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Enhancing Work Zone Mobility Through Design And Control Of Lane Closures

Troyee Saha
University of Alabama at Birmingham

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by

TROYEE SAHA

VIRGINIA P. SISIOPIKU, COMMITTEE CHAIR
ANDREW SULLIVAN
ROBERT W. PETERS

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TROYEE SAHA

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ABSTRACT

Work zones hinder mobility, affecting travelers and transportation agencies that are trying to ensure efficient traffic flow through work zones. A study by Wunderlich & Hardesty, 2002 reported that nearly 20% of the National Highway System roads have scheduled construction work during the peak construction season. Additionally, approximately 24% of non-recurring delays on freeways are caused by work zones. Given the time lost by travelers due to work zone induced traffic congestion, it is critically important to efficiently plan temporary traffic control (TTC) at work zones. However, earlier research conducted by Sisiopiku & Ramadan, 2017 confirms that the majority of State Departments of Transportation rely on their earlier experience without consideration of operational nor safety impacts. Earlier studies focused on analysis of short-term work zones TTC strategy. However, there is an evident need to study various TTC strategies for long-term work zones. This study investigated the operational impacts of two TTC strategies for work zones, namely static late and early merge control, using traffic data collected from Alabama Department of Transportation. VISSIM simulation experiments were designed to consider the factors of TTC strategy (i.e., static late and early merge); 3-to-1 lane drop configuration; and work-space length (500 – 1500 ft, with increments of 500 ft). The study findings show that long-term work zones with 3-to-1 lane closure can manage the traffic from midnight to early morning both with early and late merge traffic control for 500 ft long work zone. Short-term work zones perform better during non-peak hour both for 1000 and 1500 ft long work zones. However, no work zone traffic control was able to accommodate peak-hour short-term work zones. Under peak traffic conditions, speeds became lower than 10 mph with 1,000 ft lane closure with only one available lane for vehicle movement indicating severe congestion. The study concluded that 3-to-1 lane-drop configuration should not be scheduled for long-term duration. Maintenance work can be conducted with separate short-duration works, mostly avoiding peak-hour lane closures. These findings are expected to provide valuable guidance for agencies responsible for planning, design, and operations of work zones in the future.

Keywords: Work zone traffic control, early merge, late merge, VISSIM, simulation

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INTRODUCTION

Problem Statement

Maintenance and rehabilitation work are very important for proper functioning of roadways. Several states opt for construction work on the existing roadways to improve roadway condition and serve the traveling public. Often, lane closures are required whenever there is an active work zone. In fact nearly 20% of the U.S. National Highway System roads have construction work during the peak construction season (Wunderlich & Hardesty, 2002) and there is a possibility that a driver would confront one active work zone out of every hundred miles driven on the highway (Wolff, 2007). Work zones reduces the capacity of roadways and interrupts traffic flow at merge point (Wei, Pavithran, Yi, Yang, & Zeng, 2010). During the uncongested situation, vehicles can drive at regular speed, but speeds may decline by 31.6% to 56.1% of the regular speed at work zones (Jiang, 1999).

Researchers estimated that work zone causes approximately 24% of non-recurring delays which ranks work zone as the second largest factor of non-recurring delay on arterials (M. V. Chitturi, Benekohal, & Kaja-Mohideen, 2008). The lane closure not only affects mobility of regular travelers on the specific roadway, but also affects local business and community, and causes noise and environmental issues. Researchers indicated that the cost of congestion combining travel delay and extra fuel cost was estimated to be $115 billion in 2009 (Mallela & Sadavisam, 2011). They calculated total travel delay cost of users with passenger cars for a hypothetical 2-mile work zone to be $196,342.10 /day, assuming six lane interstate and 88% passenger cars in the regular traffic flow. Therefore, transportation agencies are trying to ensure efficient traffic flow through work zones and research is going on to enhance mobility diminishing interruptions in the traffic flow.

One strategy used to manage traffic through work zone lane closures is conventional Temporary Traffic Control (TTC). TTC methods can be static or dynamic. The choice depends on time period of work zone, traffic volume, driving behavior, etc. Selection of TTC should be based on evaluation of operational impacts of the specific strategy at specific work zone and safety considerations. Few strategies perform well with lower traffic volumes but may not be efficient when demand volume exceeds capacity. The situation becomes even worse when the queue goes upstream beyond warning signs and possibility of collision increases (McCoy & Pesti, 2001).

Given the time and money lost by travelers due to work zone induced traffic congestion, it is critically important to efficiently plan temporary traffic control (TTC) at work zones. In fact, the Federal Highway Administration (FHWA) has developed a rule according to which all state and local highway organizations should have guidelines for evaluating mobility impacts and managing safety at work zone locations for each project (M. Chitturi & Benekohal, 2010; Mallela & Sadavisam, 2011). Many state Departments of Transportation (DOT) fix a certain user delay as a measure of mobility (M. Chitturi & Benekohal, 2010). To reduce impact on traffic operation and safety, many agencies select off-peak hours for lane closures. As a result, project duration increases and setup related time and cost also increase (Tang & Chien, 2008).

Lane closures at work zones may take place for pavement repair, resurfacing, installation of pavement markers, asphalt removal, etc. Hence, planning of work zone traffic control should be done cautiously so that lane closures have minimum impacts on mobility (Kim, Lovell, & Paracha, 2001). However, earlier research confirms that the majority of State Departments of Transportation do not have formal guidelines for selecting TTC strategy for work zones; instead, they rely on their earlier experience without consideration of operational nor safety impacts (Sisiopiku & Ramadan, 2017).

Some earlier studies looked at TTC strategies for short-term work zones under a 3-to-2 lane drop scenario. However, very few studies focused on assessing the impact of TTC strategies for 3-to-1 lane configuration and no study focused on long-term work zone for 3-to-1 lane closure. Therefore, there is an evident need to study different TTC strategies for long-term and short-term work zones for 3-to-1 lane closure configuration for various work zone length so that transportation agencies can ensure maximum flow and minimum delay of road users at work zone under the 3-to-1 lane closure scenario.

Objective

The objective of the study is to investigate the operational impacts of two TTC strategies for work zones, namely static late- and early merge control, under varying traffic demand with 3-to-1 lane-drop configurations. The tasks performed to meet this objective are as follows:

1. Model a study freeway corridor under typical traffic demand conditions to establish a baseline for comparisons using the VISSIM microscopic traffic simulation platform.
2. For the same study corridor and under similar geometric and traffic conditions, develop VISSIM simulation models that represent work zone

operations with 3-to-1 lane drops with late- and early merge control for varying work zone lengths.

3. Evaluate late- and early merge control for a 3-to-1 lane closure at work zones throughout 24-hr time period and compare operational impacts on the basis of travel time, flow, speed and density as a function of traffic demand as well as length of the work zone.
4. Evaluate late- and early merge control for a 3-to-1 lane closure at work zones with lane closures imposed during peak- and non-peak time periods and compare operational impacts
5. Develop recommendations for spatial and temporal placement of freeway work zones with 3-to-1 lane closures and selection of TTC strategies.

More specifically, first the study reviewed available TTC strategies at lane closures and the current practice in different states and obtained the needed data to develop and calibration a traffic simulation model of a study corridor under current conditions. Then simulation models of the corridor representing work zone conditions with 3-to-1 lane closures were developed for both static late- and early merge control. Comparisons of performance measures were performed between these two strategies and used to develop recommendations about conditions and TTC strategies that produce best results under 3-to-1 lane closures.

Significance and Implications of the Study

The research bridges the gap between construction work scheduling and transportation planning research. Earlier simulation studies concentrating on static early and late merge mostly considered short-term work zones during off-peak.

Additionally, research and analysis of the 3-to-1 lane closure configuration is very limited. Therefore, this study contributes to better understanding of long-term work zone operation under constrained roadway capacity (3-to-1 lane closure configuration). Overall, the findings of this study yield information that transportation agencies can use to better plan future work zones, particularly those involving partial closures on freeways. Examining mobility impacts of various combinations of lane closures, TTC strategies, and work space lengths, is expected to identify those combinations that will have minimal impacts on mobility. The study findings are expected to provide valuable guidance for agencies responsible for planning, design, and operations of work zones.

Organization of Report

This report is organized in five chapters. The first chapter presents background of work zone, problem statement, objectives, and significance and implications of the study. The second chapter reviews available TTC options, current state-of-practice for selecting TTC at work zones, findings from the earlier studies considering different TTC, and simulation platforms that analyzed various TTC. The third chapter describes the characteristics of the study corridor, and discusses the approach used to develop the baseline and work zone simulation models in this study. Then, the fourth chapter shows the results and explains the significance of the findings. Finally, the fifth chapter presents conclusions, recommendations, and suggestions for future research.

LITERATURE REVIEW

Available Merge Control Strategies

Various State Departments of Transportation (DOTs) implement merge control strategies at work zones according to the procedures described in the Manual of Uniform Traffic Control Devices (MUTCD) (*Manual on Uniform Traffic Control Devices for Streets and Highways*, 2009). The literature review reveals that temporary traffic control (TTC) methods used by DOTs include static or dynamic early merge, static or dynamic late (zipper) merge, reduced speed when flashing, closure of entrance ramps during construction (Benekohal, Kaja-Mohideen, & Chitturi, 2004; McCoy, Pesti, & Byrd, 1999; Pesti et al., 2008; *Work Zone Operations Best Practices Guidebook (Third Edition)*, 2013). The main features of commonly used TTC methods are discussed next.

Static or dynamic early merge

Static early merge technique is employed by placing lane closing signs a few miles ahead of the actual closed lane at one-mile intervals. This set up gives drivers that are approaching a work zone advanced information about which lane is closed and enough time to merge in the open lane. The reason to adapt this strategy is to facilitate an orderly merge to the open lanes in advance rather than encouraging drivers to merge close to the lane drop over a short distance. Since advanced warning is placed well upstream of closed lanes, early merge can also decrease the rate of rear-end collision (Pesti et al., 2008). Static early merge control increases the amount of free merges and when this is incorporated with effective warning distance of 1-mile, the percentage of free merge becomes greater than or equal to 90 (Nemeth & Rouphail, 1982). However, early studies report that congestion may occur in the open lane(s) since many drivers merge very early abandoning the closed lane for a distance more than required, also leading to higher delays and travel time (Mousa, Rouphail, & Azadivar, 1990). This strategy may also result in lane-change crashes since drivers in the open lane might use the portion of closed lane to overtake other vehicles stuck in congestion (Pesti et al., 2008). It has also been reported that drivers face confusion about the instructions to merge early in low-volume situations (Datta, Schattler, Kar, & Guha, 2004). Another disadvantage is that maintenance of signage and other control measures becomes difficult (Beacher, Fontaine, & Garber, 2004).

Dynamic early merge technique incorporates real time traffic information in warning signs, thus the distance of warning from the closed lane varies according to the traffic demand level. Sonic detectors are attached on warning signs at ¼ to ½ mile intervals along the closed lane and the queue in open lane is monitored. Whenever any detector finds out the existence of queue, it transfers the signal to the next upstream sign. Then the flashing light turns on at the next sign post to warn drivers at that location to merge into the open lane. The length of the no-passing zone varies depending on the queue in open lane, hence it is called dynamic early merge. Field tests in Indiana confirmed smoother lane merging with dynamic early merge control than with the conventional method. The capacity of the work zone is increased during uncongested conditions and the number of free merges improved because of enough space before closure. But this control strategy becomes ineffective if the queue goes beyond the detectors when traffic demand is very high (McCoy et al., 1999; Pesti et al., 2008). Several studies revealed that capacity reduces by using this control, thus travel times increase and longer queue develops during high demand volume (Tarko, Kanipakapatnam, & Wasson, 1998).

Static or dynamic late (zipper) merge

Static late merge is a strategy where drivers remain in their respective lane up to a certain merge point closer to the lane closure and then enter into the open lane in a zipper fashion, hence it is called “zipper merge” as well. Opposed to early merge, drivers do not merge into open lane much in advance of the lane closure and do not need to worry about which lane is closed ahead of time, since all lanes can be used before the merge point. Thus, drivers of open lane feel more comfortable since they would not be passing vehicles beside them using closed lanes. The Minnesota Department of Transportation (MnDOT) has evaluated this strategy and concluded that queue length can be reduced by 40% by implementing late merge control (*Work Zone Operations Best Practices Guidebook (Third Edition)*, 2013). Other potential benefits of this method are improvements related to travel time, delay and rear-end collisions. More space can be utilized by vehicles in late merge, which reduces queue length and potential conflicts. Some studies revealed that late merge becomes more efficient when traffic volume is much higher, while early merge is less effective at congested locations (Pesti, Jessen, Byrd, & McCoy, 1999; Pesti et al., 2008). Studies report that congestion lasts longer under early merge and hence travel time is lessened using late merge, especially under high traffic demand conditions. Although these are some observed benefits of late merge, more study is recommended in the literature to focus on drivers’ behavior under lower traffic volume with higher speed scenarios and also on safety impacts related to the use of late merge strategies. With respect to safety, the possibility of conflict about right-of-way at merge point is also mentioned in one research (Walters, Pezoldt, Womack, Cooner, & Kuhn, 2000).

Dynamic late merge strategy attempts to address the problems associated with static late merge during high-speed and low traffic volumes conditions. So, dynamic late merge considers real-time information of traffic and accordingly changes merge points and controls the traffic in a fashion similar to early merge control during off-peak. When the queue is detected on open lanes, an advanced warning sign informs drivers to drive in their lane instead of merging early. But when there is no queue, this sign would be changed to warn drivers to merge to open lanes. To ensure effective use of dynamic late merge (DLM), volume and speed threshold points need to be identified for interchanging between early and late merge control (Pesti et al., 2008).

Joint merge

Joint merge is a new type of traffic control strategy where there are tapers on two sides of the road instead of one side as in early or late merge. In this technique, two lanes are reduced to form one lane, thus vehicles on the both lanes of the road get equal priority (Idewu & Wolshon, 2010). One field study was conducted in Louisiana and comparison was made with a conventional merge control on the exactly the same location (Idewu & Wolshon, 2010). It was reported that when the traffic volume was between 600 vph to 1200 vph, both strategies performed similar to each other. The researchers concluded that volumes were equally distributed in two lanes because both were getting reduced and recommended that drivers in both lanes should drive carefully while merging.

Reduced speed when flashing

This control strategy uses a flashing sign to advise drivers to reduce their speed when they approach a work zone. For the rest of the time they can maintain normal speed. The reduced speed is set at a minimum of 10 mph less than the posted limit. This strategy is used so that drivers are not forced to always drive at lower speed at work zones, rather they drive at lower speed only when some activity is going on and workers are on the roadways. If workers are not there, drivers can drive at greater speed, thus mobility is enhanced and compliance with the speed limit restriction increases.

Closure of entrance ramps during construction

During lane closures, traffic entering through ramps increases merging maneuvers and contributes to increased congestion. That is why on-ramps are kept closed at some locations to heighten mobility through work zones. Safety also increases along the corridor. Moreover, the likelihood of accidents is reduced by closing entrance ramps and congestion delay along the mainline is minimized.

Mainline merge metering

In mainline merge metering systems, a meter is mounted adjacent to the closed lane of freeway to instruct drivers to change lane at merging points. This is similar to late merge, except for the fact that merging is controlled by metering. A study (Lentzakis, Spiliopoulou, Papamichail, Papageorgiou, & Wang, 2008) considered this method in order to increase overall throughput when volume became greater than capacity. The ALINEA ramp metering algorithm was utilized and microscopic simulation was used to validate the control system. Another study (Tympakianaki et al., 2014) identified greater throughput using the same logic as the previously mentioned study, under some fixed configuration of traffic flow. But the limitation is that trucks were set to use only one lane and calibration was not reported in that study. The dynamic merge metering concept was developed by combining dynamic late merge, merge meter, and wireless technologies to be used at merge points. The method was introduced in a VISSIM study by Wei et al., but they recommended further studies to optimize operations (Wei et al., 2010).

Temporary ramp metering strategies

Since capacity of a roadway is decreased due to lane closure, vehicles entering from on-ramps can create turbulence by their turning movement. Temporary ramp metering is a way to control the vehicles entering on freeways, thus increasing the mainline flow on the freeway. One researcher (Oner, 2009) studied the performance of ramp meter on the interstate with work zones using simulation and found that shorter queues on the arterials and the rightmost lane closer to mainline merge point of the interstate. A study based on seven actual lane closure locations in Missouri where temporary ramp meters were installed was used to collect data. The data were used in a simulation model that analyzed performance under the temporary ramp metering strategy for off-peak hour (Sun, Edara, & Zhu, 2013). However, the outcome of this strategy is unknown for peak hours. More studies need to be conducted to evaluate its performance for a lane closure segment on freeway with on-ramps (Ramadan & Sisiopiku, 2015).

Table 1 presents a summary of available strategies focusing on their potential benefits and limitations as reported in the literature.

Table 1 : Summarizing the findings of different traffic control options

Type of the traffic control strategy	Potential benefits	Limitations
Static Early Merge	Reduce merge related collision, rear-end collision; Increase free merges at higher traffic volume	Congestion, Lane-change crashes, difficult maintenance of signage
Dynamic Early Merge	Varying no-passing zone based on detectors, smooth merging	Ineffective for queues beyond the detectors, higher travel time
Static Late Merge	Reduce queue length and rear-end crashes	Safety issues in low-volume and high-speed situations
Dynamic Late Merge	Changeable merge point based on real-time information	Threshold volume and speed needs to be evaluated accurately
Joint Merge	All lanes get equal priority	Insignificant change compared to conventional merge
Reduced Speed When Flashing	Reduce speed only during active work zone	Driver's perception study is needed
Closure of Entrance Ramps During Construction	Enhanced mobility	Adverse impact on arterials
Mainline Merge Metering	Increase throughput	Further study is required
Temporary Ramp Metering Strategies	Increase mainline flow	Peak-hour study is needed

Current State-of-Practice in the United States

A detailed study about the current practice to control traffic at work zones around the states had been conducted by questionnaire survey among DOTs (Ramadan & Sisiopiku, 2015). The study gathered information from 27 states over a period at more than one month. The participating states were Alabama, California, Colorado, Illinois, Iowa, Michigan, Minnesota, Mississippi, Missouri, North Carolina, South Carolina, South Dakota, Utah, Vermont, West Virginia, Wisconsin, and Wyoming, and another 10 States that remained anonymous. The response from these states about the merge control strategy during work zone lane closures identified that most of them schedule maintenance work during off-peak period and more than half of the DOTs adapt static early merge as merge control strategy, followed by static late merge control adapted by almost 20% of the DOTs that responded in the survey. The rest of the responders used conventional merge control and a few attempted dynamic lane merge control. The reason that they follow any of these strategies is merely their previous experience. Their decision also depended on safety, mobility, policy, and cost, but primarily they relied on their past knowledge. Another study indicated that the majority of states carry on the work on a lane during night or off-peak based on the type of roadway (Chatterjee, Edara, Menneni, & Sun, 2009).

Another study was conducted to identify the current practice of the Texas DOT using a questionnaire survey (Pesti et al., 2008) which revealed that more than half of the responders used arrows to encourage vehicles to merge on the open lane and 25% of them close the left lane. Almost 30% of the respondents have used late merge in lane closure situation.

Earlier studies had identified some DOTs that developed manuals for work zone traffic control and few are enriching their guidelines (Ramadan & Sisiopiku, 2015). For example, the Illinois Department of Transportation (IDOT) has maintained a manual for location, and design of roadway projects that maximize the safety of workers and travelers. They have set their target to decrease the fatality rates in work zones by 10% each year. The Texas Department of Transportation (TxDOT) has also established a manual for recognizing the project requirements so that it can be finished within the proper timeline. The Florida Department of Transportation (FDOT) has a training plan to ensure safety at work zones for workers and motorists. Their rule enforces prohibition of lane closure on interstate with two lanes to decrease delay for the travelers (Elghamrawy, 2011). The California Department of

Transportation (Caltrans) also has a manual with criteria to categorize the significance level of work zone based on the traffic delay (Scriba, Sankar, & Jeannotte, 2005).

Earlier Studies considering Different Temporary Traffic Control (TTC)

Several studies have been conducted on the Temporary Traffic Control (TTC) strategies available around the states. Some conducted field tests and some used simulation studies to evaluate the performance of different TTCs. Earlier studies and their findings are important for enabling efficient work zone planning.

Studies to compare static late merge and early merge

Researchers had conducted several studies to compare static early merge and late merge strategies at work zones. One team (Beacher, Fontaine, & Garber, 2005) from Nebraska performed a detailed study of both traffic control options at the time when the state utilized conventional merge control for its work zone situations. Computer simulations were conducted for typical work zone scenarios such as 2-to-1, 3-to-1, and 3-to-2 lane closure configurations using both traditional merge and late merge strategies to identify the difference between these two strategies. Variations in free flow speed, volume, and heavy vehicle percentage were considered to identify their effect on operational performance. Field tests were also conducted for the 2-to-1 lane closure configuration. The simulation study indicated that late merge strategy holds promise for 3-to-1 lane closure configuration for any demand volume or any percentage of heavy vehicles. The other configurations (3-to-2 and 2-to-1) also performed better under late merge control when compared to the conventional merge strategy with more than 20% of heavy vehicle. In that study, the volume in the closed lane increased by 30% with static late merge. Mean speed decreased by 7 mph and

16.1 mph under static late and static early merge respectively, when compared with standard MUTCD under uncongested traffic situation. This means vehicles can travel at higher mean speed with static late merge than with static early merge, thus highlighting the benefits of late merge TTC. It was also reported that under late merge the forced merge was reduced by 75% and the queue decreased by half. More research is recommended before actually implementing late merge in the field, specially where various amount of traffic volume occurs.

As a part of a project sponsored by the Texas Department of Transportation, researchers utilized the simulation platform VISSIM to compare impacts at work zones operating under early, late and signalized merge control strategies (Kurker et al., 2014). Network performance, safety issues, driver behavior, and driver operations were investigated to differentiate among these controls, both based on field observations and microsimulation studies. They utilized field data to increase the accuracy of the simulation model. From their study, they observed that early merge control is better for lower demand conditions. This is because the vehicles get sufficient space to merge to the open lane if less traffic are present on the roadway. This strategy also proves to increase safety and reduces delay because of the smooth merging with lower traffic. On the other hand, under increased traffic demand conditions, late merge is reported to perform better. The reason is that late merge utilizes the available lane capacity more effectively, right until the reach the actual lane closure. The researchers concluded that use of any strategy depends on the volume (V) and capacity (C) of the roadway. When V/C becomes close to 1 or greater than 1, the roadway may perform better with late merge control according to their research. The authors studied late merge with a signal system to direct drivers through work zones and found out that signalized late merge works better if volume is more than 1,800 vph/lane.

Studies to compare dynamic early and dynamic late merge

Some state DOTs try to improve mobility and safety near or at work zones locations through the use of Intelligent Transportation System applications. Researchers in Florida compared conventional practice followed by the Florida DOT, termed as Motorist Awareness System (MAS), dynamic early merge, and dynamic late merge. For the simulation, they used a 2-to-1 lane closure configuration and field data were collected for all three types of merge control and inputted in the VISSIM simulator using vehicle-actuated programming (VAP) to represent the algorithm (Harb, Radwan, & Dixit, 2012). The length of the work zone was 13 miles and workers moved the work zone and worked on almost 3 mile each day. The experimental design considered various drivers' compliance rates, different truck percentages, and different traffic volumes in the VISSIM environment. Comparison of the three controls revealed that simplified dynamic early merging system (early SDLMS) had higher throughput and lower travel time compared to late SDLMS and MAS. They recommended to study the control strategies with varying speed and other parameters in follow up studies.

Another study performed similar research focusing on 3-to-2 lane closure configuration (Harb, 2009) and focused on speed and measured speed variations in the closed lane. This variation was maximum with MAS strategy under all demand volumes and minimum using dynamic early merge control. Dynamic early merge worked better than conventional MAS when volumes ranged from 500 veh/hr to 2000 veh/hr. Moreover, dynamic late merge worked better than conventional MAS when volumes ranged between 1500 veh/hr and 2000 veh/hr but did not perform well with low volumes. Furthermore, the comparison between the two forms of dynamic merge control showed that dynamic late merge has a superior performance than dynamic early merge with higher volumes between 1500 veh/hr and 2000 veh/hr (Harb, 2009).

Studies focusing on late merge

The North Carolina DOT investigated different types of strategies on the roadways that impact merging behavior. The focus of the study was to reduce travel time. Among the various techniques considered in the scope of the project, late merge was one strategy that was included (Vaughan et al., 2018). Two types of lane closure were considered, namely 2-to-1, 3-to-2 on rural arterial, rural freeway, and suburban freeway. The sites that had zipper merge control showed an increased speed by 11 mph, meaning reduced travel time. The study reported that after implementing late merge, vehicles continued to drive in closed lanes further than without late merge strategy, thus more roadway capacity was utilized. An improvement on the safety was also observed. The study categorized types of merge and found that the most dangerous type of merge was reduced when zipper merge was used.

One study in Kentucky compared early merge with zipper merge with some documented case studies (Lammers, Pigman, Howell, & Kirk, 2017). They investigated two case studies in Kentucky, one at an interstate, and another at a bridge. When they compared the data for the interstate, they found out that late merge had better traffic flow compared to early merge and had better safety (Lammers et al., 2017). Overall, they found that late merge performs better and results in greater throughput in the area affected by construction. They recommended application of late merge in other locations, and collection and analysis of more field data that will reveal the appropriate location for implementing late merge in the future.

Studies focusing on dynamic late merge

The Maryland State Highway Administration evaluated the performance of DLM on a freeway lane closure in 2003 using occupancy as control thresholds. Portable Changeable Message Signs (PCMS) were active when occupancy was over 15% occupancy. The researchers estimated work zone throughput, volume distribution, and queue length. The results showed that DLM performs better than conventional merge control with respect to throughputs (Kang, Chang, & Paracha, 2006).

Another study investigated the usefulness of a synchronized system to warn drivers about work zones. The warning-light system proved advantageous at urban freeway for new work zones, but not at rural roadways where lane has been closed for long duration. So, it was concluded that this strategy might have better performance for short or intermediate work zones (Finley, Ullman, & Dudek, 2001).

The Michigan Department of Transportation (MDOT) applied the Dynamic Late Lane Merge System (DLLMS) on three freeways in 2006 and made a comparison with conventional merge control at a site. All work zones considered had the 2-to-1 lane closure configuration. Traffic volumes, speeds, travel time, crashes, and queues were measured using video cameras and radar guns and floating cars were used for several days to gather average travel time along the work zones. Crash reports were also collected to assess any crashes at the study site. The researchers concluded that traffic performance was enhanced and percentage of vehicle merging closer to taper increased using DLLMS instead of the conventional method. The average travel time decreased by almost 40% using DLLMS compared to conventional method and delay and speed were both increased by 60% compared to the conventional merge control. Overall, each measure of effectiveness considered showed that DLLMS outperforms early merge (Grillo, Datta, & Hartner, 2008).

Studies focusing on joint merge

The Louisiana DOT has utilized joint merge for an interstate work zone with 2-to-1 lane closure configuration and compared the operational impacts of this control to those under early merge at work zones. Field data such as traffic volumes, speeds, and type of vehicles were collected and analyzed. Overall, merging speeds were found to be relatively similar at volumes ranging from 600 to 1,200 vehicles per hour and did not affect the discharge rate at the merge outflow point. However, the experimental results did suggest that drivers were more cautious in their merging maneuvers (Idewu & Wolshon, 2010).

Table 2 shows the summary of earlier studies discussed above that are conducted by researchers focusing different temporary traffic controls and their findings are included as well.

Tools to Measure Mobility and Safety at Lane Closures

A wide variety of tools are available to measure safety and mobility at work zones. For example, the Highway Capacity Manual (HCM) 2000 has developed a system to measure capacity of work zones. It takes base capacity, work zone adjustment factors, heavy vehicle factors, and existence of nearby ramp as its input. However, this manual does not have any method for evaluating queue length (Harb, 2009).

Table 2 : Summary of earlier studies on various temporary traffic control strategies

Researchers	Strategy	Period	Lane closure configuration	Approach of analysis	Findings
(Beacher et al., 2005)	Static Late merge vs early merge	Short-term	2-to-1, 3-to-1, and 3-to-2	Microscopic simulation	Late merge is better
(Kurker et al., 2014).	Static Late merge, early merge, signalized merge	Short-term	2-to-1, 3-to-1, and 3-to-2	Microscopic simulation	Late merge is better for high volumes, Early merge is better for low volume
(Harb et al., 2012)., (Harb, 2009).	Conventional practice, Dynamic early and Dynamic late	Short-term	2-to-1, 3-to-2	Microscopic simulation	Dynamic early merge is better
(Vaughan et al., 2018).	Zipper merge	Congested time period at field site	2-to-1, 3-to-2	Field test on Freeways, arterials	Increased safety, reduced travel time
(Kang et al., 2006).	Dynamic Late merge	Field site	2-to-1	Microscopic simulation	Dynamic late merge is better than conventional
(Grillo et al., 2008)	Dynamic Late merge	Field site	2-to-1	Field test on Freeways	Reduced travel time; better than early merge
(Idewu & Wolshon, 2010).	Joint merge and early merge	Field site	2-to-1	Field test on Highways	Joint merge had higher volume in closing lane

Queue and user cost evaluation of work zone (QUEWZ) is another system that uses HCM 2000 to estimate work zone capacity and HCM 1994 to estimate queue length. QuickZone is one tool that was developed for the Federal Highway Administration (FHWA) to calculate traffic impacts of work zones. This tool can be tailored to represent a particular work zone under any state DOT. DELAY Enhanced 1.2 is another tool developed for FHWA as well to identify traffic impact of work zone. Queue length can be plotted for short-term work zones.

Several other microscopic simulation software can be used to analyze traffic impacts on work zones namely, VISSIM, CORSIM, SimTraffic, AIMSUN, ARENA, VISTA, SSAM etc. Among them, VISSIM has been used to code work zone in many studies available in the literature and several researchers provided recommendations on how to calibrate driving behavior parameters in VISSIM for closely matching to the real lane closure condition (Chatterjee et al., 2009). *Table 3* shows a summary of earlier studies that coded various lane closure merge control strategy using these available simulation platforms.

Based on the features and capabilities of the various software options, the literature suggests that VISSIM or CORSIM could meet the modeling needs of the current study the best. Thus, those two options are reviewed in greater detail next.

Table 3 : Some earlier studies using various simulation platform

Researchers	Strategy	Simulation platform
(Beacher et al., 2005)	Static Late merge vs early merge	VISSIM
(Kurker et al., 2014).	Static Late merge, early merge, signalized merge	VISSIM
(Pesti et al., 2008)	Dynamic merge	VISSIM
(Wei et al., 2010)	Dynamic merge with merge meter	VISSIM
(Lentzakis et al., 2008)	Mainline metering	AIMSUN
(Tympakianaki et al., 2014)	Mainline metering	AIMSUN
(Harb et al., 2012)., (Harb, 2009).	Conventional practice, Dynamic early and Dynamic late	VISSIM, VAP
(Sun et al., 2013)	Temporary Ramp Meter	ARENA
(Kang et al., 2006).	Dynamic Late merge	CORSIM
(Oner, 2009)	Temporary Ramp Meter	ARENA

VISSIM

VISSIM is a microscopic, stochastic, multi-modal simulation model that was developed in Karlsruhe, Germany by Planning Transport Verkehr (PTV) (Chatterjee et al., 2009; Harb, 2009). PTV VISSIM distributes the software in the United States. This software takes traffic volume, composition, lane distribution, speed, type of roadway and other parameters as inputs and analyzes roadway traffic operations based on the coded network ("VISSIM User Manual," 2011). The model is based on Wiedemann's work (Sisiopiku & Ramadan, 2017). The advantage of using this software is that it takes "psycho-physical" driver behavior into account in the simulation. The accuracy of the model relies on modeling of vehicle and driver behavior. Freeway condition is coded on the basis of the Wiedemann 99 car following model (W-99) where there are 10 user defined driving behavior parameters. Drivers take the decision to increase or decrease the speed based on threshold value of speed and distance in W-99. The model is developed in such way that drivers perceive speed, safe distance, and desired speed between two vehicles. Gap acceptance criteria are also included in the model which ensures that a driver would change lanes only when the gap is more than a set critical gap (Chatterjee et al., 2009).

Corridor-Microscopic Simulation Program (CORSIM)

CORSIM is a part of Traffic Software Integrated System (TSIS) which is a combination of NETSIM (surface street simulation) and FRESIM (freeway simulation). It is a microscopic time-step simulation model used to evaluate operation of traffic on roadways and is based on car-following and lane-changing logic (Sisiopiku & Ramadan, 2017). It is a stochastic model and takes drivers' behavior, traffic system, and vehicles into account while analyzing.

CORSIM is developed on behalf of FHWA by combining other simulation platforms into one platform. Researchers report that there might be some problems with managing high on-ramp volume with metering or managing off-ramp high volume with backups (Choa, Milam, & Stanek, 2004) but the Minnesota DOT provided a solution to such problem by addressing the integration of nodes between freeways and surface streets (*Advanced CORSIM Training Manual*, 2008).

Researchers have compared the most commonly used simulation software, VISSIM and CORSIM based on technical aspects and features (Bloomberg & Dale, 2000) and determined these two are actually similar types of platforms. It was reported that VISSIM has an advantage over CORSIM as it has the ability to simulate dynamic merge control by using the Vehicle Actuated Programming (VAP) feature. Another study was conducted to compare these two software (Choa et al., 2004) and their findings are summarized below:

- VISSIM has path-based routing option that ensures correct use of lane for closer intersections. CORSIM has link-based routing that may not perform well with lane utilization for closer intersections.
- VISSIM has built-in a detailed three-dimensional animation features to enrich visual understanding. CORSIM offers two-dimensional animation.
- Both software tools report total delay by link and are unable to evaluate control delay for turn maneuvers. Yet, CORSIM can estimate control delay for each approach.
- CORSIM can cause incorrect output at high on-ramp volume with metering or managing off-ramp high volume with backups because of the barrier between freeways and surface streets.
- VISSIM requires more time for set-up compared to CORSIM.

Earlier studies conclude that there is no perfect software that is applicable for all various types of work zone (Hardy & Wunderlich, 2009) but developing a network is easier with VISSIM as it allows the user to build a network on the aerial photo of actual location by drawing links and connectors (Bloomberg & Dale, 2000). Another benefit is that VISSIM runs based on psycho-physical driver behavior developed by Wiedemann, instead of setting a desired headway like CORSIM. Finally, VISSIM gives the user more flexibility to collect output data by specifying location of data collection points (Bloomberg & Dale, 2000). Based on the literature, VISSIM was selected as the simulation platform in this study for its superiority and ability to meet the study goals and needs.

Summary

There are various types of temporary traffic control strategies in the United States including static or dynamic early merge, static or dynamic late merge, joint merge, reduced speed when flashing, and closure of entrance ramps during construction. Some traffic control strategies are advantageous over others at some specific situations. However, findings vary by location and there is no clear guideline for implementing temporary control to improve operations at work zone lane closures. In fact, most of the state departments of transportation report using early merge control but admit that they make this decision based on their experience rather than evidence of improved performance. Research is going on to identify options for better management of work zones and improved operational performance near work zones. Many earlier studies have focused on operational and safety issues related to early and late merge control mostly for short-term work zones. The common lane closure configurations covered in the studies are 2-to-1 and 3-to-2. Only a few researchers have focused on the 3-to-1 lane closure scenario. For these studies, some simulation platforms such as VISSIM, CORSIM, AIMSUN were utilized to analyze the impact of different control strategy on traffic operation. Some major findings are that late merge performs better during high demand volume, whereas early merge is a good option when low traffic volume occurs. Late merge control is also reported to increase safety and reduce travel time. The literature review suggests that additional studies are needed, especially focusing on analysis of 3-to-1 lane closures under various TTC strategies for long- and short-term lane closures.

METHODOLOGY

Introduction

The purpose of the study is to investigate operational performance of two temporary traffic controls namely early and late merge for 3-to-1 lane closure configuration for various work zone lengths. This chapter presents how the study was conducted, and discusses the study segment, experimental design, network coding in VISSIM, calibration and validation efforts, and measures of effectiveness considered.

Study Corridor

In this study, a decision was made to employ simulation modeling for the study of operational performance of early and late merge for 3-to-1 lane closure configuration for various work zone lengths. Simulation modeling provided an opportunity for controlled experimentation and analysis as an actual work zone set up on the field was not a feasible or desirable option. Changing the traffic control strategy or length of an existing work zone frequently can be very confusing for drivers and might have undesirable effects on the safety and convenience road users. A microsimulation study, on the other hand, allowed to make changes in the work zone set up, TTC or other parameters and to observe their impacts on traffic operation through the collection and evaluation of performance measures.

In this study, a 12-mile corridor of Interstate 65 (I-65), passing through the city of Birmingham in the state of Alabama, was selected as the study site (*Figure 1*).

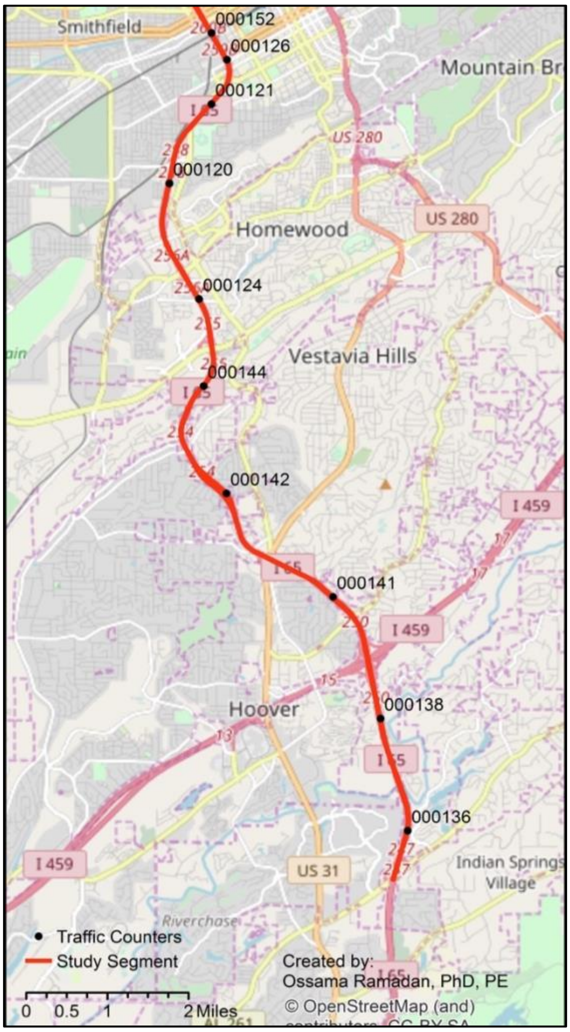

Figure 1 : Study corridor

The I-65 corridor considered in this study is located within Jefferson county, Alabama, and extends from downstream of Exit 247 near Valleydale Road to just before Exit 261A on the northbound direction where the interstate passes over 1st Ave North. The interstate has 3 traffic lanes per direction, with occasional acceleration/ deceleration lanes added near ramps to facilitate the vehicle movements. The typical lane width is 12-ft and the posted speed limit is 60 mph on the interstate and 45 mph on the ramps. *Table 4* gives detailed information about the study corridor.

Table 4 : Geometric information of the study corridor

Description of the segment	Number of lanes	Total width (ft)	Total length (ft)
From exit 247 to exit 250	4	48	12777.6
From exit 250 to exit 252	4	48	9715.2
From exit 252 to exit 254	3	36	9187.2
From exit 254 to exit 255	3	36	7339.2
From exit 255 to exit 256	3	36	5491.2
From exit 256 to exit 258	3	36	7656
From exit 258 to exit 259	3	36	6652.8
From exit 259 to exit 260	4	48	3696

Traffic Characteristics

Recent traffic volumes for the study corridor mainline were obtained through the Alabama Department of Transportation (ALDOT) for Thursday April 19, 2018, a typical weekday. The volumes were obtained for 24hrs on a hour-by-hour basis starting from 12 midnight. The Traffic Monitoring section of the Maintenance Bureau at ALDOT routinely collects and maintains traffic volume for the major roadways in the state of Alabama. For traffic coding purposes, in addition to mainline counts, on-ramp and off-ramp volumes were also needed. Those are collected periodically by ALDOT and were obtained by contacting with the personnel of ALDOT. Many of those ramp counts were not collected on April 19, 2018 but all were collected in 2018.

When the base data sheet was obtained from ALDOT for the month of April, it was observed that the data source contained both the mainline and ramp volumes for many stations in the state. Each station provided a description about its locations, that includes details such as which county it is located in, its position with respect to highway, etc. To identify the stations that fell within the study segment, a description of each station was checked and those falling in Jefferson county were extracted.

These were again scrutinized to identify which are located on I-65 and a description about nearby streets was used to get an accurate idea about the stations within the study site. Finally, to be completely assured, the ArcGIS shapefile was collected from the Regional Planning Commission of Greater Birmingham which has length and location of each traffic management center (TMC) along I-65. These were matched and checked with the findings from the raw data sheet so that no traffic counter remained unidentified. Once these were confirmed, mainline volume and ramp volumes were obtained only for these stations located within the study site and arranged together in the sequence along the I-65 study corridor (northbound and southbound direction).

After organizing the traffic volumes according to the segments along the study corridor, it was noticed that some traffic volumes did not balance. This was expected, as the ramp volumes and mainline volumes were not collected simultaneously and there is variation in traffic volumes from day to day. Therefore, while the actual mainline volumes were kept exactly as reported by the ALDOT April 19, 2018 data, a few ramp volumes were adjusted to ensure that no vehicles were disappearing from the network. The balancing exercise ensures that when off-ramp volume is subtracted from a mainline segment upstream of an exit and it is added to the on-ramp volume of that exit, it should be equal to the volume of mainline segment downstream of that exit. Finally, the traffic composition was assumed to be 90% passenger vehicles and 10% trucks throughout the simulation experiments.

Experiment Design

Once the geometric properties of the study corridor and traffic data were established, the base model was developed in VISSIM to simulate existing conditions during all 24 hours of the day. Moreover, simulation models weer developed for the work zone situation for a 3-to-1 lane closure configuration. Three different work zone lengths were considered namely 500 ft, 1000 ft, and 1500 ft. The shortest work zone length (500ft) was considered for long-term work zone operation (24hrs), as well as for short-term work zone operation during morning peak hour and non-peak hour analysis. Based on the findings from the 500 ft work zone length, other work zone lengths were tested for peak and non-peak short-term work zones. The longest work zone was tested for non-peak hour work zone only.

Table 5 shows the experiment design for this study. Each of the scenarios had 5 runs in VISSIM resulting in 60 runs total for work zone scenarios, and the predetermined measures of effectiveness were collected and averaged across the five runs. The base model was run separately for a 24hrs period as well as for the 3-hr AM peak period (6:00-9:00 AM) and a 3-hr PM non-peak period (9:00-12:00 PM), resulting in a total of 75 runs for the entire analysis.

Table 5 : Experimental design for the study

Number	Work zone length (ft)	Merge control strategy	Lane drop configuration	Duration
1.	500	Early merge	3-to-1	24-hr
2.	500	Late merge	3-to-1	24-hr
3.	500	Early merge	3-to-1	3-hr peak
4.	500	Late merge	3-to-1	3-hr peak
5.	500	Early merge	3-to-1	3-hr non-peak
6.	500	Late merge	3-to-1	3-hr non-peak
7.	1000	Early merge	3-to-1	3-hr peak
8.	1000	Late merge	3-to-1	3-hr peak
9.	1000	Early merge	3-to-1	3-hr non-peak
10.	1000	Late merge	3-to-1	3-hr non-peak
11.	1500	Early merge	3-to-1	3-hr non-peak
12.	1500	Late merge	3-to-1	3-hr non-peak

Base Model Development

Base model development procedure included network coding with proper geometry, entering of traffic volumes, and setting driver behavior parameters. Details of all steps are described below.

Network Coding

The roadway network geometry was obtained from available aerial map of VISSIM. Moreover, the number of lanes, location of auxiliary lanes, and curves were confirmed by field visits. All segments of the freeway of I-65 are drawn using links and the connector feature of VISSIM. One link can have same number of lanes throughout it. Therefore, separate links are drawn from one exit to the next one since the total number of lanes remains same for such segments except for locations where auxiliary lanes are needed. The width of each lane was set to be 12 ft. On-ramp and off-ramp segments are drawn using the link feature. To represent extra lanes for deceleration, a connector was drawn starting from the end of freeway link end extending until the starting point of off-ramp link. Acceleration lanes are also coded in a similar manner. Due to the unavailability of grade information of the interstate, no grades were added for each of the links.

In VISSIM, the type of the link selected controls the type of driver behavior. There are five types of links based on behavior namely, urban (motorized), right-side rule (motorized), freeway, footpath, and cycle-Path. Since the study corridor is on interstate, “freeway” was selected as the type of the links and connectors. Lane change behavior of vehicles was coded changing the default lane change parameters and emergency stop for connectors. Lane changing distance was varied for each connector from the default value. This distance means how much ahead of a turn the vehicle would try to change its lane to reach its destination. Various combinations were used to replicate the actual scenario. Finally, when travel time for each segment became closer to the field value, that distance was set for the next runs.

Traffic Coding

Traffic coding refers to the process of inputting correct traffic volume with correct vehicle composition for each link. Traffic demand data set was prepared based on field observed data retrieved from ALDOT data sources. In VISSIM, traffic can enter at the starting point of a link. To represent actual conditions, vehicles' entrance was coded for the very first link of interstate and for the entrance at each on-ramps. The data sheet was prepared for on-ramp volumes so that the mainline volume for all links match with actual data. Since the study focused on 24-hour duration, 24 "time intervals" were created with each interval having 3600 seconds, i.e., 1-hour slots. Then traffic volume was loaded carefully for each time interval at those above-mentioned source nodes.

As mentioned earlier, the segment typically contains 10% heavy vehicle and the posted speed limit is 60 mph. So, default vehicle types - car and HGV (truck) were used to create a composition with desired speed of 60 mph. VISSIM allows a distribution of speeds instead of a fixed one for all time, because vehicles' speed varies from time to time. Some links were coded with different ranges of desired speeds at certain time periods of the day to closely match field observations. The change of speed was based on real data collected from the National Performance Management Research Data Set (NPMRDS) and obtained through the Regional

Planning Commission of Greater Birmingham (RPCGB). Thus, vehicle composition was created and assigned to the vehicle input for the links.

Vehicles exit behavior also needed careful coding. VISSIM has various route choice decisions. Vehicle routes have a sequence of links and connectors that direct vehicles in the desired direction. For this study, the static route decision was coded before each exit. One route directs vehicle towards the off-ramp, and another route directs vehicle along the interstate. Based on the ALDOT off-ramp data, exit volumes were coded using route choice decision and the rest were entered in the straight direction of the route to make sure that no vehicles were disappearing or added automatically in the network.

Model Calibration and Validation

VISSIM is a broadly accepted microsimulation too that has been utilized for analyzing many freeways in North America. Still, in every new study, calibration and validation is needed for ensuring that VISSIM is coded properly so that it accurately replicating real field conditions.

Calibration parameters fall into two categories- one is system calibration parameters, and another is operation calibration parameters. System calibration refers to checking model input. The most commonly used calibration parameters are related to driver behavior which falls under operational calibration. Driver behavior affects how the model works and the output changes based on different driver behavior parameters. In this study, Wiedemann 99 car following model is used to control drivers' characteristics in the freeway segments. There are ten calibration parameters in VISSIM labeled as CC_0, CC_1, CC_2, CC_3, CC_4, CC_5, CC_6, CC_7, CC_8, CC_9 for freeway behavior. The operational calibration parameters that were changed in the study include car following behavior, lane changing behavior, and lane changes distances. Default parameters for lane change distance were used initially to run the model, but those values did not represent the study area close to reality. Therefore, parameters related to driver behavior were changed along with different lane changing distances and a total 25 versions of the model were run for the simulation, each having 5 runs, with various parameter combinations until the model was validated. Following are the values of the above-mentioned parameters used in the model:

- CC_0: This is the standstill distance that defines desired distance between two consecutive vehicles when vehicles have a speed, v=0 mph. The value for this one is 4.92 ft in the model.
- CC_1: This refers to the desired headway time in seconds between two consecutive vehicles. 0.9 seconds is used for this parameter in the model. Higher value of this means drivers drive in a safer manner.
- CC_2: This represents the following distance that a vehicle would maintain for safety. The model uses 13.12 ft as the following variation.
- CC_3: This refers to the time in seconds when any driver starts to decelerate because of slower moving lead vehicle to reach safety distance. The value of it is -8 seconds.
- CC_4 and CC_5: This parameters specify the speed variation between leading and following vehicle. If the value is small, this indicates more sensitive reaction from following drivers due to acceleration or deceleration of lead vehicle. The model uses -0.35 ft/s for CC_4 and 0.35 ft/s for CC_5.
- CC_6: Represents how speed oscillation depends on the distance of following condition. Higher value of the parameter means that speed oscillation increases because of increased distance from the leading vehicle. Once this

threshold following value is surpassed, then the following vehicle's speed does not depend on the leading vehicle.

- CC_7: Defines the acceleration rate during oscillation. The model uses 0.82 ft/s^2.
- CC_8: Defines standstill acceleration that is desired from standstill condition. The value for this parameter is 11.48 ft/s^2.
- CC_9: Defines rate of acceleration that is desired at a speed of 50 mph. Value of CC_9 is 4.92 ft/s^2.

The total travel time along the study corridor was selected as the validation parameter. RPCGB has a shapefile with location and length of traffic management center (TMC) along the study segment. Travel time data for each TMC for 24-hour time periods were collected for the month of April and averaged for typical weekdays (Monday, Tuesday, Wednesday, and Thursday) to make sure that the travel time is representative for a typical day. Then "Vehicle travel time measurements" segments were configured in VISSIM retrieving data from ArcGIS shapefiles and locations of each TMCs starting point and ending point were placed carefully in the model.

Table 6 shows the length of TMCs which were created in identical manner in VISSIM. These segments can measure travel time for the vehicles passing at different time slots. All versions of the model had the same travel measurement segments and was run for 5 times with each combination of parameters. Finally, one model that generated the closest value of validation parameter, i.e., travel time, was selected as the base model and work zone with different merge control strategies and zone lengths were coded by making the necessary adjustments to the main model.

Table 6 : Length of each TMC according to RPCGB record

Number	TMC	Length (ft)	Length (mile)
1.	101+04371	5524	1.05
2.	101+04372	5541.13	1.05
3.	101+04373	7584.48	1.44
4.	101+04374	5081.41	0.96
5.	101+04375	3256.79	0.62
6.	101+04376	5104.85	0.97
7.	101+04377	4137.99	0.78
8.	101+04378	130.18	0.02
9.	101+04379	373.69	0.07
10.	101+04380	1431.45	0.27
11.	101+05095	4611.84	0.87
12.	101P04371	5628.26	1.07
13.	101P04372	1130.58	0.21
14.	101P04373	2956.17	0.56
15.	101P04374	2101.63	0.40
16.	101P04375	2976.87	0.56
17.	101P04376	2262.86	0.43
18.	101P04377	1468.54	0.28
19.	101P04378	468.18	0.09
20.	101P04379	755.74	0.14

The target of the calibration and validation efforts was to fine-tune the model so that travel time from VISSIM for each hour falls within ± 15% range of actual travel time values obtained from the National Performance Management Research Data Set (NPMRDS) through RPCGB. This range demonstrates the tolerance of acceptability and is reasonable for traffic studies as there is great variation in traffic and. The calibration effort was carried on until all 24 travel times fall within acceptable range.

The plot depicted in *Figure 2* shows the comparison between the actual travel time obtained from the NPMRDS dataset through RPCGB for April 19, 2018 and the travel times obtained from the VISSIM base model. One line is generated with 15%

increase of RPC data which is termed as upper control limit (UCL) and another line is drawn with 15% decrease of RPC travel time that is defined as lower control limit (LCL).

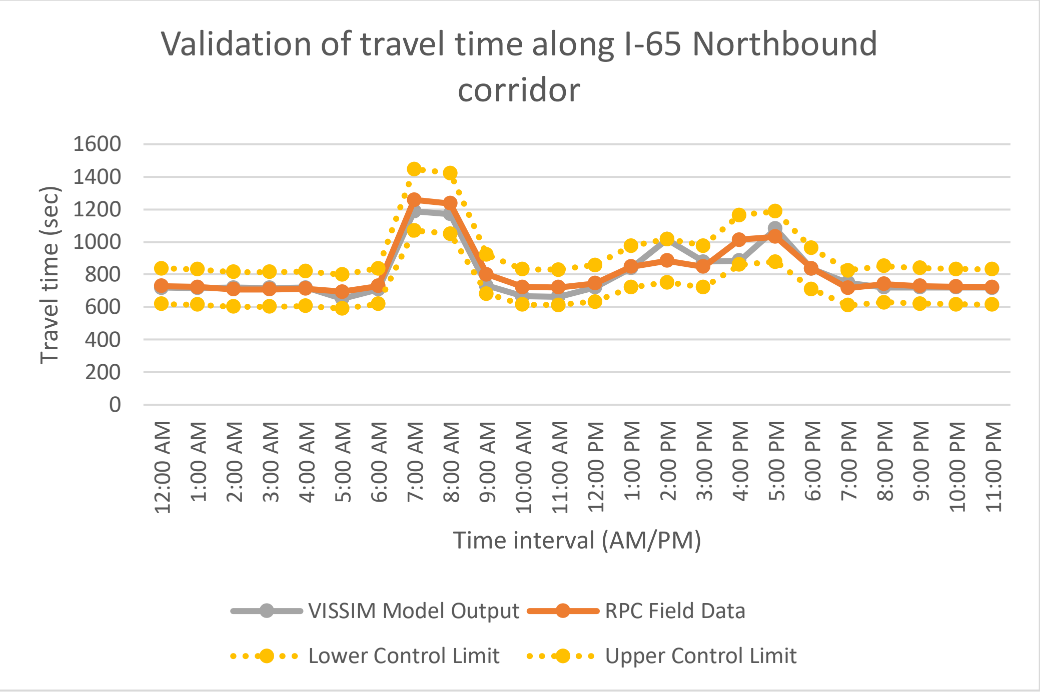

Figure 2 : Validation of travel time along northbound corridor

As shown in *Figure 2*, the line that represents the VISSIM model's travel time along the study corridor nicely matches the field data and falls within the boundary of upper limit and lower limit. This confirms that the model output is within the preset acceptable range and thus the model can be utilized for further analysis. This validation effort ensured that the model represents the actual traffic behavior observed on the selected study segment.

Work Zone Setup

Once the base model is calibrated and validated, the work zone is placed in the middle portion of the study corridor in the northbound direction. The 3-to-1 lane closure configuration closed the two right most lanes, leaving the left lane in operation through the work zone. Since, early merge control typically puts advanced warning signs 1-mile ahead of the work zone and encourages driver to merge at this point, the location of the work zone is carefully selected so that it affects the minimum number of ramps. This is because the primary objective of the study is to compare the operational impact of merge control options. The researchers wanted to reduce impacts that are attributable to closure of a ramp.

The segment of I-65 between US-31 and Lakeshore Pkwy was the location selected for placing the work zone. For this purpose, exit 254 had to be closed. This was the best way to minimize the number of ramp closures in the middle segment of the total corridor and observe the extent of destruction caused by the work zone placement on the links upstream. If the hypothetical work zone was set up at other location, more than one ramps would have to be closed. Therefore, the work zone was set up at this location. When this ramp was closed, distribution of the off-ramp and on-ramp traffic demand was taken care of by assuming that 40% of the volumes would use the previous off and on-ramp, another 40% would volume would shift to the next exit after the closure and 20% of the ramp volumes would use alternative routes. To represent the distribution pattern, the volume for the previous exit (252 exit) of ramp closure and volume of the following exit (255 exit) had to be adjusted accordingly. The other ramp volume distributions and volumes along the mainline were similar as in the base model.

Setting up late merge control

For setting up the work zone under late merge for the 3-to-1 lane drop of the two right most lanes of the northbound direction considered in this study, the segment between exits 252 and 255 was divided into three segments. The starting segment had three lanes and after certain distance, one lane was dropped using a taper. From this point onwards, the segment maintained two lanes. After vehicles merge into two lanes, they would find another taper ahead instructing them to merge again to one lane. This is the practice for 3-to-1 closure in Alabama. The reason for having a portion with two lanes is to give the drivers a transition length to merge to one open lane from all three lanes in a smooth and orderly manner.

Figure 3 shows the typical position of the sign “merge here” for late merge control and the overall configuration of arranging for dropping 2 out of 3 lanes resulting in a 3-to-1 configuration. This is how late merge control is coded in VISSIM using link structures and connectors, along with route decisions.

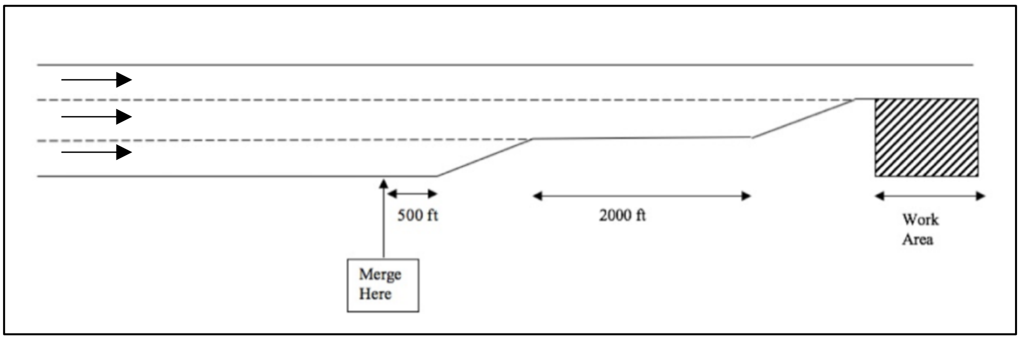

Figure 3 : Work zone with late merge control for 3-to-1 closure scenario

Setting up early merge control

The position of the work zone for early merge was exactly the same as it was with late merge control (between exit 252 and 255). The only difference here was that vehicles are directed to merge very early to the open lanes leaving the closed lane unused for almost one mile. Advanced warning signs are placed 1.0 mile ahead of the work zone. The advance warning sign encourages merging early and helps direct drivers along with the signs “merge here” or “2 right lanes closed”. The typical practice for 3-to-1 closure is shown in *Figure 4*. The intermediate segments are drawn in the same fashion for both late and early merge, but the lane change decision point is varied for these two, since early merge control requires coding that influences drivers not to use the closed lane.

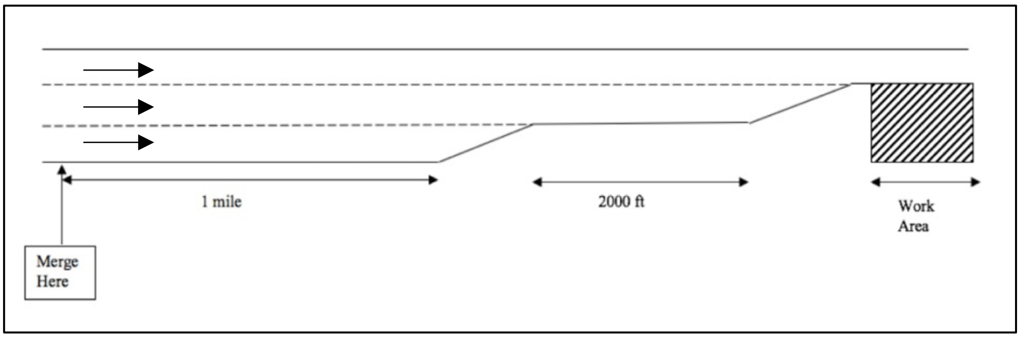

Figure 4 : Work zone with early merge control for 3-to-1 closure scenario

Measures of Effectiveness

After placing work zone in the study segment and coding the model for early merge and late merge control strategy, measures of effectiveness (MOE) were estimated and used to compare the performance of the two strategies. The MOEs considered herein are travel time, speed, density, and flow. Density refers the number of vehicles per unit length of a roadway segment. This is a very important parameter to understand the level of service of the roadway. Delay is defined as the difference between expected travel time at free flow speed and the actual travel time along a roadway. Travel time is estimated for all vehicles that enter a system during a specific period. It is a measure of travelers' perception about the performance of the routes. Traffic flow specifies the number of total vehicles passing a certain point. This measure refers to the throughput and is very important parameter for better understanding of the performance of roadway. Travel time and speed are MOEs that relate to the user's satisfaction while density and traffic flow are good measures of the facility's performance.

Simulation Parameters and Evaluation Configuration

When the base model and work zone models for temporary traffic control were coded with proper geometry and traffic characteristics, and measures of effectiveness were also decided, the researchers focused on getting the expected data from VISSIM runs correctly. In an effort to do so, a few simulation parameters and evaluations criteria were fixed for each model so that the outcome could be representative of exact similar conditions. At first, a warm-up period was needed to be set up as commonly done with traffic simulation models. The warm-up period indicates the time after which the model will start collecting data so that the model does not start from an empty network state. This technique helps to ensure that the simulation model better mimics traffic conditions in real life. Therefore, warm-up period ensures that the simulation doesn't generate output for an empty network. Warm-up period is added to the actual simulation period and the starting time of day of the simulation is set earlier by the warm-up period time. This model has an actual simulation period of 24-hour (86400 seconds), and 1 hour is taken as warm-up period. Thus, the simulation period was set as 90,000 seconds. For peak and non-peak segments, 900 seconds were taken as the warm-up period.

Simulation resolution is another parameter which means how many times the model would calculate any vehicle's position within one simulated second. The usual range can be 5-10 time steps per simulation second. If the value is higher, it ensures a smoother simulation. The model for this study used 10 time steps per simulation second.

Random seeds were also needed in the model to ensure that differences in results obtained by different models where due to the differences in the configurations studied, rather than variations in the streams of vehicles generated by the software. The random seed is a number linked to the arrival time of vehicles in the network, stochastic variability of driver behavior, etc. and ensures that the exact same sequence of vehicles is generated in each scenario that is using the same seed. In other words, if the same random seed is used for separate runs with identical inputs, the model would generate the same results. Since the purpose of the study was to compare operational impact of two merge control strategy, the same 5 random seeds were maintained for all versions of models (one for each iteration) to ensure that no change in the results were attributable to the vehicle arrival patterns. The number 42 was the random seed number for the first run (iteration) of the models. As mentioned earlier, in order to get more accurate results, each scenario of the models was run 5 times and results were averaged across those 5 runs in the final analysis. VISSIM gives the flexibility to use separate random seeds for various runs. The amount by which the first seed number increases for the next runs can be defined as random seed increment. The base model and models with work zone with early and late merge had used 20 as the increment. This means the first run started from random seed of 42, and the second run started for 62 and so on. Simulation speed was set as maximum.

Evaluation configuration specifies parameters that the model needs to evaluate from the simulation. For the study, density, vehicle travel time, speed, and flow were selected for evaluation. The time interval for which the simulation should generate results can also be defined here. The simulation model had traffic volumes for 24-hour entered by each of 24 1-hr long intervals and analysis could be by hour over the 24-hr time span. Therefore, the evaluation time interval was set as 3,600 seconds which means that the simulation model was asked to keep record for each measure of effectiveness on an hour-by-hour basis.

Summary

This chapter discussed discusses the approach used in this study to meet the study objectives and provides details about the study corridor and experimental design. Details about the location selected as the study corridor are provided along with geometric information. The traffic volumes were obtained from ALDOT and the base model was developed in VISSIM using the existing mainline traffic volume. The experimental design included both long-term and short-term 3-to-1 lane drop work zones for various work zone lengths with early and late merge control, resulting into a total of 12 models in VISSIM. The base model was calibrated and validated using the actual travel time obtained from the NPMRDS dataset through RPCGB for April 19, 2018. The validated base model was modified and used for analyzing the scenarios defined in experimental design. Flow, density, speed, and travel time were the measures of effectiveness collected from simulation runs and compared.

DATA ANALYSIS AND RESULTS

Introduction

This chapter summarizes the study findings based on measures of effectiveness (MOE), namely density, flow, speed and travel time. Comparisons are performed for MOEs obtained under early merge, late merge and base model scenarios for same time period of the day and same work zone length. For any given time period, the MOEs are extracted for the study segments located upstream of the starting point of the work zone, the segment including the work area, and the segment 1 mile after the work zone ends. Flow and density are estimated per lane and then compared against base model output.

Comparison of Merge Control for 500 ft Work Zone Length

According to the experimental design of the study, the shortest length for the work zone to be considered was 500 ft. Initially, both early merge and late merge scenarios were coded for long-term work zones, meaning the work zone was active on the roadway segment for a 24-hr period. Then based on the findings from long-term work zone study, separate models of peak and non-peak hour are also considered.

Long-term work zone analysis for 500 ft work zone

The simulation models of early and late merge scenarios with a 500ft work zone closure were run for a 24-hr period. *Figure 5* shows the flow along the segments from the start of the study corridor (i.e., upstream of the work zone) and up to one mile downstream of the work zone (a total of 7.61 mile from exit 247 to exit 255). The results show that when the volume was much less than the capacity at midnight, the placement of the work zone did not have much impact on the flow. However, when the volume started to increase from 6:00 AM in the morning, the scenario gets worse for both TTC options considered leading quickly to oversaturated conditions. One noteworthy observation is that the system is overwhelmed from the 2-lane closure and cannot recover throughout the day. This is because the one open lane cannot manage the demand and cannot clear the traffic accumulated from previous time intervals. Therefore, there is not much improvement in the flow even in the non-peak hour.

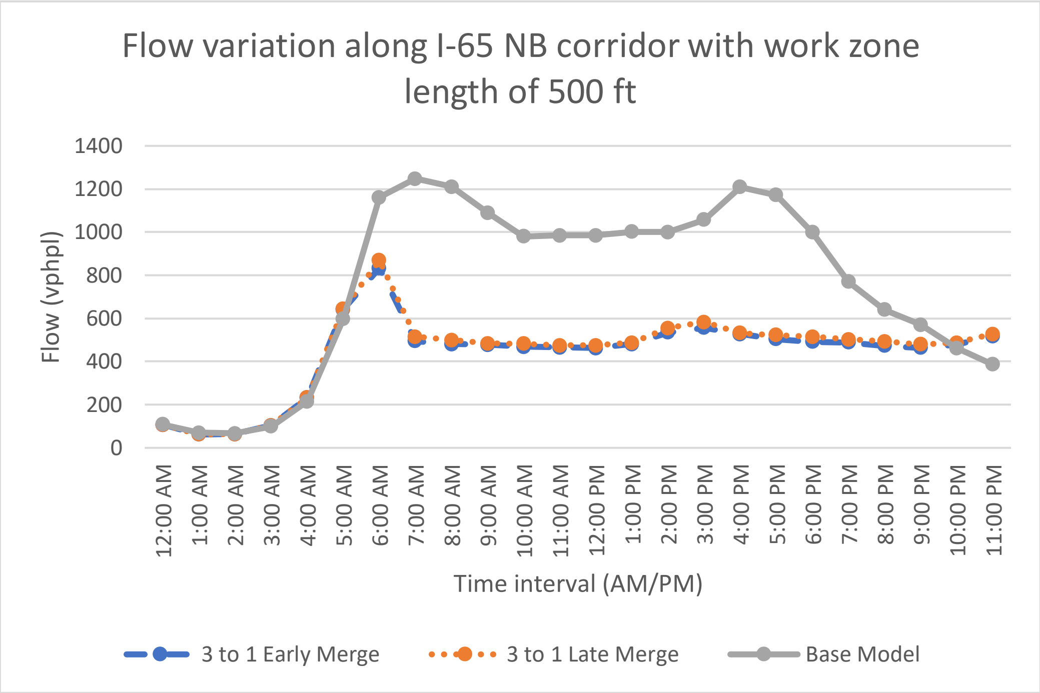

Figure 5 : Flow variation along I-65 NB corridor (work zone length: 500 ft)

For better understanding of the extent of flow reduction with respect to the base flow condition, the following formula is used:

$$\text{Percent reduction in flow} = \frac{Base\ flow - Flow\ with\ merge\ control}{Base\ flow} * 100$$

Table 7 shows the amount by which the flow throughput is reduced under the two TTC strategies considered. Up to a 60% reduction in flow was recorded in the 3-to-1 closure scenario.

Table 7 : Percentage reduction in flow for long-term 3-to-1 closure

Number	Time period starting at	Percent reduction in flow with Early merge control	Percent reduction in flow with Late merge control
1.	7 AM	60 %	58 %
2.	8 AM	60 %	58 %
3.	4 PM	56 %	56 %
4.	5 PM	57 %	55 %

Density was also analyzed as it gives a clearer idea about the level of service of freeways. *Figure 6* shows the density profile of the base model. This is the average density of the northbound direction from the start of the study section and up to 1.0

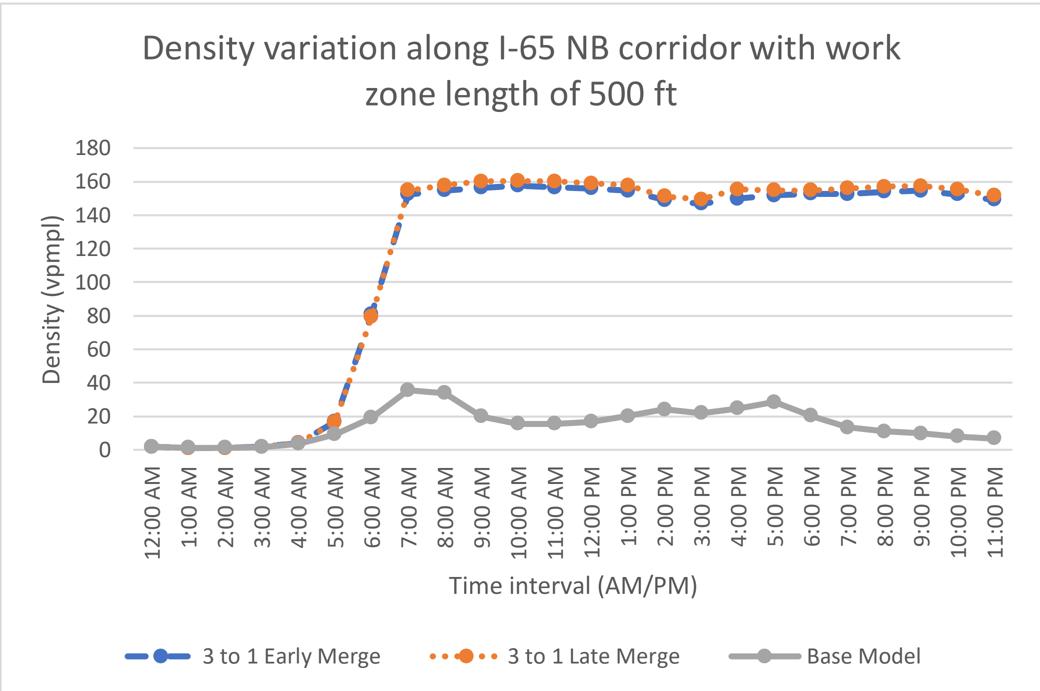

Figure 6 : Density variation along I-65 NB corridor (work zone length: 500 ft)

mile downstream of the work zone. The density profiles for the same section under late and early merge for 3-to-1 closure are superimposed to allow for comparisons

Figure 6 shows that in the presence of the 3-to-1 work zone the density starts getting affected after 5:00 AM in the morning. The density reaches the jam density during the morning peak and remains the same during the day as the roadway cannot recover and remains congested until the end of the study period (12:00 midnight).

Short-term work zone analysis (Peak period) for 500 ft work zone

Besides investigation of the impact of a long-term work zone with two lanes closing, the researchers also looked at the impact of a 3-to-1 closures for short-term work zone. Short-term work zones were analyzed for the morning peak period (6:00 AM to 9:00 AM) which is the most severe peak period along the northbound direction. For the peak period analysis, flow, speed, density, and travel time were compared for early and late merge and the results are depicted in *Figures 7-12*.

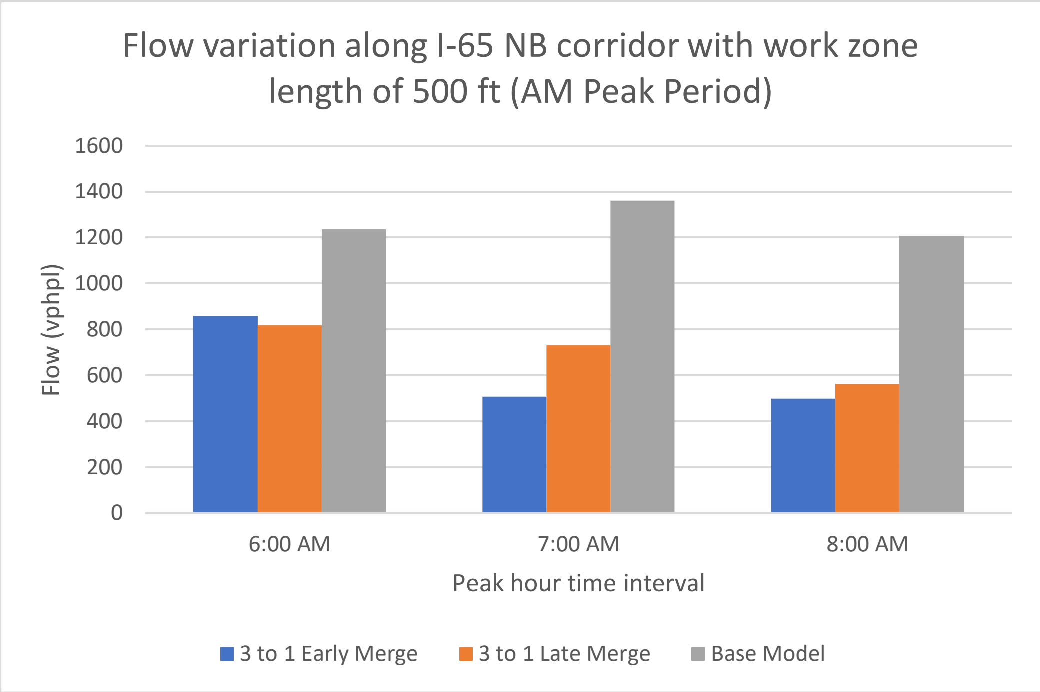

Figure 7 : Flow variation along I-65 NB corridor (work zone length: 500 ft, Peak period)

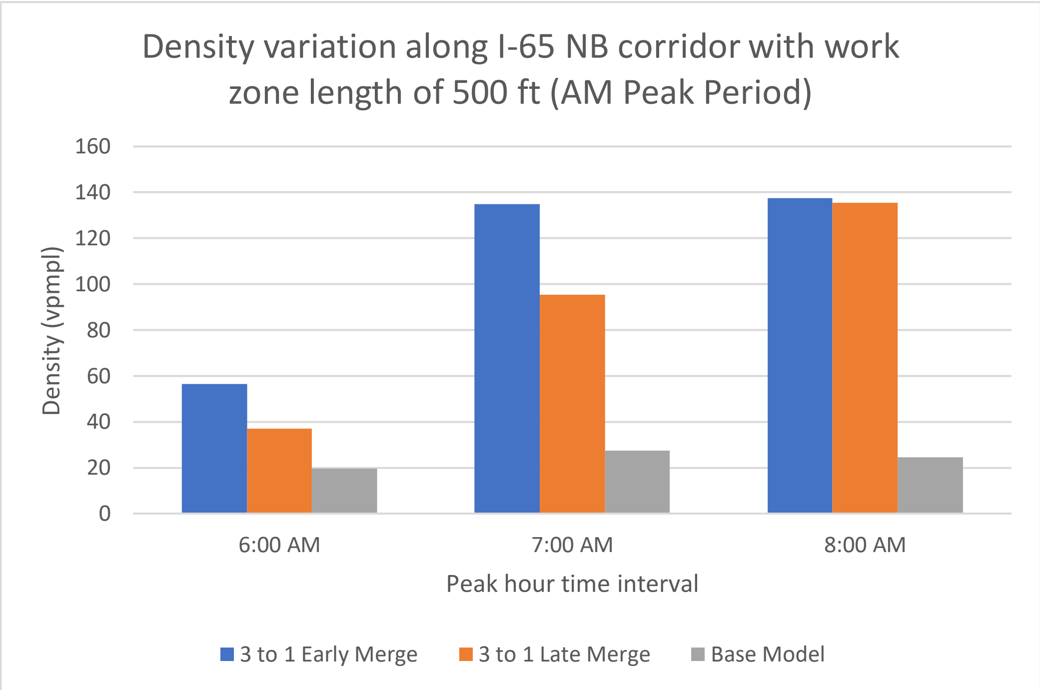

Figure 8: Density variation along I-65 NB corridor (work zone length: 500 ft, Peak period)

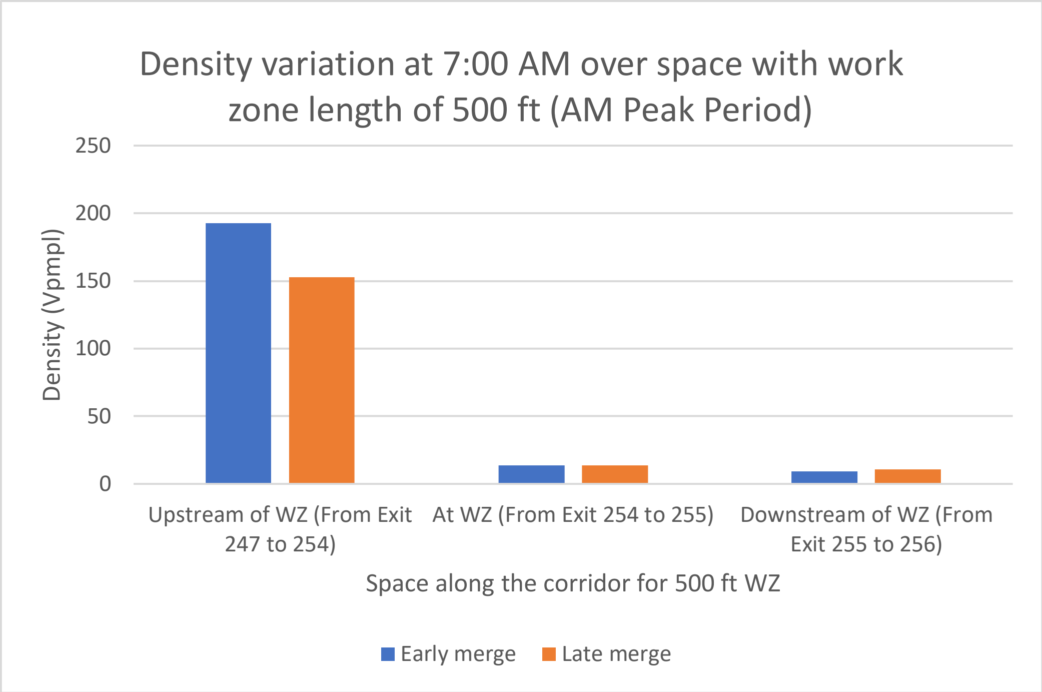

Figure 9: Density variation at 7:00 AM over space (work zone length: 500 ft, Peak period)

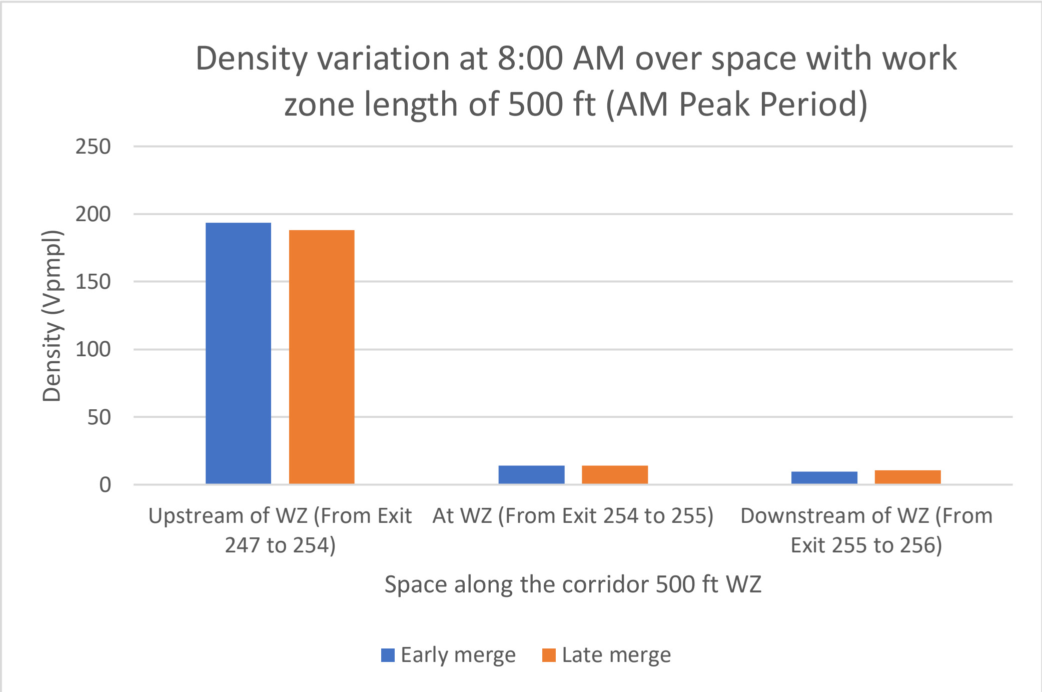

Figure 10: Density variation at 8:00 AM over space (work zone length: 500 ft, Peak period)

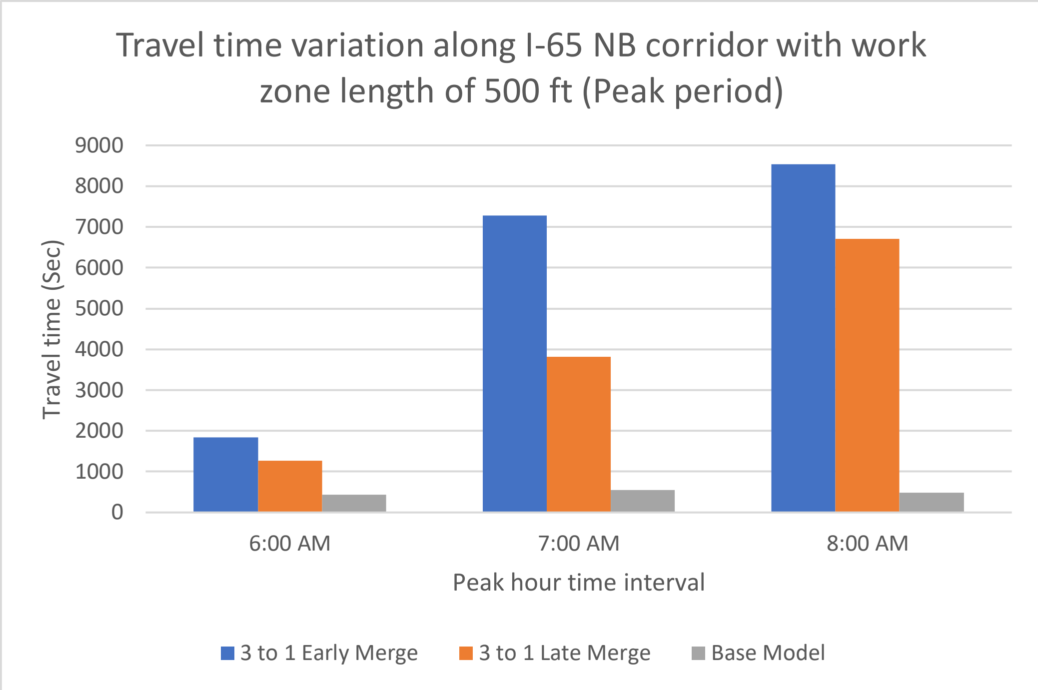

Figure 11 : Travel time variation along I-65 NB corridor (work zone length: 500 ft, Peak period)

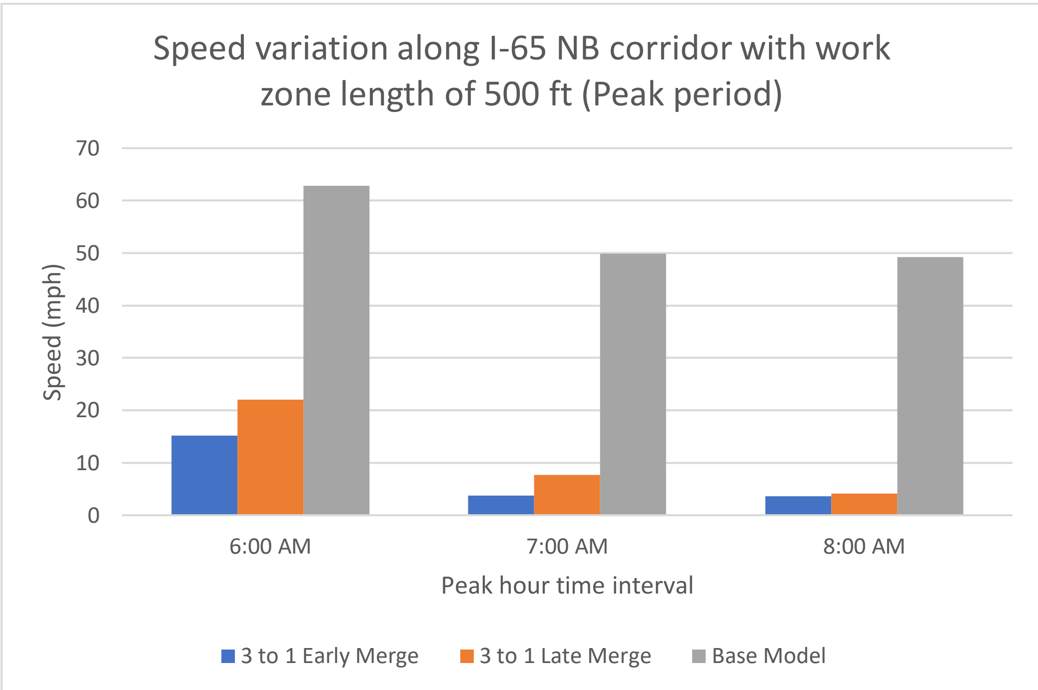

Figure 12 : Speed variation along I-65 NB corridor (work zone length: 500 ft, Peak period)

The findings from the short-term 3-to-1 work zone lane closure of 500 ft length during the AM peak showed that the base model – as expected - had clearly the highest flow and speed, and lowest density and travel time. When early merge and late merge performance were compared, it was observed that late merge resulted in slightly better performance than early merge for all MOEs considered as long as the volume-to-capacity ratio was under 1. However, under oversaturated conditions both types of merge controls failed to accommodate the demand.

Short-term work zone analysis (Non-peak period) for 500 ft work zone

Since late merge strategy performs slightly better than early merge at onset of the peak hour, it is important to confirm if the behavior remains similar for non-peak hours or not. Therefore, MOEs were collected for a non-peak time interval (9:00 PM-12:00 PM) and compared, as shown in *Figures 13-16*.

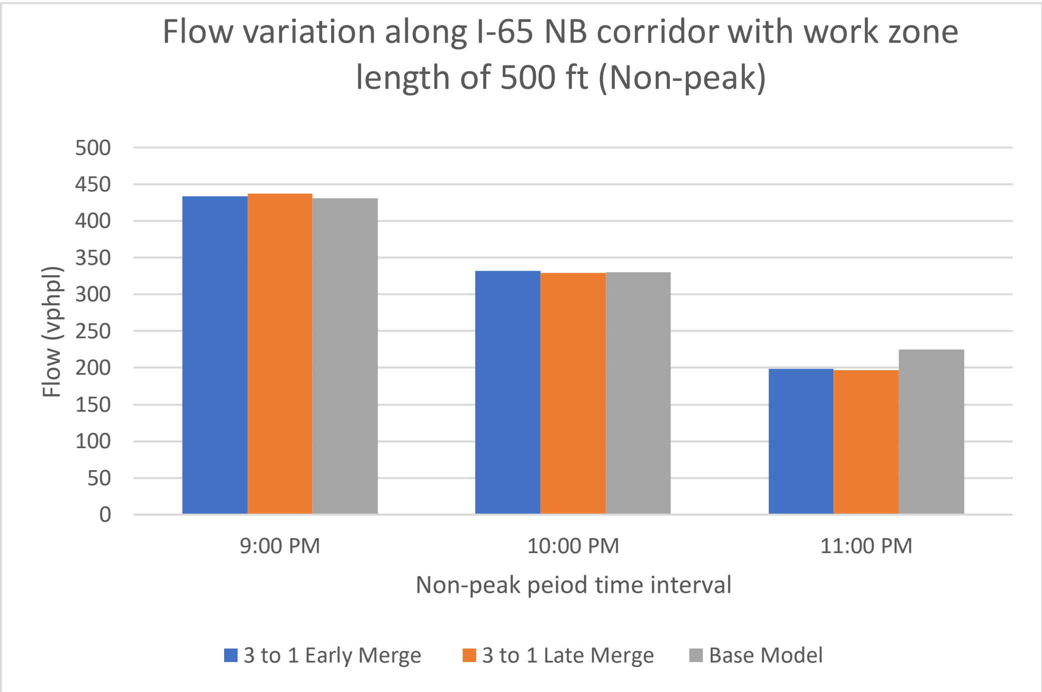

Figure 13 : Flow variation along I-65 NB corridor (work zone length: 500 ft, Non-peak period)

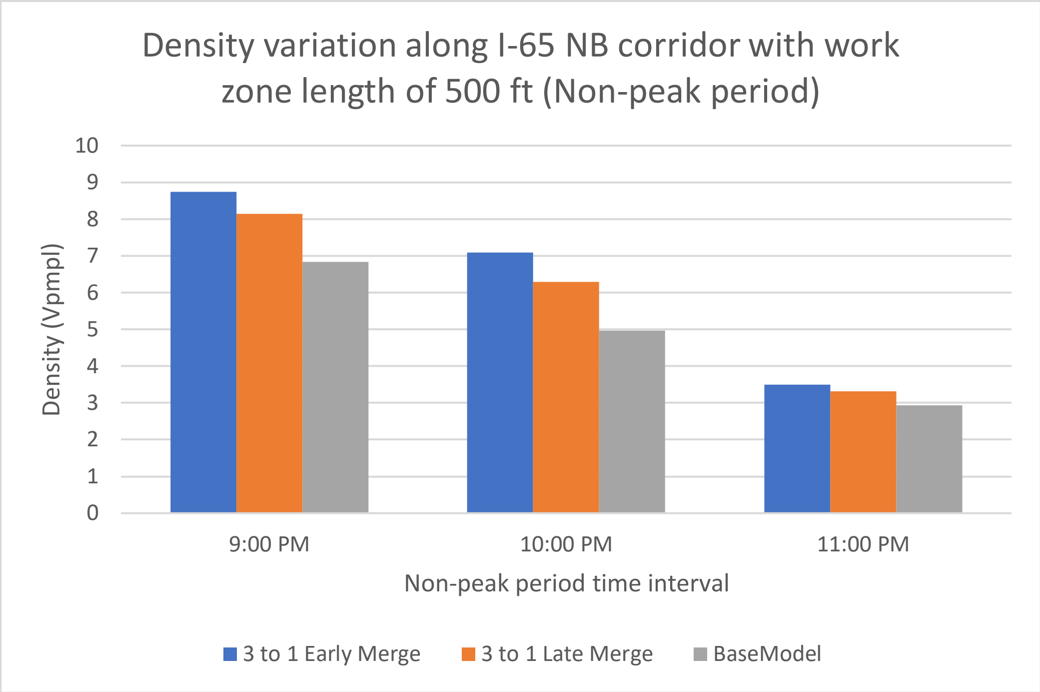

Figure 14 : Density variation along I-65 NB corridor (work zone length: 500 ft, Non-peak period)

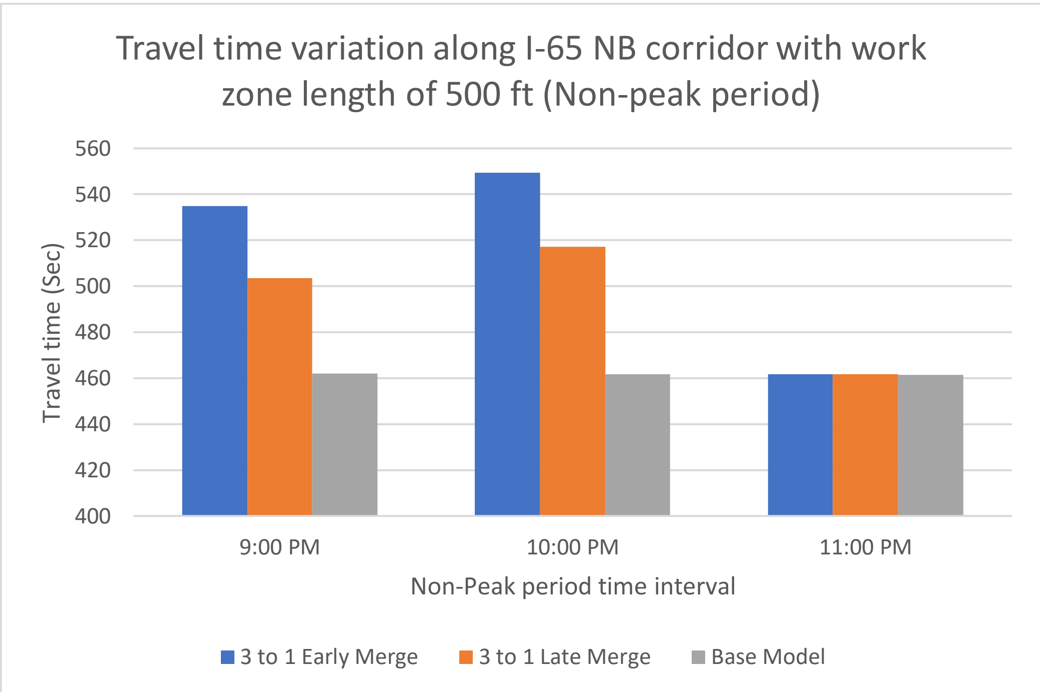

Figure 15 : Travel time variation along I-65 NB corridor (work zone length: 500 ft, Non-peak period)

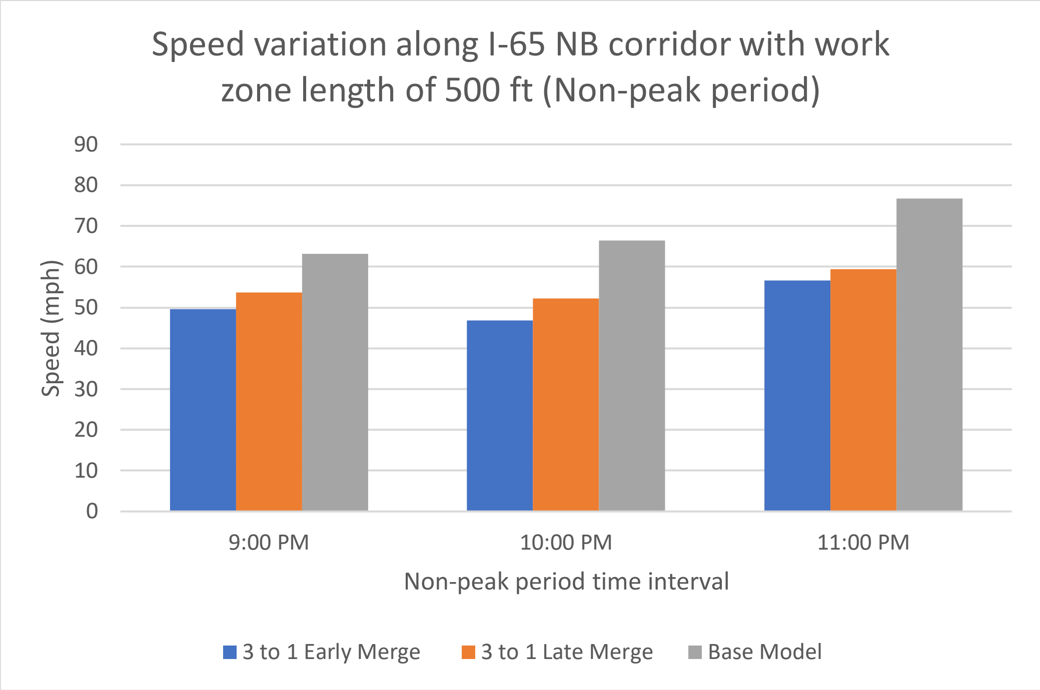

Figure 16 : Speed variation along I-65 NB corridor (work zone length: 500 ft, Non-peak period)

As far as the thought put is concerned all options perform similarly during the night non-peak time period. Given the low demand during this time period (i.e., low volume-to-capacity ratio) the performance of the network is not affected by the 3-to-1 lane closure and the remaining open lane can handle the traffic demand at that time. This observation is consistent in the results presented in *Figures 14* through *16* and all MOEs provide similar results with the late merge control showing a small advantage over early merge control, but not enough to justify its selection over its counterpart.

Comparison of Merge Control for 1000 ft Work Zone Length

After observing the impact of merge control strategy on 3-to-1 lane closure with 500 ft work zone length for long-term and short-term, it was clearly seen that long-term work zone with 3-to-1 lane closure collapses the whole system even with the shortest work zone length of 500ft. Therefore, efforts to evaluate the performance of work zones of longer length concentrated only on short-term work zones.

Short-term work zone analysis (Peak period) for 1000 ft work zone

A short-term work zone with 1000 ft length and a 3-to-1 lane drop was modeled under the AM peak period and for both late and early merge strategies. The purpose is to observe the impact of length of work zone on the performance. *Figures 17-20* show the density, flow, speed, and travel time for 1000 ft work zone with late and early merge controls in place.

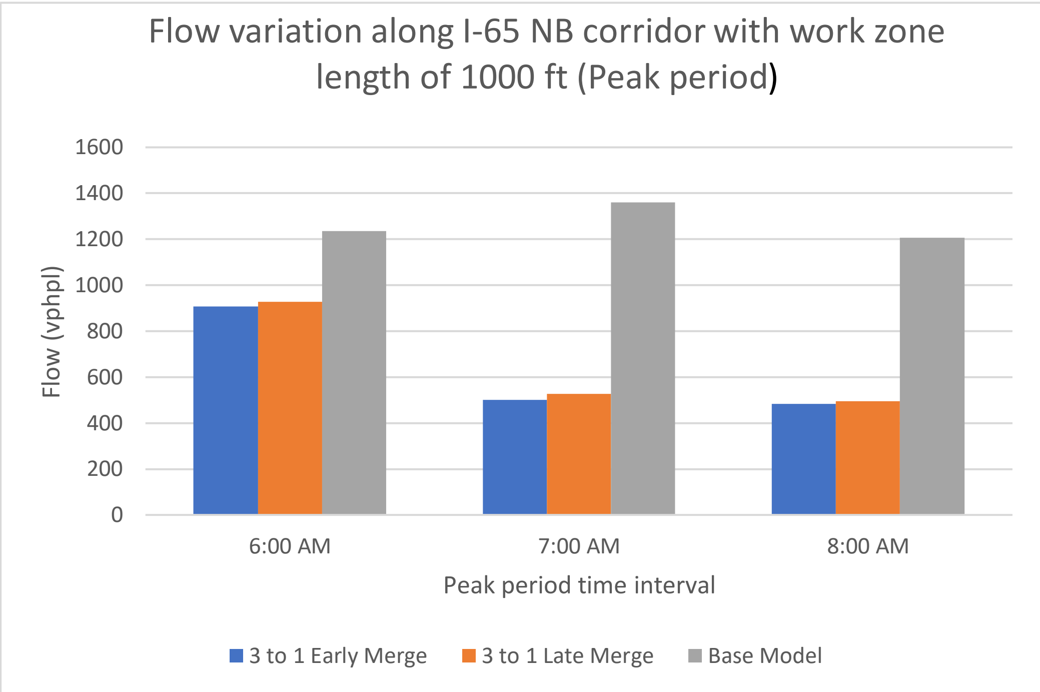

Figure 17 : Flow variation along I-65 NB corridor (work zone length: 1000 ft, Peak period)

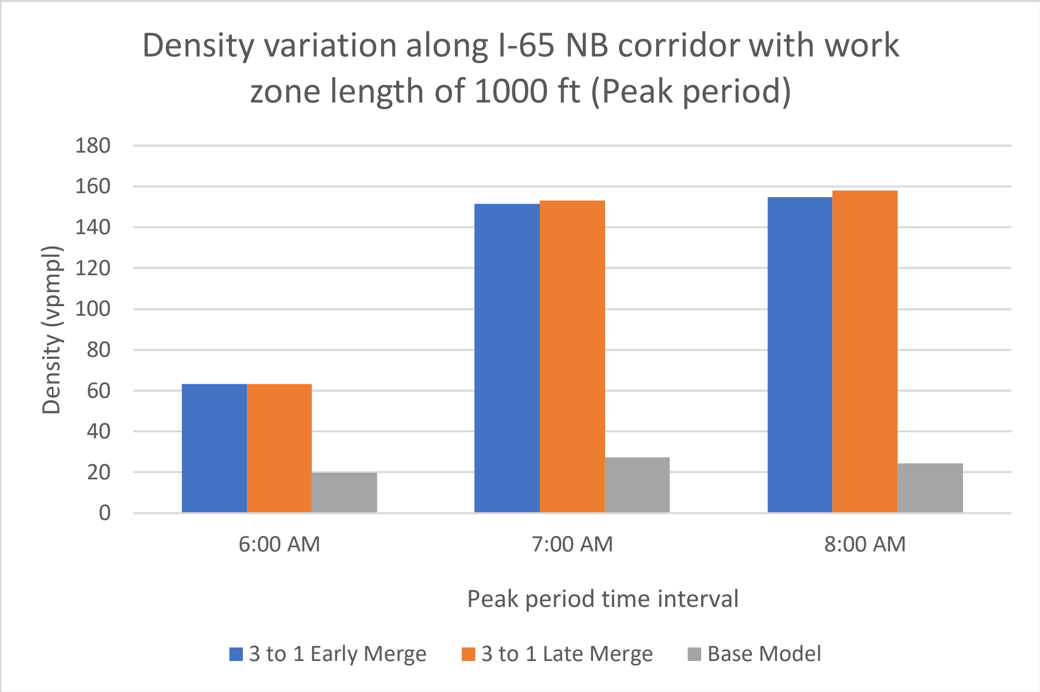

Figure 18 : Density variation along I-65 NB corridor (work zone length: 1000 ft, Peak period)

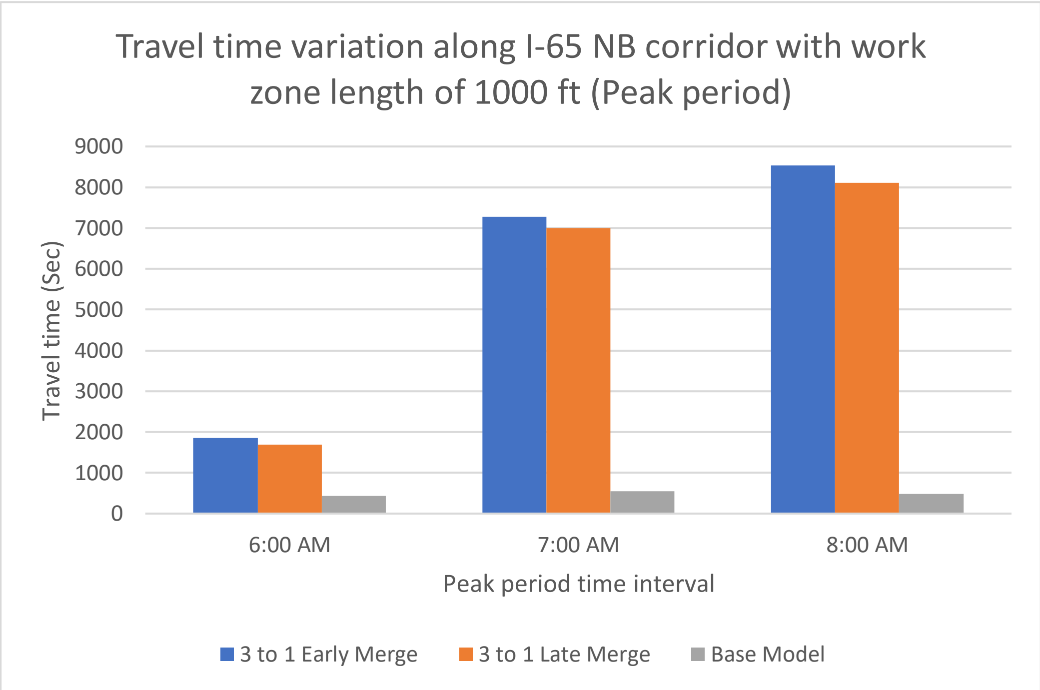

Figure 19 : Travel time variation along I-65 NB corridor (work zone length: 1000 ft, Peak period)

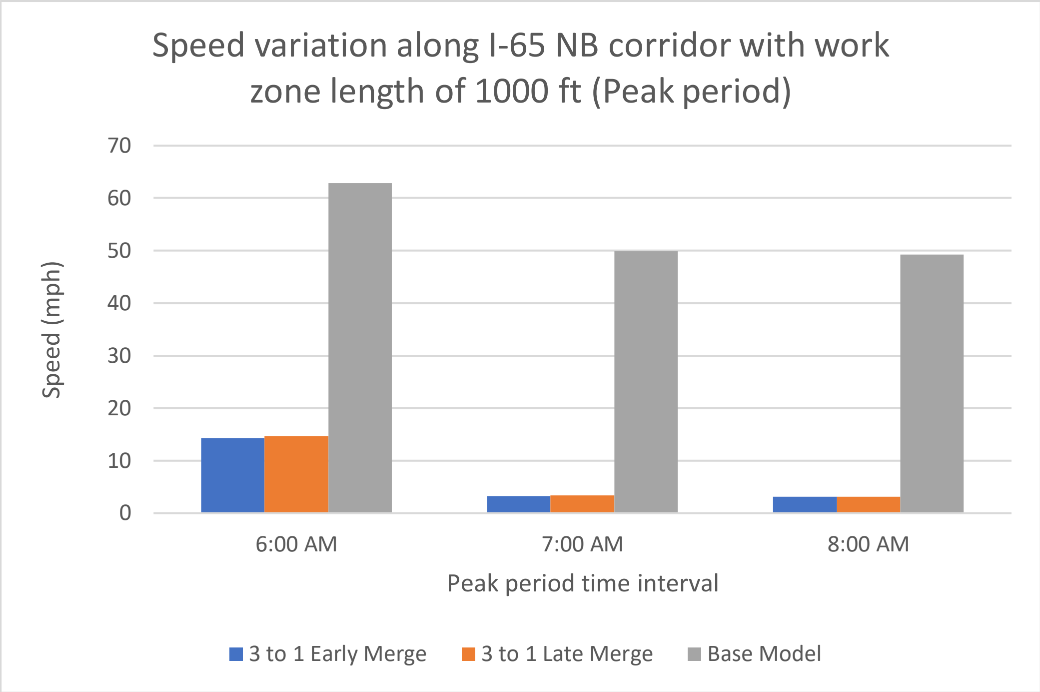

Figure 20 : Speed variation along I-65 NB corridor (work zone length: 1000 ft, Peak period)

It is found from the analysis that short-term work zones with 1000 ft or longer lane closure during peak could not serve the demand at all with 3-to-1 closure with any of the traffic control strategies considered. Therefore, it is evident that neither late merge nor early merge can accommodate the 3-to-1 closure with 1000 ft length or more during peak period.

Short-term work zone analysis (Non-peak period) for 1000 ft work zone

The short-term 3-to-1 lane closure with 500 ft work zone during non-peak does not exhibit as severe of an impact as the peak-period. Therefore, longer work zone lengths are analyzed starting with a length of 1000 ft. Flow, density, travel time and speed for the base case and late and early merge control strategies are shown in *Figures 21-24* below.

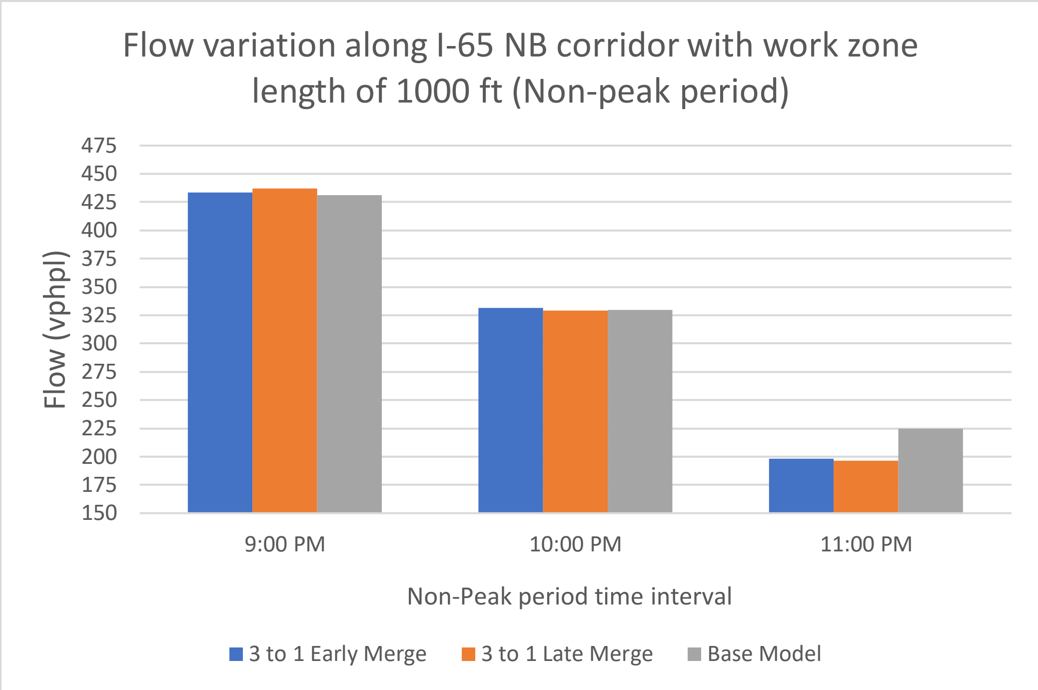

Figure 21 : Flow variation along I-65 NB corridor (work zone length: 1000 ft, Non-peak period)

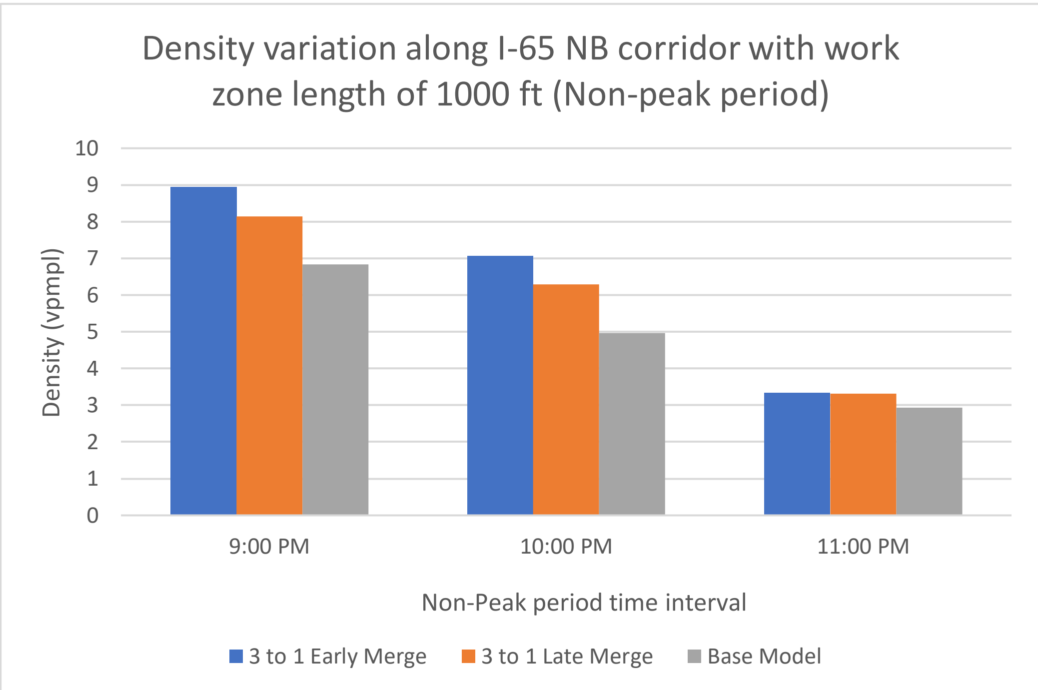

Figure 22 : Density variation along I-65 NB corridor (work zone length: 1000 ft, Non-peak period)

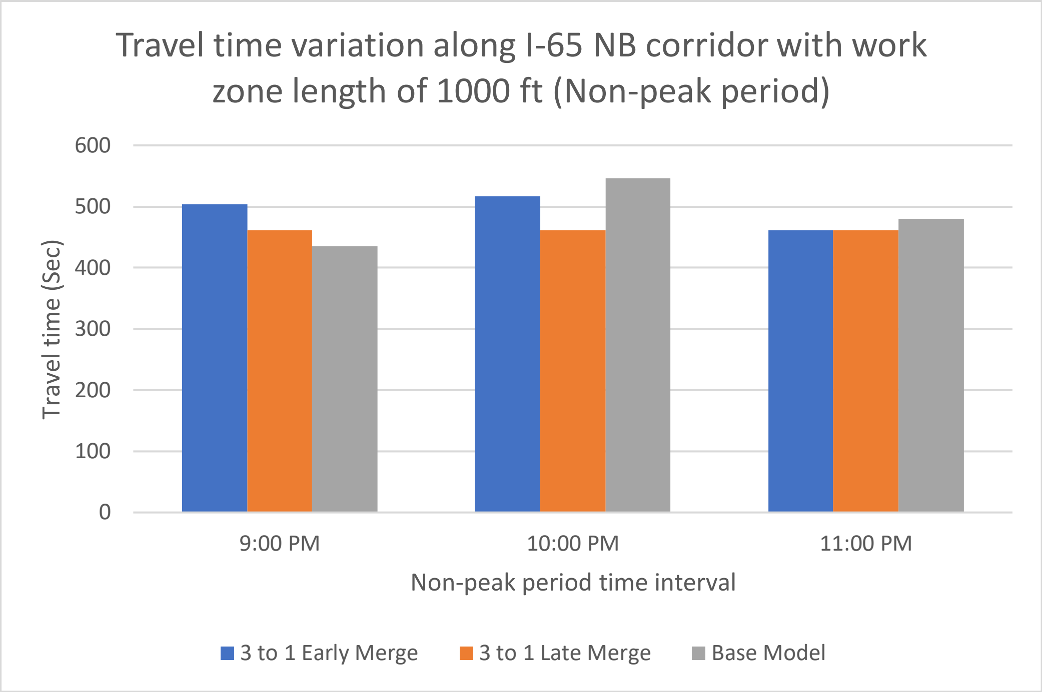

Figure 23 : Travel time variation along I-65 NB corridor (work zone length: 1000 ft, Non-peak period)

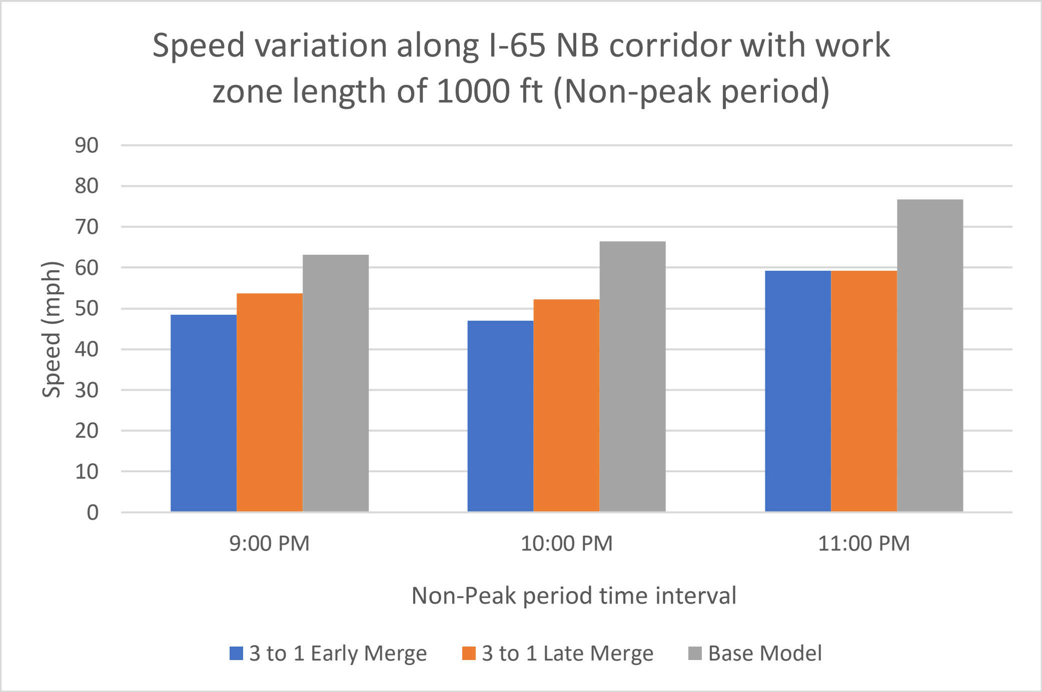

Figure 24 : Speed variation along I-65 NB corridor (work zone length: 1000 ft, Non-peak period)

As shown in *Figure 21*, flow under the late and early merge when work zone length increased to 1000 ft was close to base flow during non-peak hour. This indicates that there is minimal impact of the closure on the lower volume during night. Speed is slightly higher with late merge control at the start of the observation period but soon both TTC strategies show similar results. At some point in time, base flow has higher travel time than early or late merge. This might be attributable to the closure of a ramp (exit 254) during lane closure.

Comparison of Merge Control for 1500 ft Work Zone Length

Figures 25-28 show a comparison of flow, density, speed and travel time between base model and late- and early merge control with a 3-to-1 lane drop and for a work zone length of 1500ft under non-peak traffic conditions.

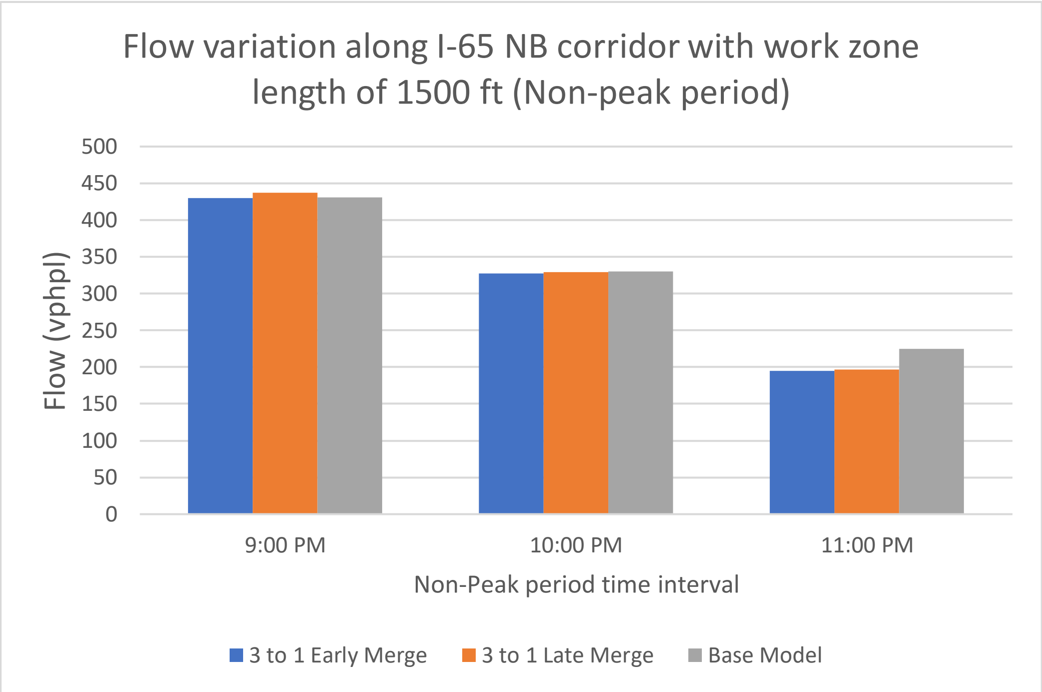

Figure 25 : Flow variation along I-65 NB corridor (work zone length: 1500 ft, Non-peak period)

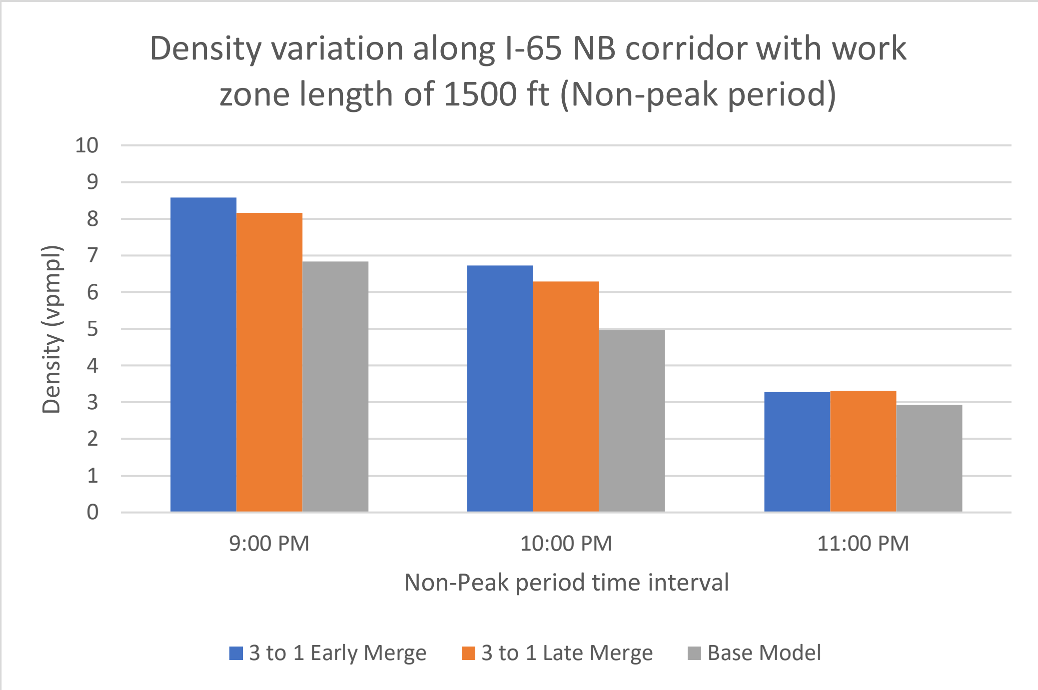

Figure 26 : Density variation along I-65 NB corridor (work zone length: 1500 ft, Non-peak period)

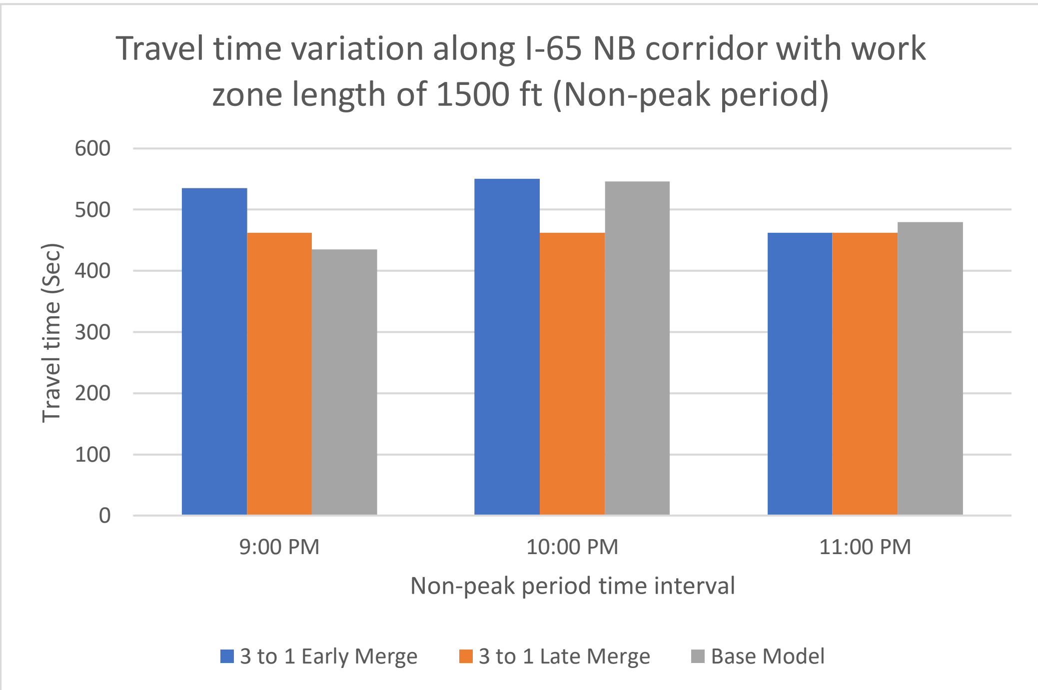

Figure 27 : Travel time variation along I-65 NB corridor (work zone length: 1500 ft, Non-peak period)

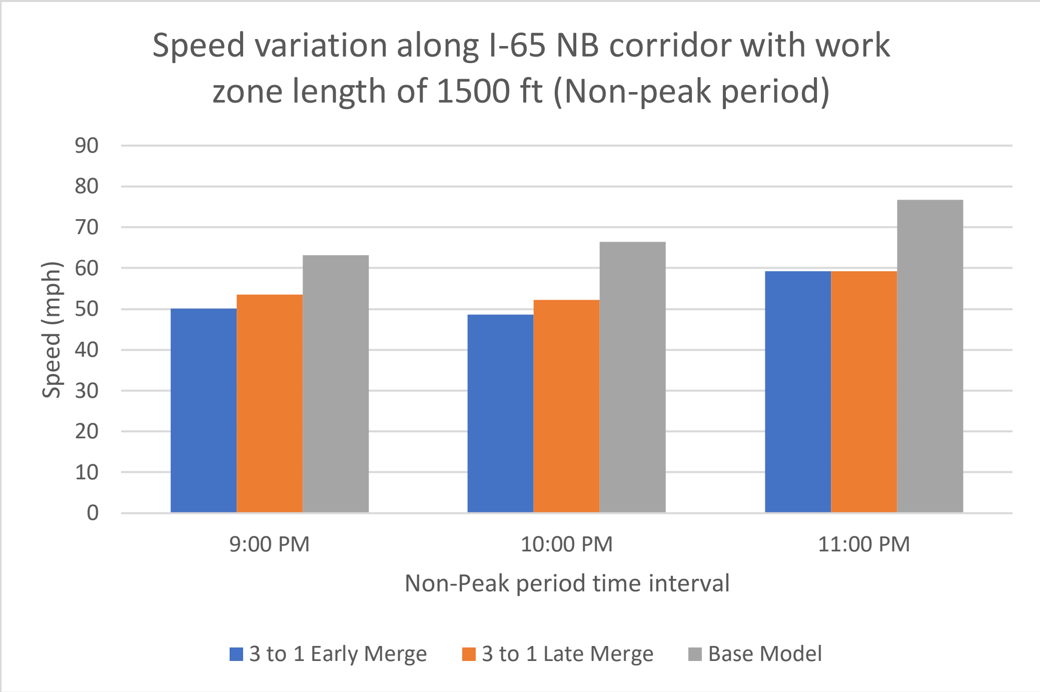

Figure 28 : Speed variation along I-65 NB corridor (work zone length: 1500 ft, Non-peak period)

The performance of late merge and early merge for the 1500 ft work zone remain almost similar to their performance with 1000 ft non-peak hour closure. Due to the low demand, flow remains the same for base, early, and late merge. Early merge causes more density in the roadways, resulting in higher travel time compared to late merge. The base model has slightly higher travel time at one point, perhaps due to ramp closure and elimination of a queue from that exit point. Overall, the late merge scenario performs slightly better than early merge during the non-peak period with 3-to-1 closure for work zone length of 1,500 ft, a finding that is consistent with those observed for work zones of 500 and 1000 ft as well.

Statistical Significance Analysis

The comparisons performed so far focused on visual inspections of MOEs estimated value. Still there is a need to study if the observed difference in the performance between early and late merge control is statistically significant. Therefore, a t-test is conducted to identify the t-score for each of the MOE for each combination. The t-score has to be more than 2.132 to ensure with 90% confidence that the MOEs are significantly different between early and late merge for two-tailed test. Two-tailed test means that one set of values can be significantly greater or smaller than another set of values.

The results from the comparison based on a two-tailed T-test and for a 90% confidence interval are shown in *Table 8*. All t-test scores are below 2.132, which confirms that for 3-to-1 lane closures, early merge and late merge strategies do not have statistically significant differences in their performance. In other words, any of these two TTC strategies will result in similar impacts in the presence of a 3-to-1 lane closure for work zone lengths varying from 500 to 1500ft under both peak and non-peak traffic conditions.

Table 8 : T-score for statistical significance analysis

Length	Time period of day	MOEs	T-score (Two-tailed test)	Significance
500 ft	Peak	Density	0.200241444	Not significant
		Speed	0.17525763	Not significant
		Travel time	0.144133745	Not significant
		Volume	0.394332176	Not significant
	Non-Peak	Density	0.100127412	Not significant
		Speed	0.036932124	Not significant
		Travel time	0.183719004	Not significant
		Volume	0.886465803	Not significant
1000 ft	Peak	Density	0.258916873	Not significant
		Speed	0.234173895	Not significant
		Travel time	0.060329507	Not significant
		Volume	0.023461693	Not significant

	Non-Peak	Density	0.169950664	Not significant
		Speed	0.182707404	Not significant
		Travel time	0.188432782	Not significant
		Volume	0.89066417	Not significant
1500 ft	Non-Peak	Density	0.219960903	Not significant
		Speed	0.182552745	Not significant
		Travel time	0.18759073	Not significant
		Volume	0.179880748	Not significant

Summary of the Analysis

Based on the existing gap to analyze 3-to-1 lane closure more extensively, an experimental design was set up for 24-hr long-term work zone analysis for this closure. Analysis started with 500 ft work zone length and concluded that a 3-to-1 lane drop cannot handle the traffic demand soon after the morning peak starts, and roadway remains hugely congested all throughout the day. Then 3-to-1 closure scenario was observed for short duration of work for 500 ft, and 1000 ft both focusing on peak and non-peak hour, and 1500 ft focusing non-peak hour closure only. From the 3-hour interval analysis during AM peak, it is found that late merge performs slightly better than early merge with 500 ft work zone but displays similar performance with work zones of 1000 ft in length. The operational performance deteriorates even for short-term closure if the 3-to-1 lane closures take place during peak-hour. Based on these findings it is recommended that maintenance and rehabilitation work requiring 2 lanes closed can be done only if the work is scheduled during non-peak and the duration is short.

CONCLUSION AND RECOMMENDATIONS

Conclusion

Work zones involving lane closures cause disruption on freeway operations leading in congestion. Almost one-fourth of the non-recurring delay is attributable to lane closures along roadways. Large amount of economic loss is also incurred due to congestion created by closing lanes. The literature review suggested that there are some available traffic control options, but most of the state DOTs do not have formal guidelines guiding the proper selection of traffic control strategies at work zones.

The objective of the study was to investigate the operational impacts of two temporary traffic control (TTC) strategies, namely static late and early merge control with 3-to-1 lane-drop configurations for a hypothetical work zone at a corridor along I-65 in Birmingham, AL. The study employed the VISSIM simulation platform for examining and comparing MOEs under different control scenarios, including flow, density, speed, and travel time.

Earlier researches focused mostly on 3-to-2 lane closure configuration for short-term work zones. Thus, this study considered 3-to-1 lane closure scenario for both long-term and short-term work zones. Hence, various work zone lengths (500 ft, 1000 ft, 1500 ft) were considered both under late merge and early merge control. The study considers long-term work zone placement, as well as short-term work zone placement during AM peak period and PM non-peak period. A total of 12 different combinations of TTC types, work zone lengths, and work zone types were examined. Some major findings from this study are summarized below:

- Between 12:00 PM and 5:00 AM, a time period that corresponds to very low demand, 3-to-1 lane closures are feasible under any type of configuration studied and have minimal impact on mobility.
- During the morning peak, the 3-to-1 lane closure deteriorates traffic conditions and the network gets overwhelmed by the excess demand and unable to cope. Thus long-term 3-to-1 lane closures are not recommended, unless other provisions are taken including traffic diversion to direct excess traffic volume away from the facility affected by the traffic lane closures.
- When considering short-term work zones during the morning peak, the late merge strategy slightly outperforms early merge with 500 ft short-term work zone when volume-to-capacity ratio is still below 1. However, both TTC strategies are unable to accommodate the demand and eventually the system breaks down during the AM peak period.
- As the work zone length increases to 1000 ft, the short-term work zone during the AM peak period shows no significant difference in the performance of late and early merge control. Both strategies completely fail to serve the demand with 3-to-1 closure. Thus, it is recommended avoiding scheduling 3-to-1 lane closures of any control type during the AM peak period.
- Late merge and early merge for a 3-to-1 lane drop perform quite similarly during the non-peak period with short-term work zones of 500, 1000, and 1500 ft length. The length of the work zone appears to have minimal impact on the performance measures considered.

- While late merge control outperforms early merge control when any noticeable differences between the two strategies are observed, the differences are not statistically significant for any of the comparisons performed in this study. Thus, there is no evidence that one or the other TTC strategy studied yields better results under the 3-to-1 scenario and either may be used when demand is low, such as during non-peak times.

Recommendations

From the results from investigation, it is recommended that long-term work zones with 3-to-1 lane closures should be avoided. Instead, short duration closures should be considered, preferably during non-peak periods in order to minimize the impact on mobility. When non-peak hour work zones are scheduled, both late merge control and early merge control strategies can be used, with late merge control showing slight advantages with respect to operational performance.

Suggestions for Future Study

This study did not consider traffic diversion during the 3-to-1 lane closures at the worksite. As a result, the traffic network quickly become oversaturated and failed to serve the demand. A sensitivity analysis is recommended to determine the percentage of traffic that needs to be diverted in order to provide an acceptable level of service to users of the facility during the 3-to-1 operation Future study can also look into the impact of 3-to-1 closure during other time intervals and consider placement of the lane closure on the left side, rather than the right.

Additionally, there are various merge control strategies that focuses on dynamic features. Evaluating the impact of the dynamic merge control for various lane closure scenarios both for peak and off-peak can be a valuable future contribution. Future study can also investigate performance of various traffic control strategies for lane closure on weekends. Finally, the study can be extended to document results from a sensitivity analysis considering impacts of varying heavy vehicle percentages, driver behaviors, and traffic demand changes on study MOEs. By considering a variety of driver behaviors and traffic conditions future studies can provide results that are easily transferable to other freeway segments with different characteristics.

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