used to calculate lane-specific volume, occupancy, and other relevant metrics. As shown in Figure 21, both sensors were mounted on masts attached to portable trailers at the roadside for nonintrusive traffic data collection. The white truck was used as a protective vehicle only during the setup time.

The benefits of using radar sensors include easy deployment on the side of the road, automated data collection, and high accuracy. Additionally, the sensors allowed for data collection over an extended period and facilitated detailed analysis.

5.1.2. Key Measures

The following key measures were collected for analysis:

- **Traffic volume**. The number of vehicles passing the location of a sensor in a given time period. A 10-minute time interval was used in the analysis. The measure helps understand the traffic load and peak traffic periods. For example, a traffic volume greater than 1,500 to 1,700 vehicles per hour can be used as a surrogate for congestion.
- **Vehicle speed**. Average and variance of speeds at the location of a sensor. The measure indicates driver compliance with posted speed limits and the congestion level. For example, an average speed of less than 20 to 35 mph can be considered congested.
- **Lane use percentage**. The proportion of vehicles using each lane when passing the sensors. The measure is critical for obtaining driver behaviors in response to traffic conditions and lane merge strategies. For example, when the same number of vehicles use both right and left lanes, the right and left lane use percentages are equal to 50%. This measure helps identify driver preferences when no lane merge instruction is provided. It also helps identify whether drivers are adhering to lane merge instructions if provided.

Figure 21. Roadside nonintrusive radar sensor

Besides the three key measures, the interactions between the three measures were investigated to evaluate driver behaviors under different traffic conditions and lane merge strategies. Through the key measures obtained from radar sensors, a comprehensive understanding of lane usage patterns helps develop work zone traffic management strategies and improve road safety and efficiency.

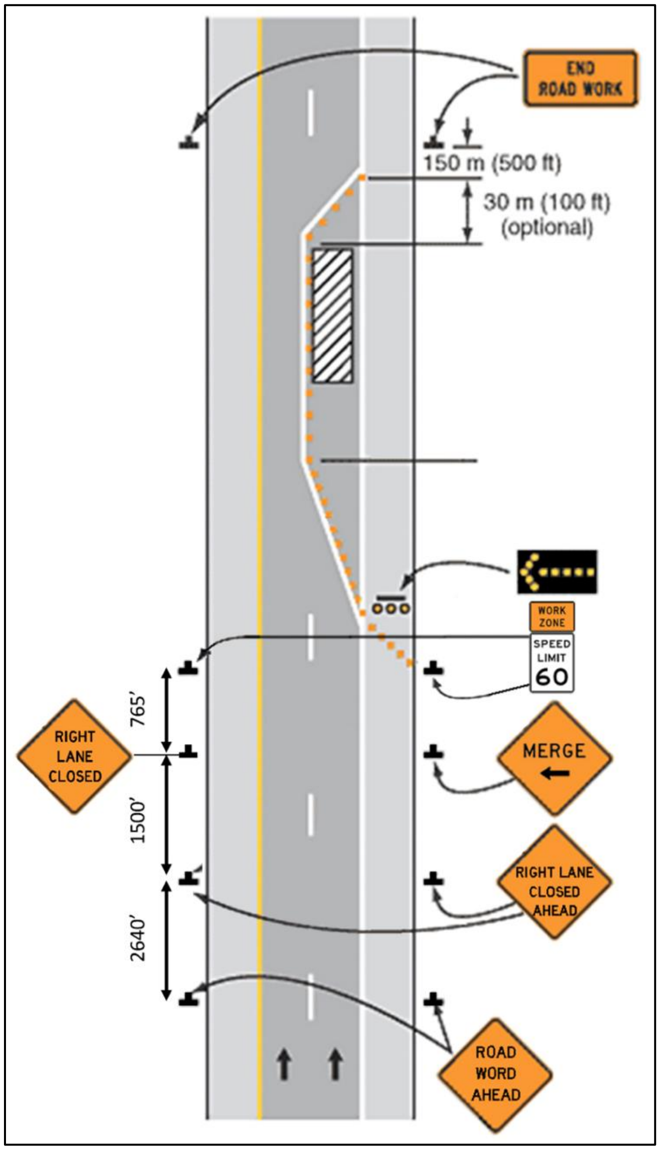
5.1.3. Work Zone Selection

In order to evaluate the impact of lane merge strategies on driver behavior, the I-44 Big Piney Rivers Bridge Repair project was chosen as the work zone evaluation site for the Missouri portion of the study. The location of the work zone is shown in Figure 22.

Map source: Wikimedia 2009

Figure 22. Location of the selected work zone in Missouri

The bridge repair project included three stages, and the field data was collected during Stage 1 when both outside lanes were closed on I-44. The work zone was a two-to-one lane closure because this is a common work zone configuration and guidance is straightforward to develop. The AADT for eastbound was 19,143 vehicles per day (vpd), and for westbound was 14,136 vpd in 2021. The posted speed limit on I-44 was 70 mph. The traffic control plan of Stage 1 is shown in Figure 23, with a work zone speed limit of 60 mph.



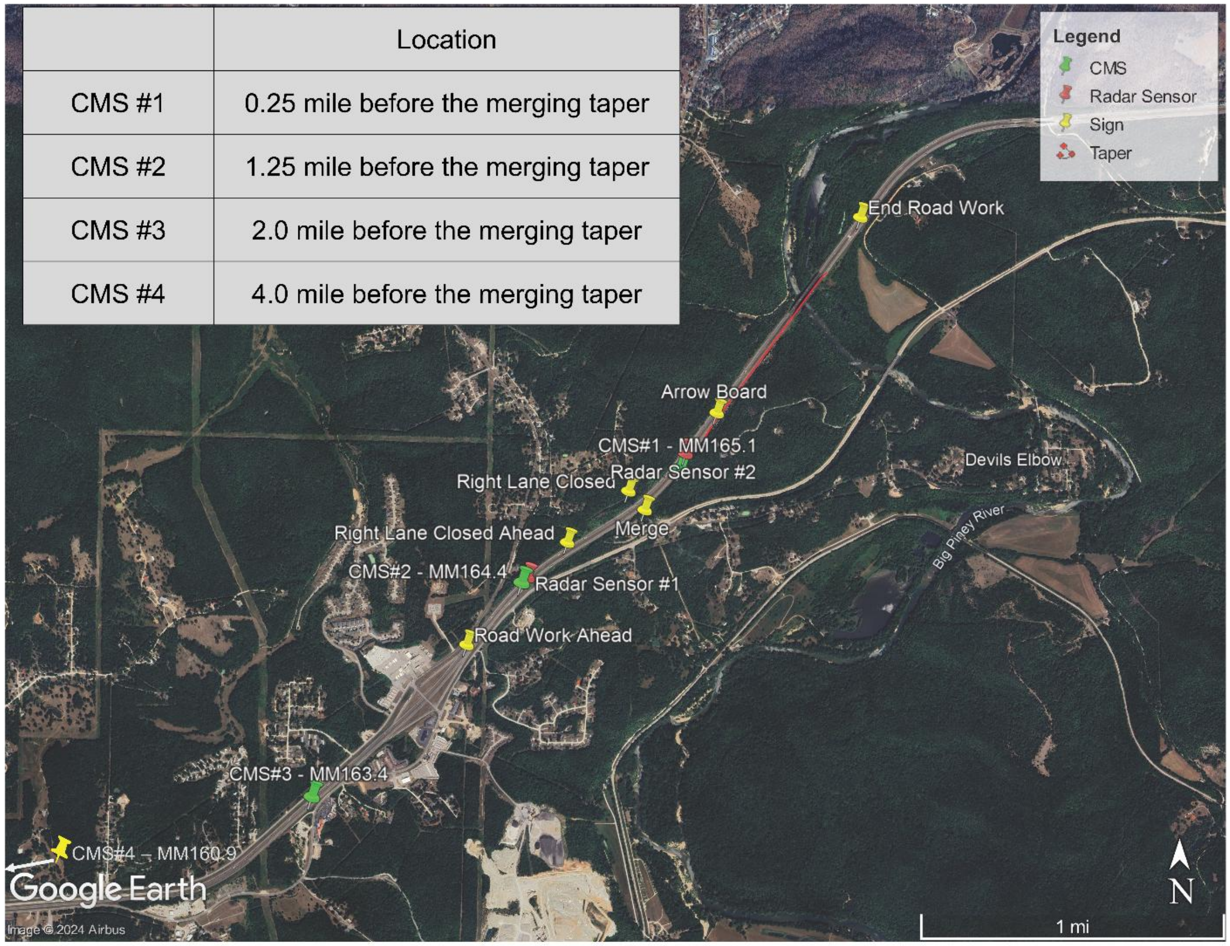
Adapted from MoDOT 2024

Figure 23. Outside lane closure traffic control plan

5.1.4. Dynamic Lane Merge System

The work zone was planned to utilize a dynamic late merge system (also known as zipper merge) through a contractor to provide drivers with guidance and queue warnings about slow or stopped traffic ahead due to the work zone and to delay merging until the lane drops to decrease queue length. While the system was set up to operate dynamically, the dynamic late merge strategy was not activated as planned due to activation errors and communication timeouts. Consequently, all data was collected under dynamic early merge conditions with traffic speed information provided using CMS. The system included eight portable CMS, with four CMS in each direction. Each CMS was equipped with a nonintrusive traffic sensor to collect traffic speed and volume data.

The locations of CMS on eastbound I-44 are shown in Figure 24. The CMS on westbound I-44 was placed at the same distance as the merging taper.



Imagery © 2024 Airbus, Landsat / Copernicus, Maxar Technologies, Map data © 2024 Google

Figure 24. Locations of CMS and other traffic control devices

The roadside CMS messages were updated based on traffic sensor data, as shown in Figure 25. Table 22 shows the messages intended to be displayed on each CMS and their activation conditions for the westbound direction. When speeds decrease below 45 mph, a dynamic late merge will get triggered, and drivers will be instructed to use all lanes until the merge point. When speeds are ≥45 mph, traffic will be warned of the lane closure ahead, and early merge behavior will occur.

Figure 25. Roadside CMS for lane merge management

Table 22. CMS messages and activation conditions for dynamic lane merge

CMS Location	>= 45 mph	< 45 mph
CMS #1 (0.25 mi to the merging taper)	RIGHT LANE CLOSED /AHEAD	ZIPPER MERGE AHEAD /USE BOTH LANES
CMS #2 (1.25 mi to the merging taper)	RIGH LANE CLOSED /1 MILE AHEAD	SLOW TRAFFIC AHEAD /USE BOTH LANES
CMS #3 (2.0 mi to the merging taper)	RIGHT LANE CLOSED /2 MILE AHEAD	SLOW TRAFFIC AHEAD /USE BOTH LANES
CMS #4 (4.0 mi to the merging taper)	RIGHT LANE CLOSED /4 MILES AHEAD	SLOW TRAFFIC AHEAD /USE BOTH LANES

The eastbound CMS system showed different messages during Stage 1 of the project to understand driver merge behavior without the dynamic late merge system. The messages displayed by the CMS system are shown in Table 23. No lane usage instructions were provided for eastbound traffic; therefore, dynamic early merge lane control was evaluated. For speeds >45 mph, the same messages are displayed as in the westbound direction. For speeds ≤45 mph, warnings are shown for slow or stopped traffic, but no lane use guidance is displayed.

Table 23. CMS messages and activation conditions for static lane merge

CMS Location	>45 mph	25–45 mph	<25mph
CMS #1 (0.25 mi to the merging taper)	RIGHT LANE CLOSED /AHEAD	SLOW TRAFFIC AHEAD /PREPARE TO SLOW	STOPPED TRAFFIC AHEAD /PREPARE TO STOP
CMS #2 (1.25 mi to the merging taper)	RIGHT LANE CLOSED /1 MILE AHEAD	CAUTION SLOW TRAFFIC /AHEAD	CAUTION STOPPED TRAFFIC /AHEAD
CMS #3 (2.0 mi to the merging taper)	RIGHT LANE CLOSED /2 MILE AHEAD	CAUTION SLOW TRAFFIC /AHEAD	CAUTION STOPPED TRAFFIC /AHEAD
CMS #4 (4.0 mi to the merging taper)	RIGHT LANE CLOSED /4 MILES AHEAD	CAUTION SLOW TRAFFIC /AHEAD	CAUTION STOPPED TRAFFIC /AHEAD

5.1.5. Radar Sensor

Although the dynamic lane merge system provided aggregated speed and volume data, it did not include lane-specific volume data. To address this, two additional radar sensors were deployed on eastbound I-44 to track individual vehicle speeds and lane use. Figure 21 shows an example of such a sensor. The radars were placed 150 ft behind CMS #2 (1.22 miles to the merging taper) and CMS #1 (700 ft to the merging taper).

5.2. Field Study Results

Data were collected from October 3, 2023, to October 27, 2023, nearly four weeks using both the dynamic lane merge system and two radar sensors. The initial field plan was to collect two weeks of work zone data with the dynamic early merge strategy and two weeks with the dynamic late merge strategy. However, the dynamic late merge strategy was not activated as planned due to activation errors and communication timeouts. Consequently, all data were collected under dynamic early merge conditions with traffic speed information provided (Table 23).

The traffic results from Radar Sensor #1 and Radar Sensor #2 are presented in Table 24. The results showed that the average speed decreased when vehicles approached the work zone, aligning closely with the posted work zone speed limit (60 mph). Additionally, 29.4% of the traffic volume completed lane merging between the two sensors. On average, 44.6% of vehicles completed lane merging before CMS #1, while 26.0% completed lane merging after CMS #2.

Table 24. Radar sensor data summary

Parameters	Radar Sensor #1 (1.22 miles upstream)	Radar Sensor #2 (700 ft upstream)	p-value of t-Test
Average speed (mph)	63.0	60.9	<0.001
85th percentile speed (mph)	77.0	76.0	-
50th percentile speed (mph)	68.0	68.0	-
Total vehicles (counts)	358,456	336,77	-
Left lane vehicles (counts)	159,816	249,292	<0.001
Left lane use percentage	44.6%	74.0%	<0.001
Right lane vehicle (counts)	198,640	87,486	<0.001
Right lane use percentage	55.4%	26.0%	<0.001
AADT (vehicles per day)	15,586	14,643	-
Truck percentage	28.4%	30.8%	-

For the investigation of the impact of speed and volume on the right (closed) lane use percentage, the results at the two locations are shown in Figure 26 and Figure 27. Each point shows the right lane use percentage and speed/volume relationship. The y-axis represents the right lane use percentage, while the x-axis represents the corresponding average speed/volume. Green dots indicate conditions at Radar Sensor #2, and red dots indicate conditions at Radar Sensor #1. The figures indicate similar trends:

1. As volume increases and speed decreases (congestion), the percentage of vehicles using the right lane decreases, indicating more vehicles are merging into the left lane early. This suggests that drivers tend to want to merge early, leading to longer queues and reduced work zone capacity.
2. When volume is low, and speed is high, the percentage of right lane usage is higher compared to when volume is high. This may be because drivers feel they can easily merge into the open lane, making them feel comfortable staying in the right lane longer, which results in a late merge effect.
3. The variance in right lane usage is significantly greater under low volume and high speed conditions. This inconsistency in driver behaviors under free-flow conditions indicates that drivers tend to make merging decisions based on their individual perceptions rather than following a uniform pattern.

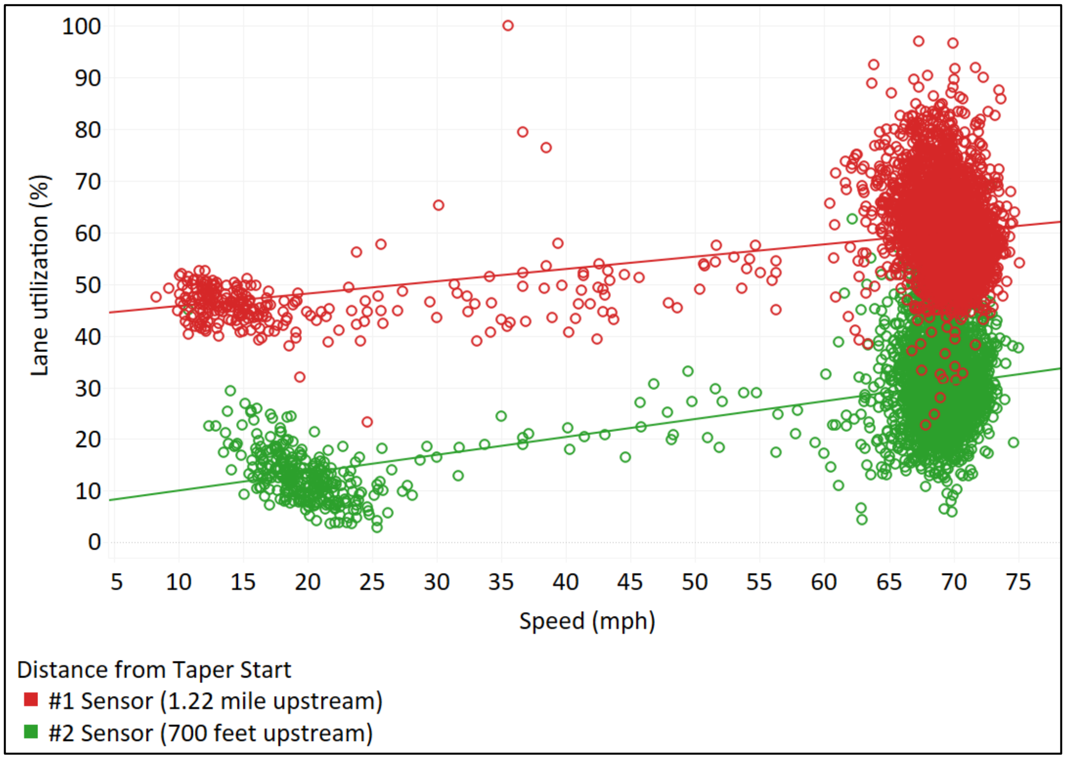


Figure 26. Closed lane use percentage at different speeds

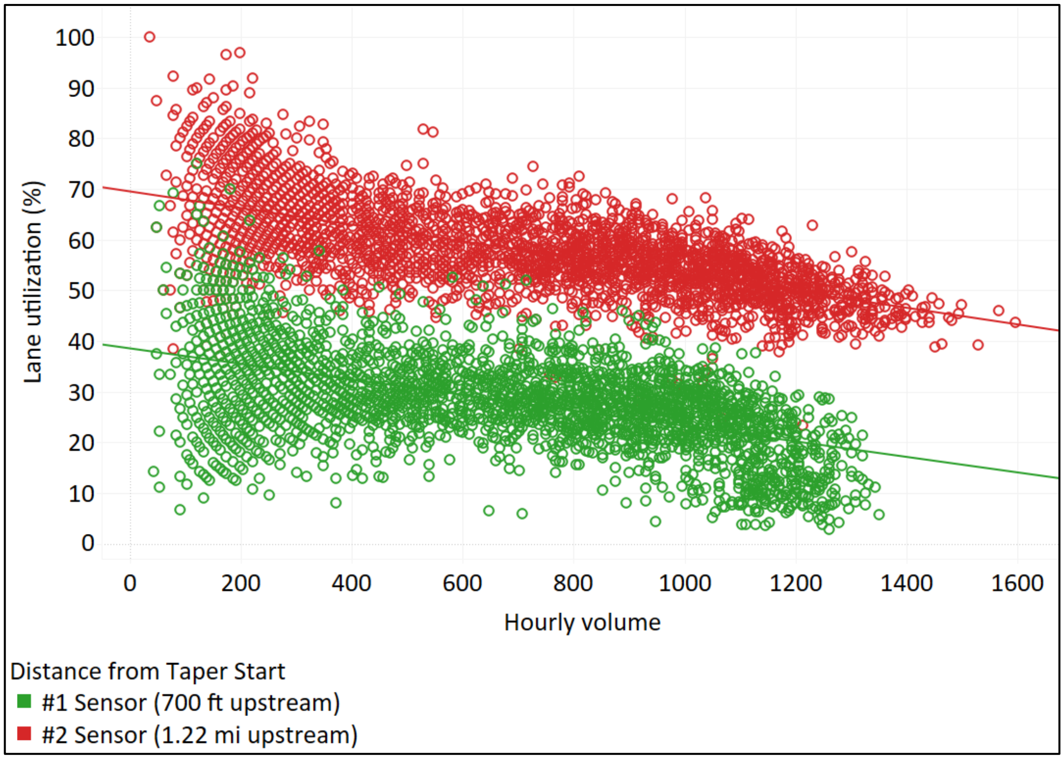


Figure 27. Closed lane use percentage at different volumes

Under the condition of a dynamic early merge scenario, traffic volume and speed are the major factors influencing when and where drivers are merging into the open lane. Drivers are prone to merge into the open lane early when traffic starts to congest while staying in the closed lane longer if the traffic is light and the speed is close to free-flow speed. The findings from the Missouri field study support the necessity of implementing zipper merge strategies in work zones. The following section of the report focuses on the Michigan field evaluation study, which assessed the effectiveness of zipper merge lane control and the factors influencing it. This study will be used to compare the results of the dynamic early merge lane control from the Missouri field study with those of the zipper merge lane control from the Michigan field study.

6. MICHIGAN FIELD EVALUATION STUDY

A series of field evaluations was conducted to assess the effectiveness of PCMS in improving the efficiency of zipper merge lane control. This efficiency was assessed by examining the lane utilization rate of the closed lane. Lane utilization is defined as the proportion of vehicles using the closed lane to the total number of vehicles. The following section elaborates on various aspects of this evaluation, including the study site selection, test sign conditions, field data collection, data reduction, and analytical methods.

6.1. Site Selection

The initial site selection was carried out in consultation with MDOT. A fixed set of criteria was defined to select sites to ensure minimum variability across sites with respect to site geometry. This included a stationary work zone site located on the freeway with two travel lanes in each direction, a two-to-one lane drop configuration (i.e., one lane closure on a two-lane freeway per direction), and moderate to high traffic volumes. After this initial screening, sites were retained if the initial temporary traffic control plan used static signage only and if the site had PCMS available to be installed at different locations throughout the work zone. Ultimately, three sites were identified in the state of Michigan for field evaluations during the summers of 2023 and 2024, as shown in Figure 28:

- Site 1: Eastbound (EB) I-94 in Macomb County from 23-mile road to county line road
- Site 2: Eastbound (EB) I-96 EB near Grand Rapids from Thornapple Drive SE to Whitneyville Avenue SE
- Site 3: Southbound (SB) M-53 in Macomb County from 22-mile road to M-59

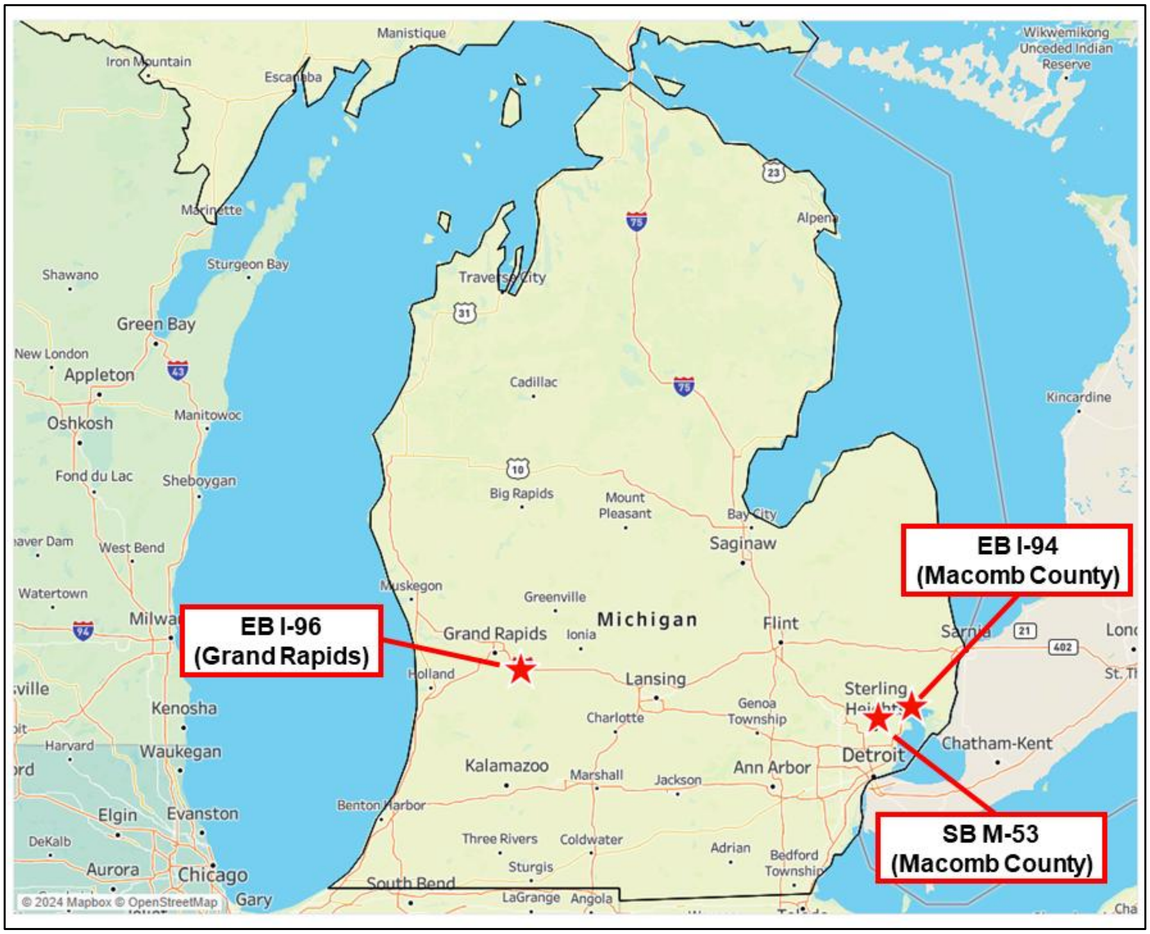


Figure 28. Location of the selected work zones in Michigan

The layout of these three sites during the field studies is shown in Figure 29, Figure 30, and Figure 31, respectively. The I-94 site involved a right-lane closure, while the other two sites included left-lane closures. All three sites were located on a freeway with a speed limit of 70 mph for passenger cars and 65 mph for heavy vehicles (trucks and buses). All of the distances shown in Figure 29, Figure 30, and Figure 31 are from the start of the taper. The AADT on analysis segments of I-94, I-96, and M-53 were 59,478 vpd, 45,049 vpd, and 50,149 vpd, respectively, for both directions of travel (MDOT 2024).

Figure 29. Layout of Site 1 (EB I-94)

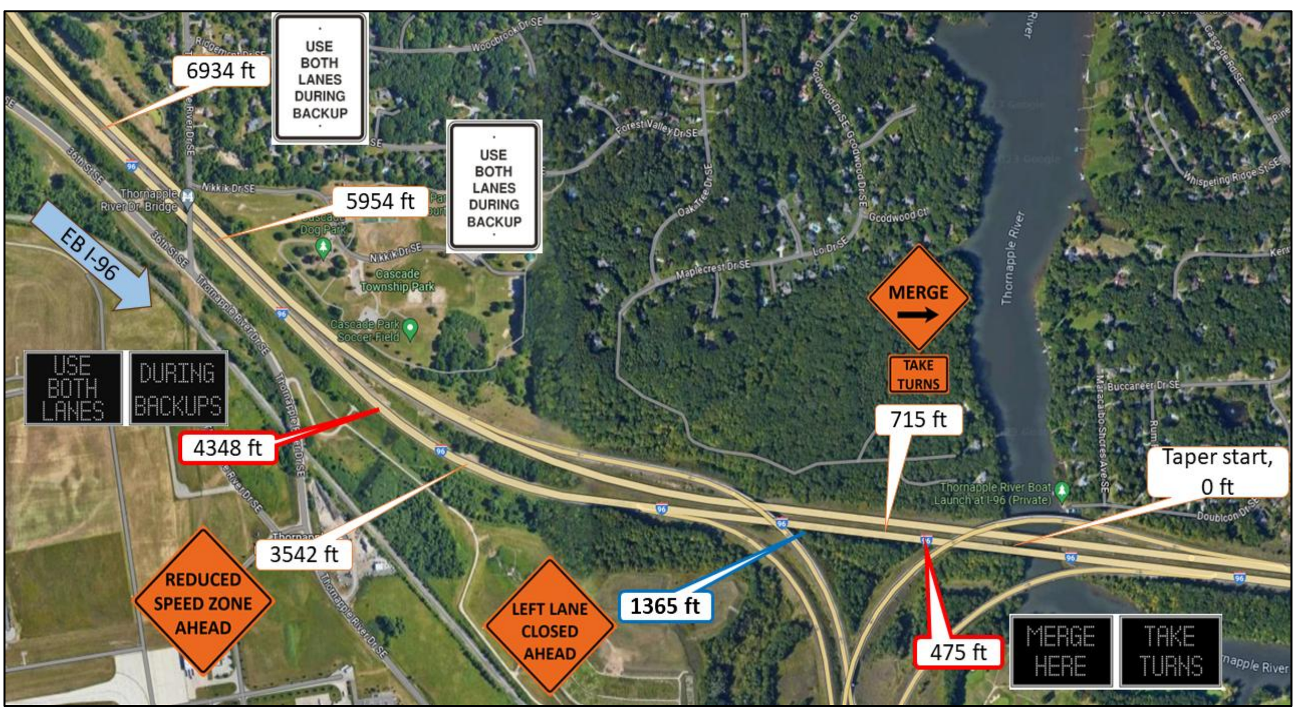


Figure 30. Layout of Site 2 (EB I-96)

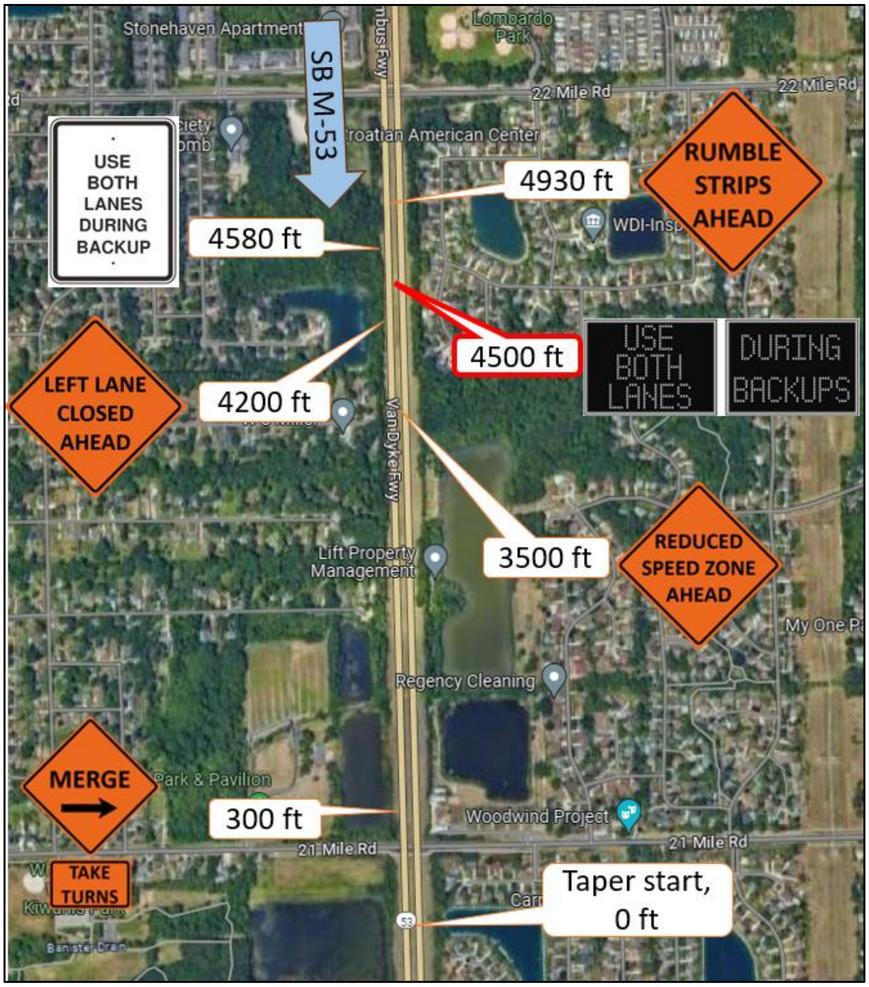


Figure 31. Layout of Site 3 (SB M-53)

6.2. Sign Test Conditions

PCMS are traffic control devices that can display a variety of messages and are designed for temporary use. The following sign test conditions were evaluated in the field using PCMS:

- **Condition A.** Static zipper merge signage (static sign condition)
- **Condition B.** Static zipper merge signage + One PCMS sign upstream (U/S) of the taper displaying USE BOTH LANES and DURING BACKUPS on alternating panels (U/S PCMS condition)
- **Condition C.** Static zipper merge signage + One PCMS sign upstream of the taper displaying USE BOTH LANES and DURING BACKUPS on alternating panels + a second downstream (D/S) PCMS sign closer to the taper alternatively displaying MERGE HERE and TAKE TURNS on alternating panels (U/S and D/S PCMS condition)

The sites on I-94 and I-96 were evaluated under all three test conditions (A, B, and C), while the work zone on M-53 was tested for only the first two conditions (A and B). The PCMS was controlled and operated by the MDOT project team at the request of the Michigan State University (MSU) research team.

6.3. Field Data Collection

Data were collected at three sites in Michigan where a zipper merge strategy was implemented for a two-to-one lane merge configuration. The data collection process began with an initial site survey conducted by a two-member team for each site. Following the survey, field data collection was conducted. The data were collected through a series of pole-mounted high-definition video cameras installed along the work zone to cover at least half a mile of distance upstream of the start of the taper. The location of the cameras varied across sites depending upon the availability of a suitable location to mount the cameras on the roadside, a sufficient distance away from the travel lane. Figure 32 shows the camera view for site I-94.

Figure 32. Field camera view for site EB I-94

At each site, video data were collected for each test condition, as described previously. At I-94, the testing order was Condition A, followed by Condition B and Condition C. The first PCMS (Condition B) was installed at a distance of 4,575 ft upstream of the taper start, and the second PCMS (Condition C) was installed at 435 ft upstream of the taper start. At I-96, the data were collected on two consecutive days. On the first day, the order of sign test conditions was Condition A, followed by Condition B and Condition C. However, the order was reversed on the second day, i.e., Condition C, followed by Condition B and Condition A. At this site, the first PCMS was installed 4,350 ft upstream of the taper start, and the second PCMS was installed 475 ft upstream. A distinctive aspect of the I-96 site was that 1,600 ft downstream from the work zone taper, there was an additional lane merge due to an incoming ramp, causing vehicles in the open lane to slow down and increasing congestion on the site location. Lastly, at M-53, the data were collected only for sign test Condition A (static signs only) and Condition B (U/S PCMS). The PCMS was installed 4,500 ft upstream of the taper start. Data for Condition C were not collected due to the unavailability of a second PCMS at this site.

6.4. Data Reduction

For every sign test condition and every camera location, 2 to 4 hours of video data were recorded. The video data were reviewed manually in the laboratory to extract relevant data during 5-minute intervals. The number of vehicles passing a fixed reference line was tabulated for both the open and closed lanes to obtain 5-minute traffic volumes. The number of vehicles by type (passenger car vs heavy vehicle) was also determined. Traffic density was also observed to consider the effect of congestion across sites. To measure traffic density, a 300 ft section was demarcated on each video, and the number of vehicles in each section was calculated and converted to an equivalent number of vehicles/mile. For each 5-minute interval, five separate density measurements were conducted at one-minute intervals, and these values were then averaged for each period. Figure 33 shows an image of grid lines (300 ft section) marked to help in the data reduction process from the camera for site I-94 in Kinovea software (version 0.9.5).

Figure 33. Grid lines to mark 300 ft section for data reduction

6.5. Statistical Methods

Ultimately, the PCMS are expected to increase the percentage of traffic utilizing the lane that is about to close. As such, the primary performance measure for this study was the percentage of all vehicles using the closed lane during the observation period. In addition to the presence/absence of the PCMS, other factors are also expected to impact lane utilization, including traffic conditions and the presence of heavy vehicles. Consequently, the data were analyzed using multiple linear regression. Lane utilization was calculated for different scenarios (i.e., sign conditions) and at various distances upstream from the start of the taper. The statistical models were estimated using SPSS software, version 29.0.2.0 (IBM Corp 2023). The general form of the multiple linear regression model is shown in equation 8:

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_k X_{ik} + \varepsilon_i, \tag{8}$$

where Y_i is the lane utilization rate of the closed lane (in percent), X_{i1} to X_{ik} are independent variables (e.g., PCMS presence, traffic volume, heavy vehicle percentage) affecting lane utilization, β_0 is an intercept term, β_1 to β_k are estimable parameters, and ε_i is a normally distributed error term.

6.6. Data Summary

The descriptive statistics of the variables used in the study are presented in Table 25. These statistics include each variable’s mean, standard deviation, minimum, and maximum values. Data were collected for a total of 653 5-minute intervals across all camera locations on I-94, 435 intervals on I-96, and 120 intervals on M-53. Lane utilization of the closed lane varied significantly across sites. The average lane utilization rates on I-94, I-96, and M-53 were 29%, 49%, and 11%, respectively. The mean traffic volume on I-94 was 1,446.8 vehicles/hour, while the traffic volumes on I-96 and M-53 were 529.8 and 939.8 vehicles/hour, respectively. Despite lower traffic volumes on I-96, the congestion at this site was relatively high, as indicated by the average traffic densities of the open and closed lanes compared to the other two sites.

Table 25. Descriptive statistics for key variables at each study location

Variables	Mean	Std	Min	Max
Site EB I-94 (n=653)				
Variables	**Mean**	**Std**	**Min**	**Max**
Static signs present	0.28	0.45	0	1
Upstream PCMS present	0.48	0.50	0	1
Upstream and downstream PCMS present	0.24	0.43	0	1
5-min open lane volume	85.52	16.78	35.00	145
5-min closed lane volume	35.05	14.97	2	73
Total hourly volume	1446.8	191.71	648	2004
Lane utilization (%)	28.94	11.29	1.74	53.01
Open lane heavy vehicle percent (%)	10.49	5.26	0	27.55
Closed lane heavy vehicle percent (%)	21.70	9.72	0	83.33
Density open lane (vehicle per mile)	75.07	23.64	7.04	147.84
Density closed lane (vehicle per mile)	35.85	21.59	3.52	100.32
Site EB I-96 (n=435)				
Variables	**Mean**	**Std**	**Min**	**Max**
Static signs present	0.33	0.47	0	1
Upstream PCMS present	0.34	0.47	0	1
Upstream and downstream PCMS present	0.33	0.47	0	1
5-min open lane volume	22.15	9.33	2	59
5-min closed lane volume	22.00	10.03	0	48
Total hourly volume	529.82	180.32	24	996
Lane utilization (%)	48.56	15.92	0	83.33
Open lane heavy vehicle percent (%)	28.19	14.68	0	100
Closed lane heavy vehicle percent (%)	7.98	12.06	0	100
Density open lane (vehicle per mile)	108.96	27.45	10.56	161.92
Density closed lane (vehicle per mile)	73.54	40.28	0	156.29
Site SB M-53 (n=120)				
Variables	**Mean**	**Std**	**Min**	**Max**
Static signs present	0.63	0.49	0	1
Upstream PCMS present	0.38	0.49	0	1
5-min open lane volume	68.36	19.59	27	112
5-min closed lane volume	8.14	4.66	1	19
Total hourly volume	939.8	262.70	396	1428
Lane utilization (%)	10.63	5.35	1.11	26.32
Open lane heavy vehicle percent (%)	8.59	4.29	0	18.75
Closed lane heavy vehicle percent (%)	3.02	10.73	0	100
Density open lane (vehicle per mile)	43.72	28.48	8.45	114.05
Density closed lane (vehicle per mile)	3.87	4.26	0	25.34

Figure 34 presents average lane utilization across sites based on sign test conditions and the PCMS's distance from the taper's start. The figure shows that the lane utilization increased as distance increased from the start of the taper across all sites. Installing the first PCMS 4,500 ft upstream of the start of the taper resulted in slightly higher lane utilization across all measurement locations. Installing the second PCMS 450 ft upstream of the taper, on the other hand, typically resulted in lower lane utilization at I-94 and increased lane utilization at I-96. The bottom right corner is blank as no data was collected for the third test condition site, M-53, as discussed earlier.

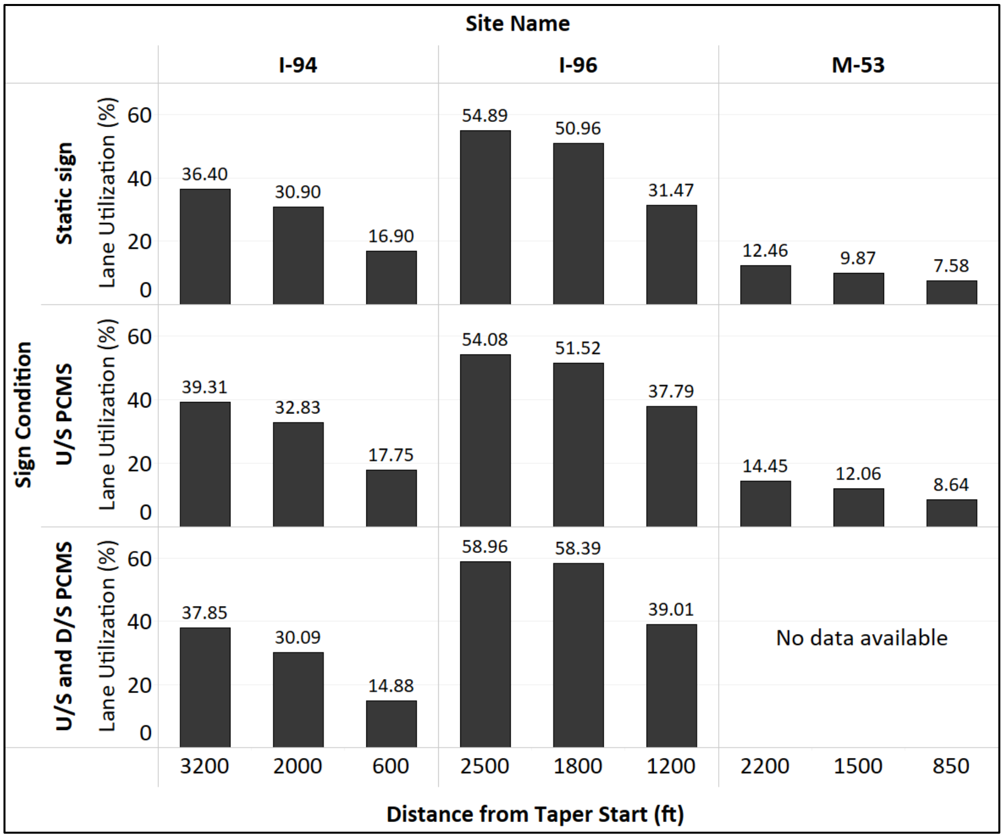


Figure 34. Lane utilization based on signage and distance from the start of the taper

6.7. Results and Discussion

In order to discern the impacts of the PCMS on lane utilization, a series of statistical analyses were conducted. The primary focus was determining the effect of different sign test conditions on lane utilization while controlling for other important site-specific factors (e.g., traffic volume and density). Separate multiple linear regression models were estimated for each of the three sites, and a fourth model was also estimated, pooling the data from all sites together. Table 26 presents the model results for each individual site, while Table 27 presents the results after combining the data for all three sites. When interpreting the model results, a positive parameter estimate means that lane utilization increases under that condition (or when that variable is increased), while a negative sign is reflective of conditions where lane utilization is lower (or where lane utilization decreases as that variable increases).

Table 26. Linear regression model results for lane utilization at different sites

Parameter		Estimate	Std. Error	p-value
Model for Site 1 EB I-94				
Parameter		**Estimate**	**Std. Error**	**p-value**
Intercept		14.908	2.871	< 0.001
Hourly volume (in 100 vehicles)		0.254	0.139	0.067
Open lane heavy vehicle percent		-0.465	0.055	< 0.001
Closed lane heavy vehicle percent		-0.037	0.025	0.144
Density open lane		0.050	0.012	< 0.001
Distance from taper: 600 ft	Static Sign		Baseline	
	U/S PCMS	2.327	1.024	0.023
	U/S and D/S PCMS	-0.043	1.197	0.971
Distance from taper: 2000 ft	Static Sign	12.977	1.133	< 0.001
	U/S PCMS	16.158	1.022	< 0.001
	U/S and D/S PCMS	13.717	1.178	< 0.001
Distance from taper: 3200 ft	Static Sign	18.162	1.132	< 0.001
	U/S PCMS	22.411	1.011	< 0.001
	U/S and D/S PCMS	20.893	1.174	< 0.001
Model for Site 2 EB I-96				
Parameter		**Estimate**	**Std. Error**	**p-value**
Intercept		16.903	4.007	< 0.001
Hourly volume (in 100 vehicles)		0.830	0.353	0.019
Open lane heavy vehicle percent		0.169	0.039	< 0.001
Closed lane heavy vehicle percent		-0.291	0.044	< 0.001
Density open lane		0.111	0.020	< 0.001
Distance from taper: 1200 ft	Static Sign		Baseline	
	U/S PCMS	3.909	2.128	0.067
	U/S and D/S PCMS	2.253	2.148	0.295
Distance from taper: 1800 ft	Static Sign	16.158	2.116	< 0.001
	U/S PCMS	17.109	2.156	< 0.001
	U/S and D/S PCMS	20.333	2.166	< 0.001
Distance from taper: 2500 ft	Static Sign	20.698	2.145	< 0.001
	U/S PCMS	20.331	2.220	< 0.001
	U/S and D/S PCMS	22.253	2.164	< 0.001
Model for Site 3 SB M-53				
Parameter		**Estimate**	**Std. Error**	**p-value**
Intercept		-2.400	3.277	0.466
Hourly volume (in 100 vehicles)		0.586	0.270	0.032
Open lane heavy vehicle percent		0.143	0.109	0.190
Closed lane heavy vehicle percent		-0.096	0.041	0.021
Density open lane		0.060	0.016	< 0.001
Distance from taper: 850 ft	Static Sign		Baseline	
	U/S PCMS	3.266	1.945	0.096
Distance from taper: 1500 ft	Static Sign	1.825	1.275	0.155
	U/S PCMS	6.923	1.801	< 0.001
Distance from taper: 2200 ft	Static Sign	5.180	1.272	< 0.001
	U/S PCMS	9.935	1.789	< 0.001

6.7.1. Effect of Portable Changeable Message Signs on Lane Utilization

A series of interaction variables were created to provide an explicit comparison as to the effects of the PCMS presence between sign/treatment conditions (A, B, and C) and the distance of the measurement location (three locations per site) from the start of the taper (three locations). This resulted in a total of nine indicator variables.

The static sign scenario (Condition A) for the observation location nearest to the work zone taper was selected as the baseline condition in all models. It was assumed that this scenario and location would generally show lower lane utilization rates. Thus, the estimates for the eight other combinations of signage and measurement location could be compared to this baseline to discern how the corresponding utilization rates compare. This would allow for comparisons as to how the effects of PCMS presence vary across locations (i.e., as drivers approach the taper) at the same site and how lane utilization varies across sites.

For example, at the I-94 site, the results from Table 26 show that lane utilization at the location 2,000 ft upstream of the taper was 3.2% higher (16.2-13.0 = 3.2%) after installing the single upstream PCMS compared to the default condition where only the static signage was present. Comparing the individual sites, it can be seen that lane utilization is consistently higher the further a location was from the start of the taper, regardless of the sign condition. For example, under the static signage scenario at the I-94 site, lane utilization at 2,000 ft upstream of the taper was 13% higher than at a distance of 600 ft upstream of the taper. At 3,200 ft upstream, lane utilization increased by an additional 5.2%. Similar increases were observed at site I-96, where lane utilization under static signage increased by 16.2% and 4.5% at 1,800 ft and 2,500 ft upstream of the taper, respectively. At the M-53 site, the increases in lane utilization were less pronounced with distance, which appears to be due, in part, to lower congestion levels.

When a PCMS was installed at the first upstream location, lane utilization increased significantly across all three sites. For distances closest to the taper (which varied from 600 ft to 1,200 ft across sites), the installation of U/S PCMS increased lane utilization by 2.3% to 3.9%. Similarly, at distances 1,500 to 2,000 ft upstream of the taper, lane utilization increased the lane utilization by 3.2% to 5.1%. Further upstream (2,200 ft to 3,200 ft from the taper), lane utilization increased by 4% to 5%. The site on I-96 showed a negligible reduction of 0.4% in lane utilization at this distance. When the data for all three sites were combined, the results showed that, on average, lane utilization increased by 1.4%, 2.3%, and 2.6% within a quarter mile, within half a mile, and beyond 1 mile from the start of the taper, respectively. It should be noted that the initial PCMS was installed at a significant distance (~4,500 ft) upstream of the taper at each site. This PCMS displayed USE BOTH LANES/DURING BACKUP, and its primary purpose was to provide drivers with more effective information about the upcoming zipper merge lane control.

The second PCMS was installed approximately 450 ft upstream of the start of the taper. This PCMS displayed MERGE HERE/TAKE TURNS alternatively to indicate the assigned merging location to the drivers. This PCMS was also accompanied by the traditional static “merge here” arrow and “take turns” sign. As discussed previously, this PCMS condition was only tested at I-94 and I-96 due to site restrictions. The installation of the second PCMS showed mixed trends across the two sites. On-site I-94, lane utilization decreased by 1.5% to 2.4% across all three measurement locations following the installation of a second PCMS compared to just one PCMS condition. On I-96, lane utilization decreased by 1.7% closest to the taper (1,200 ft upstream), while increases of 3.2% and 1.9% were observed at 1,800 ft and 2,500 ft upstream of the taper, respectively. However, lane utilization was higher when two PCMS were installed across both sites compared to static signs. When the data were combined for both sites, the results showed that installing a second PCMS only had a marginal effect on lane utilization. Compared to one PCMS condition, installing a second PCMS reduced lane utilization by 0.3% within a quarter mile of the taper, while it increased by only 0.5% and 0.2% further upstream. Overall, the results showed no substantive advantage of adding the second PCMS closer to the taper. This finding contrasts with previous driving simulator research that found that placement closer to the taper results in more desirable driver behavior (Sun et al. 2021).

Table 27. Linear regression model results for lane utilization of all sites combined

Model for All Sites Combined				
Parameter		**Estimate**	**Std. Error**	**p-value**
Intercept		2.993	2.534	0.238
Site: I-94			Baseline	
Site: I-96		19.583	1.367	< 0.001
Site: M-53		-13.911	1.290	< 0.001
Hourly volume per hundred		0.619	0.134	< 0.001
Open lane heavy vehicle percent		0.067	0.027	0.013
Closed lane heavy vehicle percent		-0.153	0.023	< 0.001
Density open lane		0.107	0.010	< 0.001
Distance from taper: within ¼ mile	Static Sign		Baseline	
	U/S PCMS	1.428	0.978	0.144
	U/S and D/S PCMS	-1.085	1.120	0.333
Distance from taper: ¼ mile to ½ mile	Static Sign	12.669	1.026	< 0.001
	U/S PCMS	14.978	0.981	< 0.001
	U/S and D/S PCMS	15.495	1.117	< 0.001
Distance from taper: More than ½ mile	Static Sign	17.786	1.025	< 0.001
	U/S PCMS	20.419	0.974	< 0.001
	U/S and D/S PCMS	20.585	1.113	< 0.001

6.7.2. Effects of Other Site-Specific Characteristics on Lane Utilization

The results discussed previously controlled for several other site-specific factors. This included traffic volume, traffic density, and truck percentage. The 5-minute traffic counts recorded for each observation period were converted to hourly volume for the analyses. The results showed that for every 100 vehicles/hour increase in traffic volume, lane utilization increased by 0.25% to 0.83% across sites. The average increase in lane utilization across all sites was 0.62% for every 100 vehicles/hour. The changes in lane utilization with varying hourly volumes for sites I-94, I-96, and M-53 are illustrated in Figure 35, Figure 36, and Figure 37, respectively. The slope of the lane utilization versus hourly volume curve differs depending on site-specific characteristics. For instance, site M-53 experienced free-flow traffic conditions, so lane utilization remained constant as hourly volume increased. In contrast, site I-96 faced stop-and-go conditions due to severe congestion, resulting in a steep slope, indicating the need for a zipper merge in high-density traffic. The I-94 site exhibited intermediate conditions between free-flow and stop-and-go, with changes in lane utilization falling between those observed at the M-53 and I-96 sites.

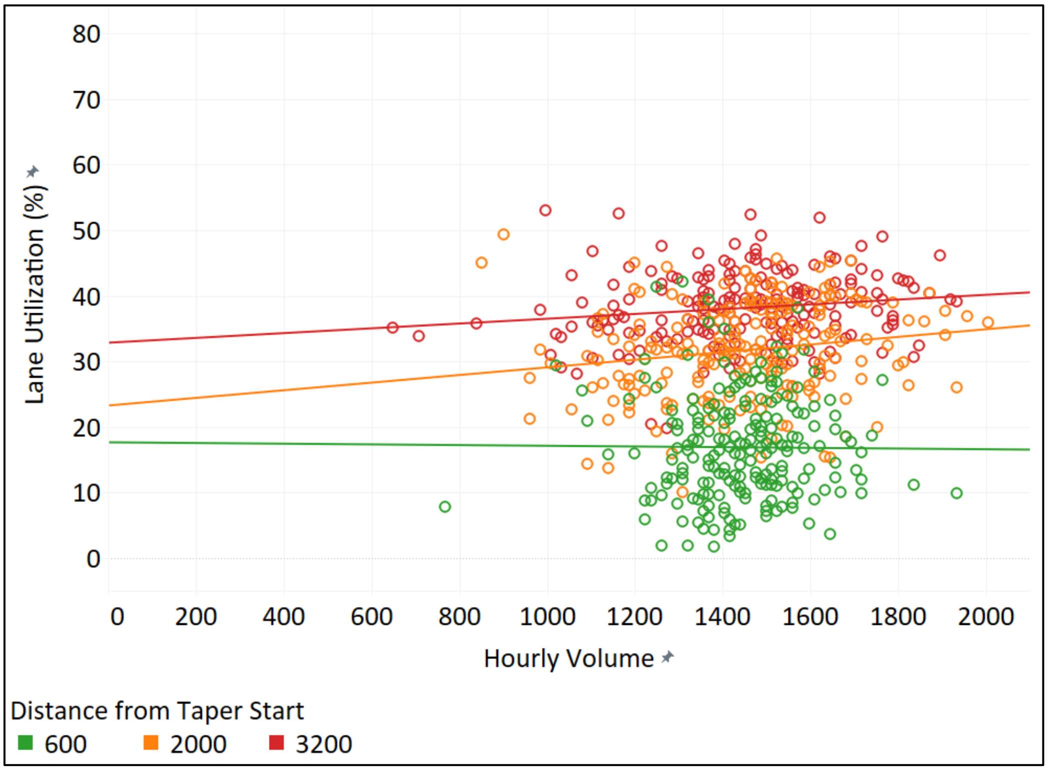


Figure 35. Effect of volume on lane utilization percentage on-site EB I-94

Figure 36. Effect of volume on lane utilization percentage on-site EB I-96

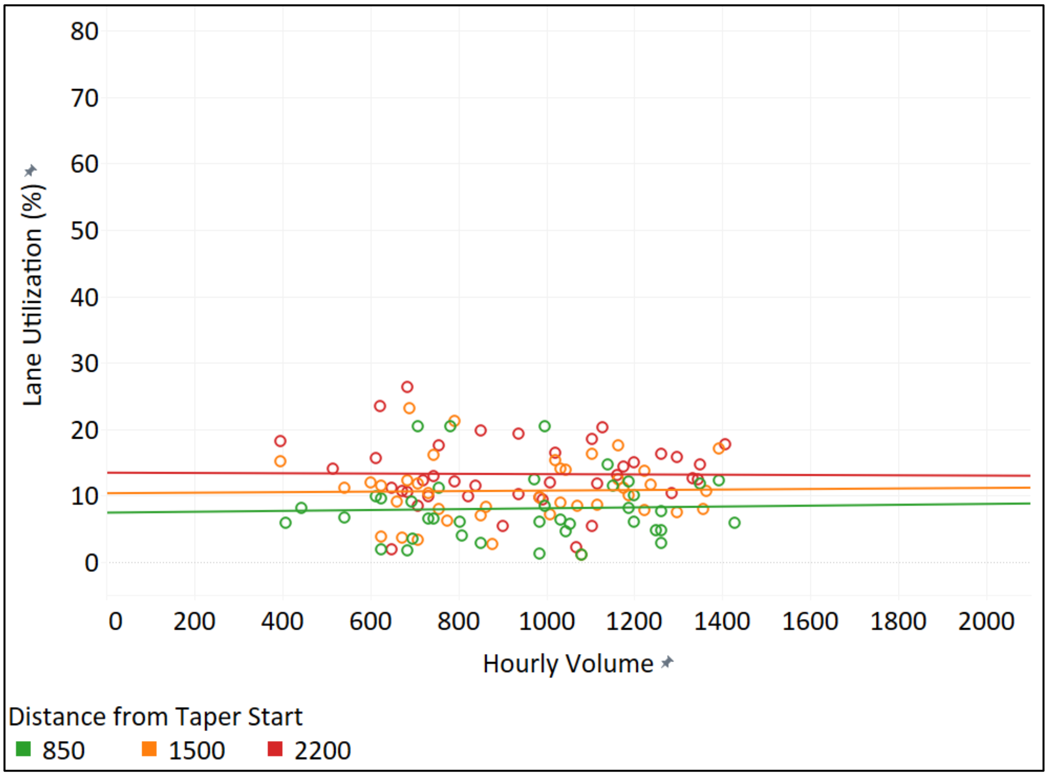


Figure 37. Effect of volume on lane utilization percentage on-site SB M-53

Additionally, the proportion of heavy vehicles in both the open and closed lanes significantly affected the percentage of vehicles utilizing the closed lane. In general, lane utilization increased with the proportion of heavy vehicles in the open lane, except at I-94, which showed an opposite trend. Lane utilization increased marginally by 0.6% for every 10% increase in truck percentage. On the other hand, the impact of truck percentage in the closed lane showed the opposite trend. On average, a 10% increase in truck percentage in the closed lane corresponded to a 1.5% reduction in lane utilization.

The relationship between closed-lane truck percentage and lane utilization was consistent across all three sites. These findings suggest passenger car drivers tend to merge later when the larger, slower-moving trucks occupy the open lane. In contrast, vehicles merge sooner when trucks occupy the lane about to close. These trends are supported by a prior study, which found that drivers were more likely to exit a lane where a heavy vehicle was present and less likely to merge into a lane where a heavy vehicle was present (Chen et al. 2016). Prior research also showed that the increase in the proportion of heavy vehicles can result in fluctuations in light vehicles' speeds and more frequent lane-changing maneuvers. This effect of heavy vehicles was found to intensify when traffic density increases (Moridpour et al. 2015). It is also interesting to note that the I-96 site had the highest traffic density among the three sites. Thus, the effects of the heavy vehicles in the closed lane were most pronounced at this site.

Continuing on this point, traffic density also played an important role. The results show that as the traffic density in the open lane increases, the proportion of vehicles using the closed lane also increases. For every 10 vehicles/mile increase in density within the open lane, the lane utilization rate within the closed lane increased by 0.5% to 1.1%. From the combined aggregate analysis, lane utilization increased by 1% for every 10 vehicles/mile increase in the open lane density on average. This finding aligns with prior research, which noted that as density increases, the lane use ratio approaches one, meaning that traffic flow becomes equal across all lanes (Lee and Park 2011). Interestingly, traffic density in the closed lane did not significantly affect lane utilization.

7. CONCLUSIONS AND RECOMMENDATIONS

This research project sought to assess driver understanding of, and compliance with, work zone lane merge control strategies. To achieve this goal, researchers conducted a synthesis of current and best practices regarding work zone lane merge control strategies in use across the United States. This included a nationwide state agency survey, which yielded responses from 45 state DOTs. A road user survey of drivers across nine SWZDI states was also conducted to better understand road users' perceptions, familiarity, and comfort with early and zipper merge lane control. The road user survey evaluates drivers' behavior under various scenarios that utilize either early merge or zipper merge control, as well as their preferences with respect to various signage strategies that are used in support of each method, including the effect of supplemental PCMS.

Based upon the results of these surveys, a series of field studies was conducted to assess lane utilization behavior under both early and zipper merge lane control in advance of single-lane closures on two-lane (per direction) freeway work zones in Michigan and Missouri. The impacts of upstream PCMS on lane utilization were also evaluated as a part of these field studies. The following subsections summarize the research performed, along with conclusions and recommendations.

The results provide important guidance as to the type and location of work zone lane merge control based on these factors and how to communicate pertinent information to drivers best to yield the anticipated results.

7.1. Conclusions and Key Findings from the State DOT Survey

7.1.1. Performance of Lane Merge Control Strategies in Work Zones

- Prior research studies have used various methods (e.g., field evaluation, simulation, driving simulator, and driver surveys) to investigate alternative lane merge control strategies, such as early and late merge, cooperative systems, and lane-based signal merge control systems. These studies have generally found that alternative lane merge control strategies are effective at increasing throughput compared to conventional lane merge strategies. However, research on the safety performance of alternative lane merge control strategies is somewhat limited.
- Prior research studies have also investigated merge configurations and signage for dynamic lane merge systems.
- DOTs that responded to the survey most often use queue length, delay, and speed as performance measures for dynamic lane merge in work zones.
- The average performance rating (1 = highly ineffective, 5 = highly effective) for dynamic lane merge in work zones by responding DOTs was 3.61 out of 5 with a standard deviation of 0.70, indicating that responding DOTs find the use of dynamic lane merge in work zones to be moderately effective. System performance can sometimes vary depending on project location.

7.1.2. DOT Practices for the Use of Lane Merge Control Strategies

- Eighteen of the 45 DOTs that responded to the survey indicated that they use dynamic lane merge in work zones, while 42 responding DOTs indicated that they use static lane merge in work zones. Eighteen responding DOTs utilize dynamic late merge, while six of those DOTs also utilize dynamic early merge.
- Dynamic lane merge (including dynamic early merge and dynamic late merge) is most often implemented on urban freeways and least often implemented on rural multilane highways. DOTs most often use dynamic lane merge for two-to-one lane drops in work zones.
- Based on the survey results, the most frequently considered factors when determining whether to implement dynamic lane merge in a work zone are AADT, peak hour volumes, and duration of work. Other factors mentioned in DOT guidance to assess the need for dynamic lane merge include queuing and encroachment on upstream intersections or interchanges.
- Responding DOTs most often utilize speed for activation or deactivation thresholds for dynamic lane merge in work zones. These speed thresholds vary among DOTs in their standards or specifications but typically range from 20 mph to 40 mph.
- Dynamic lane merge is sometimes implemented along with other smart work zone technologies in work zones, most frequently with end-of-queue warning systems (14 responding DOTs) and traveler information systems (13 responding DOTs).
- Some DOTs provide layouts for lane merge systems for work zones in their standard drawings or typical applications. These layouts include information such as locations of traffic control devices and sensors, general notes, and, in some cases, messages that should be displayed on PCMS based on location and traffic conditions.
- Other resources developed by DOTs include, but are not limited to, guidance or policy documents, special provisions, and outreach materials (e.g., websites and videos). In addition to layouts and operational parameters, these resources specify other requirements such as approval processes, maintenance of websites with travel information, materials, and measurement and payment.
- Among the responding DOTs that use dynamic lane merge, the factors perceived to be the most challenging to the implementation of dynamic lane merge in work zones are driver inattention, lack of perceived need, and the need for enforcement.
- Responding DOTs that exclusively use static lane merge cited a lack of perceived need, lack of information on benefits, lack of available guidance, and the prioritization of other work zone safety countermeasures (e.g., speed management, end-of-queue warning systems) as the primary reasons they do not utilize dynamic lane merge in work zones.

7.2. Conclusions and Key Findings from Road User Survey

The key findings from the survey of road users survey are summarized as follows.

- This road user survey provided important insights into driver understanding of lane merge scenarios and driver behavior when navigating both early and late/zipper merge control strategies at single-lane closures in freeway work zones.

- The results showed that drivers typically prefer to merge early into the open lane regardless of the lane control strategy. However, providing information more conspicuously through PCMS increased compliance, as drivers were willing to merge closer to the taper when PCMS were used in addition to static signage.
- The survey results showed that the addition of another PCMS nearer to the start of the taper showed further improvements in closed lane utilization. However, as prior field studies showed mixed results in this scenario, additional research is warranted on the optimal locations of PCMS before the taper.
- In terms of signage alternatives, drivers generally preferred signs that conveyed information both graphically and textually, followed by signs that used only text. Purely graphical signs generally showed lower preference among drivers, a result that is in contrast with some of the broader research literature (Er-hui et al. 2013, Messina 2012, Viganò and Rovida 2015).
- Generally speaking, drivers tended to slow down and allow other vehicles to merge. However, these trends varied depending on the merging strategy (early versus late/zipper) and the location of the merging maneuver with respect to the start of the taper.
- Overall, respondents were more likely to continue driving at the same speed and use the soon-to-be-closed lane more effectively when the zipper merge was in place.
- Regardless of the lane merge control strategy, driver behavior was generally more aggressive closer to the taper compared to further upstream.
- Another important and consistent finding was related to drivers' familiarity and comfortability with zipper merge. With an increase in either of these metrics, both the compliance with zipper merge and the perceived benefits of zipper merge increased.
- Moreover, older people consistently showed lower compliance rates and poorer perceptions of zipper merge. As stated earlier, the success of zipper merge depends on driver understanding and cooperation with zipper merge signage; thus, drivers need to be educated about the expected behavior during zipper merge lane control.
- To that end, drivers were also asked which platform they think has more outreach and can educate a greater number of drivers about zipper merge. Nearly 42% of participants suggested using TV advertisements and newspapers, 28% suggested using social media, and 14% suggested using public meetings and driver's license handbooks for better public outreach.
- Older drivers preferred TV advertising and newspapers, while younger drivers preferred social media for outreach purposes. This information can be used as a basis for education and outreach campaigns by road agencies to improve work zone knowledge and behavior.

7.3. Conclusions and Key Findings from Field Evaluations in Michigan and Missouri

Michigan field study evaluated the effect of PCMS on the percentage of vehicles utilizing the closed lane under zipper merge lane control. Field data related to lane utilization were collected at three work zone locations under three different zipper merge signage conditions. These included standard static zipper merge signage and the combination of the static signs with a single PCMS approximately 4,500 ft upstream of the taper and a second PCMS approximately 450 ft upstream of the taper.

- In general, introducing a PCMS was found to increase lane utilization in the lane about to be closed. These differences were least pronounced at distances far upstream (2,500 ft or more) from the taper. The PCMS showed the largest impacts at distances of 1,200 ft to 2,000 ft, though results varied significantly across sites.
- The use of a PCMS is likely to provide marginal value at lower-volume sites. For example, the M-53 site was the least congested location, and as such, the vast majority of traffic had merged into the open lane, which was more than 2200 ft upstream of the taper. While the PCMS did show 1-2% increases here, congestion was generally not an issue in these volume ranges (average of approximately 940 vehicles/hour). This is consistent with the broader literature, which suggests that zipper merge lane control works better on sites with moderate to high traffic volumes (Kurker et al. 2014, Lammers et al. 2017).
- The addition of a second PCMS near the start of the taper showed variable impacts at the two study locations where it was evaluated. At the I-94 site, lane utilization was actually lowest in this scenario, while at the I-96 site, the combination of signs showed consistently higher lane utilization when the second sign was present.
- Overall, the results from this study provide insights to aid road agencies in determining where and when to include PCMS for zipper merge scenarios.
- Optionally, a second PCMS closer to the taper may be appropriate at select locations, though further research is warranted to understand the scenarios under which this supplementary device is beneficial.
- Lane utilization improves with an increase in the density of open lanes.
- It is favorable for zipper merge compliance to have heavy vehicles in the open lane far upstream of the taper start.
- The effect of heavy vehicles on lane utilization gets more pronounced as the traffic density increases.
- For sites with higher AADT, such as those in Michigan, lane utilization tends to increase as traffic volume rises. Conversely, for sites with lower AADT, like those in Missouri, lane utilization decreases as traffic volume increases.
- Findings from the Missouri field study support the necessity of implementing zipper merge strategies in work zones, as drivers under early merge were prone to merge into the open lane earlier when traffic started to become congested.

7.4. Recommendations for Improving the Effectiveness of Zipper Merge

When deployed in work zones, the primary purpose of PCMS is to alert drivers of the need to stay in the lane they are driving in up to the start of the work zone taper. This will help to improve compliance with the zipper merge lane control strategy for lane closure on freeways. The road user survey found that installing PCMS upstream of the taper is likely to increase closed-lane utilization. The field evaluations also tested the effect of PCMS on driver behavior in zipper merge. The recommendations based on the study are presented below:

- Two PCMS were placed in the field to test their effect on the rate of drivers’ compliance with the zipper merge strategy. Installing a PCMS 4,500 ft to 1 mile upstream of the taper generally provides sufficient advance notice under most scenarios. This PCMS is required to provide advance information to drivers about the lane merge control strategy and necessary actions to take. This sign was placed close to the static USE BOTH LANES DURING BACKUPS sign. The PCMS displayed the same sign but in two frames. The first frame displayed USE BOTH LANES, and the second frame displayed DURING BACKUPS.

- If an additional PCMS is available, it should ideally be positioned within 500 to 1,000 ft upstream of the lane closure. It is also recommended that this second PCMS display the message in two frames. The message on the first frame is MERGE HERE, and the message on the second frame is TAKE TURNS. The placement of the additional PCMS is adjacent to the static sign displaying MERGE HERE TAKE TURNS.
- From the road user survey, it is recommended to use signs that convey information both graphically and textually over only graphical signs.
- Another recommendation based on the results of the road user survey is to use a sign displaying a message along with a plaque to encourage drivers to stay in the closed lane (right) as long as possible, as shown in Figure 38.
- It is also recommended that TV advertising and newspapers be used to educate older people and various social media platforms be used to educate younger drivers.

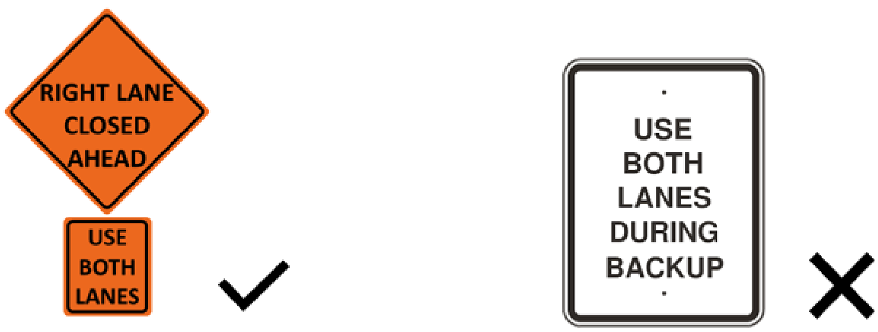


Figure 38. Preferred sign for encouraging drivers to use both lanes

7.5. Limitations and Scope for Future Work

The findings from this study offer valuable insights to assist road agencies in deciding when and where to implement PCMS for zipper merge scenarios. Generally, placing a PCMS 4,500 ft upstream of the taper provides sufficient advance notice in most situations. In some cases, an additional PCMS closer to the taper may be beneficial, though further research is needed to determine under what conditions this supplementary device is effective. There are various avenues for additional research that would provide further insights to aid in the development of temporary traffic control plans. In this study, the first PCMS consistently displayed the message USE BOTH LANES/DURING BACKUP, while the second PCMS, positioned nearer the taper, displayed MERGE HERE/TAKE TURNS. The latest edition of the MUTCD offers a range of alternative messages that can be displayed on these PCMS. Future research could investigate whether specific messages are more effective at improving capacity ahead of the lane closure. Additionally, research should explore variations in the placement of the PCMS relative to the taper. In this study, the location of the PCMS was influenced by site-specific factors. Further investigation is also needed to assess how lane utilization rates differ between left-lane and right-lane closure scenarios.

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APPENDIX A. SUMMARY OF EXISTING DOT GUIDANCE, STANDARDS, SPECIFICATIONS, AND OUTREACH MATERIALS FOR LANE MERGE IN WORK ZONES

Table A-1. Summary of DOT guidance, standards, specifications, and outreach materials for lane merge in work zones

State	Title	Reference	Hyperlink	Summary
Indiana	Operations Memorandum 20-02: Signs	INDOT 2020	Provided through survey	This indicates that zipper merge may be utilized in urban areas when there are queues for at least two hours per day for five days per week, which often block intersections or ramps. The use of zipper merge requires the approval of the district traffic engineer. Provides a layout for static signs and allows for the use of PCMS. When zipper merge is used, the district traffic engineer is required to notify the district media relations director and provide support for public outreach.
Michigan	Maintaining Traffic Typicals (340-345)	MDOT 2021	https://mdotjboss.state.mi.us/TSSD/getSubCategoryDocuments.htm?prjNumber=1403892&category=Work%20Zones&subCategory=Maintaining%20Traffic%20Typicals%20(pdf)&subCategoryIndex=subcat2Work%20Zones&categoryPrjNumbers=1403891,1525683,1403892,2173385,2173386,1403896	Provide layout drawings for early merge and zipper merge. Zipper merge drawings are provided for the left or right lane closed and shift or PCMS.

State	Title	Reference	Hyperlink	Summary
Minnesota	Traffic Engineering Manual	Minnesota 2015	https://edocs-public.dot.state.mn.us/edocs_public/DMResultSet/download?docId=17673225	Provides an overview of active and passive zipper merge. Active zipper merge utilizes smart work zone technologies to inform drivers when they should use both lanes and where to merge. Passive zipper merge informs drivers to use both lanes if a backup is present and allows drivers to decide if there is a backup. This indicates that both methods are effective, but active zipper merge results in higher compliance.
Minnesota	Minnesota Temporary Traffic Control Field Manual	MnDOT 2018	https://edocs-public.dot.state.mn.us/edocs_public/DMResultSet/download?docId=37176174	Provides layout drawings for active (mobile/short duration – 1 hour or less)) and passive (3 days or less) zipper merge on a multilane divided highway.
Minnesota	Long-Term Typical Applications (Numbers 75 and 76)	MnDOT 2024a	https://edocs-public.dot.state.mn.us/edocs_public/DMResultSet/Urlsearch?columns=docnumber,docname&folderid=38277846&currSortFieldName=docname&sortOrder=d\	Provides layout drawings for active zipper merge.
Minnesota	Zipper Merge	MnDOT 2024b	https://www.dot.state.mn.us/zippermerge/	Webpage with outreach material on dynamic late merge. Includes information on benefits and how to merge properly. Includes link to video.

State	Title	Reference	Hyperlink	Summary
Missouri	Zipper Merge	MoDOT 2022	https://www.modot.org/zipper-merge	Public outreach information on how to safely merge with dynamic late merge. Includes outreach video that uses adults in cardboard cars. Indicates that dynamic late merge reduces the length of traffic backup by 40% to 50%.

State	Title	Reference	Hyperlink	Summary
Missouri	Engineering Policy Guide (616.13.6.3 Smart Work Zone (SWZ) Strategy Selection)	MoDOT 2024	https://epg.modot.org/index.php/616.13_Work_Zone_Capacity,_Queue_and_Travel_Delay	Indicates that zipper merge should be considered for static work zones with a duration of at least two days, traffic volumes over 1500 vehicles per hour for at least two hours of the day, and estimated queue lengths that could encroach on the operation of upstream intersections or interchanges. Includes figure with layout and job special provision. Job special provision includes requirements for system, smart work zone plan, materials, system manager, operational testing, and measurement and payment. The system must detect traffic conditions for free-flow and congestion. Indicates general guidance for congestion based on speeds (less than 20 to 35 mph) or volumes (greater than 1500 to 1700 vehicles per hour). Contractors must host websites with information on the locations of system components.
Montana	Zipper Merges	MDT 2018	https://www.youtube.com/watch?v=xm0B0AdzZP4	Public outreach video for dynamic late merge.
New Mexico	Standard Drawing: Zipper (1 through 4)	NMDOT 2017	Provided by DOT in the survey	Provides layouts for passive and active zipper merge.

State	Title	Reference	Hyperlink	Summary
North Carolina	Special Provision: Dynamic Zipper Merge System	NCDOT 2023a	Provided by DOT in the survey	This includes requirements for materials and system operations, construction methods, measurement, and payment. North Carolina DOT provides the logic for programming. Software must cover three functions: Queue Warning, Driver Merge Instructions, and Lane Closure Notification. A website showing real-time speeds and posted messages is required.
North Carolina	Dynamic Zipper Merge	NCDOT 2023b	https://www.ncdot.gov/initiatives-policies/Transportation/safety-mobility/Dynamic-Zipper-Merge/Pages/default.aspx	Public outreach website that explains how dynamic late merge works. Includes video.
Oregon	Standard Details (DET 4770 – Smart Work Zone System Dynamic Late-Lane Merge)	ODOT 2019	https://www.oregon.gov/ODOT/Engineering/Details/DET4770.pdf	Shows the layout of traffic control devices and messages that should be displayed on PCMS (based on queue length and traffic conditions). Categorizes traffic conditions into six groups based on speed.
Pennsylvania	Publication 46 Traffic Engineering Manual	PennDOT 2014	https://www.dot.state.pa.us/public/PubsForms/Publications/Pub%2046.pdf	Summarizes benefits of the late merge. Indicates that field implementation of late merge in Pennsylvania has shown mixed results but encourages consideration of use when capacity is restricted. Includes layout drawing.

State	Title	Reference	Hyperlink	Summary
Tennessee	Standard Drawings (T-WZ-65: Lane Closure with Late Merge)	TDOT 2024	https://www.tn.gov/content/tn/tdot/roadway-design/standard-drawings-library/standard-roadway-drawings/design---traffic-control/t-wz-65.html	Shows the layout of traffic control devices and messages for PCMS. Messages are based on these traffic conditions: free-flow and two tiers of slow (45 mph or less or 20 mph or less).
Utah	Standard Drawings (TC 4B1: Reduced Speed Work Zone Signing General)	UDOT 2024	https://www.udot.utah.gov/connect/business/standards/	The layout for lane closure shows optional signs for zipper merge as specified by the project. CMS (instead of static sign) is required for freeways (65 mph or higher).
Virginia	Zippers and work zones – How does that work?	VDOT 2024	https://www.vdot.virginia.gov/news-events/news/staunton-district/zippers-and-work-zones--how-does-that-work.html	A webpage that provides information on the pilot program for dynamic lane merge.
Washington	General Special Provisions (1-10.3(3).OPT3.FR1: Smart Work Zone System, 1-10.3(3).OPT4.FR1: Queue Warning System)	WSDOT 2024a	https://wsdot.wa.gov/engineering-standards/all-manuals-and-standards/general-special-provisions-gsps	Smart Work Zone system should include queue detection, dynamic lane merge, and traveler information (work zone travel delay). Provides a list of vendors.
Washington	Work Zone Typical Traffic Control Plans (TCP) (151 to 176)	WSDOT 2024b	https://wsdot.wa.gov/engineering-standards/all-manuals-and-standards/plan-sheet-library/work-zone-typical-traffic-control-plans-tcp	Provides layout for queue warning system for two or three lanes and queue lengths of 6 or 9 miles. The system uses zipper merge under certain conditions. Drawings show the layout of traffic control devices and messages for PCMS based on queue location and traffic conditions (free-flow 35 mph or higher, slow less than 35 mph). The required accuracy for estimated travel times is five minutes.

State	Title	Reference	Hyperlink	Summary
Wisconsin	Facilities Design Manual (11-50-25: Smart Work Zones)	WisDOT 2024a	https://wisconsindot.gov/rdwy/fdm/fd-11-50.pdf#fd11-50-25	Provides an overview of the benefits of a dynamic lane merge system. The system only activates when there is congestion and speeds less than 40 mph. This indicates that the system should be considered for a single-lane closure on a divided highway with possible moderate to heavy congestion. Public outreach is necessary, and there are examples of public outreach documents that can be used.
Wisconsin	Standard Detail Drawings (15D12-13c: Traffic Control, Dynamic Late Merge System)	WisDOT 2024b	https://wisconsindot.gov/rdwy/sdd/sd-15d12.pdf#page=1	The layout shows device locations and messages for PCMS. PCMS messages based on location and speed (0 to 39 mph, 40 mph or higher)

State	Title	Reference	Hyperlink	Summary
Wisconsin	Standardized Special Provisions (stp-643-040 Dynamic Late Merge System, Item 643.1100.S)	WisDOT 2024c	https://wisconsindot.gov/Documents/doing-bus/eng-consultants/cnslt-rsrces/contracts/stsp/stspart.pdf	This includes requirements for device placement, programming, measurement, and payment. Vendor verification must be submitted to the engineer and Bureau of Traffic Operations 14 calendar days prior to the pre-construction meeting. A weekly summary report must be provided to the engineer. Operation is based on speed (typically free-flow = 40 mph or higher, congestion = less than 40 mph). Includes requirements for PCMs messages. Data must be archived. A website with real-time data (e.g., speeds, device locations, PCMS messages) is required.
Wisconsin	Zipper Merge	WisDOT n.d.	https://wisconsindot.gov/Pages/safety/safety-eng/zippermerge.aspx	Public outreach webpage that explains the benefits of dynamic late merge and how it works.

APPENDIX B. STATE DOT SURVEY QUESTIONNAIRE

Smart Work Zone Deployment Initiative
Merging Implementation Criteria for Work Zones
Survey
Letter to the Respondent
Dear Participant,

FHWA's Smart Work Zone Deployment Initiative (SWZDI) is sponsoring a research study titled "Merging Implementation Criteria." The research is being performed by Michigan State University and the University of Missouri. A principal objective is to conduct a review of best practices for the use of lane merge control strategies in work zones by agencies across the United States. A field study will also be performed to assess driver behavior under various lane merge control strategies in work zones. The information obtained will be used to develop guidance toward maximizing the operational and safety effectiveness of lane merge control strategies in work zones.

Your cooperation in completing this survey will help to ensure the success of this research project. You have been identified as the appropriate person at your DOT to complete this survey. The survey link that you received is unique to your DOT. If it would be more appropriate for someone else at your DOT to take this survey, please forward the email with the survey link to them or send their name and email address to Henry Brown (brownhen@missouri.edu). The identity of survey respondents will remain anonymous, but survey responses and aggregate statistics will be shown in the published research report. Additional instructions are provided at the beginning of the survey. If you would like to download a PDF version of the survey for informational purposes, please click here.

Please complete this survey by March 6, 2024. Depending on your agency's experience and level of involvement with lane merge control strategies in work zones, the survey could result in 4 to 17 questions, and we estimate that the survey will take approximately 5 to 20 minutes to complete. If you have any questions, please contact Henry Brown at (573) 882-0832 or brownhen@missouri.edu. Any supporting materials may be sent by email to Henry or uploaded in lieu of providing URLs. Thank you for participating in this survey!

Survey Instructions

1. To begin the survey, click the forward arrow at the bottom of this page.
2. To view and print the entire survey for informational purposes, click on this survey link and download and print the document.
3. To save your partial answers and complete the survey later, close the survey. Answers are automatically saved upon closing the browser window. To return to the survey later, open the original email from Henry Brown and click on the survey link.
4. To pass a partially completed survey to a colleague, close the survey and forward the original email from Henry Brown to a colleague. Note that only one person may work on the survey at a time; the survey response should only be active on one computer at a time.

5. To view and print your answers after completing the survey, submit the survey by clicking "Submit" on the final page. Download and print the PDF on the following page, which contains a summary of your responses.
6. To submit the survey, click on "Submit" on the last page.

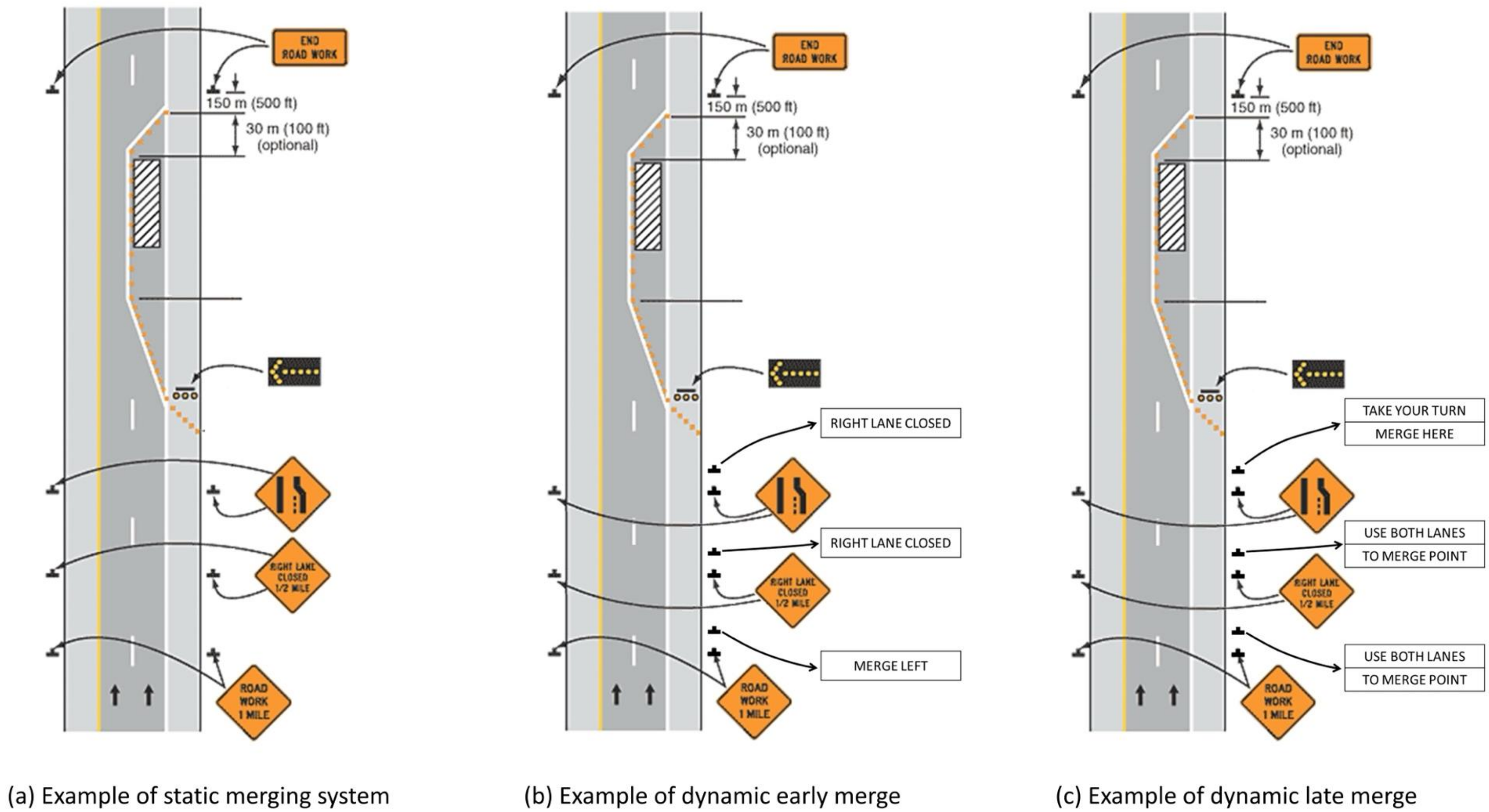
Survey Tips

1. Survey navigation is conducted by selecting the forward and back arrows at the bottom of each page.
2. If you are unable to complete the survey, you can return to the survey at any time by reentering through the survey link.

Definitions

Definitions of different types of merging systems are provided below, along with diagrams showing example layouts (Figure 1).

- **Static merging systems** (Figure 1a) use static signage to convey information to drivers regarding the merge point. The merge point does not change with traffic conditions.
- **Dynamic merging systems** allow the merging technique to vary based on traffic conditions and include dynamic early merge and dynamic lane merge.
- **Dynamic early merge** (Figure 1b) encourages drivers to leave the closed lane well in advance of the designated merge point.
- **Dynamic late merge** (also known as zipper merge) (Figure 1c) encourages drivers to stay in their lane until a designated merge point. At the designated merge point, drivers alternate moving into the open lane.



Adapted from *Manual on Uniform Traffic Control Devices* (FHWA 2009) and *Guidance for the Use of Dynamic Lane Merging Strategies* (ATSSA 2012)

Figure B-1. Example layouts for merging systems

Questions

Contact Information

Name ____________________
State ____________________
Job Title ____________________
Division ____________________
Phone Number ______________________
Email Address _______________________

Section 1: Initial Screening

1. Which of the following lane merge strategies does your agency use? Please select all that apply.

- ☐ Dynamic lane merge
- ☐ Static lane merge
  (If static lane merge is not selected, skip to Question No. 17. Otherwise, proceed to Question No. 2.)

Section 2: DOTs that use Dynamic Lane Merge

2. Which of the following dynamic lane merge strategies does your agency use? Please select all that apply.

- ☐ Dynamic early merge
- ☐ Dynamic late merge

3. Has your agency developed any policies, guidance, standards, or typical applications regarding the use of lane merge control strategies in work zones?

- ☐ Yes
- ☐ No

Please briefly describe your agency's policy, guidance, standards, or typical applications in the box below. *(Only display if the answer to Question No. 3 = yes.)*

____

Please provide the URL(s) for the relevant documents in the box below, upload files, or email files to brownhen@missouri.edu. *(Only display if the answer to Question No. 3 = yes.)*

____

Additional comments on policy, guidance, standards, or typical applications for lane merge control strategies:

____

4. For what types of lane drops does your agency use dynamic lane merge systems? Please select all that apply.

- ☐ 3 to 2
- ☐ 2 to 1
- ☐ Other (please describe) _____________

Comments:

____

5. For each of the roadway facility types listed below, please indicate the frequency with which your agency implements dynamic lane merge systems in work zones.

Facility Type	Frequently	Sometimes	Rarely	Never
Rural Freeways	☐	☐	☐	☐
Rural Multi-Lane	☐	☐	☐	☐
Urban Freeways	☐	☐	☐	☐
Urban Multi-Lane	☐	☐	☐	☐
Other (Please describe) _____	☐	☐	☐	☐

Comments:

____

6. How frequently does your agency consider the following factors when trying to determine whether to implement dynamic lane merge systems in a given work zone?

Factor	Frequently	Sometimes	Rarely	Never
AADT	☐	☐	☐	☐
Area Type (Urban or Rural)	☐	☐	☐	☐
Crash History	☐	☐	☐	☐
Duration of Work Zone	☐	☐	☐	☐
Length of Work Zone	☐	☐	☐	☐
Peak Hour Volumes	☐	☐	☐	☐
Percent Trucks	☐	☐	☐	☐
Stakeholder Input	☐	☐	☐	☐
Terrain	☐	☐	☐	☐
Type of Work Activity	☐	☐	☐	☐
Work Zone Speed Limit	☐	☐	☐	☐
Worker Presence	☐	☐	☐	☐
Other (Please describe) _____	☐	☐	☐	☐

Comments:

____

7. In determining activation or deactivation thresholds for dynamic lane merge systems, which of the following criteria does your agency typically use? Please select all that apply.

- ☐ Based on specific time periods (e.g., peak hour)
- ☐ Speed
- ☐ Volume
- ☐ Combination of multiple traffic measures
- ☐ Other (please describe) _____________

Comments:

____

8. Which of the following types of vehicle presence detectors does your agency use for dynamic lane merge systems? Please select all that apply.

- ☐ Microwave
- ☐ Pneumatic tubes

- ☐ Radar
- ☐ Video
- ☐ Other (please describe) _____________
- ☐ None of the above

Comments:

____

9. Does your agency use dynamic lane merge systems in work zones in conjunction with any of the following smart work zone technologies? Please select all that apply.

- ☐ End of queue warning system
- ☐ Traveler information system
- ☐ Other (please describe) _____________
- ☐ None of the above

Comments:

____

10. What method is most frequently used by your agency for the basis of payment for contracts (prime or subcontract) with dynamic lane merge systems in work zones?

- ☐ Measured pay item
- ☐ Lump sum pay item
- ☐ No direct payment
- ☐ Other (please describe) _____________

Comments:

____

11. What performance measures does your agency use to assess the performance of dynamic lane merge systems in work zones? Please select all that apply.

- ☐ Number of crashes
- ☐ Crash severity
- ☐ Observed conflicts/safety
- ☐ Driver compliance
- ☐ Occupancy
- ☐ Queue length
- ☐ Speed
- ☐ Delay
- ☐ Other (please describe) _____________
- ☐ My agency does not use performance measures to assess the performance of dynamic lane merge in work zones.

Comments:

____

12. On a scale of 1 to 5 (1 = Highly Ineffective, 5 = Highly Effective), how would you rate the overall effectiveness of the dynamic lane merge systems implemented in work zones under your agency's jurisdiction?

- ☐ 1 (Highly Ineffective)
- ☐ 2
- ☐ 3
- ☐ 4
- ☐ 5 (Highly Effective)

Comments:

____

13. How strongly do you agree or disagree that the following factors influence the effectiveness of dynamic lane merge systems in work zones?

Factor	Strongly Agree	Somewhat Agree	Neither Agree nor Disagree	Somewhat Disagree	Strongly Disagree
Activation Thresholds	☐	☐	☐	☐	☐
Location of Merge Point	☐	☐	☐	☐	☐
Percent Trucks	☐	☐	☐	☐	☐
Presence of Positive Protection	☐	☐	☐	☐	☐
Traffic Volumes / Congestion	☐	☐	☐	☐	☐
Type of Work Activity	☐	☐	☐	☐	☐
Use of Additional Countermeasures (e.g., Enforcement)	☐	☐	☐	☐	☐
Work Zone Duration	☐	☐	☐	☐	☐
Work Zone Length	☐	☐	☐	☐	☐
Work Zone Speed Limit	☐	☐	☐	☐	☐
Worker Proximity	☐	☐	☐	☐	☐
Other (Please describe) ______	☐	☐	☐	☐	☐

Please comment on any particular features or conditions that improve the effectiveness of dynamic lane merge systems in work zones:

____

Other comments:

____

14. Has your agency completed any formal studies to evaluate the effectiveness of dynamic lane merge systems in work zones?

- ☐ Yes
- ☐ No

Please provide the URL(s) for evaluation documents in the box below, upload files, or email files to brownhen@missouri.edu. *(Only display if the answer to Question No. 14 = yes.)*

____

Comments on evaluation studies:

____

15. What types of public outreach materials has your agency developed for dynamic lane merge systems in work zones? Please select all that apply.

- ☐ Flyer and/or pamphlet
- ☐ Website
- ☐ Social media site
- ☐ Video
- ☐ My agency uses materials from other agencies
- ☐ My agency has not developed public outreach materials for dynamic lane merge systems.
- ☐ My agency is in the process of developing public outreach materials for dynamic lane merge systems.
- ☐ Collaborating with mass media (e.g., television, radio)
- ☐ Other (please describe) _____________

Please provide the URL(s) for outreach materials in the box below, upload files, or email files to brownhen@missouri.edu. *(Only display if "My agency has not developed public outreach materials for dynamic lane merge systems" and "My agency is in the process of developing public outreach materials for dynamic lane merge systems" are not selected in Question 15.)*

____

Comments on outreach materials:

____

16. Which of the following factors is a challenge to your agency's efforts to implement dynamic lane merge systems in work zones? Please select all that apply.

- ☐ Agency understaffing
- ☐ Availability of dynamic lane merge systems/vendors
- ☐ Coordination with subcontractors
- ☐ Cost
- ☐ Driver inattention
- ☐ Lack of agency buy-in
- ☐ Lack of available guidance
- ☐ Lack of contractor buy-in
- ☐ Lack of information on benefits
- ☐ Lack of perceived need
- ☐ Need for enforcement
- ☐ Other (please describe) _____________
- ☐ None of the above

Comments:

____

Section 3: DOTs that do not use Dynamic Lane Merge Systems

17. Which of the following is a reason why your agency does not use dynamic lane merge systems in work zones? Please select all that apply. *(Only display if dynamic lane merge is not selected in Question No. 1.)*

- ☐ Agency understaffing
- ☐ Cost
- ☐ Lack of available guidance
- ☐ Lack of information on benefits
- ☐ Lack of perceived need
- ☐ Other work zone countermeasures are a higher priority (please briefly describe other countermeasures _____________)
- ☐ Other (please describe) _____________

Comments:

____

18. Has your agency developed any policies, guidance, standards, or typical applications regarding the use of static lane merge strategies in work zones? *(Only display if dynamic lane merge is not selected in Question No. 1.)*

- ☐ Yes
- ☐ No

Please briefly describe your agency's policy, guidance, standards, or typical applications in the box below. *(Only display if the answer to Question No. 18 = yes.)*

____

Please provide the URL(s) for the relevant documents in the box below, upload files, or email files to brownhen@missouri.edu. *(Only display if the answer to Question No. 18 = yes.)*

____

Additional comments on policies, guidance, standards, or typical applications regarding the use of static lane merge strategies in work zones: *(Only display if dynamic lane merge is not selected in Question No. 1.)*

____

Section 4: All DOTs

19. Please provide any additional comments that you may have regarding the use of lane merge control strategies in work zones.

____
____
____

Submittal Instructions

To complete the survey and record your answers, please click the "Submit" button.

Please note that once you click the "Submit" button, you will not be able to modify your answers. To save your partial answers and complete the survey later, close the survey. Answers are automatically saved upon closing the browser window. To return to the survey later, open the original email from Henry Brown and click on the survey link. To pass a partially completed survey to a colleague, close the survey and forward the original email from Henry Brown to a colleague. Note that only one person may work on the survey at a time; the survey response should only be active on one computer at a time. To review your answers before submitting, please select the forward and back arrows at the bottom of each page.

End of Survey

Thank you for completing this survey. Your efforts are greatly appreciated. Your responses are very important, and your feedback is welcome. For your information, a copy of your responses is provided below. You may download your responses in pdf format using the "Download pdf" link shown below. If you have any questions or comments, please contact the principal investigator, Henry Brown:

Henry Brown, P.E.
E2509 Lafferre Hall
University of Missouri
Columbia, MO 65211
(573) 882-0832
brownhen@missouri.edu

Your responses have been recorded, and you may now close your browser.

APPENDIX C. INDIVIDUAL SURVEY RESPONSES FROM STATE DOTS

Table C-1. Individual survey responses for Question 1 (use of dynamic lane merge and static lane merge in work zones)

Respondent	Dynamic Lane Merge	Static Lane merge
Alabama	-	X
Alaska	-	X
Arizona	-	-
Arkansas	-	X
California	-	X
Colorado	X	X
Connecticut	-	X
Delaware	-	X
District of Columbia	-	X
Florida	-	-
Georgia	-	X
Hawaii	-	-
Idaho	-	X
Illinois	X	X
Indiana	-	X
Iowa	-	X
Kansas	-	X
Kentucky	-	-
Louisiana	-	X
Maine	-	X
Maryland	-	X
Massachusetts	X	X
Michigan	X	X

Respondent	Dynamic Lane Merge	Static Lane merge
Minnesota	X	X
Mississippi	-	X
Missouri	X	X
Montana	X	X
Nebraska	-	X
Nevada	-	-
New Hampshire	X	X
New Jersey	-	X
New Mexico	-	X
New York	-	-
North Carolina	X	X
North Dakota	X	X
Ohio	-	X
Oklahoma	X	X
Oregon	X	X
Pennsylvania	X	X
Rhode Island	-	X
South Carolina	-	X
South Dakota	-	X
Tennessee	X	X
Texas	-	X
Utah	-	-
Vermont	X	X
Virginia	X	X
Washington	X	-
West Virginia	-	-
Wisconsin	X	X

Respondent	Dynamic Lane Merge	Static Lane merge
Wyoming	-	X
Total	**18**	**42**

Table C-2. Individual survey responses for Question 2 (use of dynamic early merge and dynamic late merge in work zones)

Respondent	Dynamic Early Merge	Dynamic Late Merge
Colorado	X	X
Illinois	X	X
Massachusetts	X	X
Michigan	X	X
Minnesota	-	X
Missouri	-	X
Montana	-	X
New Hampshire	X	X
North Carolina	X	X
North Dakota	-	X
Oklahoma	-	X
Oregon	-	X
Pennsylvania	-	X
Tennessee	-	X
Vermont	-	X
Virginia	-	X
Washington	-	X
Wisconsin	-	X
Total	**6**	**18**

Table C-3. Individual survey responses for Question 3 (development of policies, guidance, standards, or typical applications regarding the use of lane merge control strategies in work zones)

Respondent	Response Text
Colorado	No
Illinois	Yes
Massachusetts	Yes
Michigan	Yes
Minnesota	Yes
Missouri	Yes
Montana	No
New Hampshire	No
North Carolina	Yes
North Dakota	No
Oklahoma	Yes
Oregon	Yes
Pennsylvania	Yes
Tennessee	Yes
Vermont	No
Virginia	Yes
Washington	Yes
Wisconsin	Yes

Summary of responses: Yes = 13, No = 5

Table C-4. Text descriptions for Question 3 (development of policies, guidance, standards, or typical applications regarding the use of lane merge control strategies in work zones)

Description
For reoccurring lane closures in work zones that are expected to create significant traffic impacts, a dynamic lane merge system should be considered. In this sense, a reoccurring lane closure is a lane closure where the taper location is not changed over several work shifts.
We recently completed a Late (zipper) Merge Standard to detail changeable message boards, sensors, spacing, and messaging.
The information is located in MoDOT's EPG Spec book.

Description
Minnesota has a full suite of guidance and standards documents and typical applications, which can be found on our work zone website. Information is found in our MN MUTCD, Temporary Traffic Control Field Manual, Traffic Engineering Manual, Speed Limits in Work Zones Guide, and Long-Term Typical Applications.
Project Specifications and typical traffic control plans.
Static lane closure and merge requirements can be seen graphically in IDOT Highway Standards 701200 through 701700. Guidance on Work Zones, in general, is found in Bureau of Design and Environment Manual chapters 13 and 55. Specifications on Work Zone Traffic Control and Protection are found in Division 700 Section 701 of IDOT Standard Specifications for Road and Bridge Construction. Files related to Dynamic Lane Merge systems are unpublished and will be forwarded via email.
We have a few layouts but do not have a lot of justification as to when to use them.
The Virginia Work Area Protection Manual provides the standards for static lane drops and is the Virginia-adopted version of part 6 of the MUTCD. A draft special provision has been developed by VDOT for dynamic late merge/zipper merge operation, but to date, it has only been deployed on a limited basis and has not been officially adopted. I will email it.
Our recommended guidance: Consider a DLMS if the project has a single-lane closure on a freeway, expressway, or multilane route with the potential to experience moderate to heavy congestion. We also have special provisions and standard detail drawings that can be used.
ODOT has minimal guidance in the TCP Design Manual. ODOT classifies the Late Merge System as a smart work zone. ODOT has a standard detail and boilerplate specification language for the Smart Work Zone - Late Merge system.
While “Late Merge” is not required or specified (yet), it is encouraged as a viable option/alternative to traditional lane merge directives. Late merge is discussed in Publication 46, “Traffic Engineering Manual,” chapter 6. A standard drawing is also included as an exhibit, although district and regional offices often develop site-specific plans for these methods. Discussions are ongoing as to moving away from traditional lane merge practices and adopting Late Merge as the preferred method. Additional pilots and studies are needed to support that move.
For two-to-one long-term lane closures on interstates, Dynamic Zipper merges are almost always used.

Table C-5. Resources submitted for Question 3 (development of policies, guidance, standards, or typical applications regarding the use of lane merge control strategies in work zones)

State	Title	URL
Illinois	Bureau of Design and Environmental Manual	https://public.powerdms.com/IDOT/documents/1881647
Illinois	Standard Specifications for Road and Bridge Construction	https://public.powerdms.com/IDOT/documents/2677373
Illinois	Revision #227 of Highway Standards	https://public.powerdms.com/IDOT/documents/2677373
Michigan	Maintaining Traffic Typicals (340-345)	https://mdotjboss.state.mi.us/TSSD/getSubCategoryDocuments.htm?prjNumber=1403892&category=Work%20Zones&subCategory=Maintaining%20Traffic%20Typicals%20(pdf)&subCategoryIndex=subcat2Work%20Zones&categoryPrjNumbers=1403891,1525683,1403892,2173385,2173386,1403896
Minnesota	Minnesota MUTCD	https://dot.state.mn.us/trafficeng/publ/mutcd/index.html
Minnesota	Temporary Traffic Control Field Manual	https://dot.state.mn.us/trafficeng/publ/fieldmanual/index.html
Minnesota	Traffic Engineering Manual	https://dot.state.mn.us/trafficeng/publ/tem/index.html
Minnesota	Speed Limits in Work Zones Guide	https://edocs-public.dot.state.mn.us/edocs_public/DMResultSet/download?docId=25956316
Minnesota	Long-Term Typical Applications	https://www.mndot.org/trafficeng/workzone/ttcdestools.html
Missouri	Engineering Policy Guide (616.13 Work Zone Capacity, Queue, and Travel Delay)	https://epg.modot.org/index.php/616.13_Work_Zone_Capacity,_Queue_and_Travel_Delay
Missouri	Dynamic Late Merge System (Zipper Merge) JSP-16-07A	https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fepg.modot.org%2Fforms%2FJSP%2FJSP1607.docx&wdOrigin=BROWSELINK
North Carolina	Dynamic Lane Merge System- I-5912 Beginning of Project Setup	-
North Carolina	Special Provision: Dynamic Zipper Merge System	-

State	Title	URL
Oregon	Standard Detail 4770 (Smart Work Zone System Dynamic Late-Lane Merge)	https://www.oregon.gov/ODOT/Engineering/Details/DET4770.pdf
Oregon	Traffic Control Plans Design Manual	https://www.oregon.gov/odot/Engineering/Docs_TrafficEng/TCP-Design-Manual.pdf
Oregon	Special Provisions (Section 00229: Smart Work Zone Systems)	https://www.oregon.gov/ODOT/Business/BPSP2024/24_SP00229.docx
Tennessee	Standard Drawings (T-WZ-65: Lane Closure with Late Merge)	https://www.tn.gov/content/tn/tdot/roadway-design/standard-drawings-library/standard-roadway-drawings/design---traffic-control/t-wz-65.html
Virginia	Virginia Work Area Protection Manual	https://www.vdot.virginia.gov/doing-business/technical-guidance-and-support/technical-guidance-documents/work-area-protection-manual-and-pocket-guide/
Washington State	General Special Provision (Smart Work Zone System	https://wsdot.wa.gov/publications/fulltext/projectdev/gspspdf/1-10.3(3).OPT3.FR1.PDF
Washington State	General Special Provision (Queue Warning System)	https://wsdot.wa.gov/publications/fulltext/projectdev/gspspdf/1-10.3(3).OPT4.FR1.PDF
Washington State	Work Zone Typical Traffic Control Plans (151 to 176)	https://wsdot.wa.gov/engineering-standards/all-manuals-and-standards/plan-sheet-library/work-zone-typical-traffic-control-plans-tcp
Wisconsin	Facilities Development Manual (Section 11-50-25)	https://wisconsindot.gov/rdwy/fdm/fd-11-50.pdf#fd11-50-25
Wisconsin	Standard Detail Drawings (15d12)	https://wisconsindot.gov/rdwy/sdd/sd-15d12.pdf#page=1
Wisconsin	Special Provisions (643-040)	https://wisconsindot.gov/Documents/doing-bus/eng-consultants/cnslt-rsrces/contracts/stsp/stspart.pdf

Table C-6. Comments for Question 3 (development of policies, guidance, standards, or typical applications regarding the use of lane merge control strategies in work zones)

Comment
We also use a more generic Smart Work Zone system without the late merge messaging for improved long-term queue protection.
Statewide policy, guidance, standards, or typical applications for dynamic lane merge control using smart work zone devices are in development, but many deployments have occurred in the last several years.
We follow FHWA guidance, which is currently available. We have used Dynamic Merge (zipper) only on a few projects. Generally, the Agency uses static merge applications.
MassDOT's dynamic lane merge systems consist of temporary traffic sensors and PCMS that change from early merge to late merge based on live traffic conditions. Late merge is activated during significant congestion, and early merge is activated at all other times.
So, we have general guidance for dynamic merging; since this guidance is still being determined, we will adapt this from project to project. We take the information from each project and see how to implement dynamic merging in the next project. We are also working on increasing our education piece as it cannot be very clear to the traveling public to have work zones with a dynamic merge, and then the following work zone they drive does not have one. So, we are working with our PO to educate the traveling public better.
Typically use MUTCD standards but have tried different approaches depending on the situation. No real formal policies.
We use our standard drawings mostly with the static merge. We have used the zipper merge in select locations based on traffic volumes.
The layouts listed above are pretty new and are also field-adjusted when placed on a project.
We are still in the experimental phase of late, merging both static and dynamic.
Ours is largely directed by designers on larger projects working with contractors to deploy lane merge strategies. Most smaller projects use static merge. Dynamic merge strategies are used on larger projects with SWZ systems specifications.
If you have any questions, please let me know.

Table C-7. Individual survey responses for Question 4 (types of lane drops used with dynamic lane merge)

Respondent	3 to 2	2 to 1	Other
Colorado	X	X	-
Illinois	X	X	-
Massachusetts	X	X	X
Michigan	-	X	-
Minnesota	X	X	-
Missouri	-	X	-
Montana	-	X	-
New Hampshire	X	X	-
North Carolina	-	X	-
North Dakota	-	X	-
Oklahoma	X	X	-
Oregon	-	-	X
Pennsylvania	-	X	-
Tennessee	-	X	-
Vermont	-	X	-
Virginia	-	X	-
Washington	X	X	-
Wisconsin	X	X	-
Total	**8**	**17**	**2**

Table C-8. Other text responses for Question 4 (types of lane drops used with dynamic lane merge)

Other - Text
Any single-lane closure
Use Dynamic Late-Lane Merge for over-capacity work zones on freeways.

Table C-9. Survey comments for Question 4 (types of lane drops used with dynamic lane merge)

Comment
Tried the late merge on three lanes and did not perform well.
We have only used late merge on one project. RITIS and crash data after the project found that we only had one serious accident resulting from the end of the queue and had queues far less than our predictions.
We have one design project where we are proposing to implement a dynamic lane merge for a 3 to 1 scenario. In this case, we will only provide the dynamic lane merge messaging for the first (most upstream) lane closure.

Table C-10. Individual survey responses for Question 5 (frequency of use of dynamic lane merge in work zones by facility type)

Respondent	Rural Freeways	Rural Multi-Lane	Urban Freeways	Urban Multi-Lane	Other
Colorado	3	3	3	3	-
Illinois	3	2	3	2	-
Massachusetts	2	1	3	1	-
Michigan	2	2	3	2	-
Minnesota	3	3	4	4	-
Missouri	2	3	2	2	-
Montana	3	2	4	2	-
New Hampshire	3	2	3	2	-
North Carolina	4	3	2	1	-
North Dakota	2	2	3	2	-
Oklahoma	2	2	3	3	-
Oregon	2	1	3	2	-
Pennsylvania	3	2	3	3	-
Tennessee	3	3	3	3	1
Vermont	2	1	2	1	-
Virginia	2	1	1	1	-
Washington	3	2	3	2	-
Wisconsin	3	1	3	1	-
Average	**2.6**	**2.0**	**2.8**	**2.1**	**1.0**
Standard Deviation	**0.6**	**0.8**	**0.7**	**0.9**	**-**
Number of Responses	**18**	**18**	**18**	**18**	**1**

Average calculated based on these values: Frequently = 4, Sometimes = 3, Rarely = 2, Never = 1.

Table C-11. Comments for Question 5 (frequency of use of dynamic lane merge in work zones by facility type)

Comment
Overall, the Grand Rapids and Lansing areas are the two common locations this is used. I-96 and I-69 are the common routes.
We only use the dynamic late merge on freeways/expressways uninterrupted flow roadways.
Historical field observations have shown that Late Merge usually works better in lower-speed urban work zones than in higher-speed rural work zones. However, rural districts are experimenting with alternate approaches to enhance late merge operations in these work zones.
We only implement dynamic lane merge where significant traffic impacts are expected; therefore, these tend to be in more urban areas.
Normally used on longer-term projects, bridge replacement/repair, normally on rural highways.
Dynamic late merge use is currently relatively rare in Virginia, with only two active projects currently using it. It is still largely considered experimental.

Table C-12. Individual survey responses for Question 6 (factors considered when trying to determine whether to implement dynamic lane merge in a given work zone)

Respondent	AADT	Area Type (Urban or Rural)	Crash History	Duration of Work Zone	Length of Work Zone	Peak Hour Volumes	Percent Trucks	Stakeholder Input	Terrain	Type of Work Activity	Work Zone Speed Limit	Worker Presence	Other
Colorado	3	3	3	3	3	3	3	3	3	3	3	3	-
Illinois	4	4	4	4	4	4	4	3	4	4	2	4	4
Massachusetts	4	1	3	4	1	4	2	2	1	1	1	1	-
Michigan	4	3	4	3	3	4	3	3	3	4	2	2	-
Minnesota	4	3	3	4	4	4	3	3	3	3	3	3	-
Missouri	4	3	3	4	4	4	4	3	4	4	3	4	-
Montana	3	-	3	4	4	4	-	-	-	4	4	4	-
New Hampshire	4	3	2	3	3	3	1	2	2	3	3	3	-
North Carolina	4	4	3	4	4	4	4	4	3	3	4	4	-
North Dakota	3	3	3	3	1	1	1	1	1	3	3	3	-
Oklahoma	4	4	1	2	2	4	1	1	1	4	3	4	-
Oregon	4	4	4	4	4	4	4	4	4	-	-	-	-
Pennsylvania	3	4	3	3	1	4	4	1	3	1	1	1	-
Tennessee	3	3	3	3	3	3	3	1	2	1	1	1	-
Vermont	3	1	1	3	3	3	3	1	1	1	3	3	-
Virginia	4	4	4	4	4	4	4	4	4	4	4	4	4
Washington	2	2	1	3	1	3	2	1	2	1	4	3	-
Wisconsin	4	4	4	4	4	4	1	2	1	1	1	1	-
Average	**3.6**	**3.2**	**3.0**	**3.5**	**3.1**	**3.6**	**2.8**	**2.5**	**2.6**	**2.8**	**2.7**	**2.9**	**4.0**
Standard Deviation	**0.6**	**0.9**	**0.8**	**0.5**	**1.0**	**0.6**	**1.0**	**0.9**	**1.0**	**1.2**	**1.0**	**1.1**	**0.0**
Number of Responses	**18**	**17**	**18**	**18**	**18**	**18**	**17**	**17**	**17**	**18**	**17**	**17**	**2**

Table C-13. Other text responses for Question 6 (factors considered when trying to determine whether to implement dynamic lane merge in a given work zone)

Other - Text
Interchange Density
Likelihood of queuing

Table C-14. Comments for Question 6 (factors considered when trying to determine whether to implement dynamic lane merge in a given work zone)

Comment
Note that the table above should be viewed with a grain of salt since we have only deployed two dynamic late mergers. The factors above were considered in the selection of the locations where we deployed the system.

Table C-15. Individual survey responses for Question 7 (criteria for activation or deactivation thresholds for dynamic lane merge in work zones)

Respondent	Based on specific time periods (e.g., peak hour)	Speed	Volume	Combination of multiple traffic measures	Other
Colorado	X	X	X	X	-
Illinois	-	X	-	-	-
Massachusetts	-	X	-	-	-
Michigan	X	-	-	-	-
Minnesota	-	-	-	X	-
Missouri	-	X	X	-	-
Montana	-	X	-	X	-
New Hampshire	-	-	-	X	-
North Carolina	-	X	X	-	-
North Dakota	-	X	X	-	-
Oklahoma	-	X	X	-	-
Oregon	-	X	X	X	-
Pennsylvania	-	-	-	-	X
Tennessee	-	-	-	X	-
Vermont	X	-	-	-	-
Virginia	-	X	-	-	-
Washington	-	X	-	-	-
Wisconsin	-	X	-	-	-
Total	**3**	**12**	**6**	**6**	**1**

Table C-16. Other text responses for Question 7 (criteria for activation or deactivation thresholds for dynamic lane merge in work zones)

Other–Text
Static Late Merge is all that PA has explored to date.

Table C-17. Survey comments for Question 7 (criteria for activation or deactivation thresholds for dynamic lane merge in work zones)

Comment
Dynamic merge was based on daily projected queues along I-75 north of Knoxville. We predicted daily queues of over 10miles. The thinking was that dynamic merge could normalize traffic speeds in advance of queues and reduce queue length.
We use speed as an indication of congestion. When speeds are low, we assume that congestion is present.

Table C-18. Individual survey responses for Question 8 (types of vehicle presence detectors used with dynamic lane merge in work zones)

Respondent	Microwave	Pneumatic tubes	Radar	Video	Other	None of the above
Colorado	X	-	X	X	-	-
Illinois	X	-	X	-	-	-
Massachusetts	-	-	X	-	-	-
Michigan	-	-	X	-	-	-
Minnesota	X	-	X	-	-	-
Missouri	X	-	X	X	-	-
Montana	-	-	X	X	-	-
New Hampshire	X	-	X	-	-	-
North Carolina	X	-	X	-	-	-
North Dakota	-	X	-	-	-	-
Oklahoma	-	-	X	-	X	-
Oregon	-	-	X	-	-	-
Pennsylvania	-	-	-	-	X	X
Tennessee	X	-	-	-	-	-
Virginia	X	-	X	-	-	-
Washington	-	-	X	-	-	-
Wisconsin	-	-	X	-	-	-
Total	**8**	**1**	**14**	**3**	**2**	**1**

Table C-19. Other text responses for Question 8 (types of vehicle presence detectors used with dynamic lane merge in work zones)

Other - Text
Bluetooth
Programmed PCMS

Table C-20. Survey comments for Question 8 types of vehicle presence detectors used with dynamic lane merge in work zones)

Comment
We are open to different types of technologies as long as they achieve the goal, but so far, we have only seen radar be used.
The type is not currently specified, but the most commonly seen are radar and microwave.

Table C-21. Individual survey responses for Question 9 (use of other smart work zone technologies with dynamic lane merge in work zones)

Respondent	End of queue warning	Traveler information	Other	None of the above
Colorado	X	X	-	-
Illinois	X	X	-	-
Massachusetts	X	X	-	-
Michigan	X	X	-	-
Minnesota	X	X	-	-
Missouri	X	X	-	-
Montana	X	-	-	-
New Hampshire	-	X	-	-
North Carolina	X	X	-	-
North Dakota	-	-	-	X
Oklahoma	X	-	-	-
Oregon	X	X	-	-
Pennsylvania	X	X	-	-
Tennessee	X	-	-	-
Vermont	-	-	-	X
Virginia	-	X	-	-
Washington	X	X	X	-
Wisconsin	X	X	-	-
Total	**14**	**13**	**1**	**2**

Table C-22. Comments for Question 9 (use of other smart work zone technologies with dynamic lane merge in work zones)

Comment
New Hampshire has a Traffic Management Center.
Work zone delay times.
I do not know the extent of using a combination of technologies, but they have been used together.

Table C-23. Individual survey responses for Question 10 (basis of payment for dynamic lane merge in work zones)

Respondent	Response Text
Colorado	Other
Illinois	Measured pay item
Massachusetts	Lump sum pay item
Michigan	Measured pay item
Minnesota	Lump sum pay item
Missouri	Lump sum pay item
Montana	Lump sum pay item
New Hampshire	Lump sum pay item
North Carolina	Other
North Dakota	Other
Oklahoma	Measured pay item
Oregon	Measured pay item
Pennsylvania	Lump sum pay item
Tennessee	Measured pay item
Vermont	Lump sum pay item
Virginia	Other
Washington	Measured pay item
Wisconsin	Measured pay item

Summary of responses: Measured pay item = 7, Lump sum pay item = 7, No direct payment = 0, Other = 4.

Table C-24. Other text responses for Question 10 (basis of payment for dynamic lane merge in work zones)

Other - Text
Not sure
Not sure
Paid weekly or monthly with all other SWZ systems
Lump sum for the deployment of the system, per day once installed, and per move, if the system has to be relocated (such as to the other direction of travel for a new construction season)

Table C-25. Survey comments for Question 10 (basis of payment for dynamic lane merge in work zones)

Comment
Not sure
We are developing new specifications that will move away from lump sum and are proposing the system to be paid for by each item (i.e., item for each radar, PCMS). The central system required to run the system, logic, and programming will have its own item.
Most commonly, components of the system have been measured and paid for by the calendar week of deployment. However, that is currently under review.
Our PQWS (portable queue warning system) is paid per DAY, which is a calendar day.

Table C-26. Individual survey responses for Question 11 (performance measures for dynamic lane merge in work zones)

Respondent	Number of crashes	Crash severity	Observed conflicts/safety	Driver compliance	Occupancy	Queue length	Speed	Delay	Other	My agency does not use performance measures to assess the performance of dynamic lane merge in work zones.
Colorado	X	X	-	X	X	X	X	X	-	-
Illinois	-	-	-	-	-	-	-	-	-	X
Massachusetts	X	X	-	-	-	X	X	X	-	-
Michigan	-	-	-	-	-	-	-	-	-	X
Minnesota	-	-	-	-	-	X	X	X	-	-
Missouri	-	-	-	-	-	X	X	X	-	-
Montana	-	-	-	-	-	X	X	-	-	-
New Hampshire	-	-	-	-	-	-	-	-	-	X
North Carolina	-	-	-	X	X	X	X	X	-	-
North Dakota	X	X	X	-	-	X	X	X	-	-
Oklahoma	-	-	X	X	-	X	-	X	-	-
Oregon	-	-	X	-	-	-	-	-	-	X
Pennsylvania	X	-	X	X	-	X	X	X	-	-
Tennessee	X	-	-	-	-	X	X	-	-	-
Vermont	X	-	-	X	-	-	-	X	-	-
Washington	X	-	-	-	-	X	X	X	-	-
Wisconsin	-	-	X	-	-	X	-	X	-	-
Total	**7**	**3**	**5**	**5**	**2**	**12**	**10**	**11**	**0**	**5**

Table C-27. Comments for Question 11 (performance measures for dynamic lane merge in work zones)

Comment
Nothing officially
We used AASHTOware and RITIS.

Table C-28. Individual survey responses for Question 12 (effectiveness of dynamic lane merge systems)

Respondent	Response Text
Colorado	3
Illinois	4
Massachusetts	4
Michigan	3
Minnesota	3
Missouri	4
Montana	3
New Hampshire	4
North Carolina	5
North Dakota	3
Oklahoma	3
Oregon	3
Pennsylvania	3
Tennessee	4
Vermont	4
Virginia	3
Washington	5
Wisconsin	4

Average = 3.61, Standard Deviation = 0.70

Table C-29. Comments for Question 12 (effectiveness of dynamic lane merge systems)

Comment
It depends on the location, but this has been used and worked and also failed, so it is hit or miss.
Initial results after one week were very positive.
This is just a guess. We have not done any studies or formal observations to determine this.
To date, systems have been deployed on two rural interstate work zones. Levels of congestion and queuing were not high, which limited activation of the system in the late merge mode, so the rating above reflects a lack of activation as opposed to a lack of performance. It highlighted the need to identify appropriate locations for deployment.
We are still evaluating the best approach on PA; however, we are ever interested in normalizing this approach to freeway work zones.
No studies have been completed at the deployment locations, only anecdotal observations.

Table C-30. Individual survey responses for Question 13 (factors that affect the performance of dynamic lane merge in work zones)

Respondent	Activation Threshold	Location of Merge Point	Percent Trucks	Presence of Positive Protection	Traffic Volumes/Congestion	Type of Work Activity	Use of Additional Countermeasures	Work Zone Duration	Work Zone Length	Work Zone Speed Limit	Worker Proximity	Other
Colorado	4	4	3	4	4	3	4	4	4	4	4	-
Illinois	5	5	5	4	5	4	5	4	4	5	4	5
Massachusetts	5	4	4	2	5	3	4	5	2	2	2	-
Michigan	4	5	5	1	5	4	5	4	2	2	2	5
Minnesota	4	4	4	4	4	4	4	4	4	4	4	-
Missouri	5	5	5	3	5	3	5	3	4	3	4	-
Montana	5	4	4	3	5	5	4	3	4	4	5	-
New Hampshire	3	3	3	3	3	3	3	3	3	3	3	-
North Carolina	5	5	5	3	5	3	3	4	3	3	3	-
North Dakota	3	3	3	3	3	3	3	3	3	3	3	-
Oklahoma	5	3	2	3	4	3	5	5	4	5	5	-
Oregon	5	5	4	3	5	3	4	5	4	4	4	-
Pennsylvania	4	4	4	3	4	3	4	3	2	3	2	-
Tennessee	4	3	4	3	4	3	4	2	2	2	2	-
Vermont	3	4	3	4	5	3	4	4	5	5	4	-
Virginia	5	5	5	4	5	4	3	5	5	4	4	-
Washington	5	4	4	2	4	3	3	4	3	4	3	-
Wisconsin	5	5	4	3	5	3	3	5	3	3	3	-
Average	**4.4**	**4.2**	**3.9**	**3.1**	**4.4**	**3.3**	**3.9**	**3.9**	**3.4**	**3.5**	**3.4**	**5.0**
Standard Deviation	**0.8**	**0.8**	**0.9**	**0.8**	**0.7**	**0.6**	**0.8**	**0.9**	**1.0**	**1.0**	**1.0**	**0.0**
Number of Responses	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**2**

(5=Strongly Agree, 4=Somewhat Agree, 3=Neither Agree nor Disagree, 2=Somewhat Disagree, 1=Strongly Disagree)

Table C-31. Other text responses for Question 13 (factors that affect the performance of dynamic lane merge in work zones)

Other - Text
Media Coverage / public awareness
Education

Table C-32. Text responses for features or conditions for Question 13 (factors that affect the performance of dynamic lane merge in work zones)

Feature or Condition
The merge taper should be located away from on-ramps. Effectiveness can be impacted by the grade and % of trucks on the route. High truck volumes combined with steep grades can result in "rolling roadblocks," which may mitigate the effectiveness of the late merge.
Increased education is key to effectiveness.
Having reports in the new focusing on this. There is no ramp traffic merge upstream of the zipper or just before.
We have not officially measured any of the performance, so it is difficult to answer.
We find them more effective when there is little to no advance warning of which lane is closed during zipper condition and no pre-construction media attention about upcoming zipper merge.

Table C-33. Comments for Question 13 (factors that affect the performance of dynamic lane merge in work zones)

Comment
The biggest factors that we have noticed are the starting location and other access points. If there is an on or off-ramp, that can cause issues. One location had a navigation app telling the driver to go up the off-ramp and back on, as that was less time than staying on the freeway.

Table C-34. Individual survey responses for Question 14 (completion of evaluation studies for dynamic lane merge in a work zone)

Respondent	Response Text
Colorado	No
Illinois	No
Massachusetts	No
Michigan	No
Minnesota	No
Missouri	Yes
Montana	No
New Hampshire	No
North Carolina	No
North Dakota	No
Oklahoma	No
Oregon	No
Pennsylvania	No
Tennessee	No
Vermont	No
Virginia	No
Washington	No
Wisconsin	No

Summary of responses: Yes = 1, No = 17

Table C-35. Comments for Question 14 (completion of evaluation studies for dynamic lane merge in a work zone)

Comment
Studies are underway but not complete yet.
Always look forward to learning more about how to effectively deploy late and dynamic merge practices in PA. Thanks for considering us.
We will be looking closer at the effectiveness of dynamic merge. We have run data on the effectiveness of smart work zone tech versus the use of trucks for queue protection and found the smart tech to be much more effective and cheaper than the use of PTQ trucks. Can share this upon request.
We have a formal zipper merge study currently in progress. Not yet completed.
We have not done any formal evaluations but are extremely interested in doing so
MoDOT has done studies with the Smart Work Zone Deployment Initiative pooled fund. - https://swzdi.intrans.iastate.edu/ University of Missouri-Columbia has done many projects for MoDOT.

Table C-36. Individual survey responses for Question 15 (types of outreach materials developed for dynamic lane merge in work zones)

Respondent	Flyer and/or pamphlet	Website	Social media site	Video	My Agency uses materials from other .	My agency has not developed public outreach materials for dynamic lane merge systems.	My agency is in the process of developing public outreach materials for dynamic lane merge systems.	Collaborating with mass media (e.g., television, radio)	Other
Illinois	X	-	X	X	-	-	X	-	-
Massachusetts	-	-	-	-	-	X	-	-	-
Michigan	-	-	-	-	-	-	-	X	-
Minnesota	X	X	X	-	-	-	-	X	-
Missouri	X	X	X	X	-	-	-	-	X
Montana	X	X	X	X	-	-	-	X	-
New Hampshire	-	-	-	-	-	X	-	-	-
North Carolina	-	X	-	X	-	-	-	-	-
North Dakota	X	X	X	-	-	-	-	-	-
Oklahoma	-	-	-	-	-	-	X	-	-
Oregon	-	-	-	-	-	X	-	-	-
Pennsylvania	-	-	X	X	-	-	-	-	-
Tennessee	-	-	-	X	-	-	-	X	-
Vermont	-	X	X	-	-	-	-	X	-
Virginia	-	X	X	-	-	-	-	X	-
Washington	-	-	-	-	-	X	-	-	-
Wisconsin	X	-	-	X	-	-	-	-	-
Total	**6**	**7**	**8**	**7**	**0**	**4**	**2**	**6**	**1**

Table C-37. Resources submitted for Question 15 (types of outreach materials developed for dynamic lane merge in work zones)

State	Title	URL
Minnesota	Zipper Merge	https://www.dot.state.mn.us/zippermerge/
Missouri	Zipper Merge	https://www.modot.org/zipper-merge
Montana	Zip It, Billings: MDOT Says to Merge Like a Zipper at I90 Bridge	https://kmhk.com/zip-it-billings-mdot-says-to-merge-like-a-zipper-at-i90-bridge/
North Carolina	Dynamic Zipper Merger	https://www.ncdot.gov/initiatives-policies/Transportation/safety-mobility/Dynamic-Zipper-Merge/Pages/default.aspx
Tennessee	Zipper Merge Video	https://drive.google.com/file/d/1_zvM79AgRQHjKDoAXDMHKlaYqvNISaY4/view?usp=sharing
Virginia	Zipper and Work Zones – How Does That Work?	https://www.vdot.virginia.gov/news-events/news/staunton-district/zippers-and-work-zones--how-does-that-work.html
Wisconsin	Zipper Merge	https://wisconsindot.gov/Pages/safety/safety-eng/zippermerge.aspx

Table C-38. Survey comments for Question 15 (types of outreach materials used for dynamic lane merge systems in work zones)

Comment
An informational video was developed by the regional District office press and played on CCTV in rest areas and welcome centers to inform motorists on how to proceed into the work zone.
There have just been news articles and coverage at the beginning of each construction season.
They work better in the field if there is NOT a project-specific media outreach.
This is something that we thought would be good to do but have not done so yet.

Table C-39. Individual survey responses for Question 16 (challenges in implementing dynamic lane merge systems in work zones)

Respondent	Agency understaffing	Availability of dynamic lane merge	Coordination with subcontractors	Cost	Driver inattention	Lack of agency buy-in	Lack of available guidance	Lack of contractor buy-in	Lack of information on benefits	Lack of perceived need	Need for enforcement	Other	None of the above
Colorado	-	X	X	X	-	X	X	-	X	X	X	-	-
Illinois	X	-	-	-	X	-	X	-	-	X	X	-	-
Massachusetts	-	-	-	-	-	-	-	-	-	-	-	X	-
Michigan	-	-	X	-	X	X	-	X	-	X	X	-	-
Minnesota	-	-	-	-	X	-	-	-	-	-	X	-	-
Missouri	X	-	-	X	X	-	-	-	-	-	-	-	-
Montana	X	-	X	-	X	X	X	X	X	X	-	-	-
New Hampshire	-	-	-	-	-	-	-	-	-	-	-	-	-
North Carolina	-	-	-	X	-	-	-	X	-	-	-	-	-
North Dakota	-	-	-	-	-	-	-	-	-	-	-	-	-
Oklahoma	-	X	-	-	X	-	-	-	X	X	X	-	-
Oregon	-	X	X	-	-	-	-	-	X	X	-	-	-
Pennsylvania	-	-	-	-	X	X	X	-	-	-	-	-	-
Tennessee	-	-	X	-	-	-	-	-	-	X	-	-	-
Vermont	-	-	-	-	-	-	-	-	-	X	X	-	-
Virginia	-	X	-	X	-	-	-	-	-	-	-	-	-
Washington	X	-	-	-	X	-	-	-	-	-	-	-	-
Wisconsin	X	-	-	-	-	-	-	-	-	-	-	-	-
Total	**5**	**4**	**5**	**4**	**8**	**4**	**4**	**3**	**4**	**8**	**6**	**1**	**0**

Table C-40. Other text responses for Question 16 (challenges in implementing dynamic lane merge systems in work zones)

Other - Text
Lack of design consultant understanding

Table C-41. Comments for Question 16 (challenges in implementing dynamic lane merge systems in work zones)

Comment
Typically, we include them in our larger interstate project, but not really based on any real data other than we think they provide some additional level of safety for the traveling public.
Without consistent guidance from state to state, out-of-state drivers' education is a main hurdle. Heavy vehicles regulating traffic get in the way of good operation of dynamic merge.

Table C-42. Individual survey responses for Question 17 (reasons for non-use of dynamic lane merge)

Respondent	Agency understaffing	Cost	Lack of available guidance	Lack of information on benefits	Lack of perceived need	Other work zone countermeasures are a higher priority	Other
Alabama	-	-	-	X	X	-	-
Alaska	X	X	-	-	X	-	-
Arkansas	-	-	-	X	X	-	-
California	-	-	X	X	-	-	-
Connecticut	-	-	-	X	X	-	-
Delaware	-	-	X	-	-	-	X
District of Columbia	-	-	X	X	X	-	-
Georgia	-	-	X	-	-	-	-
Idaho	-	-	-	-	-	X	-
Indiana	-	-	-	-	X	-	-
Iowa	-	-	-	-	-	X	X
Kansas	X	-	-	-	-	X	-
Kentucky	-	-	-	-	-	-	-
Louisiana	-	-	X	X	-	-	-
Maine	-	-	-	-	-	X	-
Maryland	-	-	X	-	X	X	-
Mississippi	-	X	-	-	-	X	X
Nebraska	-	-	-	-	X	-	-
Nevada	X	-	-	X	X	X	-
New Hampshire	-	-	-	-	-	-	-
New Jersey	X	-	-	-	X	-	X

Respondent	Agency understaffing	Cost	Lack of available guidance	Lack of information on benefits	Lack of perceived need	Other work zone countermeasures are a higher priority	Other
New Mexico	X	X	X	X	-	-	-
Ohio	X	-	-	X	X	-	-
Rhode Island	X	-	X	X	-	-	-
South Carolina	-	-	-	X	X	-	-
South Dakota	-	-	X	-	-	-	X
Texas	-	-	-	X	X	-	-
Utah	X	-	-	X	X	X	X
Wyoming	-	X	-	-	-	X	-
Total	**8**	**4**	**9**	**13**	**14**	**9**	**6**

Table C-43. Other work zone countermeasures for Question 17 (reasons for non-use of dynamic lane merge)

Other Work Zone Countermeasures
Automated Speed Enforcement, Work Zone Speed Limit Reduction
Mitigate high speed
Generally, the KDOT will utilize Advanced Queue Warning Systems in Work Zones.
Most of UDOT's projects use UDOT Standards and Specifications with Region Special Provisions to revise the Standards as needed.
We have deployed smart work zones in an effort to give warnings to motorists about slowed or stopped traffic.
Iowa strives to avoid lane closures that lead to queuing.
Proper tapers and maintenance of TCDs.
Variable Speed
Most of our work is in a true stationary lane closure that is taken down at the end of the shift. We just rolled out a pilot project for a smart work zone for end-of-queue notification.

Table C-44. Other text responses for Question 17 (reasons for non-use of dynamic lane merge)

Other - Text
Driver understanding. Dynamic lane merges can be effective when several criteria are met: 1) The closure is in place long-term. 2) Congestion from merging is constant, not just during peak hours. 3)Traffic is mostly repeat drivers
Driver education on how to use correctly so that early stacking does not occur in the active lane.
Lack of demonstrated benefits. States that I've talked to about this have indicated that public education and public acceptance/compliance are significant factors to a successful deployment of late merge signing.
We are starting to message for dynamic late merge during periods of congestion on the interstate around our two largest cities. It requires a lot of public education. Also, we are just using portable changeable message boards for this, not any active detection or automated messages.
I'm aware of some pilot projects, but these Smart Systems are not common practice.
If it works, there is no need to change.

Table C-45. Comments for Question 17 (reasons for non-use of dynamic lane merge)

Comment
Not much is needed when 97.5% of the roads are not close to capacity.
We are looking at the use of Late Merge Signing for Work Zones.
We use both a static lane merge system and a zipper merge system, but not a dynamic version of the zipper merge.
I've never heard of a Dynamic Lane Merge before, so I would say the reason we haven't considered using it is perhaps because we haven't been made aware of it in the first place.
Dynamic lane merges are allowed but rarely used.
I want to implement a dynamic lane merge. Not getting much participation.

Table C-46. Individual survey responses for Question 18 (development of policies, guidance, standards, or typical applications for static lane merge)

Respondent	Response Text
Alabama	Yes
Alaska	No
Arkansas	Yes
California	Yes
Connecticut	Yes
Delaware	No
District of Columbia	No
Georgia	Yes
Idaho	No
Indiana	Yes
Iowa	Yes
Kansas	Yes
Louisiana	Yes
Maine	No
Maryland	No
Mississippi	No
Nebraska	Yes
Nevada	Yes
New Jersey	Yes

Respondent	Response Text
New Mexico	Yes
Ohio	No
Rhode Island	No
South Carolina	Yes
South Dakota	Yes
Texas	Yes
Utah	Yes
Wyoming	No

Summary of responses: Yes = 17, No = 10

Table C-47. Resource descriptions for Question 18 (development of policies, guidance, standards, or typical applications for static lane merge)

Resource Description
Zipper merges are allowed during traffic maintenance when there is a lane reduction, and queueing is anticipated to last for at least two hours a day on five days during a typical week.
Lane merge direction is provided in Nevada DOT standard plans.
Pretty much follows the MUTCD with additional signage to reduce speed and the addition of PCMS.
We do not have a written policy on the use of a zipper merge but will use it in higher volume areas or where we are experiencing queues.
The current Lane closure TCP includes lane closed ahead signs, merge signs, and an arrow board in the taper. TCP schemes are in line with MUTCD guidance and standards and may have additional required signage and speed reduction for certain facilities in lieu of MUTCD minimum.
TxDOT’s direction is to follow the TxDOT Traffic Standards that are shown at the link below.
NMDOT policy consists of standard drawings for early merge lane closures and four standard details for a late merge (zipper)
Maintain traffic capacity by adjusting work hours or providing temporary pavement.
UDOT uses (4) Policies/Procedures for Traffic Engineer Orders, Crashworthiness, Work Zone Speed Limits, and Work Zone Safety. UDOT uses (1) Standard Specifications for Traffic Control and (48) Standard Drawings for various Work Zone Traffic Control setups that are based on the 2011 Ed. of the Utah MUTCD.
See NJDOT Standard Construction Details 2016
We have "standard plates" for maintenance and construction, which are basically the MUTCD TAs but tailored to our crews. They give a table for taper lengths, etc., and they give any additional notes.

Resource Description
We have standard details for various lane closure scenarios that mostly resemble guidance from the MUTCD. Page 11 of the PDF shows our standard lane closure detail for a 4-lane divided roadway during nighttime closures on construction projects. Page 27 of the PDF shows a few other various applications.
At Caltrans, our traffic engineers develop standard plans for our use.
Standard Traffic Control Plans, Special Provisions and Specifications, E&C -40, Work Zone Safety and Accessibility, E&C-46 - Systematic Consideration of Work Zone Impacts
Standards for lane closures - 9100, 9102, 9106, 9107 see link below.
Traffic volume threshold - 1500 vehicles/hour/lane. Only used when two-lane traffic is merged with one lane on divided highways. The minimum setup duration is four weeks in the same location. Less than 5% of commercial vehicles. Other considerations regarding the utilization of late lane merge (static and dynamic): How will queue location interact with adjacent interchanges? Are there any concerns about visibility? How long of a queue is anticipated? Speed Limits prior to Work Zone and in Work Zone. Previous experience with Late Lane Merge on a section of roadway.
The Department has standard drawings for static lane closures for interstate, primary, and secondary routes. Also restricts the use of closures during times when volumes are higher than 1200 vehicles per hour per lane for interstates and 800 vehicles per hour per lane for secondary and primary routes.

Table C-48. Resources submitted for Question 18 (development of policies, guidance, standards, or typical applications for static lane merge)

State	Title	URL
Alabama	Traffic Control Detail Library	https://www.dot.state.al.us/publications/Design/TrafficControlDetailLibrary.html
Arkansas	Arkansas Welcome Center (Construction Plans)	https://www.ardot.gov/wp-content/uploads/030585_plans.pdf
California	Standard Plans	https://maintenance.onramp.dot.ca.gov/maintsafetyequiptrain/2022-standard-plans
Connecticut	Policy No. E&C-40 (Work Zone Safety and Accessibility)	-
Connecticut	Policy No. E&C – 46 (Systematic Consideration and Management of Work Zone Impacts)	-
Connecticut	Various Specifications and Typical Applications	-

State	Title	URL
Georgia	Construction Standards and details	http://mydocs.dot.ga.gov/info/gdotpubs/ConstructionStandardsAndDetails/00-2024%20CSD%20BOOK_00-2024.pdf
Iowa	Design Manual Chapter 9: Traffic Control	https://iowadot.gov/design/design-manual#555672686-chapter-9--traffic-control
Indiana	Operations Memorandum 20-02: Signs	-
Nebraska	Standard Plan No. 926: Typical Lane Closure Plan for Multilane Roadways	https://dot.nebraska.gov/media/5c5nrkdj/standard.pdf
Nebraska	Typical Traffic Control Plan: Zipper Merge System (Long Term) for Multilane Roadways	-
Nevada	Standard Plans	https://www.dot.nv.gov/home/showpublisheddocument/21537/638150725828230000
New Jersey	Standard Construction Details	https://nj.gov/transportation/eng/CADD/v8/stdconsdtls.shtml
New Mexico	Zipper Signing Layout Drawings	-
South Carolina	Engineering Directive ED-32: Hourly Restrictions for Lane Closures on Interstate and Primary Routes	http://info2.scdot.org/ED/ED/ED-32.pdf
South Carolina	Standard Drawings (610)	https://www.scdot.org/business/standard-drawings.aspx
South Carolina	Standard Specifications (610)	https://www.scdot.org/business/standard-specifications.aspx
South Dakota	Traffic Control for Maintenance Projects	-
South Dakota	Standard Plates Index	https://dot.sd.gov/doing-business/engineering/design-services/standard-plates
Texas	Traffic Control Plan Standards	https://www.dot.state.tx.us/insdtdot/orgchart/cmd/cserve/standard/toc.htm#TRAFFICCONTROLPLANSTANDARDS
Utah	Standard Drawings (TC 4B1 – TC 4B4)	https://www.udot.utah.gov/connect/business/standards/
Utah	Section 01554: Traffic Control	-

Table C-49. Comments for Question 18 (development of policies, guidance, standards, or typical applications for static lane merge)

Comment
Currently, our agency follows the MUTCD for standard lane closure operations. We also utilize our Work Zone Management Manual as a guide for implementing TMPs, MOT, and TCP for all arterial roadways within the District of Columbia.
There are a number of design elements to be considered when deploying a Late Merge system, and there doesn't appear to be consistency among the states regarding these design elements. I found that there are still a fair number of states that do not use late merge signing. I have concerns over the use of static late merge signing systems in work zones.
These drawings are the only policies NMDOT has on lane merges.
We follow what's in the MUTCD for static lane merge.
We have a typical application showing the static lane merge when closing a lane. We also just developed a standard that uses temporary portable rumble strips in advance of the merge point.
Currently, the typical applications for work zone signage are followed.

Table C-50. Comments for Question 19 (general comments)

Comment
Guidance would be beneficial on what road types this would best support, such as Urban or Rural.
Would like to attain more information on dynamic merges.
The majority of roadways in the District of Columbia are urban roadways, with 10% freeways. We have established the use of our permanent overhead message signs on various freeway projects to notify motorists of closures, detours, and alternate routes. In addition, our internal Department Communication Team provides assistance with notifications and informs the public of upcoming projects to mitigate delays along all roadways. These coordination efforts have proven to be effective measures in minimizing accidents and delays -thus enhancing safety through and around project locations.
There is a lane closure website on the Traffic Conditions web page that allows contractors to post the upcoming lane closures by location, start and end points, date, and time. https://www.udottraffic.utah.gov/#:Alerts https://www.udot.utah.gov/connect/current-conditions/traffic-conditions/
We would like to implement more dynamic merge systems and would appreciate any guidance you can share.
Iowa has a dynamic lane closure system included in our state-wide IWZ contract, but we have not used it because conditions have not met our criteria for successful deployment (i.e., long-term, recurring, commuter traffic.) We are open to using it if the conditions are right.
I think the dynamic use of all traffic control is critical to getting people to pay attention in this

Comment
information overload era. The traffic control must match the work. Consistency and education are the hardest things to accomplish, and that is where I think these newer (or less often utilized) types of TCP lose traction and don’t get systematic implementation/buy-in. Must try to solve that and explain places they best fit and then use them where they make sense.
We have tried out dynamic lane merge (zipper merge) in a few locations, but so far, there is no policy yet for system-wide application. It’s still on a per-project basis.
INDOT has had very limited experience with late-lane merges and has tried them on just a few projects.
SCDOT is currently developing standard drawings for late merge conditions.
I believe that if ARDOT were shown that the benefits of implementing dynamic lane merge applications exceeded the cost, we would more than likely consider using it.
It’s difficult to answer many of the questions due to the lack of staff that could possibly evaluate the benefits of dynamic traffic control. The Department believes in including all measures that will provide a benefit. With that being said, we have also had much success with more traditional static measures. The more dynamic systems do a better job at adjusting to real-time conditions, but in cases where we anticipate heavy traffic volumes, we tend to move this work to nights to minimize traffic impacts...which creates its own problems.
We are exploring future efforts to develop guidance for the use of dynamic early and late merge.
I would like to eliminate the competitiveness at the merge of any work zone. Accidents and delays could be greatly reduced if, somehow, we can get merged without fighting for a spot.

APPENDIX D. ROAD USER SURVEY QUESTIONNAIRE

Greetings!

You are invited to participate in a research survey pertaining to merging strategies for lane closures at road construction zones. This survey is being conducted by Michigan State University as part of research sponsored by the Smart Work Zone Deployment Initiative.

You will be asked a series of multiple-choice questions during the survey, which should take less than 5 minutes to complete. Your participation in this survey is voluntary. You may refuse to participate or may exit the survey at any time without penalty. Your voluntary agreement to participate is indicated by completion of the survey.

If you have questions about the survey or the research study in general, you may contact the lead investigator, Peter Savolainen, Ph.D., P.E., via phone at 517-355-5107 or via email at pete@msu.edu

Thank you!

SWZDI Road User Survey

Section A- General Information:

Q1. What is your age?

- Under 18
- 18-24
- 25-34
- 35-44
- 45-54
- 55-64
- 65-74
- 75-84
- 85 or older

(Skip to end the survey if "Under 18" is selected)

Q2. What is your gender?

- Male
- Female
- Other. Please specify__________
- Prefer not to say

Q3. Do you have a valid driver's license?

- ○ Yes
- ○ No

(Skip to end the survey if "No" is selected)

Q4. Do you have a valid commercial vehicle driver's license?

- ○ Yes
- ○ No

Q5. Approximately how many miles did you travel in 2023?

- ○ Do not drive
- ○ 4,000 or less
- ○ 4,001 to 8,000
- ○ 8,001 to 12,000
- ○ 12,001 to 16,000
- ○ 16,001 to 20,000
- ○ More than 20,000

(Skip to end the survey if "Do not drive" is selected)

Q6. What is your race?

- ○ Hispanic
- ○ Non-Hispanic – White
- ○ Non-Hispanic – Black or African American
- ○ Asian
- ○ Other. Please specify__________
- ○ Prefer not to say

Q7. What is your yearly income?

- ○ Less than 10,000
- ○ 10,000 – 24,999
- ○ 25,000 – 49,999
- ○ 50,000 – 75,999
- ○ 75,000 – 99,999
- ○ 100,000- 149,999
- ○ More than 150,000
- ○ Prefer not to say

Q8. What is your highest education level?

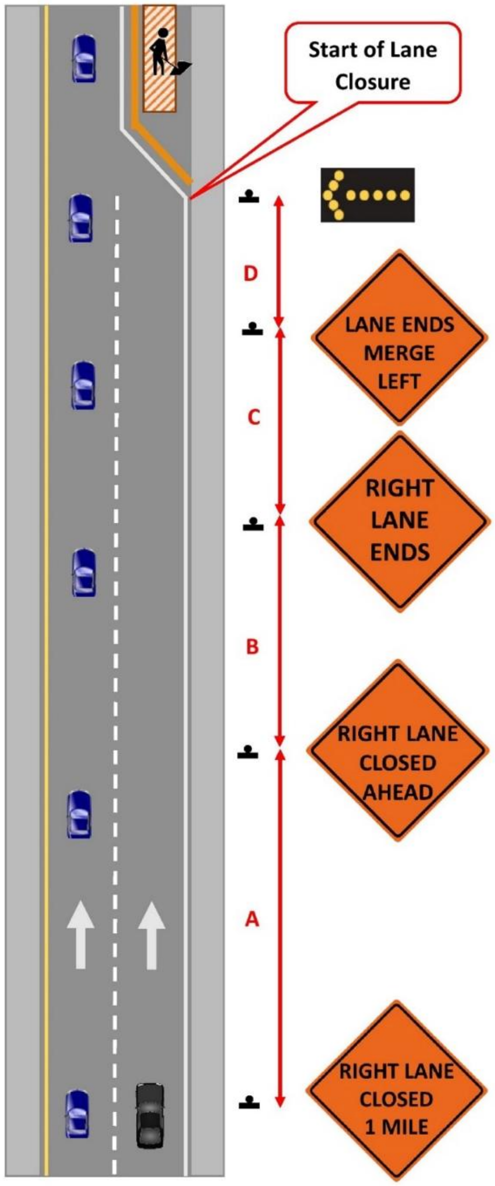
- Less than high school
- High school graduate
- Some college
- 2-year degree
- 4-year degree
- Graduate or Professional Degree

Q9. What is your state of residency?

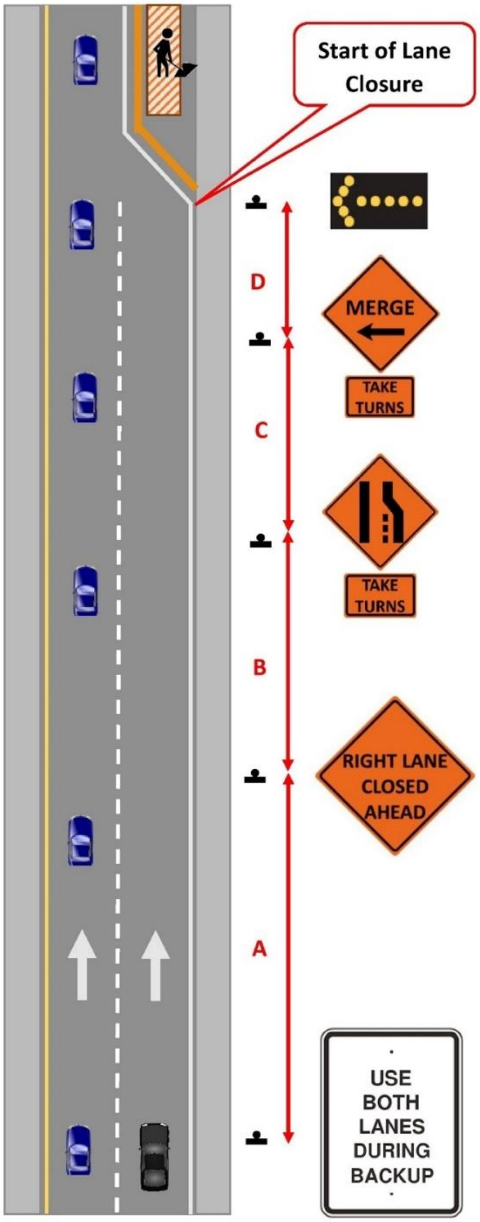
- Drop down menu of all the states in the U.S.A.

Section B- This section is designed to evaluate your driving behavior as you approach a right lane closure on a freeway.

Q10. Suppose you are driving the black car in the right lane, as shown below, and notice that the right lane is about to close. Assuming the signing configurations shown in the figure, where would you prefer to merge into the left lane?

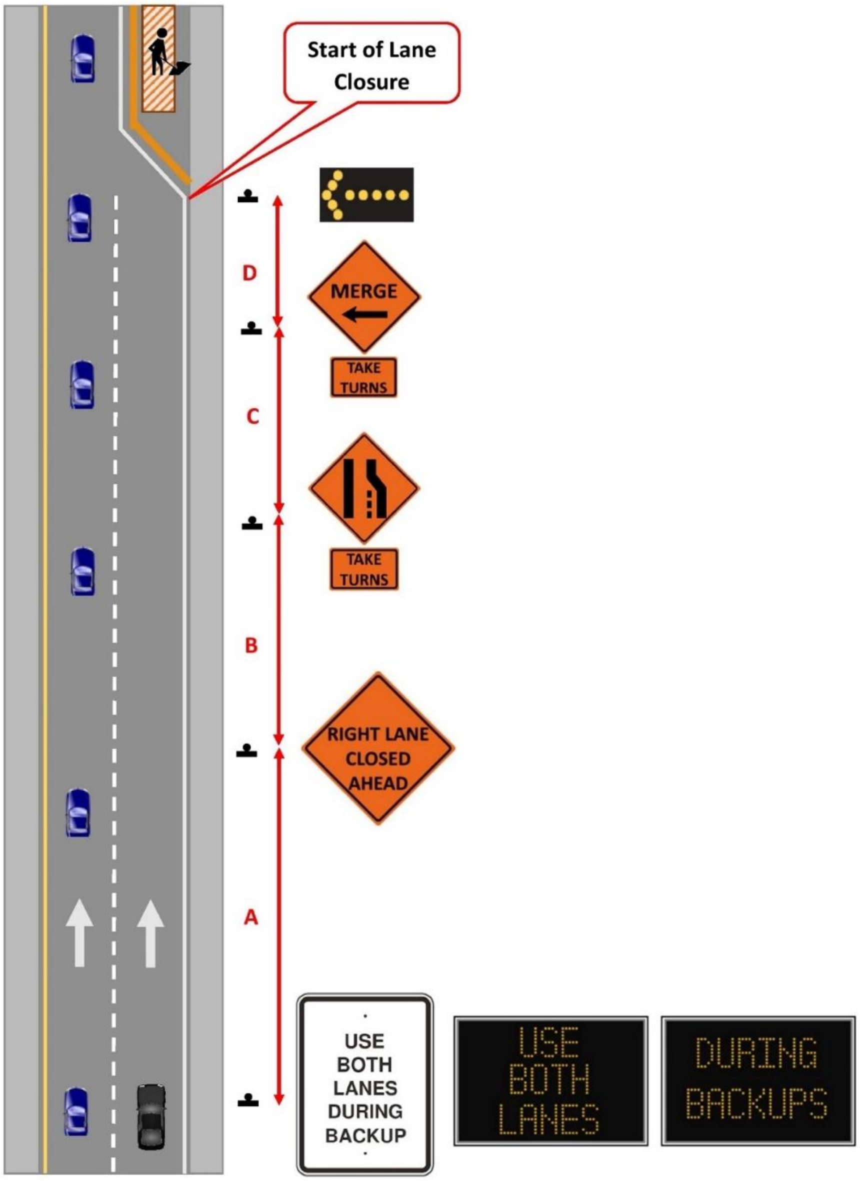
a. 

- Merge into the left lane in section A
- Merge into the left lane in section B
- Merge into the left lane in section C
- Merge into the left lane in section D



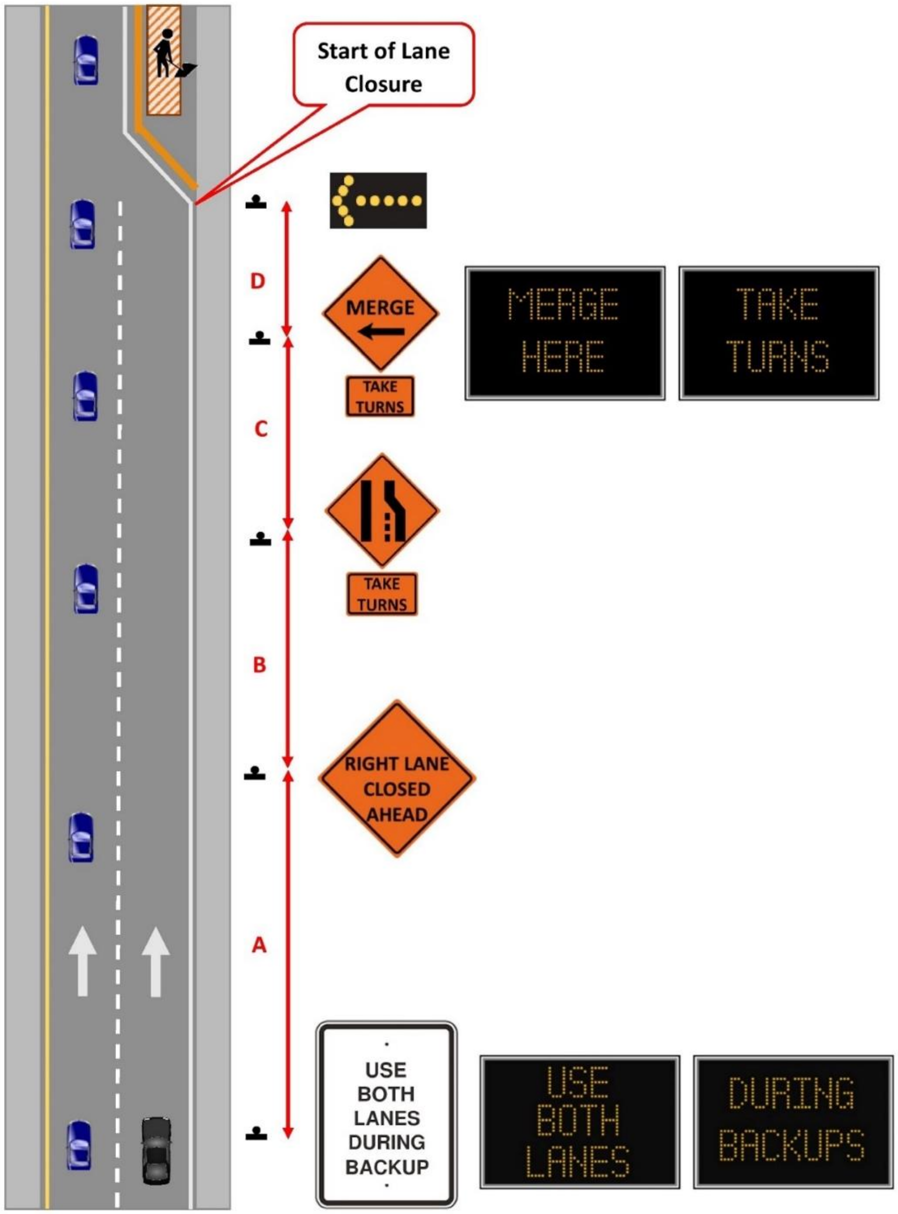
b.

- Merge into the left lane in section A
- Merge into the left lane in section B
- Merge into the left lane in section C
- Merge into the left lane in section D



c.

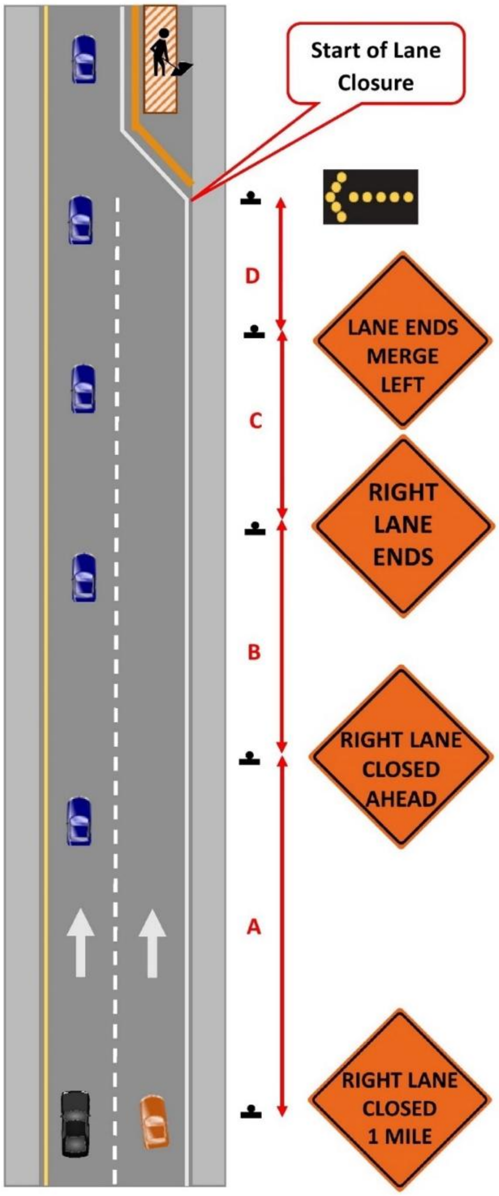
- Merge into the left lane in section A
- Merge into the left lane in section B
- Merge into the left lane in section C
- Merge into the left lane in section D



d.

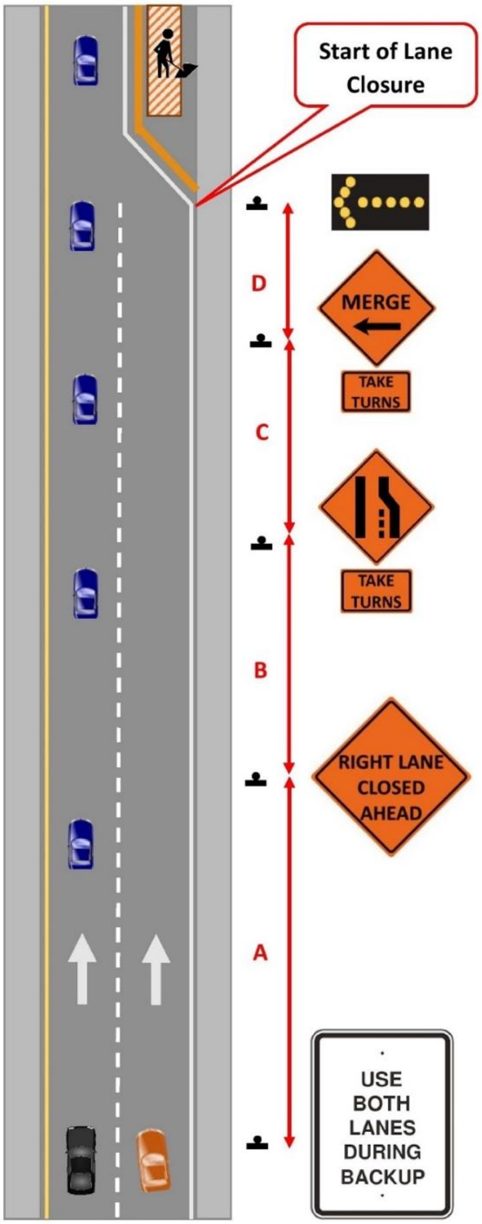
- Merge into the left lane in section A
- Merge into the left lane in section B
- Merge into the left lane in section C
- Merge into the left lane in section D

Q11. Suppose you are driving a black car in the left lane and notice that the right lane is about to close. Assuming the signing configurations shown in the figure, what would you do when you see the orange car trying to merge into the left lane?



a.

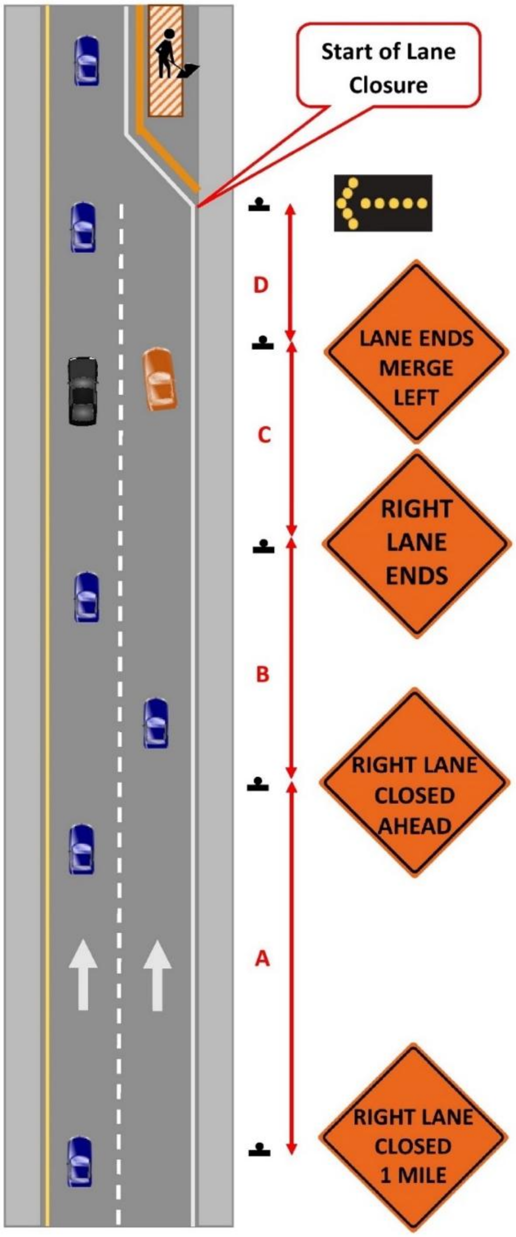
- Slow down and allow the orange vehicle to merge in front of you.
- Continue driving at the same speed without giving any consideration to the orange vehicle.
- Accelerate to prevent the orange vehicle from merging in front of you.
- Other. Please specify _________



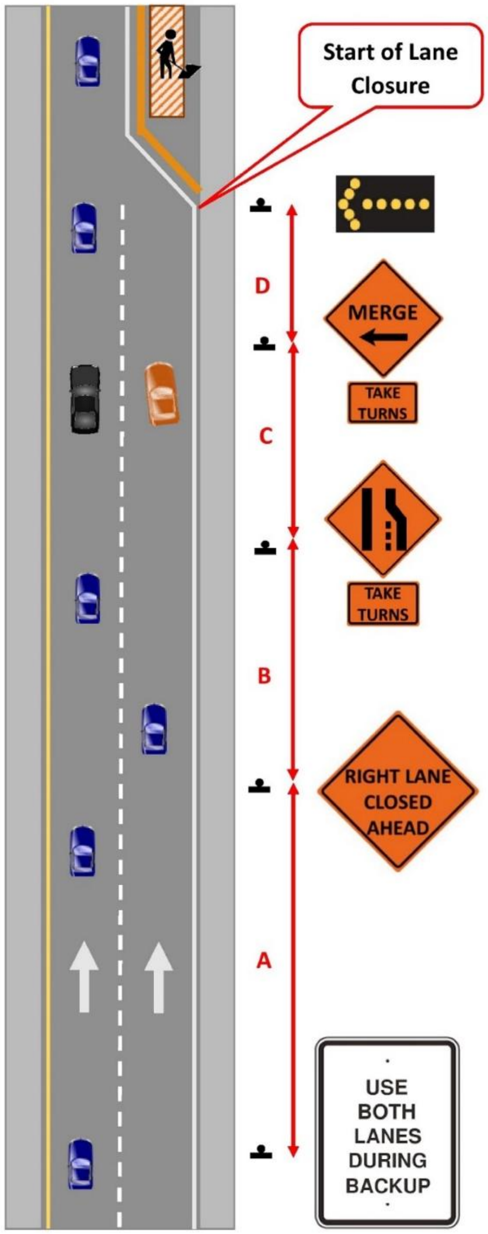
b.

- Slow down and allow the orange vehicle to merge in front of you.
- Continue driving at the same speed without giving any consideration to the orange vehicle.
- Accelerate to prevent the orange vehicle from merging in front of you.
- Other. Please specify _________

c.



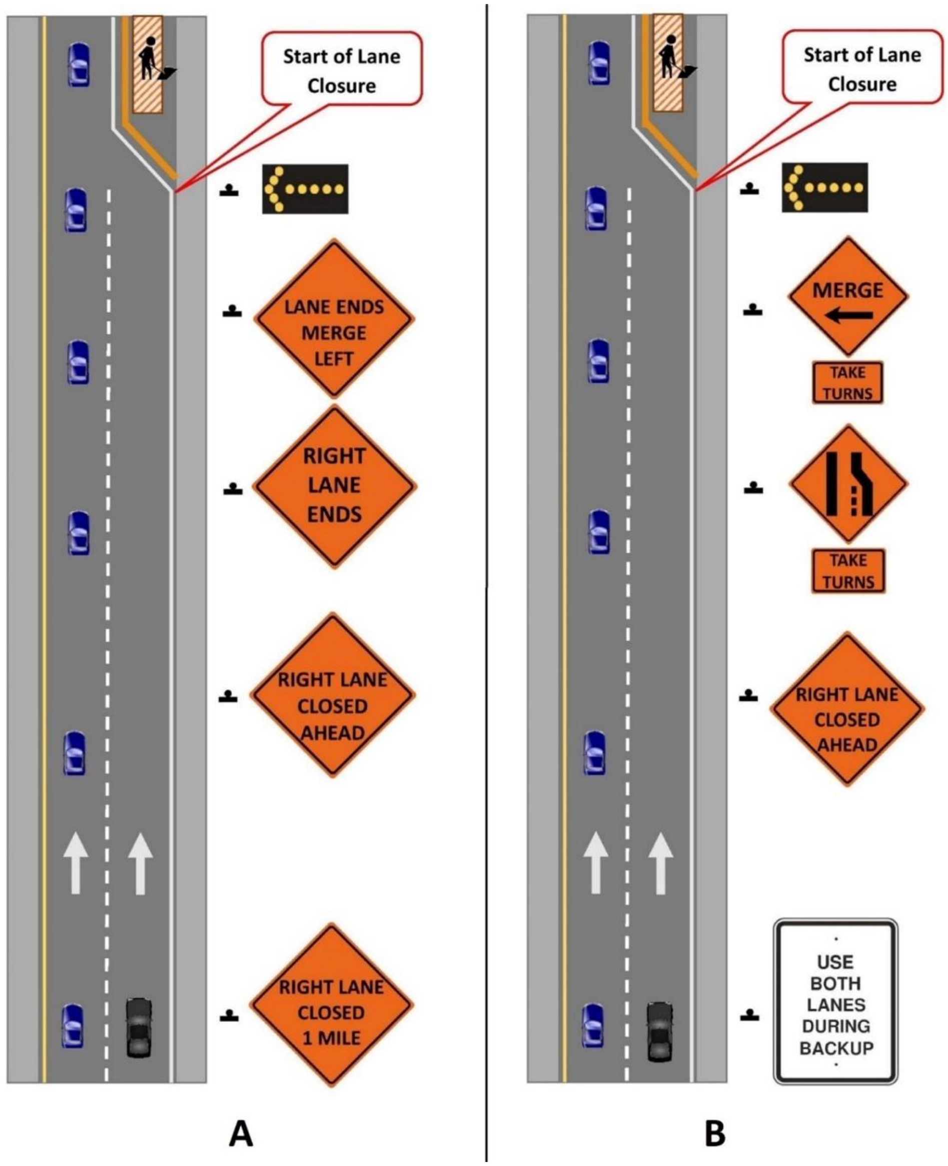
- Slow down and allow the orange vehicle to merge in front of you.
- Continue driving at the same speed without giving any consideration to the orange vehicle.
- Accelerate to prevent the orange vehicle from merging in front of you.
- Other. Please specify _________



d.

- ○ Slow down and allow the orange vehicle to merge in front of you.
- ○ Continue driving at the same speed without giving any consideration to the orange vehicle.
- ○ Accelerate to prevent the orange vehicle from merging in front of you.
- ○ Other. Please specify _________

Q12. Suppose you are driving a black car in the right lane and notice that the right lane is about to close. You observe these two different signing configurations while driving on two different days.



a. In which of the following sign configurations would you merge as early as possible?

- A
- B
- None of them
- Both of them

b. In which of the following sign configurations would you merge as late as possible?

- A
- B
- None of them
- Both of them

Q13. Are you familiar with the zipper (late) merge strategy at lane closures?

- ○ Yes
- ○ No
- ○ Maybe
- ○ Other. Please specify_________

Zipper Merge.mp4

Section C- This section is designed to gain insights into your choice of work zone-related signage.

Q14. Which of the signs do you think better conveys the message that the right lane is closed ahead?

○

○

Q15. Which of the signs do you think better conveys the message for motorists to begin merging while taking turns?

○ 

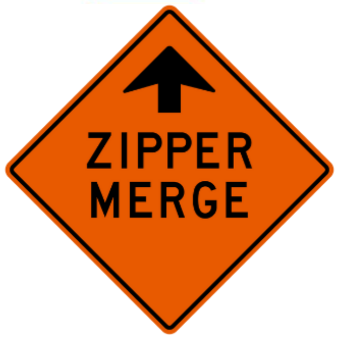
○ 

Q16. Which of the signs do you think better conveys the message for drivers to stay in the right lane as long as possible before merging left?

○ 

○ 

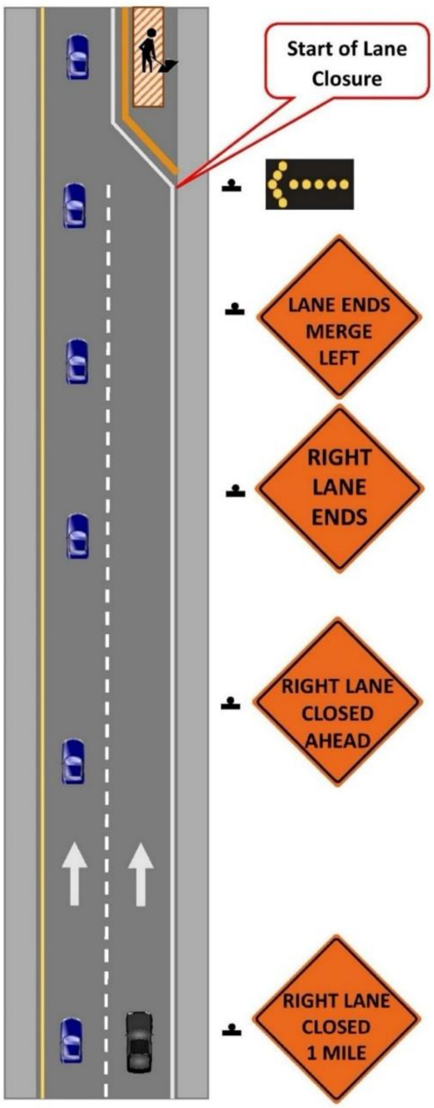
- 

- 

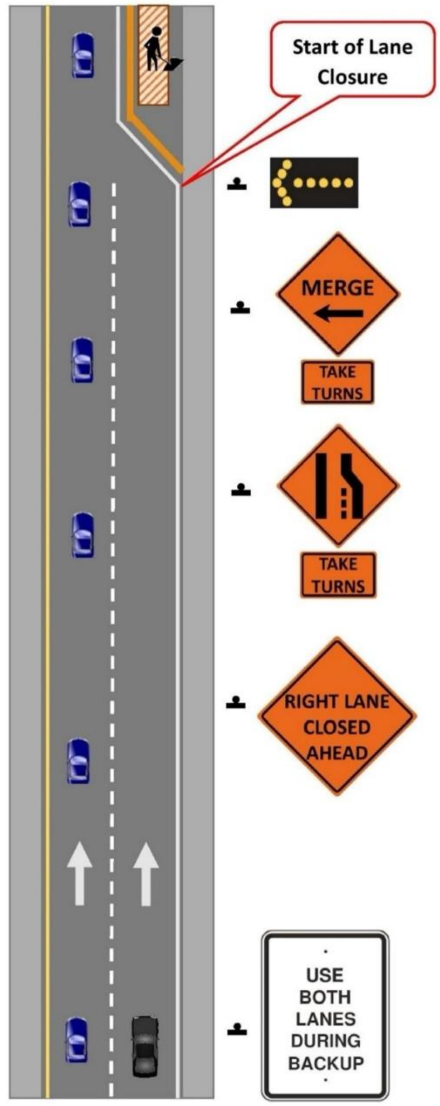
Section D- General questions related to zipper merge

In the standard merge, drivers are encouraged to merge as soon as practical after encountering the first lane closed ahead sign.

In zipper merge, drivers stay in the closed lane until the start of the taper. It involves vehicles taking turns merging at the taper (i.e., like a zipper).
Below are the typical sign configurations for standard and zipper merge, respectively.



Standard (Early) Merge



Zipper (Late) Merge

Q17. Do you think a zipper (late) merge is better than a standard (early) merge in terms of safety while merging? __________

Strongly Disagree (1) to Strongly Agree (5)

Q18. Do you think a zipper (late) merge is better than a standard (early) merge in terms of reducing congestion and backups leading into the work zone? __________

Strongly Disagree (1) to Strongly Agree (5)

Q19. Do you feel more comfortable using a zipper (late) merge compared to a standard (early) merge? __________

- o More Comfortable with zipper (late) merge
- o More Comfortable with standard (early) merge

Q20. Which platform do you think has more outreach and can educate a greater number of people about different lane merge strategies?

- o MDOT public meetings
- o Radio
- o Newspaper
- o TV advertisement
- o Facebook
- o Twitter
- o Other. Please specify __________

Q21. Any other comments or feedback related to the survey? _____________