RESEARCH & DEVELOPMENT

The Effects of Late Lane Merges on Travel Times

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NCDOT Project 2015-08

FHWA/NC/2015-08

April 2018

The Effects of Late Lane Merges on Travel Times

Technical Report Documentation Page

19. Report No. **FHWA/NC/2015-08**	20. Government Accession No.	21. Recipient's Catalog No.
4. Title and Subtitle **The Effects of Late Lane Merges on Travel Times**		22. Report Date **April 2, 2018**
		Performing Organization Code
Author(s) **Christopher Vaughan, PE, Christopher Cunningham, PE, Shannon Warchol, Daniel Findley, Chris Carnes, Scott Sallade, Geoffrey Oyler, Daniel Coble, Brendan Kearns**		Performing Organization Report No.
Performing Organization Name and Address **Institute for Transportation Research and Education North Carolina State University Centennial Campus Box 8601 Raleigh, NC**		Work Unit No. (TRAIS)
		Contract or Grant No.
Sponsoring Agency Name and Address **North Carolina Department of Transportation Research and Analysis Group 104 Fayetteville Street Raleigh, North Carolina 27601**		Type of Report and Period Covered **Final Report August 2014 to April 2018**
		Sponsoring Agency Code **2015-08**
Supplementary Notes:		

Abstract

The Institute for Transportation Research and Education at North Carolina State University conducted a study for the North Carolina Department of Transportation (NCDOT) observing various treatments on roadways for affecting merging behavior in order to improve travel times. These included zipper merge signage wide dotted white lane lines, and elongated route shields for pavement markings. The zipper merge was implemented at three sites across central and eastern North Carolina, with one being a rural arterial permanent two-to-one lane drop, another being a suburban freeway permanent three-to-two lane drop, and the last being a rural freeway two-to-one temporary lane drop inside of a work zone. Lane utilization was not proven to be greatly affected by this treatment, with the greatest increase in ending lane traffic at any site being five percent, although this is likely due to sign misunderstanding. Travel times at these sites generally decreased modestly, with some increases as well. The increases may be due to outside factors like crashes, but the actual cause is unknown. The most significant increase was at the work zone site, which utilized a dynamic zipper merge setup and saw a decrease in travel time of one minute, which equates to an 11 mile per hour increase in space mean speed. The biggest improvement observed with the implementation of the zipper merge was the safety improvement, as far fewer vehicles entered the shoulder in order to merge after implementation of the zipper merge. As for the wide dotted line sites, particularly at the freeway site studied, entering vehicles merged sooner and exiting vehicles merged later, which was determined to be a positive finding as it meant fewer interactions between vehicles while they were attempting to leave or enter the auxiliary lane between ramps. Lastly, the elongated route shield sites studied did not appear to see a significant change in crashes after having these pavement markings installed.

Key Words Zipper Merge, Dynamic Merge, Static Merge, Early Merge, Late Merge, Elongated Route Shield, Wide Dotted White Lane Line	Distribution Statement		
Security Classif. (of this report) Unclassified	Security Classif. (of this page) Unclassified	No. of Pages 67	Price

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

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ACKNOWLEDGMENTS

The research team acknowledges the North Carolina Department of Transportation for supporting and funding this project. We extend our thanks to the project Steering and Implementation Committee members:

Ron King
Chris Howard
Brian Mayhew
Shawn Troy
Joseph Geigle
Steve Kite
Kevin Lacy
Neil Mastin
Ernest Morrison

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1. INTRODUCTION

There is much debate around the topic of drivers merging late from a closing lane. Many drivers in North Carolina tend to argue that people who merge late are 'cutting in line' and that these drivers cause disruptions in traffic, while those drivers who do the late merging insist that they are using the lane the way it was intended to be used, and in effect, both are correct. Ultimately, if pavement is present without any barriers, it is generally intended to be used by drivers in order to reduce queue lengths and utilize the roadway's capacity. However, most drivers prefer to merge early and insist that if all drivers did the same, traffic would flow more smoothly through the lane drop location.

Oftentimes, the confusion among drivers regarding appropriate merging behavior can be due to a number of issues. These include driver education and misinformation, as well as inadequate signage. These issues can affect both types of drivers: commuters and tourists, as commuters are familiar with certain roadways and know when to merge early (or late), while tourists are not familiar with the roadways on which they are traveling and therefore need information regarding changing traffic patterns in the form of signage and lane markings. Likewise, even everyday commuters are susceptible to poor signage in areas like work zones.

This project serves to determine if various treatments intended to improve traffic flow in areas where lane drops and lane splits occur are sufficient, or even safe. Particularly, much of the data collection effort in this project involved observing the effects of treatments like the zipper merge and wide dotted white lane lines, but the project also briefly examined elongated route shields for potential safety benefits or losses.

The zipper merge is a relatively new treatment that has been used across the Northeast and Midwest in recent years to encourage drivers to merge late during congested travel periods, while also telling drivers to take turns merging and allowing other drivers into the continuing lane. The thought process is that more drivers merging later will better utilize the existing roadway capacity, and that a more polite merging behavior in locations where lane drops occur will result in smoother merging and therefore higher speeds and better travel times through the lane drop area. The zipper merge has been used with dynamic and static signage elsewhere in the U.S., as dynamic signage has been found to be more effective, but also more expensive.

Wide dotted white lane lines are intended to provide visual cues to drivers that a lane is ending or diverging. These were included in the 2009 Manual on Uniform Traffic Control Devices (MUTCD), Chapter 3 as the standard in the following locations *(1)*:

- As a lane drop marking in advance of lane drops at exit ramps to distinguish a lane drop from a normal exit ramp
- In advance of freeway route splits with dedicated lanes

- To separate a through lane that continues beyond an interchange from an adjacent auxiliary lane between an entrance ramp and an exit ramp
- As a lane drop marking in advance of lane drops at intersections to distinguish a lane drop from an intersection through lane
- To separate a through lane that continues beyond an intersection from an adjacent auxiliary lane between two intersections

Elongated route shields are installed as an overlay on top of the pavement and are typically used in diverging segments on freeways to indicate to drivers which roadway they will be on if they stay in a particular lane. These are also briefly included in Chapter 3 of the MUTCD as alternative ways to guide drivers, but they are not required.

1.1. Research Need

In recent years, NCDOT noted that travel times had increased due to infrequent and aggressive late mergers and sought to find a way to improve travel times on roadways, particularly interstates, through the use of signage and lane markings to change the behavior of these aggressive drivers or that of the other drivers on the road. Discouragement of the practice of late merging came to the forefront but was ruled out as it would result in lost capacity and ultimately was seen as a near impossibility because it was suspected these drivers would continue this behavior, especially in lane drop locations. Therefore, one treatment that was decided upon for observation for this research project was the zipper merge, as it has been effective in other areas of the country.

Likewise, the NCDOT understands that other problem areas that exist for drivers are locations where lanes split, or diverge, and where two lanes merge together. Drivers, particularly those unfamiliar with an area, can find these locations confusing because they don’t know when a merging lane might end or how far they can travel before a diverging lane actually split from the main travel lane(s). Merging drivers might find themselves feeling anxious about merging onto the freeway and therefore merging before they have reached the appropriate speed. Likewise, diverging drivers may begin decelerating too soon, causing a disruption in traffic for the vehicles behind them, or in inadequately marked locations, these drivers might wait too long to change lanes and find themselves making erratic and abrupt movements in order to get into the desired lane. This is particularly troublesome where auxiliary lanes are present on freeways, meaning a lane that acts as both an entry lane and an exit lane between two ramp terminals. Because of these concerns, and because of recently updated MUTCD standards, the NCDOT desired to conduct a before-after study in locations where these wide dotted lines would be installed with travel behavior compared before and after their installation.

Lastly, the NCDOT had already been using elongated route shields, or pavement shield markings, across the state and wanted to know their effectiveness. Unfortunately, the research team was not able to conduct a before-after observational traffic study where these markings are in place because there were none scheduled to be installed anywhere in North Carolina during the course of this study. Therefore, the research team decided to attempt a before-after crash analysis on sites where pavement shield markings were already in place with the goal of determining if there were any safety benefits or detriments from installing this treatment.

1.2. Scope and Objectives

The primary goal of this research project was to determine if there are measures currently used in North Carolina and/or elsewhere across the country that could safely and effectively influence travel behavior in a way that improved travel times or safety on roadways with varying design features. Ultimately, the NCDOT and the research team decided to test the zipper merge by conducting a before-after study at sites all with unique features, as the zipper merge had not yet been implemented in North Carolina, and to conduct a before-after study on wide dotted lines, as well as a crash analysis on elongated route shields.

By testing the zipper merge, the research team sought to determine two things: whether or not a lane that is closing has higher utilization and if travel times would improve. Both of these situations could only be tested during congested time periods, as this is the only time that a zipper merge is necessary or effective. In observing sites where wide dotted lines were installed, the research team sought to determine if merging behavior changed due to their presence. Lastly, as stated above, the research team attempted to observe whether or not there was a safety improvement or loss due to the presence of pavement shield markings.

2. LITERATURE REVIEW

2.1. Merge Comparison

Harb, Radwan and Dixit simulated traffic flow around lane closures using VISSIM. They were testing effectiveness of early merging and late merging with different traffic volumes and driver compliance rates *(2)*. They found that the dynamic early merge was the best in terms of throughputs and travel time through the work zone, regardless of the volume of traffic and driver compliance. The study did not consider possible safety concerns with each method of merging. This is interesting because most of the other studies found that as traffic increased, it was better to switch from early merging to late merging. The team did create a table of best merging methods based on volume, compliance and truck percentage that could serve as a guide for a given scenario.

The FHWA Dynamic Lane Merging Guidance offers a guide of when to implement different types of merging strategies and what signage should be used *(3)*. They recommended basing the decision to switch between early and late merging on traffic speed rather than volume or another metric. They also recommended having a higher speed threshold that would trigger a switch from late to early merge (traffic is becoming less congested) and a lower speed required to trigger a switch from early to late merge (traffic is becoming more congested). They also compiled reference tables (on the next page) of previous research findings regarding positive and negative impacts of each merging strategy. There is much more research showing advantages to using late merge, but because the early merge has been shown to improve throughput and travel time during off-peak hours, it is the recommended strategy during these times. The numbers in the first row refer to an entry in their references. Many of these references are summarized in this literature review, so this table also serves as a good summary of the overall findings of this literature review.

Table 1 Early Merge vs. Late Merge Literature Review

Early Merge															
Effective Metric	**1**	**2**	**3**	**4**	**5**	**6**	**11**	**12**	**14**	**15**	**17**	**18**	**21**	**23**	**26**
Aggressive Driving															
Benefit/Cost Ratio															
Capacity								*							
Crashes															
Number of Stops															
Queue Length											†				
Speed Differentials Between Lanes															
Traffic Throughput							*			*			*		
Travel Time							*				†		*	*	
* Positive change † Negative change Note: blank cells indicate not studied.															
Late Merge															
Effective Metric	**1**	**2**	**3**	**4**	**5**	**6**	**11**	**12**	**14**	**15**	**17**	**18**	**21**	**23**	**26**
Aggressive Driving		*				*						*			

Benefit/Cost Ratio						*			*						

Capacity				*				*				*			*
Crashes						*									
Number of Stops					*	*									
Queue Length									*		*	*	*		
Speed Differentials Between Lanes						*									
Traffic Throughput	*		*	*			*		*	*	*		*		
Travel Time	*	*			*	*							*		*

* Positive change
Note: blank cells indicate not studied.

Kang and Chang ran extensive simulations evaluating the effects of static early merging, static late merging and dynamic late merging on the same merging condition with different traffic conditions as a means of providing guidance to properly manage merging at any given site *(4)*. They found that the static early merge was the best method at less traffic volumes. Static late merge and dynamic late merge were comparable solutions under increased traffic volume. Static late merge speeds were generally faster than the other methods. The dynamic late merge may not be the best solution in situations where there is great variation in traffic speed because this variation is magnified by the switch between early and late merging strategies. They suggest using variable speed limit technology if using a dynamic late merge under these conditions.

2.2. Specific Systems

2.2.1. Zipper Merge

Minnesota DOT has implemented a late merge procedure on several large construction projects with positive effects *(5)*. MnDOT noted that the use of variable message boards to change between the conventional merge and the late merge were not always necessary, as they saw improved travel times through construction zones with signs stating, “During Backups Use Both Lanes.” Drivers were good at recognizing when a backup was occurring and started using both lanes, executing a zipper merge at the merge point. MnDOT pointed out that this method reduced the difference in speed between merging lanes, making merging safer and easier; it also decreased the length of the backup by around 40%, and because both lanes are moving at approximately the same speed, driver frustration is reduced. They do note that while the zipper merge produces a safer merging situation and a shorter backup, it did not reduce travel time through a construction zone in this case.

2.2.2. SMART Merge

The portable changeable message sign company ADDCO set out to determine a merging solution around construction sites that accounts for changes in traffic volume along the road *(6)*. One method summarized is the Dynamic Early Merge, a method of merging that encourages drivers to merge as soon as they see signs of a lane closure. The Late Lane Merge is also summarized, a method of merging that encourages drivers to continue using both lanes until the merge point, at which point drivers should take turns merging. ADDCO describes their “SMART Lane Merge” solution as a combination of these two methods. They suggest using variable message boards connected to sensors that can detect queue length. During off-peak hours when there is not a queue, the message boards encourage an Early Merge configuration. If a queue begins to form, the message boards switch to telling drivers to not pass and merge, thus alleviating the congestion at the merge point. At peak hours, the message boards switch to a dynamic late merge with a zipper merge at the merge point so that the full capacity of all lanes can be used as long as possible.

2.2.3. CALM System

The Midwest Smart Work Zone Deployment Initiative goal for this study was to evaluate and compare what they refer to as the “CALM” system with conventional traffic controls for an early merge *(7)*. This dynamic control consisted of five variable message signs which operated in one of three modes (Early, Late, or Incident) based on average speeds recorded by sensors located at the signs. It is not clear in the report what static signage was in place along with the variable message signs. Their study found that drivers tend to comply at a higher rate after a “training” period and once this training occurs the system operates much more effectively. It is important to note that this study was conducted on a lane merge of three lanes to two and not two lanes to one as have been most other studies encountered by this research team. Additionally, there were multiple entrance and exit ramps along the tested corridor that could cause variations in traffic. The authors specifically acknowledge that drivers tended to merge earlier due to the incoming traffic which opposed the goals of a late merge design.

2.3. Lane Closure Configurations

A study conducted by Beacher et. al. evaluating the Late Merge Work Zone Traffic Control Strategy consisted of a simulation study using VISSIM as well as a field study on the static late merge in a two lanes to one work zone lane drop *(8)*. While the simulated late merge increased throughputs and decreased travel time in each configuration, the improvements were only statistically significant across scenarios in a three lanes to one configuration. Further, lane configurations of three lanes to two and two lanes to one only saw a significant increase in throughput with higher heavy vehicle percentages. Their field test showed similar results; however, no testing was done on freeways based on how they defined applicable sites. No crash analysis was conducted because their test sites were only implemented for short periods of time. Appropriate signage for a three to one lane configuration was not specified and is in need of further development. Drivers in the field study seemed reluctant to changing driving patterns and therefore, development of more appropriate signage and wording is needed.

Researchers Qi and Zhao evaluated the safety impacts of regulating a lane closure merge with traffic signals *(9)*. They said that the late merge, which many other researchers seem to favor, is a dangerous situation that negatively impacts the upstream traffic. The team also stated that a signal could increase the potential for rear-end collisions. The model used a two phase signal that alternated which lane was allowed through the merge point. The team observed a lane drop of five lanes to four, rather than the two to one lane merge that many of the other reviewed projects observed. They found that the use of a signalized merge greatly reduces the number of lane change conflicts, but increases the risk of rear end conflicts, especially with short cycle lengths.

Radwan et al. evaluated the dynamic lane merge in work zones with variable speed limits *(10)*. The team used VISSIM to model a two lane to one lane work zone to evaluate the use of a variable speed limit in the presence of a dynamic merge scenario. Of all the scenarios they tested, the late dynamic lane merge coupled with the variable speed limit provided the greatest throughput; however, there was no statistically significant difference from the use of a normal dynamic merge with variable message boards.

Harb, Radwan, and Shaaban conducted a study evaluating three different merging systems implemented at the same three-to-two lane drop work zone for six days each *(11)*. The team wanted to determine which method of merging (traditional, dynamic early, or dynamic late) was optimal. The work zone they studied was rural, geographically and environmentally similar across its length and had no on/off ramps over the duration of the work zone. As other teams have found, under lower volumes (less than 1,500 vph), the dynamic early merge is the optimal merging strategy. Under higher volumes (1,500-2,000 vph), the dynamic late merge is optimal. For volumes higher than 2,000 vph, conclusions could not be drawn because of a limited sample size. This research also provides empirical evidence that the early and late merge are effective in scenarios besides a two-to-one merging scenario.

2.4. Research Methodologies

A study conducted by McCoy, Pesti and Byrd evaluated several work zone merge strategies, including NDOR merge (Nebraska Department Of Roads Merge – Nebraska's standard), the Indiana Lane Merge (a dynamic early merge strategy), the late merge, and the dynamic late merge *(12)*. Computer simulations showed under lower traffic volumes (500 and 1,000 vph), there was little difference between the NDOR merge and the late merge strategies, but at volumes of 1,500 and 2,000 vph, the late merge performed better in that there were fewer delays and more vehicles being processed through the merge point.

This study used the following measures of effectiveness in field tests: volume at the merge area, lane distribution, speed distribution, and traffic conflicts in the merge area. A Video Data Acquisition System (VDAS) was used with an Autoscope video image analysis system that recorded video and could automatically determine vehicle presence and passage, vehicle speed and length, flow rate, volume lane occupancy, and headway over time. The video recordings were also reviewed manually to identify traffic conflicts. Camcorders were also mounted at other points. Laser guns (for speeds) and manual counting (for traffic flow and lane distribution) were used to collect speed data when video was not possible. One of the mobile recording platforms was always stationed behind the taper. Upstream traffic was recorded from overpasses or from other points on the roadside. The late merge field collections were conducted at a work zone on northbound I-79 in Pennsylvania. The data was collected on four days, mainly during high-flow periods.

Results of the field study showed that in uncongested flow, lane distribution was similar to other merge concepts, but in congested flow, drivers stayed in their lane longer, with the exception of trucks (95% of trucks were already in open lane at the sign 1500 feet from the drop). Capacity was slightly larger (8%) for late merge compared to NDOR merge, but when converted to passenger car equivalent it was 18% higher (due to 2% grade more than 1.5 miles). Standard deviations of speed distributions were lower for late merge, suggesting lower speed variance and lower accident potential. At high densities, late merge had 75% fewer forced merges and 30% fewer lane straddles than NCDOR merge.

Kong, Guo and Hou also modeled the effects that a dynamic late merge has on traffic flow through a construction zone or other lane closure *(13)*. The team came to the same conclusion that others have – that having variable message boards that respond to traffic back-up and switch between early and late merge scenarios have a positive impact on queue length and merging safety. Interestingly, this model showed that travel time through the construction zone was reduced with a dynamic merge, whereas MnDOT had said previously *(5)* that the dynamic late merge (specifically, the zipper system) did not improve travel time. This may be a shortcoming of the model used in this research or it may mean that the dynamic merge does improve driving time through restricted sections of roadway.

The Minnesota Department of Transportation collected data on a conventional merge and a dynamic late merge setup in the same location using loop detectors already embedded in the pavement on US 10 that collected traffic volume and occupancy data and continuously transmitted it to the Regional Traffic Management Center (RTMC) *(14)*. Existing cameras with the ability to transmit data to the RTMC were used to measure queue length, and the images downloaded every minute and archived for use in recording traffic conditions. A virtual drive-through could be done with the camera images.

The study used a “before-and-after” approach, with approximately one week of data for each merge configuration. Lane distributions in the afternoon peak period showed vehicles staying in the closed lanes for longer periods of time when using the dynamic late merge system. Typical queue lengths decreased by approximately 35% when compared to the conventional merge method. Average travel times were not statistically different and the variability in travel times was greater using the dynamic late merge method. Throughput decreased slightly using the dynamic late merge system. It was noted that the system was only deployed for a short time and that driver compliance to the signing appeared to be increasing as time passed.

A dynamic late merge system was implemented on three sites in Michigan and studied by the Wayne State University Transportation Research Group *(15)*. Before data was not available, so for the westbound I-94 test data, an eastbound I-94 work zone was used as a control site. The other two sites on I-69 did not have control sites, and therefore are not mentioned much in the results.

Data collection included travel time, number of stops in the queue, volume, queue length, merge locations, spot speed, and crashes. The floating car method was used to collect travel time by driving through the area multiple times. The beginning point was the first message sign and the ending point was the arrow at the taper. The number of times stopped due to congestion was noted. Average travel speed and delay were calculated with this data. Average delay was calculated by subtracting the actual travel time from the expected travel time (distance times the speed limit). Digital video cameras were used at an overpass to record traffic and vehicle merges. The number of vehicles entering the work zone was extracted from the video in 5 minute increments and was used to determine the throughput (vehicles per hour) of the work zone. Heavy vehicles were counted separately. Queue data was also collected from the overpass, using two people counting and recording queue length (number of vehicles in queue) every minute per lane. Vehicles were considered to be in the queue when the speed was less than 5 miles per hour. Speed data was collected using radar guns at two locations.

The measures of effectiveness included mean travel time delay, the mean travel speeds, and the crash frequencies. For I-94, the study showed a statistically significant reduction in mean travel time and an increase in mean travel speed, but no significant change in crashes. Although the I-69 sites were not directly comparable to the control site, it was noted that one showed positive differences and the other showed negative differences.

Note that many of the references mentioned above are also provided in the Excel workbook provided as Appendix Section 8.2. This workbook contains spreadsheets with tables diagraming numerous merge configurations. These were researched by this team to provide insight into how other transportation agencies implement their merge strategies.

2.5. Pavement Markings

The research team of Horberry, Anderson and Regan performed a simulation-based study comparing driving under wet conditions with enhanced road-markings to driving in the same conditions with standard highway markings *(16)*. The team points out that pavement markings give drivers information without them having to look away from the road. The study concluded that enhanced centerline and edge markings – meaning paint with high retroreflectivity – helped drivers maintain their position in the lane and travel more confidently.

Ullman et al.'s preliminary research and literature review revealed that many existing standard markings are often misunderstood by drivers *(17)*. They listed route signs printed in driving lanes, exit only lanes, and optional exit lanes as areas of confusion in current marking strategies. Diagrammatic guide signs showing arrows for each lane are helpful for drivers. In determining optimal signage, the team tested comprehension, layout preference and order of information preference. In their study, participants said that interstate symbols (elongated pavement shield markings) within lanes were helpful in identifying where their lane would go and another study indicates that drivers actually prefer the elongated route shields over just text markings with route numbers (*18*). They also concluded that drivers prefer a line application of horizontal route markers as opposed to staggered markings across lanes. For interchanges with optional exit lanes, putting arrows along with route shields in the lane improved driver comprehension of where each lane will go. Additionally, if horizontal markers are used in some lanes, they should be used in all lanes to avoid confusion about where some lanes lead. The team concluded that including route shields and directional arrows directly in each lane improved driver decisions about switching lanes and drivers also made lane changes further upstream from the interchange. They also suggested that there may be safety benefits because of the operational benefits of earlier and fewer lane changes.

Gross et al.'s article does not directly correlate to late lane merges, but it does concern low-cost means of reducing rear-end collisions *(19)*, which is of interest in merging methodologies. They determined that STOP AHEAD signs could be expected to reduce intersection collisions by 15%. They also said that STOP AHEAD signs may be more effective at locations where driver awareness of the intersections might be an issue. This may translate to late lane merges as evidence that proper upstream signage of lane merges can reduce rear-end collisions and (as suggested by ADDCO) reduce driver frustration at heavy traffic.

The purpose of the study conducted by Hallmark et al. was to determine which driving maneuvers were most detrimental to overall traffic flow at merge points *(20)*. The maneuvers the team identified were forced and late merges, lane straddling and queue jumping (moving from the open lane to the closing lane and back again). They also noted that queue jumping usually leads to a forced and/or late merge. Additionally, other drivers will sometimes straddle lanes or otherwise try to block queue jumpers. The team suggested the late merge, work zone information boards, and longitudinal and transverse rumble strips as methods of mitigating the observed dangerous driving maneuvers.

3. Methodology

As stated, a number of treatments were observed for various changes in behavior at multiple sites across North Carolina. These treatments include the zipper merge, wide dotted white lane lines, and pavement shield markings. For the zipper merge and wide dotted line sites, merge behavior was observed to determine if the safety of those roadways improved by reducing aggressive lane changes due to the presence of the new treatment.

For the zipper merge sites alone, travel times were also observed for changes as they have the potential to be reduced with the presence of the zipper merge. Likewise, lane utilization at the zipper merge sites was observed for changes in the percentage of vehicles using the closing lane because lane utilization can heavily favor the continuing lanes in locations with lane drops, which can reduce the capacity of a roadway unnecessarily. The data collected at the zipper merge sites was collected only during congested time periods, as this is when the zipper merge is intended to be effective. Traffic was considered congested either when several consecutive vehicles were within one to two passenger car lengths of one another or when vehicles came to a stop or near stop while in view of the camera. However, if vehicles were stopped for a prolonged period of time, this was usually because of a collision downstream that was causing significant backups and thereby not due to the lane drop, which resulted in this data being excluded from the analysis.

As for the wide dotted line sites, the merge area was observed for changes in the location where drivers merge into or out of a diverging lane. The research team felt that earlier merges were preferred for these sites, especially for vehicles merging into the continuing lane of the roadway, as this would mean fewer instances of sudden stopping or aggressive late lane changes. This is particularly true for the freeway site studied, as drivers who merge late when merging onto the freeway (i.e., into the continuing lanes) tend to reduce their speed to avoid missing their opportunity to join traffic, which creates hazardous situations for drivers already in that lane, as they suddenly have to slow down if the merging driver merges in front of them. This is also true for exit ramps. However, in the case of the freeway site that received this treatment, the ramp served as an auxiliary lane for vehicles entering and exiting the freeway. Because this creates a weaving segment, later merges are acceptable and even preferred for drivers exiting the freeway, as vehicles in the diverging auxiliary lane are already slowing down and this also allows vehicles merging onto the freeway time and space to merge without having to decrease their speed if they are caught behind an exiting driver in the auxiliary lane.

Lastly, for the elongated route shields, because the markings were already installed and had been in place for an extended period of time, the only observation that was made for this project was with regards to safety. Crash analysis was conducted on three sites with elongated route shields. Whereas before-after analysis was performed on the other two treatment types, no before-after analysis could be conducted on the operations of a segment containing these markings because none were being installed within the time frame of the project.

3.1. Zipper Merge

Three locations temporarily received the zipper merge treatment signage: I-85 in Durham County near the merge with NC-147; NC-58 in Carteret County near the intersection with NC-24; and I-85 in Vance and Warren Counties just south of the Virginia State Line. The first two sites, in Durham and Carteret Counties, are permanent lane drops, while the third, in Vance and Warren Counties, was in a work zone. All of the sites involved only a right lane drop since NCDOT stated that most, if not all future permanent lane drops would be right lane drops.

These sites were observed for lane utilization rates, which would help determine if the zipper merge increased the utilization rate of the ending lane. NCDOT expressed concern that these lanes were being underutilized, creating unnecessarily long queues in the continuing lane(s) and decreasing the capacity of the roadway up to the lane drop. These sites were also observed for the merge location of the vehicles using the dropped lane, which could help determine the safety and effectiveness of the signage directing traffic to merge further downstream, as late merges contradict the common school of thought among drivers and could cause safety concerns if the merges are occurring too late. Cameras observing merging behavior at these sites were placed in such a manner that they would provide a good field of view of vehicles that merged at reasonable distances while also capturing vehicles that merged far too late – meaning they were driving on the shoulder before the vehicle began to merge into the adjacent through lane. In all, more than 750 merging vehicles were counted during each before and after period at each site, as this would ensure a 90% confidence level. A vehicle was counted at various distances as merging when the front left tire had crossed the lane line, as these locations all had right lane drops. For almost all of the sites, the cameras that captured the merging vehicles were placed at or very near the end of the lane drop, with the only exception being the Henderson Zipper Merge location, as there was no adequate mounting location at the end of the lane drop at this site. Therefore, for almost all of the sites, a merge that did not begin while in view of the camera is considered a dangerous movement, as this means the vehicle was traveling on the shoulder of the roadway.

Bluetooth detection devices were also installed at each of these sites as a means to determine typical travel times along each of these corridors, particularly from behind the typical back of queue to beyond the lane drop. These devices do not capture the travel time of every vehicle that travels past them, but simply the vehicles that have devices inside of them with Bluetooth activated (cellular phones, hands free devices, tablets, etc.). However, by sampling the vehicles passing the Bluetooth devices, the research team was able to gather a reasonable expectation as to what the typical travel time was along each corridor, which was used to determine if travel times improved, declined, or remained the same as a result of the zipper merge being implemented in these locations.

All of the zipper merge sites are described in greater detail in Section 4.1.

3.1.1. Zipper Merge signage

The NCDOT had predetermined unconventional plaques that they wanted to use for the zipper merge in conjunction with other conventional signs and message boards. The new plaques were discussed internally among NCDOT staff, and then presented to the research team. One of the plaques instructed traffic to “Merge Like a Zipper”, with a picture showing the comparison of traffic taking turns merging beside a picture of a zipper. The other sign was implemented in two phases, both of which simply picture a zipper closing. The NCDOT received feedback from the public after the first orange zipper sign was installed suggesting that it was difficult to see because the picture was too thin, which brought about the second orange zipper sign (Figure 1c), which featured a thicker, more visible rendition of the first sign’s zipper. These signs are pictured in Figure 1a, b, and c.

a) “Merge Like a Zipper” sign b) Thin zipper sign c) Thick zipper sign

Figure 1 Zipper Merge signage

Other conventional signs used include signs that directed traffic to “Use All Lanes”, which was intended to counteract the traditional early merge ideology. Likewise, message boards were strategically placed at the two permanent lane drop sites in Durham and Carteret Counties which informed drivers that they were approaching the zipper merge and to use all of the available lanes until reaching the merge point. The merge point at the Carteret and Vance/Warren County sites was identified using plaques that indicated “Take Turns Merging Here”.

3.1.2. Zipper Merge Press Release

Through discussions with other state DOTs, the research team realized the importance of media outreach and public education in order for the zipper merge to have the best chance to succeed. For example, members of the Michigan Department of Transportation indicated in correspondence with the research team that public outreach was vital to the success of one of their implementations of the zipper merge. They indicated that there was a zipper merge implementation in both directions on I-96 in lower-mid Michigan, but only the eastbound morning drivers and westbound evening drivers saw improvements, which included a 50% reduction in queue length and improved travel times. This was because only media outlets in West Michigan picked up the press release distributed by the MDOT and ran this story in the morning before the morning peak, and media outlets in mid-Michigan did not. Stories like these from MDOT and other

DOTs solidified the importance of media outreach for zipper merge implementation, and the research team and the NCDOT Communications Office produced a press release that was distributed to central and coastal North Carolina news agencies.

While members of this project team did see a number of articles and TV spots related to the zipper merge, some of them followed the press release format provided to them and some did not. For those who did not follow this format, this was not a problem, but it did change the way information was conveyed to the general public. Ultimately, as long as it was being discussed in the media, this provided more information to the general public, which was a positive outcome. However, note that a press release does not have to be picked up by news agencies, as was demonstrated in the case of the mid-Michigan media outlets, and the research team is not aware of all agencies that did and did not run stories on the zipper merge. The press release that was distributed to news agencies in the piedmont and coastal regions of North Carolina is included in the Appendix of this report.

3.2. Wide Dotted White Lane Lines

There were two wide dotted white lane line study locations. These sites were observed for merging behavior on roadway segments where an auxiliary lane was present, as wide dotted white lane lines are intended to “distinguish a lane drop” from through lanes *(1)*. Both of the study sites had another form of lane marking that did not meet MUTCD standard, but received the wide dotted white lane line treatment during the study, allowing the research team to conduct before-after analysis on this treatment for changes in merging behavior. Unlike the zipper merge locations, congestion was not necessary for data analysis, as wide dotted lines are intended to be effective in influencing traffic during all times of day. In particular, the research team hypothesized that ideally, traffic during uncongested time periods at auxiliary lanes would merge early into and out of the extra lane. Therefore, these sites were observed for merging location to determine if the presence of the new markings might change where vehicles merge into and out of the through lanes. Each site is described in further detail in Section 4.2.

Traffic at both sites was captured using an unmanned aerial vehicle, or drone, that was equipped with a high resolution camera. Removing the requirement for congestion at these sites allowed a high number of merges to be collected in a short period of time. The pre- and post-treatment data collection at both sites occurred in one day. In the case of the site in Dunn, ramp volumes and merge distances were counted separately for each ramp, with each count having an associated freeway volume that was counted as vehicles passed the gore point of each ramp. This resulted in a total freeway volume that varied for each ramp because the UAV could only fly for short periods of time, resulting in multiple short videos. As such, only vehicles that hadn’t yet passed the gore point when the video started or those that had already passed the gore point at the end of the video were counted for that ramp’s dataset, resulting in total freeway volumes that varied even among the entry and exit ramp datasets. This was not an issue at the Cary site, as there was only one merge point at this site.

3.3. Elongated Route Shields

Another treatment observed for this study was elongated route shields, or pavement shield markings. These markings are most often installed on freeways to indicate diverge segments to drivers, particularly where two freeways diverge. These are intended to reduce driver confusion and because these markings generally start more than one mile before a diverge segment, they have the potential to greatly reduce last second lane changes that cause crashes. An example of an elongated route shield is shown in Figure 2.

Figure 2 Example of elongated route shield

The research team attempted a before-after crash analysis on freeway segments across North Carolina that have received this treatment to determine if there is indeed a safety improvement due to these markings. This was also influenced by the fact that none of these markings were being installed during the study period, which eliminated the opportunity to conduct an analysis on the operational changes due to the presence of these markings. The before-after study had varying observation periods at each treatment and comparison site, with only sideswipe, rear-end, and lane departure crashes being analyzed because these are the crash types that the research team and the NCDOT expected might be influenced the most by the presence of the elongated route shields. Data was gathered and partially analyzed by the NCDOT Safety Evaluation Group, with further analysis being conducted by the research team. Detailed descriptions of the study sites are in Section 4.3.

4. FINDINGS

4.1. Zipper Merge

4.1.1. I-85 in Durham County

Site Description

The lane drop observed at the Durham site reduces from three lanes to two, with the right lane being the one that drops. This site is a freeway with a posted speed limit of 65 miles per hour. Congestion is irregular at this site, meaning it isn't a daily occurrence for commuter, weekday work traffic. Congestion at this site can occur because of heavy traffic flows during typical peak periods but also can occur due to holiday travel to the western part of the state. Likewise, heavy truck traffic can create backups and slowdowns at this location due to the steep upgrade directly downstream from this lane drop and further upgrade sections over the next few miles of Interstate 85. Traffic was observed on weekdays in May, June, July, and August of 2016 with the zipper merge being implemented on July 20, 2016. A diagram of this site is shown below in Figure 3 with the blue stars representing the Bluetooth locations and the red stars representing the camera locations.

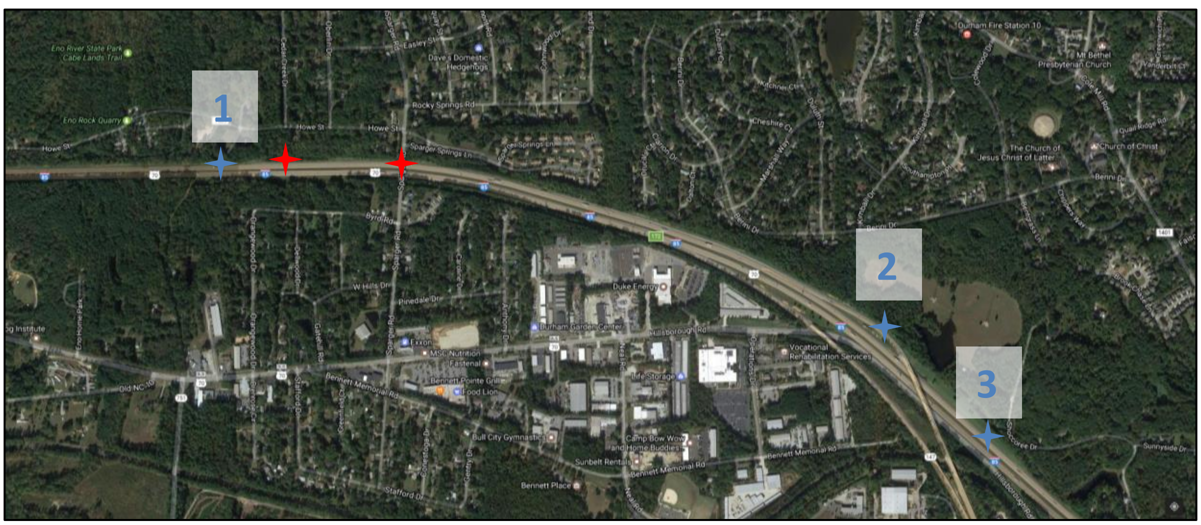

Figure 3 Durham I-85 site diagram

Three cameras were installed at this site. Two cameras were installed on the Sparger Road bridge that overpasses the freeway (only shown as one star), with one facing upstream to capture lane utilization rates prior to the lane drop before the right lane begins to taper and the other facing downstream traffic towards the lane drop. A third camera was installed on a sign post approximately 300 feet from the end of the lane drop on the right shoulder of the freeway. This camera was used to determine the merge location of vehicles in the ending lane. This location was chosen because it was close enough to the end of the lane, with only six feet of lane width available in the right lane, while still allowing the camera to observe merging vehicles prior to the end of the lane. Noted earlier, a vehicle was considered merging when the vehicle's front left tire crossed the lane line, and if the front left tire did not cross the lane line, the merge occurred past the camera, meaning the vehicle would have been traveling at least partially on the shoulder of I-85. The third camera facing downstream from the bridge was used as a backup in case either of the other two cameras malfunctioned. Figure 4 shows the location and orientation of the cameras at the Durham site.

Figure 4 Durham I-85 site camera configuration

Bluetooth detection devices were installed in three locations around this lane drop. The upstream devices were referenced against a device that was installed approximately 350 feet downstream from the lane drop (Unit 1 in Figure 3). Because two freeways merge upstream of this lane drop (I-85 and NC-147/Durham Freeway), a Bluetooth device was installed on each of these freeway sections prior to the merge. On NC-147, the device was installed just beyond the bridge overpassing I-85 (Figure 3, Unit 2), approximately 1.3 miles from the end of the lane drop. On I-85, a device was installed on the shoulder of the freeway not far from the end of the Cole Mill Road interchange entrance ramp (Figure 3, Unit 3), approximately 1.5 miles from the lane drop. The location of these devices was chosen due to proximity to the ideal data capture location and proximity to a post or tree which the devices could be attached for security purposes.

Some issues that were experienced at this site included tampering with cameras by the public and damaged equipment. This created some problems as the two cameras installed on the Sparger Road bridge were pried open and subsequently experienced water damage due to rain after the boxes were opened. Camera wires were also cut at this site, as pedestrians often traversed this bridge to get from the neighborhoods on the north side of the bridge to the stores on the south side of the bridge. Fortunately, this did not prevent the capture of all necessary video, but simply prolonged the amount of time the equipment had to remain in place. Also, the travel time data capture resulted in relatively low sample sizes, particularly for the route from NC-147 to the end of the lane merge. This is likely due to the low occurrence of congestion combined with the infrequency of drivers having Bluetooth activated on devices in their vehicles, as only vehicles with Bluetooth devices activated (phone or vehicle) can be captured using this equipment.

Merge Data Analysis

For the Durham zipper merge site, 28,292 vehicles were counted for the study sample from the cameras on the bridge before the zipper merge was installed, having the following lane utilization:

Table 2 Durham-Before Lane Utilization

Lane	Vehicles	% of Total
Merge Lane	3540	12.51%
Middle	11914	42.11%
Median	12838	45.38%
All Lanes	28292	100.00%

After the zipper merge was installed, the study sample totaled 22,104 vehicles observed and had the following breakdown:

Table 3 Durham-After Lane Utilization

Lane	Vehicles	% of Total	Significant change?	p-value
Merge Lane	2380	10.77%	Yes	0
Middle	9521	43.07%	Yes	0.03
Median	10203	46.16%	Yes	0.0801
All Lanes	22104	100.00%	-	-

The percentage of vehicles using the ending, or merge, lane decreased slightly between the before and after periods, with 29.8% of the vehicles in this lane continuing to within view of the camera at the merge point for the before period (1,056 vehicles), and 31.8% continuing downstream to within view of the merge camera for the after period (756 vehicles), meaning that although a lower percentage of vehicles utilized the ending lane from the before to the after period, these vehicles continued in the ending lane further during the after period when compared to the before period, utilizing more of the roadway's capacity. The percentage of total merging vehicles in each merging zone was compared. The merging zones for this site were as follows:

- *Beyond 200 feet* – vehicles that were in the closing lane and within view of the camera observing merges that merged before coming within 200 feet of the camera
- *100-200 feet* – vehicles that merged from the closing lane to the adjacent through lane at a distance between 100 and 200 feet from the camera
- *0-100 feet* – vehicles that merged within 100 feet of the camera
- *Past Camera* – vehicles that had not yet begun merging before passing the camera (i.e., vehicles driving on the shoulder)

As can be seen in Figure 5, dangerous merges – defined as vehicles merging past the camera – decreased significantly (p-value = 0). This means that driver merging behavior was much safer during the after period. Also, it appears that drivers merged more fluidly while moving as a result of the zipper merge, as drivers did not continue in the right lane all the way to the end of the lane drop, but rather merged shortly before the lane drop, likely at higher speeds, instead of waiting until the last possible moment to merge into the left lane. Figure 5 shows the changes in merging behavior in each of the merging zones between the before and after periods, each with a p-value of virtually zero.

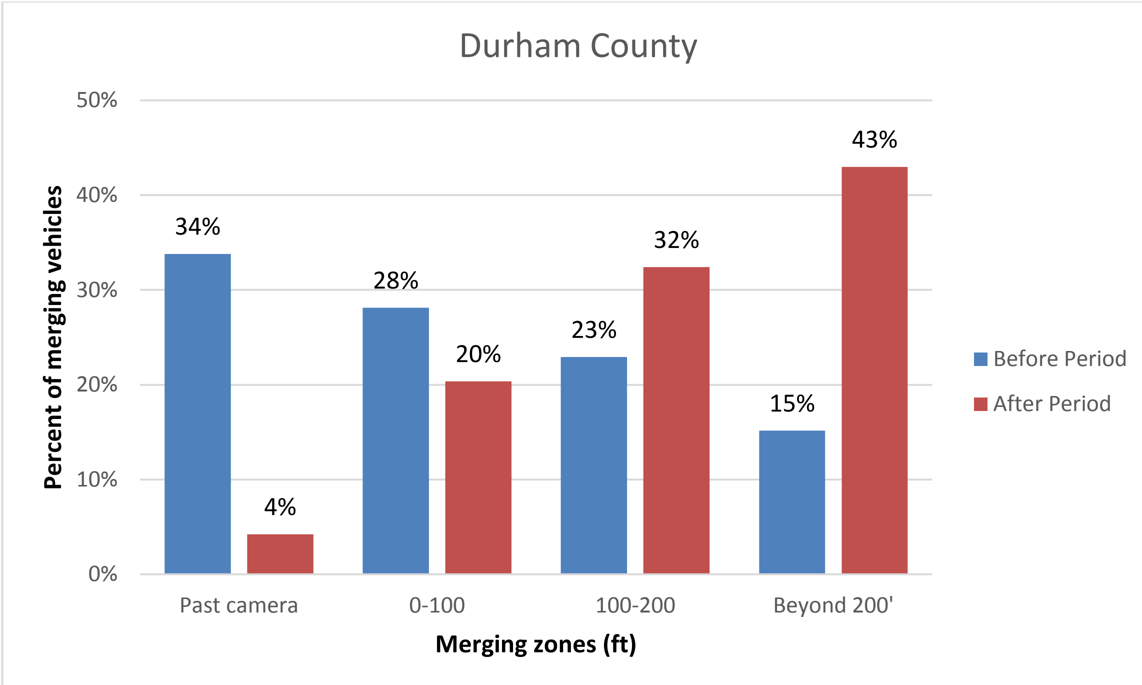

Figure 5 Durham County site merge distance comparison

Travel Time Data Analysis

For vehicles that only traveled on I-85, travel times decreased only slightly during two periods at the end of May and middle of June having an average travel time of one minute and 29.5 seconds over the 1.5 mile stretch (n=524 vehicles). After installation of the zipper merge, this same stretch of roadway saw an average travel time drop slightly to one minute and 28.5 seconds (n=215 vehicles). An independent samples t-test was performed to compare average travel time in the Before and After conditions. A statistically significant difference in average travel time was found at the 90% confidence level between the Before (M=1.492, SD=0.115, n=524) and the After (M=1.475, SD=0.114, n=215) conditions; t(737)=1.81, p=0.0708. The average travel time decreased by 0.017 minutes (or 1.020 seconds) between the two periods. This decrease in travel time equates to an increase of approximately one mile per hour when comparing the space mean speed (SMS) of the After period to that of the Before period.

For vehicles that traveled from NC-147 to I-85, travel times decreased a little more once the zipper merge was implemented. Before the zipper merge was installed, vehicles had an average travel time of one minute and 17.6 seconds (n=183 vehicles). After installation of the zipper merge, vehicles had an average travel time of one minute and 14.2 seconds (n=55 vehicles). An independent samples t-test was performed to compare average travel time in the Before and After conditions. There was a statistically significant difference in average travel time at the 99% confidence level between the Before (M=1.293, SD=0.093, n=183) and the After (M=1.237, SD=0.102, n=55) conditions; t(236)=3.79, p=0.0002. The average travel time decreased by 0.056 minutes (or 3.360 seconds) between the two periods. Over the 1.3-mile corridor, this equates to an increase in average space mean speed (SMS) of 2.8 miles per hour after installation of the zipper merge.

4.1.2. NC-58 in Carteret County

Site Description

The Carteret County site is a permanent lane drop on an arterial that drops from two lanes to one before crossing the ocean sound into Emerald Isle, NC. This site has a 45 mile per hour posted speed limit and experiences heavy congestion during peak spring and summer vacation holidays. The before period was observed on and around Memorial Day weekend 2016. The zipper merge signage was installed on June 28, 2016. There were two after periods observed for this site: one on and around the July Fourth holiday and the other surrounding Labor Day weekend, both in 2016. The main reason for conducting two after period studies at this site was because extra signage was installed between these study periods which was intended to influence drivers to use both through lanes on southbound NC-58 going through the intersection with NC-24. It was observed during the first after period that drivers may not understand that the right through lane was indeed a through lane because it opens up around a curve, giving drivers the impression that it may be a right turn lane, discouraging them from utilizing it properly. Therefore, a sign which stated "Use Both Through Lanes" was installed at the location where the right through lane opened up on southbound NC-58 as a way to inform drivers that it is a through lane. A diagram of this site is shown in Figure 6, once again with the blue stars representing the Bluetooth device locations and the red stars representing the camera locations. Figure 7 shows a closer perspective of the lane closure and the cameras used to observe the corridor.

Figure 6 Carteret County site diagram

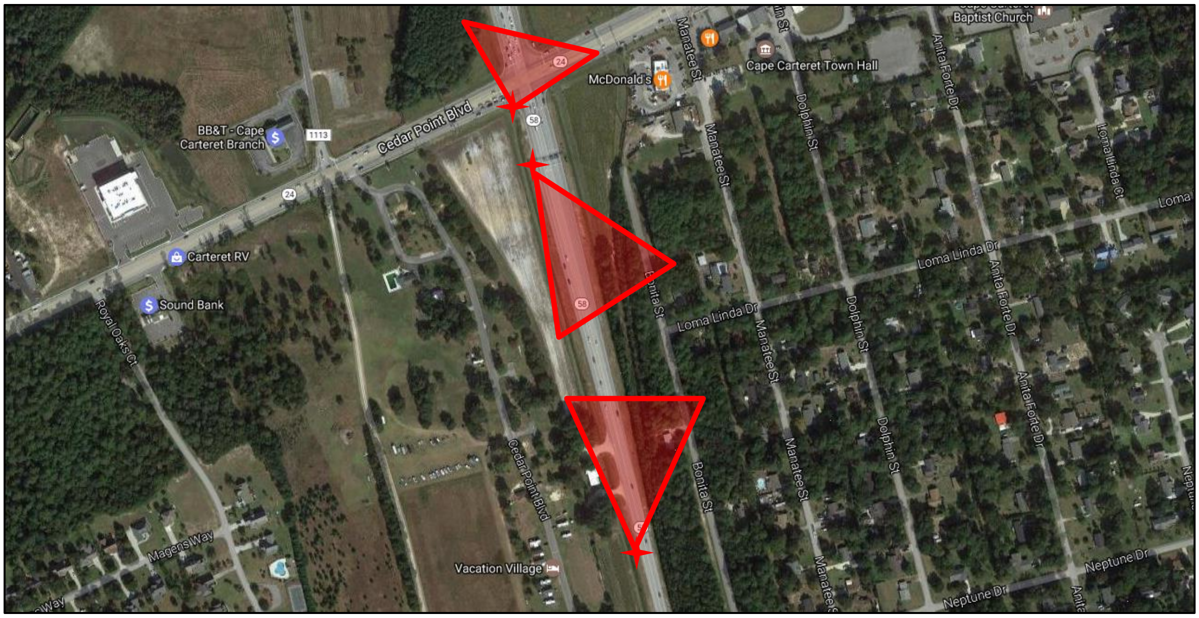

Figure 7 Carteret County site camera configuration

Three cameras were installed at this site to monitor traffic along the southern leg of the intersection, which includes the lane drop. One camera was installed at the intersection as a means of capturing lane utilization through the intersection to determine if the right lane leading up to the lane drop was being more heavily utilized as a result of the zipper merge, which was desired by the local NCDOT representatives because that lane is typically underutilized, which results in lower throughput through the intersection. Another camera was attached to a sign gantry approximately 250 feet south of the intersection, which would serve as a backup if either of the other cameras malfunctioned, as it faced downstream on NC-58 toward the lane drop. The third camera captured the lane drop itself and was placed on a sign approximately 150 feet from the end of the right lane. At this location, there is less than five feet of pavement remaining in the right lane adjacent to this camera, making it ideal to catch drivers making unsafe merges at the end of the taper. This means that a vehicle that had not yet begun merging into the left lane before passing the camera was driving at least partially on the shoulder of NC-58.

There were five Bluetooth detection devices installed at this site. One device (Figure 6, Unit 1) was placed just before the bridge on NC-58 as the reference point for all of the other devices, as this would provide the travel times between each of the other units and this one unit through the lane drop. Two other units were located on eastbound NC-24 west of the intersection with NC-58. These two devices were placed for the right-turning traffic coming from the western leg of the intersection, as this movement tends to see high volumes and long queues during holiday travel periods and the research team was unsure of how long the queue would be. The first of these units (Figure 6, Unit 2) was placed 1.2 miles west of the intersection, or 1.8 miles from the reference unit that was beyond the end of the lane drop, and the second (Figure 6, Unit 3) was 0.3 miles west of the intersection, or 0.9 miles from the reference unit. One unit was installed on the northbound side of NC-58 for the purpose of capturing southbound traffic on NC-58 (Figure 6, Unit 4). This unit was 0.5 miles north of the intersection, or 1.1 miles from the reference unit and likely did not capture the back of queue, as the research team was unsure of the length of this queue prior to installation. Lastly, another unit (Figure 6, Unit 5) was installed on the eastern side of the intersection, on the shoulder of westbound NC-24, to capture vehicles that would turn left at the intersection to go across the Emerald Isle bridge. This unit was one mile east of the intersection, or 1.6 miles away from the reference unit.

Merge Data Analysis

On NC-58 in Carteret County, 7,708 vehicles were observed traveling through the merge area during the before period, with 69% of the vehicles already positioned in the left lane before reaching the merge location and 31% of vehicles being in the right, or dropped, lane.

After the zipper merge was installed in late June, 5,576 vehicles that traveled through the merge area were observed during the July Fourth holiday weekend and after, with 64% being prepositioned in the left lane and 36% being in the right lane, which was a significant increase (p-value = 0) when compared to the data collected prior to the zipper merge being installed.

Before the Labor Day holiday, a new sign was installed on southbound NC-58 prior to reaching the intersection with NC-24 which indicated when the highway opens from one lane to two, the extra lane is also a through lane, which the research team believes most drivers incorrectly assume to be a right turn lane. This is especially evident around holidays, as many tourists are traveling to the nearby beaches for vacation. It was important to the research team that drivers understand that this lane was indeed a through lane, as this had the potential to increase the amount of vehicles in the right lane which traveled through the intersection (adding capacity), and ultimately merging downstream at the merge location. For this second after period in September, 5,981 vehicles were observed traveling through the merge area, with 67% being in the left lane and 33% being in the right lane before reaching the merge location. This increase in vehicles in the right lane was statistically significant when compared to the before period (p-value = 0.0308), albeit only a modest increase. However, it was a decrease when compared to the July data, which is a pattern that follows for all of the data at this site.

The merge zones for the Carteret County site were the same as the Durham site and the comparisons of the before and after periods are shown below in Figure 8 and Figure 9.

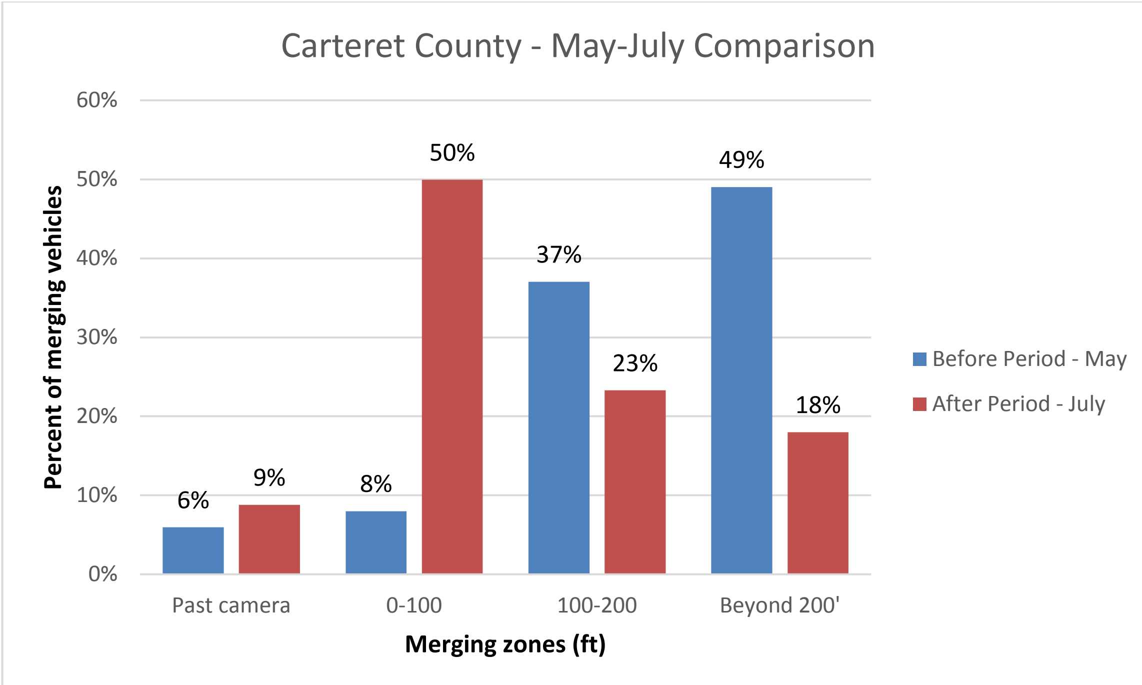

Figure 8 Carteret County site merge distance comparison (May-July)

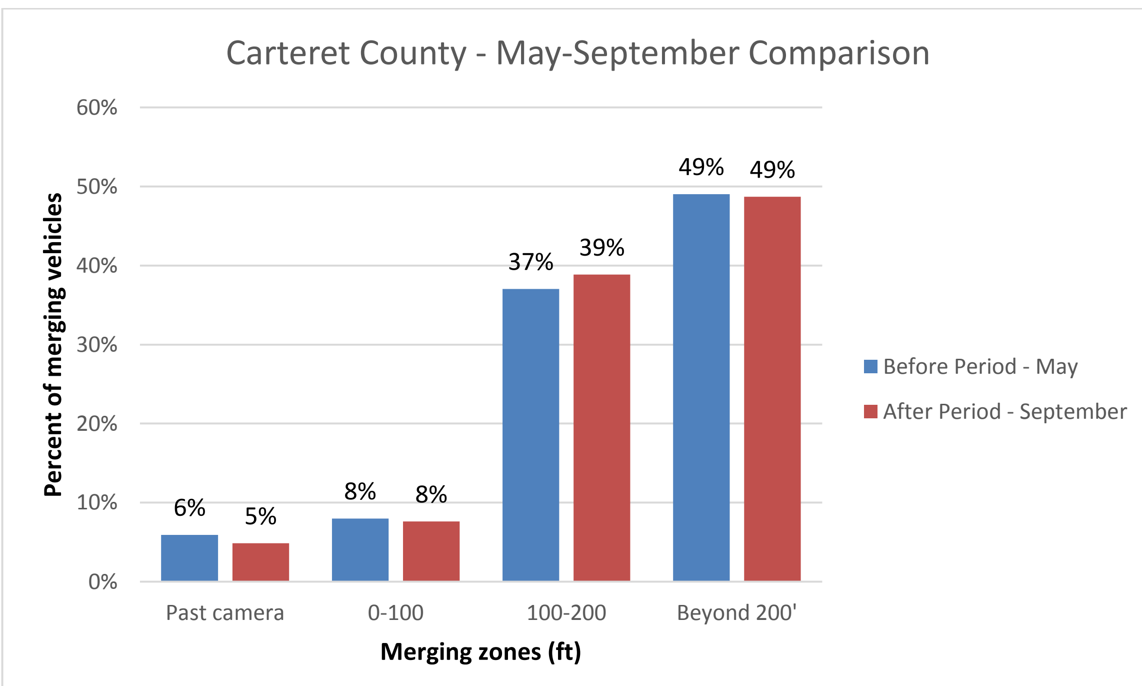

Figure 9 Carteret County site merge distance comparison (May-Sept)

As can be seen in Figure 8, drivers did not merge any safer in the "Past camera" merge zone, with more drivers actually merging past the camera. The p-value for this comparison was statistically significant at 0.03, but this increase was modest at best. Even more interesting was the sharp increase in merges that occurred in the 0-100 merge zone directly upstream from the camera (significant at p = 0). In this range at this site, vehicles could still be fully within the right lane without driving on the shoulder of the roadway. Also, this site is a minor arterial according to the Federal Highway Administration *(21)*, whereas the other two study sites are freeways, which means speeds are always lower than at the other two sites, meaning later merges are safer here than at the other two study corridors. The higher number of merges in the 0-100 merge zone could also be attributed to the media blitz that occurred shortly before the first implementation of the zipper merge in both central North Carolina and in Carteret and adjacent counties, as drivers were instructed in the press release to merge late instead of early if congestion was occurring.

The press release timing is also possibly to blame for the lack of significant change between the May and September study period merge behavior (Figure 9), as there were no new media spots that occurred after the initial implementation of the zipper merge in this area. It is possible that the people vacationing during the July 4 holiday are not necessarily the same as those traveling for Labor Day. Another possibility is that drivers may have reverted back to their original behavior because of the lack of information being disseminated regarding the second test of the zipper merge around the Labor Day holiday.

Travel Time Data Analysis
The Carteret County lane drop was downstream from a major intersection in the county, with vehicles coming from three different directions to traverse this corridor. Vehicles could travel east on NC-24 and turn right onto NC-58 to cross the Emerald Isle bridge, travel west on NC-24 to turn left onto NC-58 to cross the bridge, or travel south on NC-58 and come straight through the NC-24/NC-58 intersection.

For the unit farthest west on NC-24, 154 vehicles were captured prior to installation of the zipper merge and had an average travel time of two minutes and 49.3 seconds (Space Mean Speed, or SMS = 38.3 mph). Immediately after the installation of the zipper merge at the end of June, 35 vehicles were captured, with an average travel time of two minutes and 54.3 seconds (SMS = 37.2 mph). There was no statistically significant difference in average travel time between the Before (M=2.822, SD=0.458, n=154) and the July Fourth After (M=2.905, SD=0.941, n=35) conditions; t(187)=0.51, p=0.6114. The average travel time increased by 0.083 minutes (or 4.980 seconds) between the two periods. Over the 1.8-mile corridor, this equates to a decrease in average space mean speed of 1.1 miles per hour after installation of the zipper merge. For the time period around Labor Day, 91 vehicles were captured and had an average travel time of three minutes and 30.3 seconds (SMS = 30.8 mph). An independent samples t-test was performed to compare average travel time in the Before and After conditions. There was a statistically significant difference in average travel time at the 99% confidence level between the Before (M=2.822, SD=0.458, n=154) and the Labor Day After (M=3.505, SD=1.232, n=91) conditions; t(240)=5.08, p<0.0001. The average travel time increased by 0.683 minutes (or 40.980 seconds) between the two periods. Over the 1.8-mile corridor, this equates to a decrease in average space mean speed of 7.5 miles per hour during the Labor Day data collection period.

Similarly, for the closer unit on the west side of the intersection, 148 vehicles had an average travel time of one minute and 38.4 seconds (SMS = 32.9 mph) before the zipper merge was installed, while 29 vehicles had an average travel time of one minute and 28.4 seconds (SMS = 36.7 mph) on June 30, immediately after installation of the zipper merge. There was a statistically significant difference in average travel time at the 95% confidence level between the Before (M=1.640, SD=0.694, n=148) and the July Fourth After (M=1.473, SD=0.228, n=29) conditions; $t(175)=2.35$, $p=0.0202$. During the second observed zipper merge test in Carteret County (Labor Day traffic), 72 vehicles had an average travel time of two minutes and 25.9 seconds (SMS = 22.2 mph). There was a statistically significant difference in average travel time at the 99% confidence level between the Before (M=1.640, SD=0.694, n=148) and the Labor Day After (M=2.432, SD=1.319, n=72) conditions; $t(218)=4.78$, $p<0.0001$.

For traffic traveling south on NC-58 and going through the intersection to cross the Emerald Isle bridge, 76 vehicles had an average travel time of two minutes and 50.2 seconds (SMS = 23.3 mph) prior to the zipper merge installation, while 39 vehicles traveling around the July Fourth holiday had an average travel time of two minutes and 45.8 seconds (SMS = 23.9 mph). There was no statistically significant difference in average travel time between the Before (M=2.836, SD=0.838, n=76) and the July Fourth After (M=2.763, SD=0.777, n=39) conditions; $t(113)=0.45$, $p=0.6546$. The average travel time decreased by 0.073 minutes (or 4.38 seconds) between the two periods. Over the 1.1-mile corridor, this equates to an increase in average space mean speed of 0.6 miles per hour during the Labor Day data collection period. During the Labor Day data collection period, 41 vehicles had an average travel time of four minutes and 21.5 seconds (SMS = 15.1 mph). There was a statistically significant difference in average travel time at the 99% confidence level between the Before (M=2.836, SD=0.838, n=76) and the Labor Day After (M=4.358, SD=1.925, n=41) conditions; $t(115)=4.82$, $p<0.0001$. The average travel time increased by 1.522 minutes (or one minute and 31.320 seconds) between the two periods. Over the 1.1-mile corridor, this equates to a decrease in average space mean speed of 8.2 miles per hour between the Memorial Day and Labor Day data collection periods.

Finally, for vehicles traveling from the east side of the intersection and making a left turn onto NC-58, 68 vehicles had an average travel time of four minutes and 11.6 seconds prior to the zipper merge installation, which equates to a space mean speed of 22.9 miles per hour. For the period surrounding July Fourth, 45 vehicles were captured and had an average travel time of three minutes and 43.6 seconds, which is a space mean speed average of 25.8 miles per hour. There was a statistically significant difference in average travel time at the 90% confidence level between the Before (M=4.193, SD=1.509, n=68) and the July Fourth After (M=3.726, SD=1.167, n=45) conditions; $t(111)=1.76$, $p=0.0816$. The average travel time decreased by 0.467 minutes (or 28 seconds) between the two periods, which is an increase in average speed of 2.9 miles per hour. Travel time was not captured for the time period surrounding Labor Day for this movement due to the malfunction of the upstream unit.

4.1.3. I-85 in Vance and Warren Counties

Site Description

The only zipper merge site that was in a work zone and not implemented at a permanent lane drop was in Vance and Warren Counties, near the border with southern Virginia. The NCDOT and the research team felt it was necessary to test the zipper merge in at least one work zone. This work zone had been ongoing for several years, although the exact location of the work shifted periodically. The work zone consisted of lane drops and lane shifts over several miles of interstate. The speed limit along this corridor is typically posted at 65 miles per hour through the areas unaffected by construction; however, the posted speed limit was 55 miles per hour through the work zone. Likewise, this portion of the corridor is two lanes, but dropped to one lane in the study locations. Data was collected starting on August 19, 2016 for the before period. The zipper merge was implemented during the first week of October, with the after period data collection occurring until November 2, 2016. Congestion during these periods was almost always on weekdays during mid- to late afternoon, including the peak commuter periods of 4-6 PM.

For the after study period, the NCDOT enlisted one of their regular contractors to install dynamic signage in the zipper merge corridor. When any vehicle was detected going below 40 miles per hour, this equipment would activate flashers attached to signs telling drivers to “Use All Lanes When Flashing” and “Merge Ahead When Flashing” upstream from the lane drop and to “Take Turns Merging Here When Flashing” near the end of the right lane, and these flashers would deactivate whenever average speeds reached above 50 miles per hour. Images of these signs installed at this site are in Figure 10.

a) “Use All Lanes When Flashing” b) “Merge Ahead When Flashing” c) “Take Turns Merging Here When Flashing”

Figure 10 Work Zone Zipper Merge Signage

One major incident occurred that changed the After data collection period. Due to some miscommunication and the presence of numerous work zones around this study site, the zipper merge signage was installed at a location that was not observed during the before period data collection. This resulted in the research team having to collect data at two locations on the northbound side of I-85 instead of the two original locations – one observing northbound traffic and the other observing southbound traffic. This meant that a direct comparison to the zipper merge location could not be made from the before period, but traffic along this stretch of I-85 is fairly similar and consistent from Henderson, NC to the Virginia state line, allowing the research team to still be able to use the Before data from northbound I-85. Figure 11 displays the before and after period data collection locations, with the Before period study area being represented by blue lines and the After period study areas being represented by red lines.

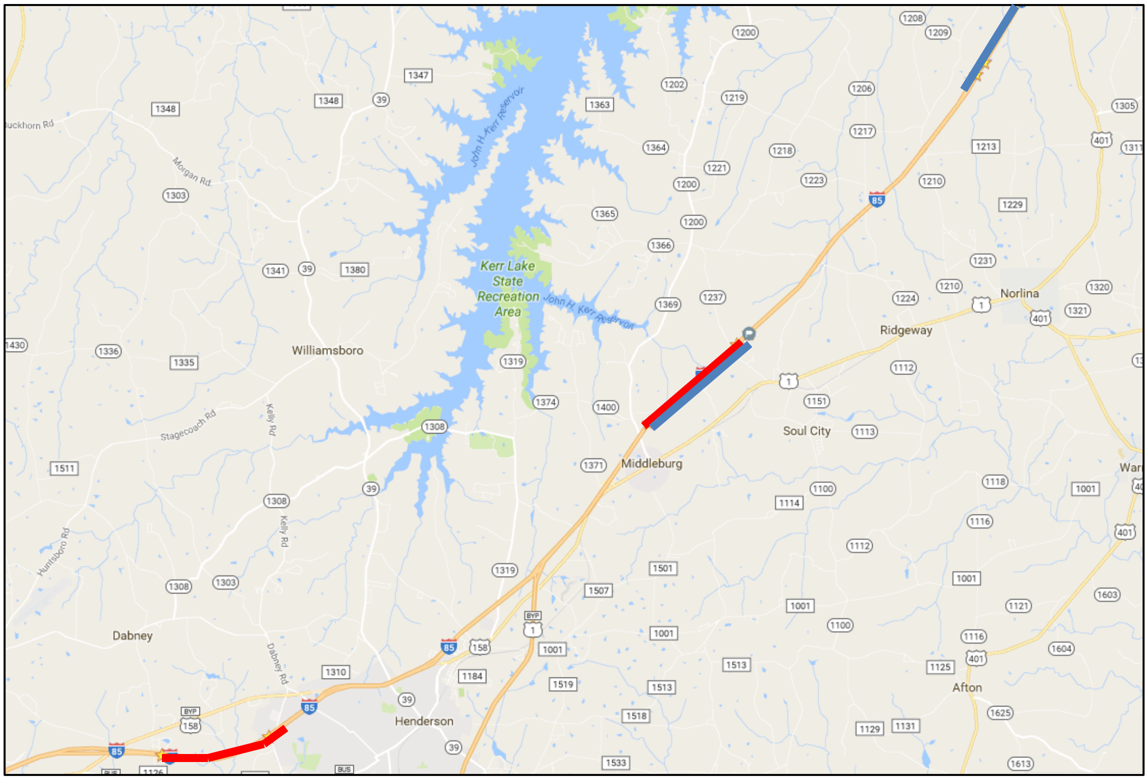

Figure 11 Vance/Warren County site diagram

Four cameras were installed at this site during both study periods. For the before period, two cameras were installed in the northbound direction and two were installed in the southbound direction. On each side of the interstate, one camera observed oncoming traffic while looking upstream from the beginning of the lane drop, while the other camera observed traffic as it entered the lane drop segment. In each case, the camera facing upstream traffic captured lane utilization and the camera facing merging traffic captured the merge location of vehicles entering the left lane from the right lane. The cameras observing northbound traffic were installed on sign posts near the interchange with Manson-Drewry Road, whereas the cameras on the southbound side were both attached to an arrow board being utilized by the contactor to indicate the lane drop, which was simply because this was the only location available that could provide a good vantage point of the lane drop. For the northbound Before period data, a vehicle that had not yet begun merging into the left lane before passing the camera would have been driving beyond the temporary solid white lane line and therefore was not in compliance with the temporary lane configuration. There was only about two feet of available space remaining in the right lane adjacent to this camera. Likewise, barrels were in place on the temporary shoulder on the opposite side of the temporary solid white line, but still allowed room for late merging vehicles to pass.

For the After period, the cameras previously stationed on the northbound side of the interstate remained in place, which allowed for a direct comparison to the Before data. Although not implemented at this location, the zipper merge was upstream from this original northbound location, which provided the potential to capture any proximal effects from the upstream zipper merge signage. The other two cameras were placed further south on the northbound side of I-85 at an adjacent work zone, as this was where the zipper merge was implemented. These cameras were placed similarly to those on the southbound side during the before period, on an arrow board at the beginning of the lane drop. The cameras used during the After period data collection effort captured the same information as the cameras in the before period. However, because a camera was not placed near the end of the lane drop at the zipper merge location, a dangerous late merge would have been coded differently than at the downstream site. The camera at the downstream site faced upstream traffic (i.e., vehicles traveling toward the camera) from very near the end of the lane merge. However, the camera capturing merges at the upstream zipper merge site faced downstream (i.e., vehicles traveling away from the camera) and was not near the end of the lane drop because there was nowhere to adequately mount the camera in that location. Ultimately, it was decided to only compare the merge location of vehicles at the downstream non-zipper merge site between the Before and After periods, as merge location could be compared directly because this was the same site. However, lane utilization rates could be compared between the Before period data at the downstream non-zipper merge site and the After period data at the upstream zipper merge site. The data at the zipper merge site was only collected when the zipper merge signage was activated.

Similar to the camera installation, Bluetooth devices were installed on both sides of I-85 for the Before period, but only on the northbound side during the After period. In all cases, the upstream units were placed approximately two miles upstream from the corresponding lane drop, while the downstream units were around 1,000 feet from the end of the lane drop. Travel time data, similar to the lane utilization rates, could be compared between the downstream, Before period site on northbound I-85 and the After period, upstream, zipper merge site.

Merge Data Analysis

Before installation of the zipper merge, 15,199 vehicles were observed traveling through the merge area on northbound I-85, with 15% of them using the right lane drop section and the remainder using the continuing left lane.

After installation of the zipper merge signage on the upstream work zone, the research team observed 4,657 vehicles traveling through this corridor when the zipper merge signs were active. The right lane saw an increase in lane utilization to 17%, and although this is minor, it was still statistically significant due to the number of vehicles observed (p-value = 0).

As can be seen in the following figure, the percentage of dangerous merges decreased by a small but statistically significant amount at the downstream lane drop that did not have zipper merge signage. Likewise, as stated in the site description, there were only two feet of available lane in the ending lane adjacent to the camera capturing the merge area, meaning that for this location, even merges that occur within view of the camera (particularly in the 0-100 feet merging zone) could be dangerous, as vehicles still only had less than six feet of available lane in the right lane within which to pass in relation to the temporary solid lane line at a point 100 feet from the camera, which is different than the site in Carteret County. Therefore, the sharp reduction in merges in the 0-100 feet merging zone shows a vast improvement with regards to safety. Likewise, as observed at the Durham site, drivers merged before the right lane tapered too much, possibly in order to maintain higher speeds and thereby more fluid merges. It could be that drivers at the Durham and Vance/Warren County sites were expecting to merge earlier because they were on higher speed corridors, in comparison to the Carteret County site. Each of these changes in behavior in the merging zones is significant at the 90% confidence level, with all changes in merging that occurred before the camera having a p-value of 0.

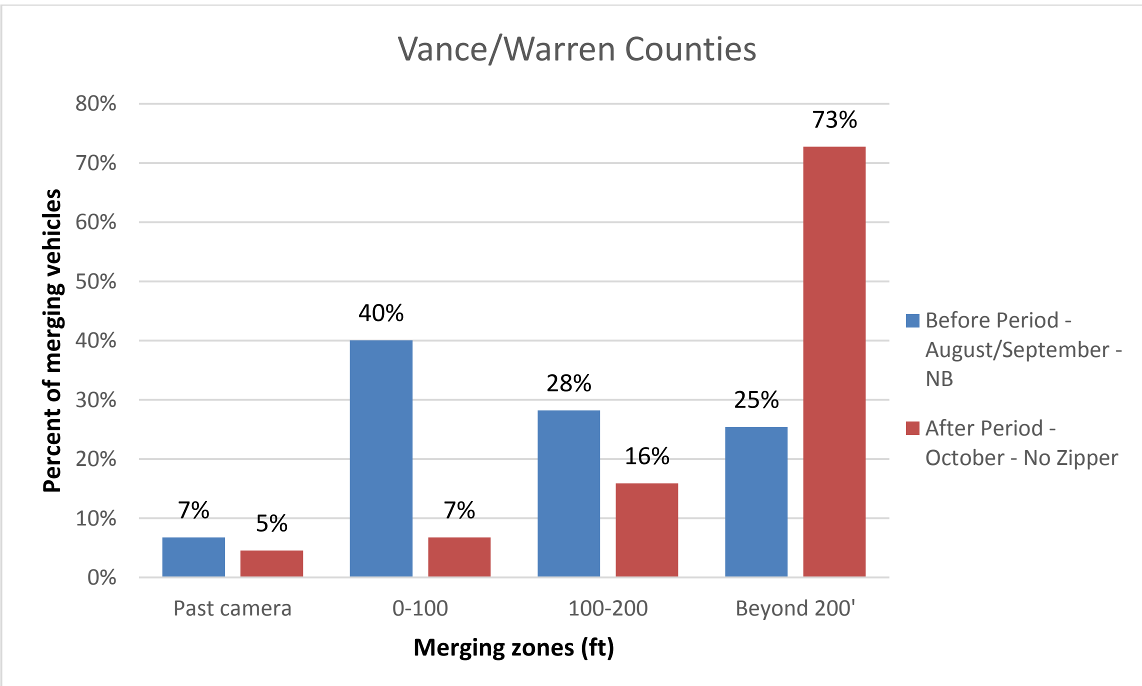

Figure 12 Vance/Warren County site merge distance comparison

Travel Time Data Analysis

Before the zipper merge was installed at the upstream lane closure, 194 vehicle travel times were captured with an average of four minutes and 37.0 seconds at the downstream lane drop on northbound I-85. The Bluetooth units at this location were 2.2 miles apart, which means the space mean speed average for the Before period was 28.6 miles per hour. After installation of the zipper merge at the upstream lane drop, 68 vehicle travel times were captured during activation of the zipper merge signage with an average of three minutes and 36.5 seconds, which is a space mean speed average of 39.9 miles per hour, as the Bluetooth units were 2.4 miles apart at the upstream zipper merge work zone. For the Before period at the downstream lane drop, there were no obvious outliers, as all travel times were below 10 minutes and video showed that traffic never stopped for an extended period of time, which may have indicated congestion caused by a wreck or some other outside factor. For the After period at the upstream lane drop, which had the zipper merge signage installed, all but three excessively high travel times were during one period on the same day, indicating this congestion was also likely caused by a wreck or some other outside factor. The lowest travel time during this period was 11 minutes and 45 seconds and they were as high as 20 minutes over the 2.4-mile corridor (12.3 and 7.2 mph averages, respectively). Therefore, the outliers above 10 minutes were removed from the dataset. There was a statistically significant difference in average travel time at the 99% confidence level between the Before (M=4.616, SD=1.489, n=194) and the July Fourth After (M=3.609, SD=1.938, n=68) conditions; $t(260)=4.42$, $p<0.0001$. The average travel time decreased by 1.007 minutes (or one minute) between the two periods, which is an increase in average speed of 11.3 miles per hour.

4.2. Wide Dotted White Lane Lines

4.2.1. Ten-Ten Road in Cary, NC

Site Description

Ten-Ten Road is a major arterial that traverses southern Wake County and connects the rapidly growing municipalities of Apex and Garner, as well as the already established Town of Cary and City of Raleigh. This site is downstream from a busy intersection with Kildaire Farm Road. Within 2,000 feet of this intersection to the east and west, Ten-Ten Road has a single lane in each direction, and then widens to have a turn lane in the middle of the road and auxiliary lanes that start before this intersection and continue for several hundred feet on each side before reducing back to a single lane. A diagram of this site is shown in Figure 13 (note: the image is oriented to true North, meaning the traffic traveling to the right on this image is the direction of interest to this project). This image shows the previous lane markings, as satellite imagery has not been updated to show the most recent lane markings.

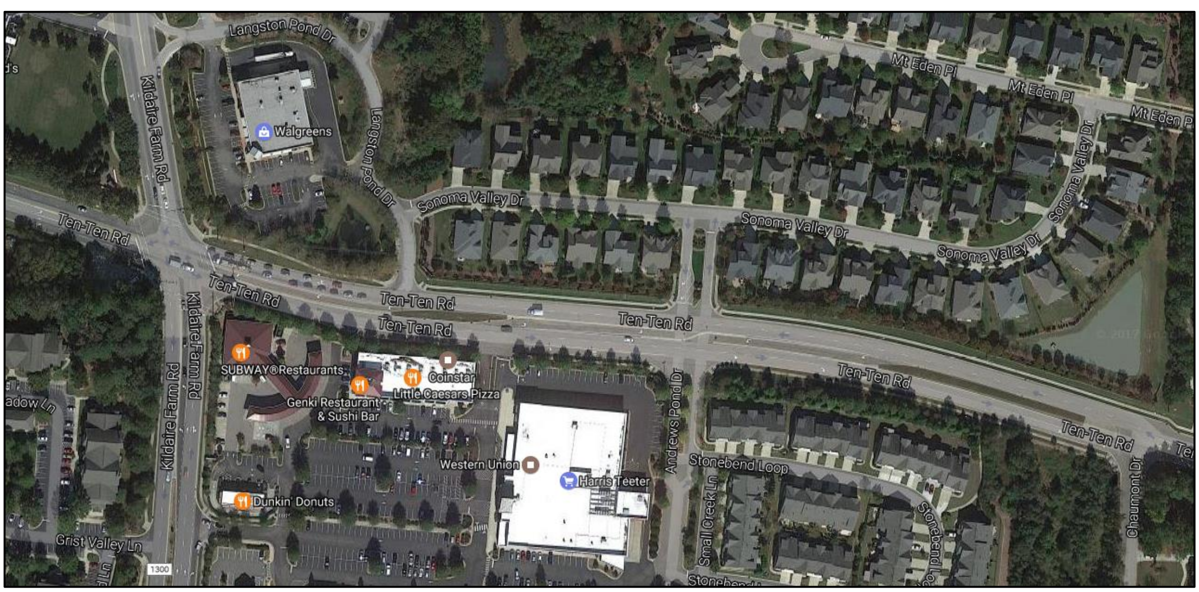

Figure 13 Ten-Ten Road site diagram

In the eastbound direction of Ten-Ten Road, the auxiliary lane opens approximately 400 feet before reaching the intersection and continues for approximately 1,500 feet beyond the intersection.

Previously, the marking that separated the two through lanes was a standard skip line (10-foot long markings 30 feet apart) with a solid white line starting about 600 feet from the end of the lane. This lane drops at the intersection with Chaumont Drive, which is a residential street. The neighborhood adjacent to Chaumont Drive is still being developed and therefore does not receive heavy commuter traffic. However, some drivers will use the auxiliary lane as a way to get through the intersection with Kildaire Farm Road and pass other drivers to continue down Ten-Ten Road. The speed limit of this portion of Ten-Ten Road is 45 miles per hour.

During this project, the auxiliary lane was restriped from Andrews Pond Drive (approximately 800 feet from the Kildaire Farm Road intersection) to have wide dotted white lane lines for approximately 300 feet before continuing to the original solid white line just before the end of the lane drop. Previously, this corridor was a standard skip line from Kildaire Farm Road to just after the intersection with Andrews Pond Drive, continuing to a solid white lane line for the remaining 630 feet until the Chaumont Drive intersection. Therefore, about 75 of the previous standard skip line and 225 feet of the previous solid line changed to the new wide dotted white lane line. Other than MUTCD compliance, the intent of this lane drop was to prevent erratic and aggressive lane change maneuvers through this corridor.

This site was observed over two days, one for the before period and one for the after period. Ideally, the presence of the new markings would encourage drivers to merge sooner in order to avoid dangerous, last-second movements. Because this segment is relatively short compared to the zipper merge sites, an unmanned aerial vehicle (UAV) was used to capture video footage of traffic during these days from the northeast corner of the corridor. The research team marked distances of every 100 feet with traffic cones during the before period that could be used to distinguish where vehicles merged into the continuing lane. These merging zones are indicated in the image below (Figure 14) taken from the video captured by the UAV that observed this site, and they are as follows:

- *Zone 1: 0-100 feet* – Vehicles that merged within 100 feet of the intersection with Andrews Pond Drive,
- *Zone 2: 100-200 feet* – Vehicles that merged between 100-200 feet from this intersection,
- *Zone 3: 200-300 feet* – Vehicles that merged between 200-300 feet from this intersection,
- *Zone 4: 300-400 feet* – Vehicles that merged between 300-400 feet from this intersection,
- *Zone 5: 400-500 feet* – Vehicles that merged between 400-500 feet from this intersection,
- *Zone 6: After 500 feet* – Vehicles that merged farther than 500 feet from the Andrews Pond Drive intersection but before the end of the right lane.

Figure 14 Diagram of merging zones for Ten-Ten Road site

There were a couple of minor issues experienced with this site. One issue was that the battery life of the UAV was very short, meaning it had to have numerous battery changes throughout the data collection, which resulted in short video clips for each flight (about 8-15 minutes per recording). Another issue was that the UAV pilots collected after period video before the new markings were in place because the research team was informed by the contractor that the markings would be installed by a certain date but they were not. Therefore, this required an extra data collection trip by the UAV pilots because they were unaware that the wide dotted lines had not been installed during the first after period data collection. However, data was still collected for both the before and after periods.

Merge Data Analysis

Prior to the installation of the wide dotted white lane lines at the site in Cary, 1,022 vehicles were observed traveling through the study corridor over a period of one hour and 44 minutes, a volume of 588 vehicles per hour, with 53 of those vehicles (5.2%) starting in the right lane and merging into the through lane. The merging pattern of these vehicles is shown in Figure 15. As can be seen in this figure, late merges did not appear to be a large problem at this site during the data collection that occurred prior to the installation of the wide dotted white lane lines. This is likely due to the solid white lane line starting shortly downstream from the Andrews Pond Drive intersection, which already discourages late merges.

After installation of the treatment, 1,770 vehicles were observed traveling through the study corridor over a period of three hours and 36 minutes, a volume of 490 vehicles per hour with 147 of those vehicles (8.3%) starting in the right lane and merging into the through lane. The merging behavior of those vehicles is shown in Figure 15. This figure shows that, in comparison to the Before period, some drivers waited slightly longer to merge but overall merging behavior did not change very much. The slightly later merges are likely due to the fact that the solid white lane line did not start until further downstream in the After period when compared to the Before period, which means the dashes extend further than they did before treatment installation. These later merges simply show that traffic is utilizing the extra merging space.

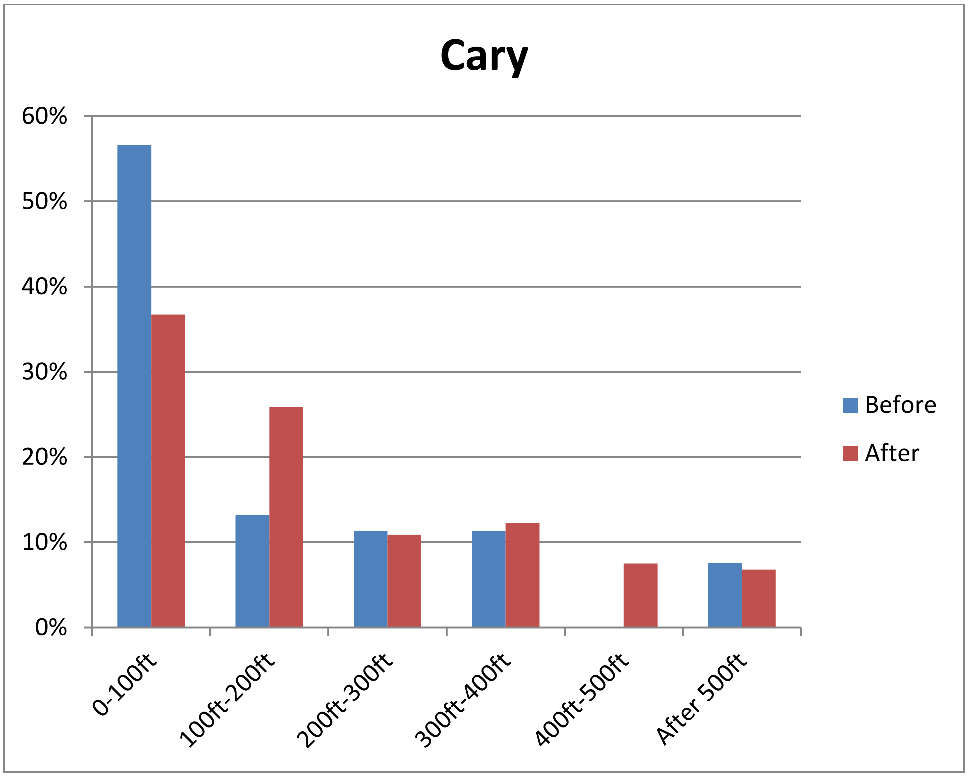

Figure 15 Merging behavior of Ten-Ten Road site before and after treatment

4.2.2. I-95 in Dunn, NC

Site Description

The site in Dunn, NC on I-95 was chosen because it was supposed to receive repaving and restriping during the study period and required updating to the new MUTCD standard of wide dotted white lane lines. This provided the research team with two freeway auxiliary lanes for observation as both directions of travel were observed at this location. Similar to the Ten-Ten Road site, restriping did not occur as early as was stated, resulting in extra before period data being captured that was intended to be after period data. Likewise, for an unknown reason, only one direction of the freeway received the new treatment, meaning the other direction could not be used in the before-after data comparison. However, the team was still able to capture after period data on one side of the freeway once the restriping did occur, resulting in another wide dotted white lane line study site, which was greatly beneficial to this research.

I-95 carries heavy truck traffic and vacation traffic through North Carolina and Dunn is a rural town in the southeastern part of the state. The speed limit on this portion of I-95 is 65 miles per hour. The interstate has two through lanes in each direction through Dunn. This site is between Exits 72 and 73, which are approximately 3,000 feet apart from bridge to bridge, with the auxiliary lanes being about 1,500 feet long from gore to gore. The auxiliary lane was previously marked with standard skip lines from gore to gore in each direction, but once this portion of I-95 was repaved, the northbound auxiliary lane was marked with the wide dotted white lane lines for the full length of the lane. Note that construction activity was not immediately adjacent to the study area during data collection and therefore did not affect the data collection or driver behavior. An aerial image of this site is shown in Figure 16.

Figure 16 I-95 site diagram

As was done at the site in Cary, NC, a UAV was used to collect video at this site. The UAV was able to go up several hundred feet into the air in order to capture the entire study corridor from one vantage point. The research team used the light posts along the side of the interstate to indicate merge distances, as cones were not easily visible from the height the UAV was flying in order to capture the entire corridor, and because the light posts are spaced fairly evenly apart. For this site, the research team was observing merge locations for vehicles entering and exiting I-95. For the northbound direction, which received the treatment, the merging zones for both the entrance and exit ramps are shown in Figure 17 and were as follows:

- *Zone 1: Gore Point-100 feet* – Vehicles that merged within 100 feet of the entrance ramp gore point
- *Zone 2: 100-330 feet* – Vehicles that merged between 100-330 feet from the entrance ramp gore point,
- *Zone 3: 330-560 feet* – Vehicles that merged between 330-560 feet from the entrance ramp gore point,
- *Zone 4: 560-790 feet* – Vehicles that merged between 560-790 feet from the entrance ramp gore point,

- *Zone 5: 790-1,020 feet* – Vehicles that merged between 790-1,020 feet from the entrance ramp gore point,
- *Zone 6: 1,020-1,250 feet* – Vehicles that merged between 1,020-1,250 feet from the entrance ramp gore point,
- *Zone 7: 1,250-1,480 feet* – Vehicles that merged between 1,250-1,480 feet from the entrance ramp gore point,
- *Zone 8: 1,480-Gore Point (1,585 feet)* – Vehicles that merged between 1,480 feet from the entrance ramp gore point to the exit ramp gore point (1,585 feet from the entrance ramp gore point),
- *Zone 9: Gore Point-1,810 feet* – Vehicles that merged beyond the exit ramp gore point, but before the beginning of the ramp median grass (1,710 feet from the entrance ramp gore point).

Figure 17 Merging distances on northbound I-95 in Dunn, NC

For the southbound direction, which did not receive the treatment, the merging zones for both the entrance and exit ramps are shown in Figure 18 and were as follows:

- *Zone 1: Gore Point-255 feet* – Vehicles that merged within 255 feet of the entrance ramp gore point
- *Zone 2: 255-485 feet* – Vehicles that merged between 255-485 feet from the entrance ramp gore point,
- *Zone 3: 485-715 feet* – Vehicles that merged between 485-715 feet from the entrance ramp gore point,
- *Zone 4: 715-945 feet* – Vehicles that merged between 715-945 feet from the entrance ramp gore point,
- *Zone 5: 945-1,175 feet* – Vehicles that merged between 945-1,175 feet from the entrance ramp gore point,

- *Zone 6: 1,175-Gore Point (1,255 feet)* – Vehicles that merged between 1,175 feet from the entrance ramp gore point to the exit ramp gore point (1,255 feet from the entrance ramp gore point),
- *Zone 7: Gore Point-1,405 feet* – Vehicles that merged beyond the exit ramp gore point, but before the beginning of the ramp median grass (1,405 feet from the entrance ramp gore point).

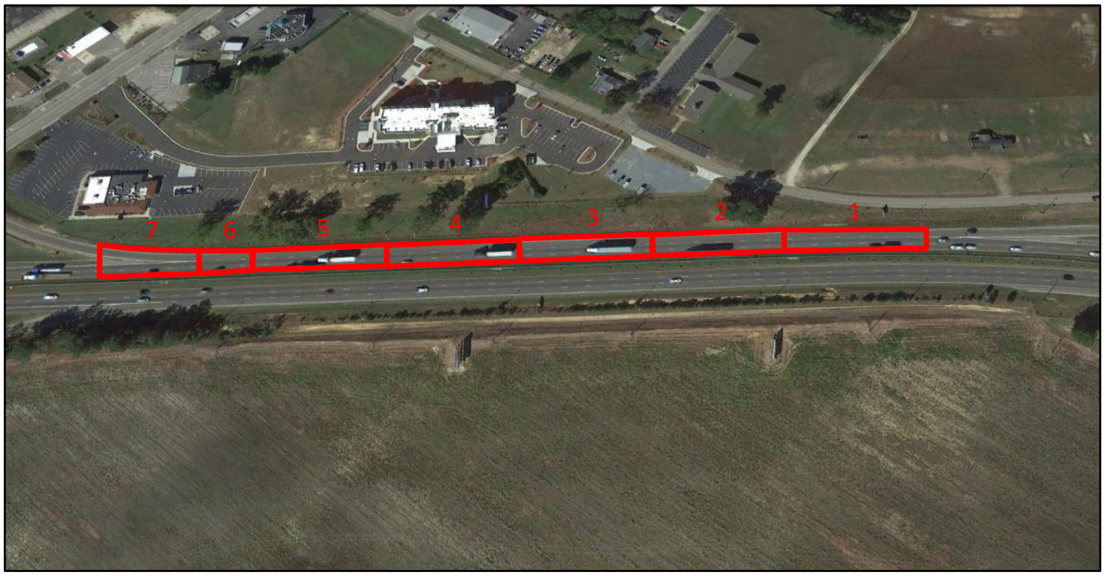

Figure 18 Merging distances on southbound I-95 in Dunn, NC

Note that for both directions, the area between the grass median separating the on ramp from the freeway and the marked gore point was observed for merging traffic, but no traffic merged in this area in either direction. Likewise, as can be seen in the following figures, little to no traffic was observed merging beyond the gore point at the exit ramp.

Merge Data Analysis

Prior to installation of the wide dotted white lane lines at the I-95 site in Dunn, NC, the northbound direction of traffic, which received the treatment, saw 1,988 vehicles traveling in and adjacent to the entrance ramp at the gore point of this ramp – 122 vehicles in the auxiliary lane (6.1%), 1,032 vehicles in the lane directly adjacent to the auxiliary lane (51.9%) and 834 in the lane adjacent to the freeway median (42.0%). After installation of the wide dotted white lane lines on the northbound side, 5,591 vehicles were observed at the entry ramp gore point – 259 vehicles in the auxiliary lane (4.6%), 2,589 vehicles in the lane directly adjacent to the auxiliary lane (46.3%) and 2,743 vehicles in the lane adjacent to the median (49.1%). As shown in Figure 19, the distribution of merging behavior changed for this ramp, shifting from a normalized distribution to a right-tailed distribution. This means that vehicles were merging earlier into the continuing freeway lanes from the auxiliary lane after the wide dotted white lane lines were in place, as opposed to merging halfway down the auxiliary lane and later, which was the behavior prior to the treatment. These distributions were compared using a chi-squared test, which showed that these changes were statistically significant at the 99% confidence level with a p-value less than 0.0001. The on ramp in the northbound direction is approximately 875 feet long from the top of the ramp to the gore point, providing ample distance for vehicles to achieve free flow speeds, so the earlier merging is desirable, as this means drivers were not waiting to merge late anymore, which can often result in merging drivers cutting off other drivers already in the through lane in order to avoid having to exit.

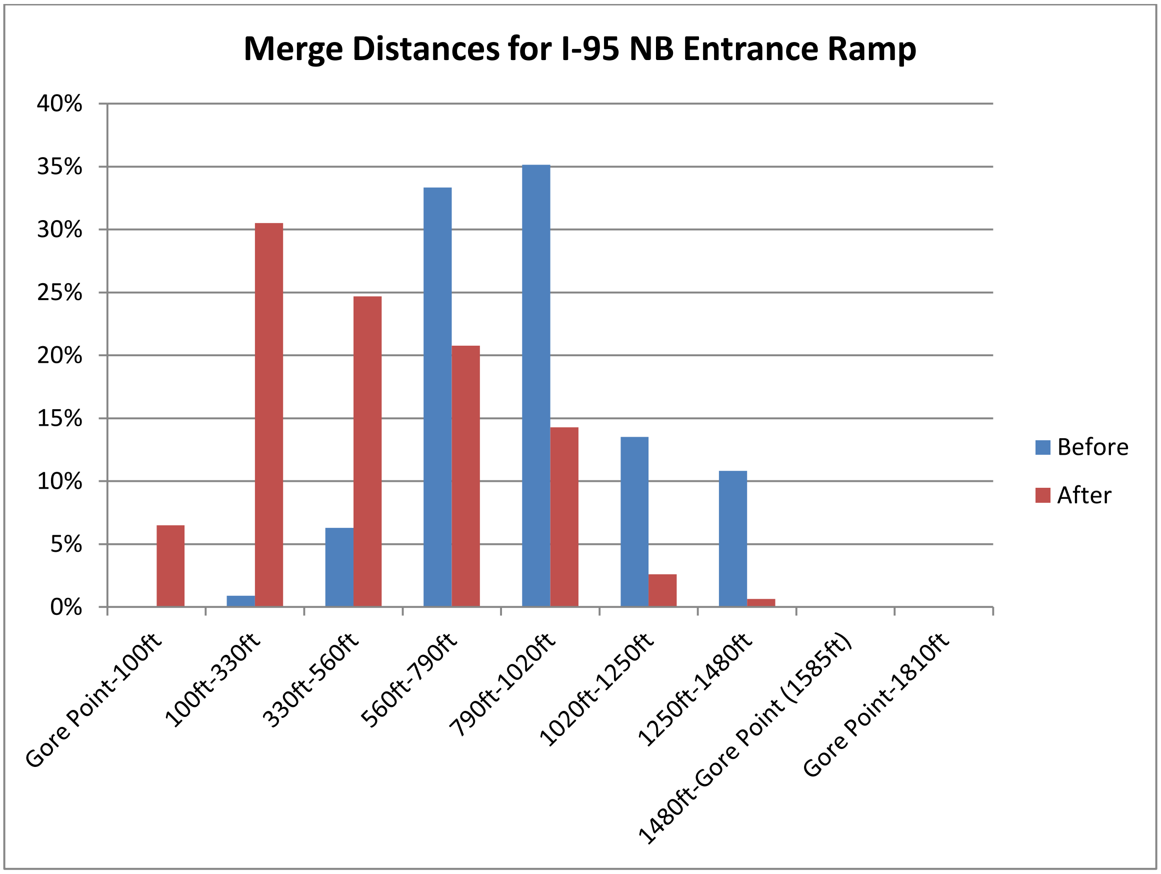

Figure 19 Entrance ramp merge distributions before and after treatment on NB I-95 in Dunn, NC

Likewise, prior to receiving the treatment, the northbound side of traffic had 2,060 vehicles at the exit ramp gore point – 238 vehicles in the auxiliary lane (11.6%), 1,027 vehicles in the lane directly adjacent to the auxiliary lane (49.8%) and 795 in the lane adjacent to the freeway median (38.6%). After receiving the treatment, 5,733 vehicles were observed adjacent to the northbound exit ramp gore point – 534 vehicles in the auxiliary lane (9.3%), 2,438 vehicles in the lane directly adjacent to the auxiliary lane (42.5%) and 2,761 vehicles in the lane adjacent to the median (48.2%). As can be seen in Figure 20, the distribution changed for this ramp, shifting from a right-tailed distribution to one that is left-tailed, which means vehicles were merging into the auxiliary lane to exit the freeway later. This is a favorable outcome, as this means that vehicles merging onto the freeway were allowed time to merge into traffic without being disrupted by exiting vehicles that would be slowing down in the auxiliary lane – a decrease in interactions between vehicles entering and exiting the freeway. A chi-squared test of these merging zones before and after the installation shows that there was in fact a significant difference at the 99% confidence level (p-value < 0.0001).

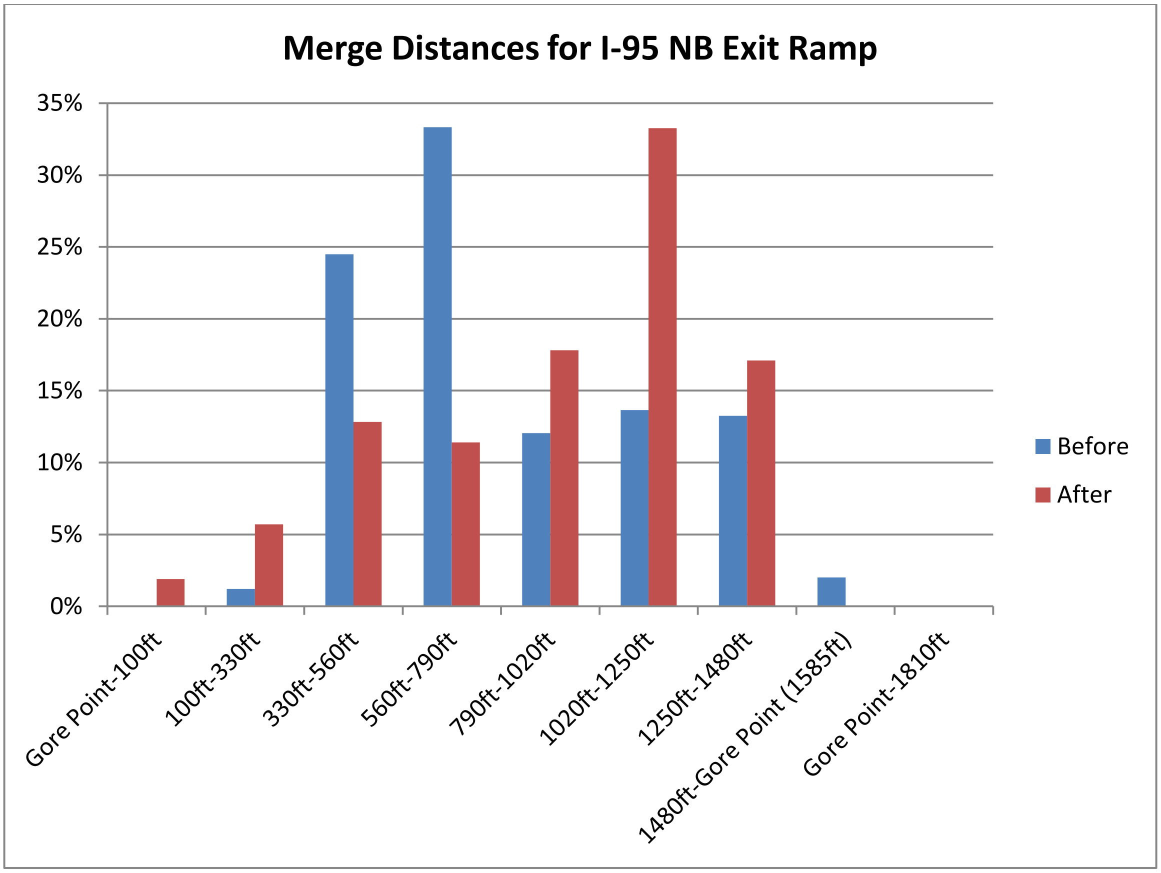

Figure 20 Exit ramp merge distributions before and after treatment on NB I-95 in Dunn, NC

On the southbound side of the freeway, 2,310 vehicles were observed traveling in and adjacent to the entrance ramp at this ramp's gore point prior to treatment on the northbound side – 247 vehicles in the auxiliary lane (10.7%), 939 vehicles in the lane directly adjacent to the auxiliary lane (40.6%) and 1,124 in the lane adjacent to the freeway median (48.7%). After installation of the wide dotted white lane lines on the northbound side, 5,728 vehicles were observed adjacent to the entrance ramp gore point on the southbound side – 560 vehicles in the auxiliary lane (9.8%), 2,323 vehicles in the lane directly adjacent to the auxiliary lane (40.5%) and 2,845 vehicles in the lane adjacent to the median (49.7%). When the merge distance distributions for this ramp (shown in Figure 21) were compared using a chi-squared test, the difference between the two was significant at the 99% confidence level (p-value < 0.0001), as vehicles previously merged early and now are merging later, very similar to the northbound entrance ramp merge behavior. This is an interesting finding, as the southbound side of the freeway did not receive the wide dotted white lane line treatment. It is suspected that the change in behavior on the northbound side translated to the southbound side, possibly because of the familiarity of drivers who travel through this corridor in both directions regularly.

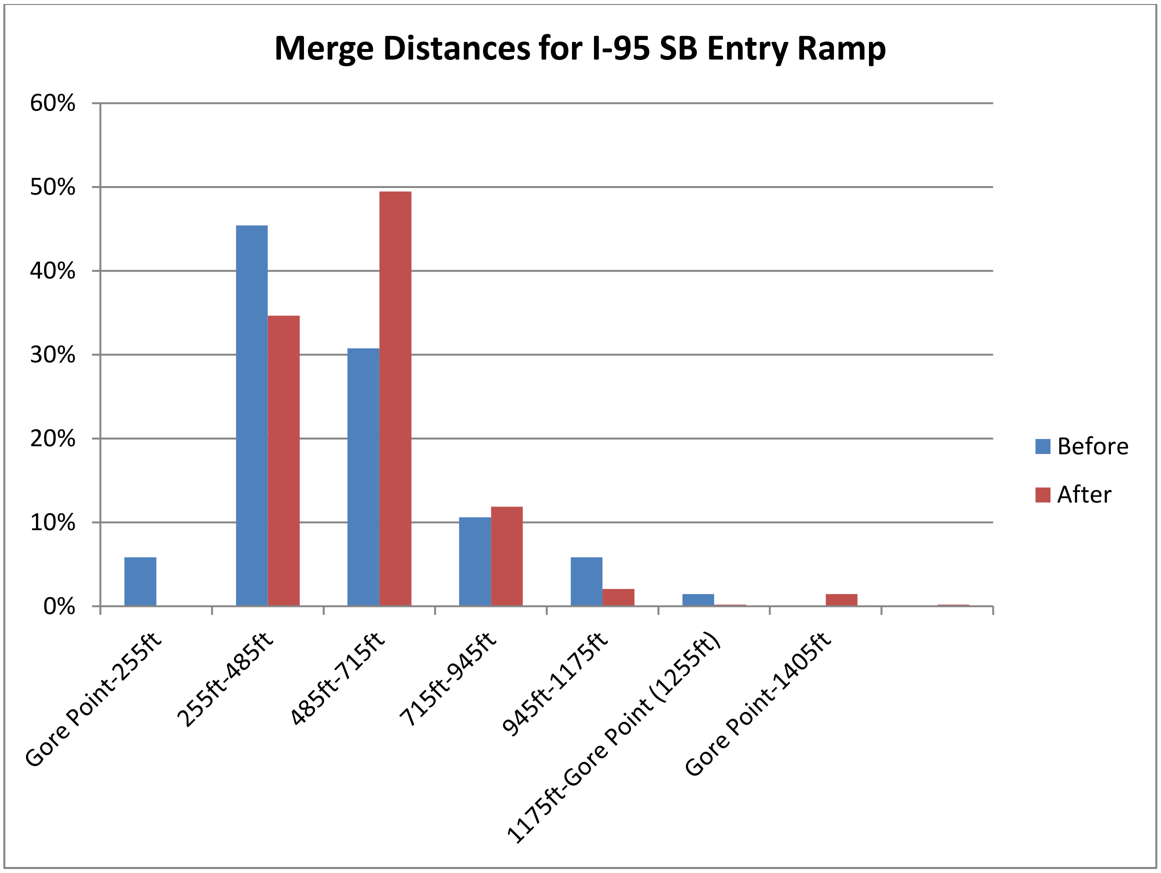

Figure 21 Entrance ramp merge distributions before and after treatment on SB I-95 in Dunn, NC

At the southbound exit ramp gore point, 2,330 vehicles were observed prior to treatment on the northbound side – 108 vehicles in the auxiliary lane (4.6%), 1,098 vehicles in the lane directly adjacent to the auxiliary lane (47.1%) and 1,124 in the lane adjacent to the freeway median (48.3%). After installation of the wide dotted white lane lines on the northbound side, 5,845 vehicles were counted adjacent to the southbound exit ramp – 182 vehicles in the auxiliary lane (3.1%), 2,779 vehicles in the lane directly adjacent to the auxiliary lane (47.6%) and 2,884 vehicles in the lane adjacent to the median (49.3%). The distributions of merges for the periods before and after treatment installation for the southbound exit ramp are shown in Figure 22. These distributions are very different, as the before period observations were right-tailed and the after period observations were left-tailed. This was confirmed in the chi-squared test performed on this data, which resulted in a p-value less than 0.0001, indicating that the two distributions were different. Once again, note that the southbound side did not receive the treatment, so this change may indicate that drivers traveled both directions regularly and their behavior changed in both directions because of the markings on the northbound side.

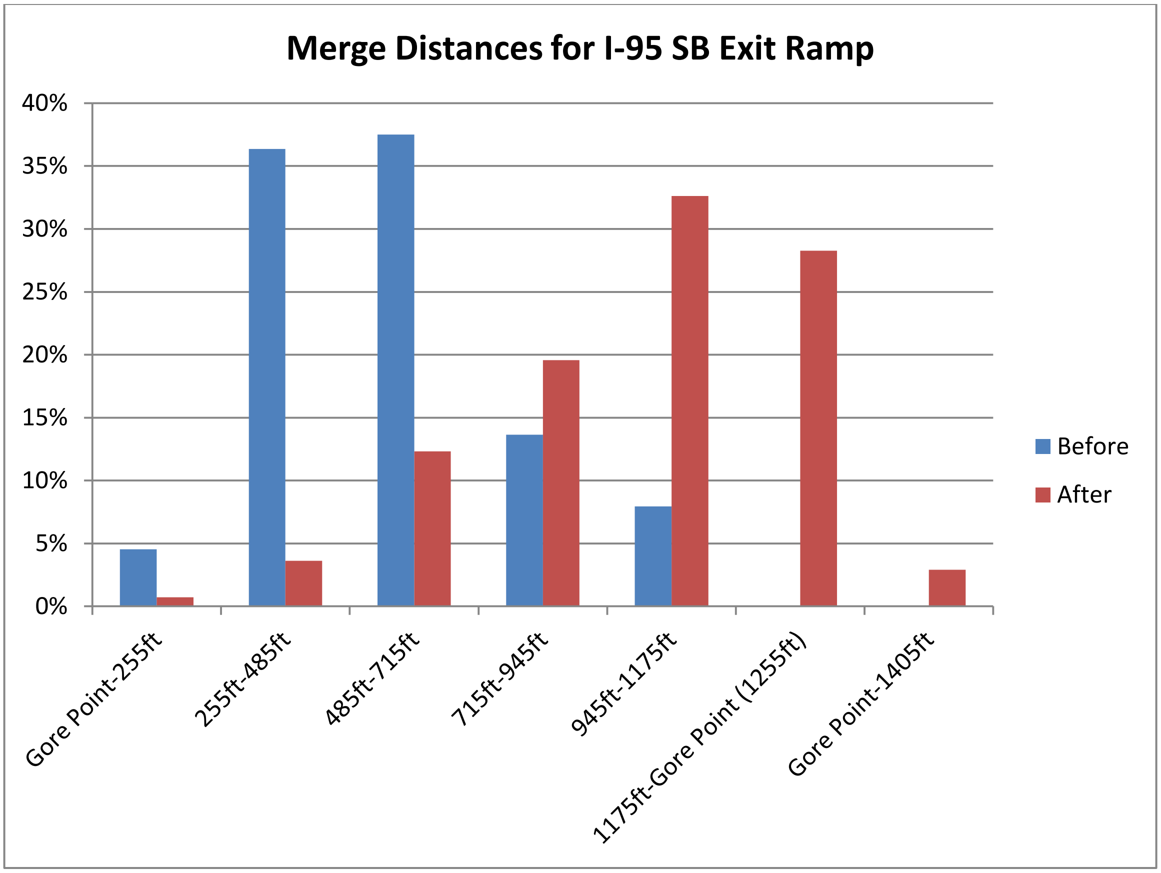

Figure 22 Exit ramp merge distributions before and after treatment on SB I-95 in Dunn, NC

4.3. Elongated Route Shields

4.3.1. Site Descriptions

Site descriptions of each of the elongated route shield sites is provided in this section along with each of the representative comparison sites considered as part of the analysis. In the site description subsections, only comparison sites of similar roadway characteristics (a freeway-to-freeway diverge section), including number of lanes for each direction of travel at the diverge, are described in detail. At each location, only one such comparison site exist within a reasonable distance of each treatment site (assumed to be 15 miles) to account for seasonality and historical effects.

Although not described in detail, due to low sample of similar proximal diverge sections, a larger set of comparison sites was considered using data from nearby intersections at interchange ramps. Although the sites differ in geometric configuration, the increasing or decreasing trends in crashes over time may provide a better understanding of the seasonality impacts should the representative comparison sites be based on similar geometry (described below) not prove useful. Although not always intuitive to analysts, in many ways, the data from nearby intersections within 1-2 miles (and not 10 miles) would likely account for weather related impacts in a more appropriate manner. Therefore, the team considered three additional intersections at nearby ramp interchanges and looked at the combination of comparison sites that would be most appropriate (if any) for the comparison group analysis methodology. These nearby intersections, along with the similar diverge site, are provided on a map along with a more detailed description and aerial of the diverge site.

I-40 and I-73 in Greensboro, NC

This site is on the western side of Greensboro on I-40 East, just before the split with I-73. Three and a half years of crash data were analyzed for both the before and after periods at this site, with the before period stretching from October 1, 2007 to March 31, 2011 and the after period stretching from June 1, 2011 to November 30, 2014, as the shield markings were installed in May of 2011. No other after data was collected because the shield markings were already extremely worn and never replaced. The area analyzed for this site started approximately two miles before the diverge point. There are other interchanges within this area, but it was necessary to capture the entire area where shield markings and signs are present notifying drivers of the split. This corridor had an AADT of 111,000 vehicles per day during the before period (2009) and 115,000 vehicles per day during the after period (2013). There are six lanes on I-40 before reaching the split, with four lanes splitting to remain on I-40 (three of the original lanes and one additional lane) and three diverging to I-73. A diagram of this diverge segment is displayed in Figure 23.

One freeway comparison site, the interchange of I-40 and I-85 on the other side of Greensboro, was utilized and was approximately 13 miles from the treatment site. This interchange contains five lanes on I-40/85 which split to continue three lanes on I-40 and three onto I-85 (two of the original lanes and one additional). The AADT was 105,000 vehicles per day in 2009, during the before period, and 112,000 vehicles per day during the after period (2013). A diagram of this diverge is shown in Figure 24. In addition, four signalized intersections at nearby interchanges were chosen to provide several comparison group combinations for consideration in the analysis. These intersections are in much closer proximity and will likely account for seasonality better than the freeway segment. Figure 25 shows the treatment site, freeway comparison site, and three nearby intersection comparison sites.

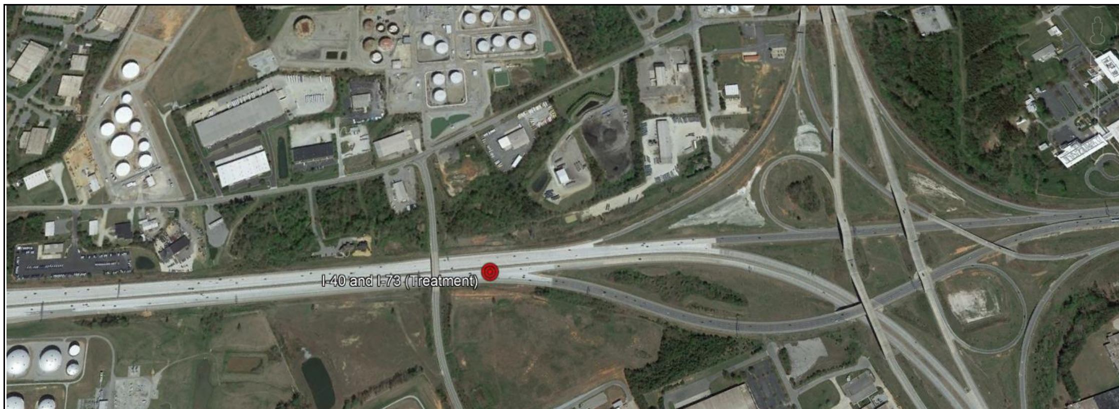

Figure 23 I-40 and I-73 treatment site

Figure 24 I-40 and I-85 comparison site

Figure 25 I-40 and I-85, treatment and comparison sites (includes 3 additional *intersection* comparison sites from nearby interchanges)

I-40 and I-40 Business in Winston-Salem, NC

This site is between Greensboro and Winston-Salem on I-40 West prior to the I-40 Business split. The shield markings were installed sometime in 2012, but the exact date is unknown; therefore, 2009-2011 was analyzed as before data for the treatment and comparison sites, while 2013-2015 was analyzed as the after data for these sites. No other after data was collected because the shield markings were showing signs of wear and scheduled to be maintained in the near future (date unknown). For both the treatment and comparison sites, the area that was analyzed stretched two miles back from the diverge point. The AADT for the treatment site, I-40 and I-40 Business, was 103,000 vehicles per day in 2010, during the before period, while the AADT was 114,000 vehicles per day during the after period, in 2014. This site has four lanes which split to two in each direction. An aerial image of this site is shown in Figure 26.

The freeway comparison site matched with this treatment site was I-40 East and I-74 on the southeast side of Winston-Salem, approximately ten miles from the treatment site. The AADT at the comparison site was 76,000 vehicles per day in 2010 and 90,000 vehicles per day in 2014. This site has three lanes prior to the diverge point with two lanes continuing on I-40 and one lane continuing on I-74 plus an additional lane. A picture of this site is shown in Figure 27. In addition, four signalized intersections at nearby interchanges were chosen to provide several comparison group combinations for consideration in the analysis. These intersections are in much closer proximity and will likely account for seasonality better than the freeway segment. Figure 28 shows the treatment site, freeway comparison site, and four nearby intersection comparison sites.

Figure 26 I-40 and I-40 Business in Winston Salem (Treatment Site)

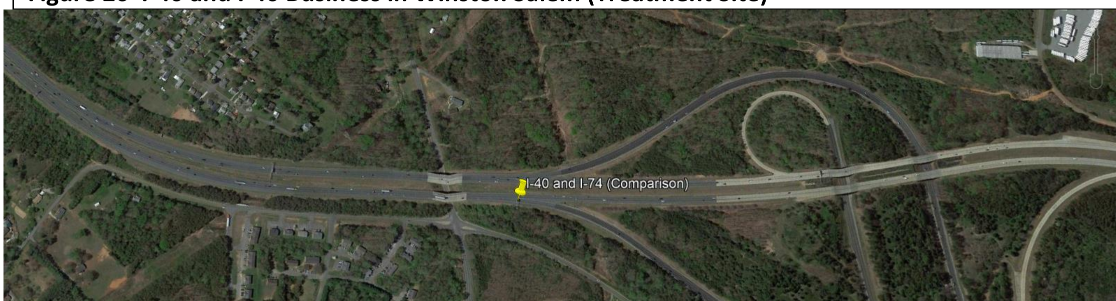

Figure 27 I-40 and I-74 in Winston Salem (Comparison Site)

Figure 28 I-40 and I-40 Business, treatment and comparison sites (includes 4 additional intersection comparison sites)

I-85 and I-85 Business in Greensboro, NC

There are another group of pavement shield markings in southern Greensboro, NC on I-85 North at the diverge with I-85 Business. These were also installed in 2012. The before period that was analyzed for this project for this treatment site and its comparison site was 2009-2011 and the after period was 2013-2015. Once again, the area observed at both of these sites was from two miles behind the split up to the diverge point. Because the markings are only present in one direction on I-85, the other side of this same corridor was chosen as the comparison site, which also has a split with I-85 and I-85 Business. The AADT for the before period was 80,000 vehicles per day in 2010 and in the after period was 91,000 vehicles per day in 2014. For the treatment site, northbound I-85, there are five lanes which split to three continuing onto I-85 and two continuing onto I-85 Business with an additional lane joining these two lanes. An aerial is provided in Figure 29.

Shown in Figure 30, the freeway comparison site has five lanes which split to three continuing onto I-85 and two continuing onto I-85 Business. In addition, shown in Figure 31, four signalized intersections at nearby interchanges were chosen to provide several comparison group combinations for consideration in the analysis. These intersections are in much closer proximity and will likely account for seasonality better than the freeway segment. Figure 31 shows the treatment site, freeway comparison site, and three nearby intersections.

Figure 29 I-85 and I-85 Business in Greensboro (Treatment Site)

Figure 30 I-85 and I-85 Business in Greensboro (Comparison Site)

Figure 31 I-85 and I-85 Business, treatment and comparison sites (includes 4 additional intersection comparison sites)

General Site Summaries

Table 4 provides a description of the complete data sets provided for analysis. Two of the sites had three years of before and after data, respectively. The third site had four years of before and after data, respectively. Data were not included for the analysis during the year the pavement marking was installed for two reasons. First, it could not be determined exactly when the pavement marking was installed; however, the NCDOT was confident with the year that the marking was installed. Second, a burn-in period was able to be provided by including some of the data after the installation during the installation year (assuming that installation more likely happened in the 9-10 months prior to the end of the year).

Table 4 Crash Data Received by Year

Treatment site	Before period	Year Shield Marking Installed	After period
I-40 @ I-73 (Greensboro)	2007-2010 (4 years)	2011	2012-2014 (4 years)
I-40 @ I-40Bus. (Winston-Salem)	2009-2011 (3 years)	2012	2013-2015 (3 years)
I-85 @ I-85Bus. (Greensboro)	2009-2011 (3 years)	2012	2013-2015 (3 years)

As described early, the closest similar diverge site was used as a comparison site along with the closest upstream and downstream interchange signals (3-4 intersections depending on the design). The primary reason nearby intersections were considered was proximity to the treatment site. Two of the three diverge comparisons were ten miles or further from the treatment site. In addition, there were no other similar diverge locations in close proximity that could be considered. For reference, the distance from each of the three treatment sites to each of the comparison sites is provided in Table 5.

Table 5 Descriptive Data for Each Comparison Site in Relation to the Treatment Sites

Treatment Site	Comparison Type	Distance from Treatment Site (miles)	Comparison Site
I-40 @ I-73 (Greensboro)	Diverge	13.96	1. I-40 and I-85
	Intersection	0.84	2. I-40 and Gallimore Dairy Rd.(SPUI)
	Intersection	1.08	3. I-40 and Guilford College Rd. (WB Ramp)
	Intersection	1.08	4. I-40 and Guilford College Rd. (EB Ramp)
I-40 @ I-40 Bus. (Winston-Salem)	Diverge	10.38	1. I-40 and I-74
	Intersection	1.96	2. I-40 and Macy Grove Rd. (WB Ramp)
	Intersection	1.93	3. I-40 and Macy Grove Rd. (EB Ramp)
	Intersection	0.98	4. I-40 and Sandy Ridge Rd. (WB Ramp)
	Intersection	1.03	5. I-40 and Sandy Ridge Rd. (EB Ramp)
I-85 @ I-85 Bus. (Greensboro)	Diverge	1.33	1. I-85 and I-85 Bus.
	Intersection	0.22	2. I-85 and Groomtown Rd. (WB Ramp)
	Intersection	0.29	3. I-85 and Groomtown Rd. (EB Ramp)
	Intersection	1.22	4. US-29 and S. Holden Rd. (WB Ramp)
	Intersection	1.24	5. US-29 and S. Holden Rd. (EB Ramp)

4.3.2. Safety Analysis

As discussed in Section 3.3, the comparison group analysis method was employed to account for seasonality and historical effects. Since sites were primarily chosen for operational reasons, regression-to-the-mean was assumed to be null and Bayesian methods were not considered. Five crash categories were analyzed based on the available sample sizes: total crashes (by site and combined), daytime crashes (by site and combined), and each of the collision types identified as most likely be impacted by elongated shields (lane departure, sideswipe, and rear end crashes). The three crash types were only analyzed for the combination of all sites due to sample size issues. Daytime crashes were used to see if there was a difference in visibility compared to nighttime/dusk/dawn conditions. Table 6 shows the summary statistics for each crash type analyzed.

Table 6 Comparison Group Analysis Findings

Crash Type		Comparison Sites[1]	Odd's Ratio		Before		After		Theta	Std. dev. around theta
			m(o)	s(o)	Treat.	Comp.	Treat.	Comp.		
Total Crashes	Combined	n/a[2]	0.977	0.169	138	417	177	554	0.96	0.13
	I-40 @ I-73	Intx's 1 and 3	0.951	0.180	43	144	41	134	0.99	0.25
	I-40 @ I-40 Bus.	Intx's 1 and 3	0.894	0.031	42	127	57	174	0.96	0.23
	I-85 @ I-85 Bus.	Diverge + Intx's 2 and 4	0.941	0.215	53	146	79	246	0.86	0.19
	Lane Departure	n/a[2]	0.950	0.110	62	192	70	240	0.89	0.18
	Sideswipe	n/a[2]	0.950	0.110	42	142	59	172	1.13	0.26
	RearEnd	n/a[2]	0.950	0.110	34	83	44	142	0.73	0.20
Daytime Crashes	Combined	n/a[2]	0.950	0.110	89	247	90	316	0.78	0.13
	I-40 @ I-73	Intx's 1 and 3	0.951	0.180	30	87	24	91	0.73	0.23
	I-40 @ I-40 Bus.	Intx's 1 and 3	0.894	0.031	23	76	35	121	0.91	0.28
	I-85 @ I-85 Bus.	Diverge + Intx's 2 and 4	0.941	0.215	36	84	31	104	0.67	0.19
	Lane Departure	n/a[2]	0.951	0.180	37	176	20	164	0.56[a]	0.17

[a] *Statistically significant at the 90th percentile confidence interval*
[1] *The location and descriptions of comparison sites can be found in Section 3.3*
[2] *The combination of all site data means that all comparison site data were added together for this category (i.e. Total crashes/combined/comparison sites is the sum of the comparison sites for individual sites above this cell)*

An odd's ratio was calculated for each treatment/comparison site pair. As noted in Section 3.3, four or five comparison sites were chosen for each treatment site (one diverge segment and three or four nearby intersections depending on the interchange form adjacent to the treatment site). Each comparison site and the subsequent combinations (4 or 5 factorial) of comparison sites were analyzed for best fit. The mean of the odd's ratio for the best combination of comparison sites was chosen based how close the mean, m(o), was to 1 and the smallest standard deviation (which had to be less than 0.2). The combination of comparison sites that best fit is shown above along with the mean and standard deviation of the odd's ratio. Interestingly, each treatment site matched the nearest comparison intersection in the same direction of travel, and the only diverge freeway segment that matched with the two intersections was the one next to the treatment site (and not 10+ miles away).

Next, sample sizes are provided for each crash type analyzed by a) before and after periods and b) treatment or comparison sites. Note here that the sample sizes for daytime collisions are very low, therefore only lane departure, outside of the site specific data, was conducted. Last, the treatment effect (theta) and standard deviation are calculated. As noted earlier, a confidence interval of 90% and 95% were used to determine if the effect of elongated shields was statistically significant. With the exception of sideswipe collisions during daytime hours, all sites showed a decrease in crashes. Only one collision category was statistically significant at the 90th percentile confidence interval – lane deviation crashes during daytime hours. However, it is notable that although most of those are not statistically significant, they are practically significant in that they all decrease with the exception of one crash category.

5. CONCLUSIONS

5.1. Zipper Merge

The primary positive finding from this study in regards to the zipper merge was the unforeseen safety benefit. Overall, drivers merged at much safer distances after installation of the zipper merge at these sites than before the zipper merge was in place. Likewise, drivers at the freeway sites – Durham and Vance/Warren Counties – merged shortly before the end of the right lane, which seemed to create more fluid merging conditions and therefore merges at higher speeds. This could be because these sites are high speed corridors and drivers were already expecting to merge slightly earlier than at the Carteret County site, a rural arterial, because of their speeds and the fact that they were on a freeway. In this regard, it would be beneficial in future studies to be very specific in public outreach and in signage to tell drivers precisely where to merge and to be very specific that they not merge earlier than prompted. It is evident in this study that drivers in the continuing lane were much more cordial once the zipper merge was in place than before, so the task at hand now is to ensure that more drivers in the ending lane continue all the way to the merge point before changing lanes. This should result in a shorter queue, as seen in previous studies elsewhere, and possibly even greater reductions in travel time than were seen in this study.

Also, it is important to note that the safety of drivers is not the only safety benefit possible, but also the safety of construction workers. There has been a big push in national research recently to find a way to influence safer driving in and around construction zones, and the zipper merge may be one way to encourage safer driving, as drivers were far less likely to drive on the shoulder regardless of barrier type once the zipper merge was in place.

While all sites saw safety improve, it was the site in Vance and Warren Counties that saw the greatest benefit in safety and operations, and this is almost certainly due to the dynamic signage used at this location. Dynamic merge signage has been demonstrated to be the most effective at influencing driver behavior when compared to static signs, and this was further proved in this study. However, note that this setup can become very expensive and will be the most cost effective in long term lane closure situations.

Lastly, as demonstrated in the case of the Cape Carteret site, public outreach through press releases and other methods are vital to the success of the zipper merge each time they are implemented, even if there are multiple implementations over time at the same site. Every implementation of the zipper merge must be accompanied by aggressive public outreach, or else the zipper merge is likely to be ineffective.

5.2. Wide Dotted White Lane Lines

It is evident through this study that drivers are acutely aware of lane markings. Not only did drivers merge in a more desirable manner once the wide dotted lines were in place, but as demonstrated at the Cary site, drivers utilized any extra space available to them when the solid line was shortened and the dash line extended. This is reassuring in that it indicated compliance to whatever lane markings were in place, including solid lane lines.

As mentioned, these markings seemed to influence oncoming traffic to merge sooner and exiting traffic to merge later. This is desirable in the fact that it seemed to separate entrance and exit ramp traffic, because entering traffic merged earlier than before, which allowed more room for exiting traffic and neither appeared to impede the other drivers.

Also noteworthy is the influence that wide dotted white lane lines placed in one direction appeared to have on drivers in the other direction, as observed at the Dunn site. This could be beneficial in locations that have not yet been restriped with wide dotted lines if upstream interchanges are in fact striped correctly with the new standard of wide dots instead of the previous standard skip lines. It is uncertain the extent to which this effect is transitive, but it is noteworthy that there does appear to be some proximal effect on drivers in the vicinity of these wide dotted lines.

5.3. Elongated Route Shields

Elongated shield markings were installed at three freeway diverge locations in Greensboro and Winston-Salem, NC. A before and after comparison group safety evaluation was employed to determine the safety effectiveness of these sites. Three collision types were used: lane departure, sideswipe, and rear end collisions. Sites were analyzed separately and in combination as well as during daylight hours. The findings from the safety study are that safety generally showed improvements in all crash types analyzed with the exception of one category. Only one of the findings was statistically significant within 90 percent confidence – lane departure during daytime hours. However, the trend in reduced collisions in almost every crash category seems to indicate some practical significance in the findings.

6. OPPORTUNITIES FOR FUTURE RESEARCH

The research team feels strongly that a useful future study would be to conduct a simulator study of the zipper merge on drivers using varying signs to determine how drivers respond to each one, as this could determine the most effective signage to use when implementing a zipper merge. It became glaringly evident to the research team that transportation agencies across the country are essentially guessing as to the most appropriate signage with regards to the zipper merge. Every agency has their own ideas for signage and their own reasons why this is the most effective signage, but none of them seem to be aligned with one another. While this was frustrating, it also provides a good starting point for a simulator study, as there are dozens of slightly or vastly different signs being used currently across the country in these treatment sites. As noted in the above section, identifying the most effective signage could enhance the benefits seen in this and other studies, including safer merge locations, better lane utilization and therefore shorter queues, and shorter travel times due to more fluid merge locations.

As for wide dotted white lane lines, the research team found most interesting the effect that wide dotted lines on one side of the freeway had on drivers on the other side of the freeway. This is almost certainly due to local drivers using both directions of travel when commuting to and from work of recreation, but it would be interesting to see if this effect is only temporary or if it continues for the entire time wide dotted lines are on the other side of the road. To be sure, both sides of this freeway should have had wide dotted white lane lines installed at the Dunn site, but construction crews have a tendency to forget about new standards, or simply continue old standards until someone enforces the new standards. With transportation agencies already struggling due to budget cuts, oversight is an unavoidable issue, so utilizing any advantage possible could benefit these agencies when mistakes are made and can't easily be corrected, like in the case of the Dunn site where striping is incorrect in one direction, but was caught before striping the other direction.

Future evaluations of elongated shield markings should look at observational studies of lane changing behavior in the weaving segment of the freeway just before the diverge. The limited amount of crash data makes analysis of the sites very challenging to say the least. A direct evaluation of the average weaving distance in the prepositioning sections of the freeway diverge area would likely be more promising.

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8. APPENDICES

8.1. Press Release

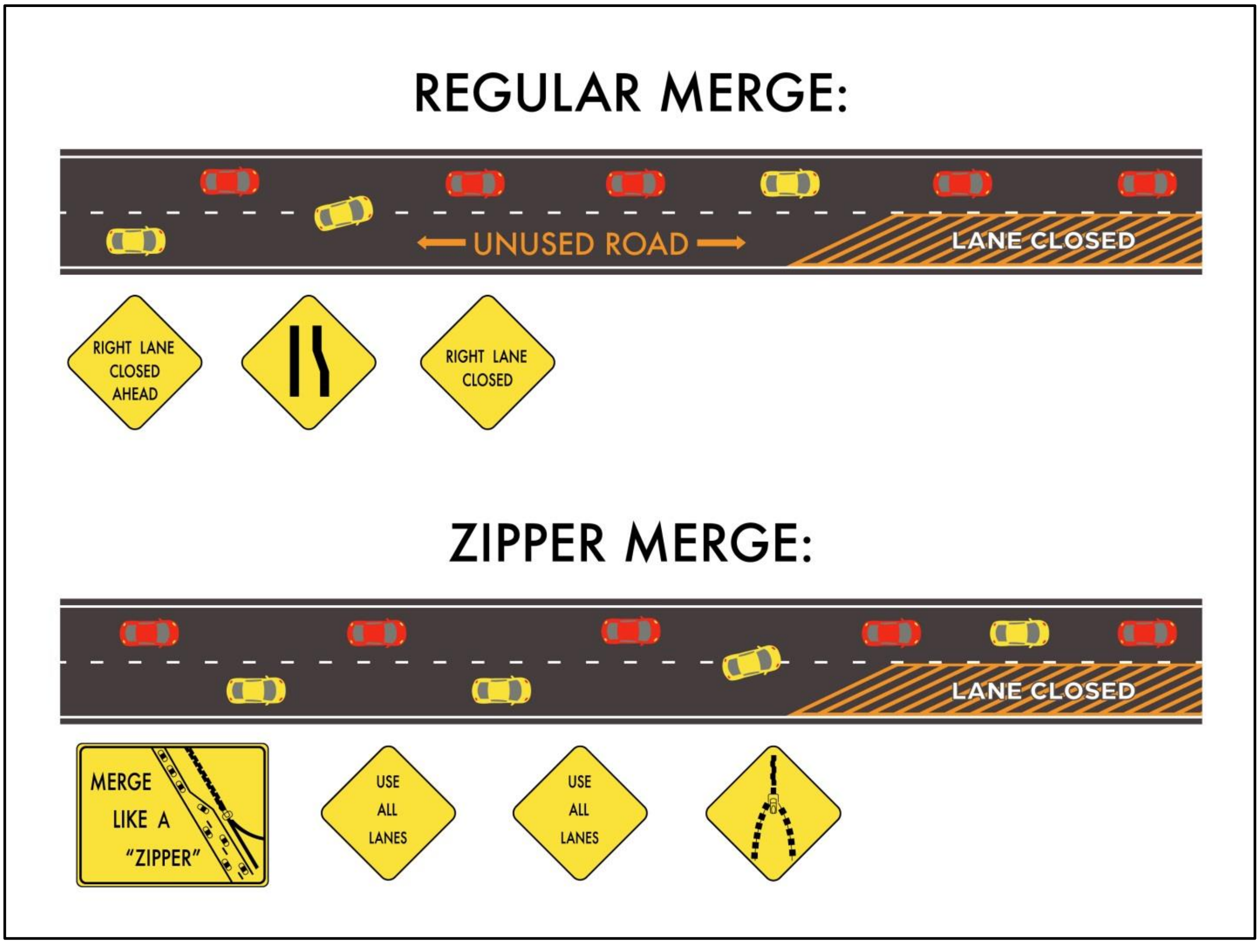
State Studying 'Zipper Merge' to Help Reduce Congestion at Emerald Isle Bridge

RALEIGH – Researchers at North Carolina State University say a new traffic treatment called a “zipper merge” has the potential to reduce backups by as much as 50 percent. The state transportation department is working with N.C. State to determine if this new style of merge can be successful on N.C. 58 just before the bridge over to Emerald Isle in Carteret County.

The "zipper merge" encourages drivers faced with lane closures to work together and take turns where the lanes merge, not only reduce congestion for all vehicle, but also to improve safety.

"While this goes against the grain of what we like to do as drivers, the zipper merge allows both lanes to be used to their full capacity," said Kevin Lacy, state traffic engineer. "With a little extra courtesy, we could greatly reduce the length of traffic jams, decrease travel times and increase safety."

The DOT is installing signs today directing drivers to follow the zipper merge pattern. The signs ask drivers to stay in their lane until they reach a specified point. They then follow the directions of signs to make the merge. Drivers in the open lane are asked to take turns allowing vehicles from the closing lane to merge in front of them as depicted in the picture below.



Engineers with N.C. State studied backups at the bridge over a two-week period in May and June that included the Memorial Day holiday. They will compare that data to the data they observe over the next two weeks to determine whether the “zipper merge” was effective at changing driver behavior to reduce delays and increase safety.

Michigan and Minnesota are among several states that have implemented the zipper merge and have been able to greatly decrease the length of backups and create safer, smoother driving conditions.

"One zipper merge site in Michigan saw congestion reduced from 6 miles to 3 miles," said Chris Vaughan, research associate with N.C. State's Institute for Transportation Research and Education. "The time spent in traffic also decreased dramatically at this site, saving drivers an average of 15 to 25 minutes. This is predicated on compliance, meaning that cooperation with other drivers is the only way this will work. While this seems daunting, we are confident that a little southern hospitality can go a long way.”

The zipper merge will be installed at other locations for this summer, including I-85 South just past the N.C. 147 interchange in Durham. The other site has not been determined.

During congested periods, NCDOT urges drivers in these areas to be extra courteous to other drivers and understand that those in closing lanes are not simply trying to “cut in line” in front of drivers in the open lane.

"By taking turns, you are all, in fact, helping everyone’s travel time go down," Vaughan said. "Please remember that by working together, your travel time and safety will improve, as will everyone else’s around you."

For real-time travel information at any time, call 511, visit the Traveler Services section of the NCDOT website or follow NCDOT on Twitter. You can also access NCDOT Mobile, a version of the NCDOT website especially for mobile devices. Visit m.ncdot.gov from your mobile browser.

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8.2. Merge Signage Strategies of Other Transportation Agencies

An Excel workbook containing multiple spreadsheets with merge implementation strategies of other transportation agencies is included with the submission of this report.