Optimizing Future Work Zones in New England for Improved Safety and Mobility

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Prepared for
The New England Transportation Consortium
March 15, 2018

NETCR104 **NETC 14-4**

ACKNOWLEDGMENTS

The project team would like to thank the New England Transportation Consortium (NETC) for providing financial support to this research. Also, the team would like to thank all participants of the Virtual Reality (VR) driving simulation study. The following are the members of the Technical Committee that developed the scope of work for the project and provided technical oversight throughout the course of the research. The team would like to thank the following project technical committee members for providing invaluable comments and guidance:

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NETCR104	N/A	N/A

4. Title and Subtitle	5. Report Date
Optimizing Future Work Zones in New England for Improved Safety and Mobility	March 15, 2018
	6. Performing Organization Code N/A
7. Author(s) Yuanchang Xie, Nathan H. Gartner, Polichronis Stamatiadis, Tianzhu Ren, and Gustavo Salcedo	8. Performing Organization Report No. NETCR104
9. Performing Organization Name and Address Department of Civil and Environmental Engineering University of Massachusetts Lowell One University Ave Lowell, MA 01854	10. Work Unit No. (TRAIS) N/A 11. Contract or Grant No. N/A
12. Sponsoring Agency Name and Address New England Transportation Consortium C/O Transportation Research Center University of Vermont, Farrell Hall 210 Colchester Ave. Burlington, VT, 05405	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code NETC14-4 a study conducted in cooperation with the U.S. DOT

15. Supplementary Notes
N/A

16. Abstract

This study addresses two critical aspects of highway work zone traffic operations, mobility and safety, by focusing on speed control and merge control strategies. It innovatively utilizes the Naturalistic Driving Study (NDS) data for analyzing work zone crash and near-crash events characteristics, and generates useful insights into how crashes and near crashes develop and occur in highway work zones. It also develops and applies a Virtual Reality (VR) based driving simulator for investigating work zone speed control strategies. Additionally, this study proposes a New England Merge (NEM) control that demonstrates promising mobility and safety performance based on VISSIM simulation and Surrogate Safety Assessment Model (SSAM) analysis results. The proposed NEM can be readily implemented when all vehicles are connected and automated. Without connected and autonomous vehicles, this method is still practical given driver compliance and proper law enforcements, which are also required by the well-known early merge and late merge strategies that have been field implemented.

17. Key Words	18. Distribution Statement
Work Zone, Safety, Mobility, Naturalistic Driving Study, Virtual Reality, Driving Simulation, VISSIM, SSAM, Early Merge, Late Merge, New England Merge, Speed Control	This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	143	N/A

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

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

DISCLAIMER

EXECUTIVE SUMMARY

This study addresses two critical aspects of highway work zone traffic operations, mobility and safety, by focusing on speed control and merge control strategies. It innovatively utilizes the Naturalistic Driving Study (NDS) data for analyzing work zone crash and near-crash events characteristics, and generates useful insights into how crashes and near crashes develop and occur in highway work zones. It also develops and applies a Virtual Reality (VR) based driving simulator for investigating work zone speed control strategies. Additionally, this study proposes a New England Merge (NEM) method that demonstrates promising mobility and safety performance based on the VISSIM simulation and Surrogate Safety Assessment Model (SSAM) analysis results. The proposed NEM can be readily implemented when all vehicles are connected and automated. Without connected and autonomous vehicles, this method is still practical given driver compliance and proper law enforcements, which are also required by the well-known early merge and late merge strategies that have been field implemented.

The analysis of the NDS crash data suggests that distraction is the most important endogenous factors contributing to work zone crashes and near crashes followed by fatigue driving and speeding. Stop-and-go traffic, sudden slowdown of lead vehicle, and unsafe merging maneuvers of vehicles in adjacent lanes are identified as top exogenous factors. The NDS crash data also suggests that when the traffic flow is in levels of service B, C, and D, crash and near-crash events are more likely to happen. These findings confirm the importance of proper speed and merge control for improving work zone safety. Due to the lack of observations from the same (or similar) work zones in the NDS data set, it is concluded that the NDS data used in this research is insufficient for analyzing driver behaviors in work zones.

A comprehensive review of existing work zone speed and merge control methods is conducted in this study. The review results suggest that law enforcements are the most effective but expensive means of controlling speeds in work zones. The review of merge control methods identifies four major strategies: no control, static/dynamic early merge, static/dynamic late merge, and signalized merge. It is generally believed that early merge is better for uncongested traffic conditions, late merge is more suitable for congested traffic, and signalized merge is better for extremely heavy traffic.

Based on the literature review, three speed control strategies are identified and six work zone scenarios are developed and tested under daytime and nighttime conditions using the VR driving simulator. In addition, a survey is conducted to find out how drivers value different speed control strategies. Both the VR simulation and the questionnaire results show that radar speed sign/dynamic speed display can effectively reduce speed in work zones. Tubular makers may also implicitly affect driver speed and reduce speed variation, although most participants think that tubular makers have insignificant impacts on their speed choices.

For the proposed NEM, the approach to a work zone is divided into a meter zone followed by a merge zone. Vehicles approaching the work zone are instructed to increase their gaps with lead vehicles in the meter zone. The meter zone is used to provide adequate distance for vehicles to

adjust their gaps and prepare them for the upcoming merge. Lane change is prohibited in the meter zone but allowed in the following merge zone. VISSIM is used to evaluate the NEM and other well-known merge control methods identified in the literature review. Two types of work zones are simulated: (1) Type I: two-lane highway with the right lane closed, and (2) Type II: three-lane highway with the right-most lane closed. The simulation results show that NEM performs significantly better than no control, early merge, and late merge under medium to extremely heavy traffic conditions. It also consistently outperforms signalized merge under all flow conditions.

The SSAM tool developed by the Federal Highway Administration (FHWA) is utilized in this research to analyze the safety performances of various merge control methods. It is found that the proposed NEM generates much less conflicts than the remaining methods under medium to high input flows for Type I work zones. For Type II work zones, NEM still produces the lowest numbers of rear-end conflicts under medium to high traffic conditions. Although NEM results in the highest number of lane-change conflicts for the heavy input flow condition, this is attributed to its significantly higher throughput (i.e., higher lane-change/merge risk exposure) than other methods and its large number of lane changes prior to the meter zone (not at the merge point).

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LIST OF ACRONYMS

AADT	Annual Average Daily Traffic
ABS	Anti-lock Braking System
ACC	Adaptive Cruise Control
AFT	Adaptive Fine-Tuning
ASCE	American Society of Civil Engineers
CM	Conventional Merge
CTDOT	Connecticut Department of Transportation
DLM	Dynamic Late Merge
DMM-Tracs	Dynamic Merge Metering Traffic Control System
DOT	Department of Transportation
DUI	Driving Under the Influence
EM	Early Merge
FHWA	Federal Highway Administration
GPS	Global Positioning System
HOV	High Occupancy Vehicle
IMLS	Indiana Merge Lane System
LBDM	Lane-Based Dynamic Merge
LM	Late Merge
LMTCS	Lane Merge Traffic Control System
LOS	Level of Service
MaineDOT	Maine Department of Transportation
MassDOT	Massachusetts Department of Transportation
MOE	Measures of Effective
MUTCD	Manual on Uniform Traffic Control Devices
NADS	National Advanced Driving Simulator
NCHRP	National Cooperative Highway Research Program
NDOR	Nevada Department of Road
NDS	Naturalistic Driving Study
NEM	New England Merge
NETC	New England Transportation Consortium
NHDOT	New Hampshire Department of Transportation
NYSDOT	New York State Department of Transportation
PCMS	Portable Changeable Message Sign
RADAR	RAdio Detection And Ranging
RSFS	Radar Speed Feedback Sign
SDLMS	Simplified Dynamic Lane Merging Systems
SHRP 2	Strategic Highway Research Program 2

SM	Signalized Merge
SPE	Speed Photo-radar Enforcement
SSAM	Surrogate Safety Assessment Model
SWZ	Smart Work Zone
TCD	Traffic Control Device
TRB	Transportation Research Board
TTC	Time to Collison
TTCP	Temporary Traffic Control Plan
UTO	Uniformed Traffic Officer
VR	Virtual Reality
VSL	Variable Speed Limit

1. INTRODUCTION

In the 2013 American Society of Civil Engineers (ASCE) report, America's infrastructure received an overall rating of "D+". It was estimated that more than $3.6 trillion is needed by 2020 to fix the infrastructure problems. Table 1 below shows the rating of highways and bridges in New England. The results are also summarized in Figure 1 through Figure 3. It is anticipated that there will be many work zones in New England in the coming years due to highway and bridge construction and maintenance activities.

1.1. Background

Work zones often require lane/shoulder closure or lane shift that lead to traffic congestion and increased crash risk, particularly rear-end and angle crashes due to stop-and-go traffic and unsafe merge behaviors. Therefore, work zone safety [*1*,*2*,*3*,*4*] and mobility [*5*,*6*,*7*,*8*] has attracted much attention in the past few decades. A comprehensive and detailed review of these studies has been conducted in this research and the detailed report is presented in Section 3.1 in this report. The following paragraphs summarize the existing work zone safety and mobility studies and point out their limitations. Based on the summary, the objectives of this research are then introduced in Section 1.2.

Many work zone safety studies are based on crash reports filled out by police officers. Statistical models are then developed to establish connections between crash frequency/injury severity and explanatory factors such as speed limit, horizontal and vertical curves, and lane width. This modeling approach is useful for identifying key work zone crash contributing factors. However, a major limitation is that it relies on data collected after a work zone crash has occurred. Such data cannot objectively and accurately reveal what happened to the driver before the crash and how the driver responded. As a Maine Department of Transportation (MaineDOT) study [*9*] suggests, the top four driver offenses in work zone related crashes in Maine during 2010 were: (1) driver inattention/distraction (183 crashes), (2) following too closely (89 crashes), (3) illegal and unsafe speed (58 crashes), and (4) failure to yield right of way (50 crashes). The Maine data again shows the importance of understanding driver behaviors in work zones, especially how drivers react to work zone speed and merge control strategies, layouts, and warning signs.

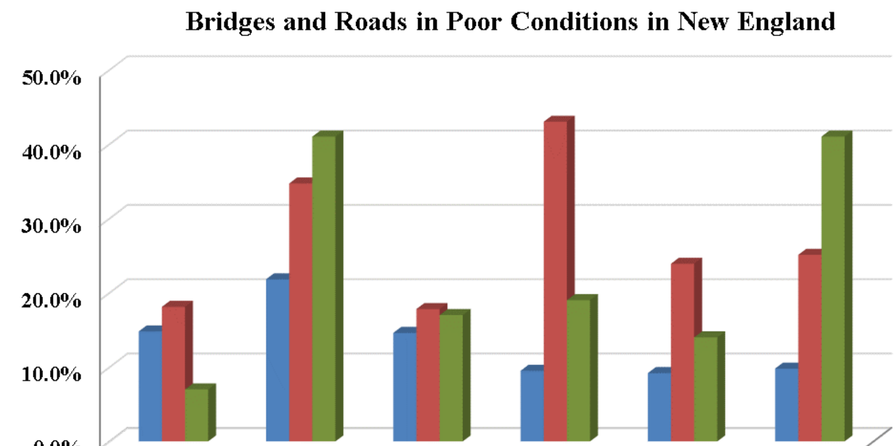
Other work zone safety studies either collect field data or rely on driving simulations. These studies are largely focused on work zone speed control (e.g., speed reduction strategies and variable speed limit), as speeding and large speed variations have been considered as two major work zone crash contributing factors. Field data collection is typically costly and it is difficult to have a fair comparison of different strategies under the same traffic and highway geometry conditions. Although driving simulator can to some extent address the fair comparison issue, traditional driving simulators based on projector or multiple flat screens are not sophisticated enough to give participants realistic driving experience, thus they often cannot generate credible high-fidelity driving behavior data. Some high-fidelity driving simulators such as the National Advanced Driving Simulator (NADS) available at the University of Iowa are extremely expensive and very few research groups can afford to own and operate them.

Table 1 Facts on Bridges and Roads in New England

State	Bridge		Road	
	Grade	**Key Facts**	**Grade**	**Key Facts**
Maine	C-	• 356 of the 2,408 bridges in Maine (14.8%) are considered structurally deficient. • 436 of the 2,408 bridges in Maine (18.1%) are considered functionally obsolete.	D	• Maine has 22,871 miles of public roads. • Maine has 2,568 miles major roads, 7% of which are in poor condition.
Rhode Island	NA	• 167 of the 766 bridges in Rhode Island (21.8%) are considered structurally deficient. • 266 of the 766 bridges in Rhode Island (34.7%) are considered functionally obsolete	NA	• Rhode Island has 6,480 miles of public roads. • Rhode Island has 983 miles of major roads, 41% of which are in poor condition.
New Hampshire	C	• 355 of the 2,438 bridges in New Hampshire (14.6%) are considered structurally deficient. • 435 of the 2,438 bridges in New Hampshire (17.8%) are considered functionally obsolete.	C-	• New Hampshire has 16,105 miles of public roads. • New Hampshire has 1,811 miles of major roads, 17% of which are in poor condition.
Massachusetts	NA	• 487 of the 5,136 bridges in Massachusetts (9.5%) are considered structurally deficient. • 2,207 of the 5,136 bridges in Massachusetts (43%) are considered functionally obsolete.	NA	• Massachusetts has 36,330 miles of public roads. • Massachusetts has 7,340 miles of major roads, 19% of which are in poor condition.
Vermont	C	• 251 of the 2,731 bridges in Vermont (9.2%) are considered structurally deficient. • 652 of the 2,731 bridges in Vermont (23.9%) are considered functionally obsolete.	C-	• Vermont has 14,291 miles of public roads. • Vermont has 1,658 miles of major roads, 14% of which are in poor condition.
Connecticut	NA	• 413 of the 4,218 bridges in Connecticut (9.8%) are considered structurally deficient. • 1,059 of the 4,218 bridges in Connecticut (25.1%) are considered functionally obsolete.	NA	• Connecticut has 21,431 miles of public roads. • Connecticut has 3,350 miles of major roads, 41% of which are in poor condition.
United States	C+	• In total, one in nine of the nation's bridges are rated as structurally deficient, while the average age of the nation's 607,380 bridges is currently 42 years.	D	• Currently, the Federal Highway Administration estimates that $170 billion in capital investment would be needed on an annual basis to significantly improve conditions and performance.

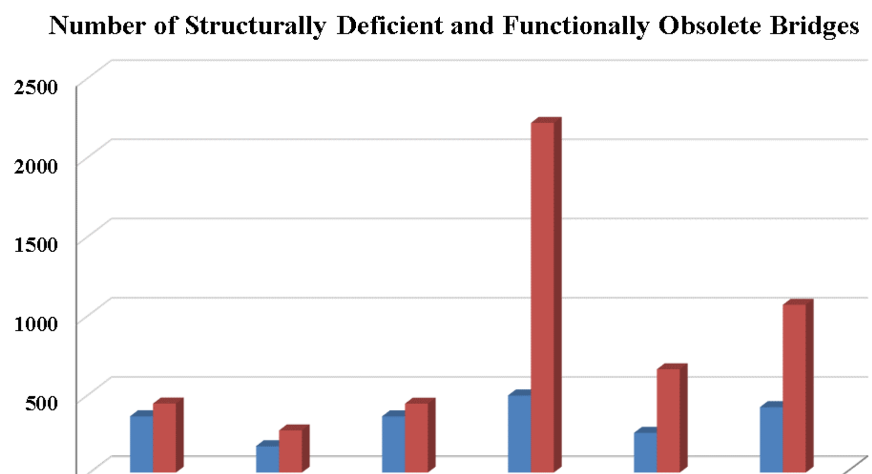
***A** = Exceptional; **B** = Good; **C** = Mediocre; **D** = Poor; **F** = Failing; and **NA** = Not Available*

Both field implementation and computer simulations have been widely used in previous work zone mobility research, which has been mainly concentrated on merge control strategies. Some of the well-known merge control strategies include early merge, late merge, and signalized merge. Similar to work zone safety research, conducting field mobility studies is costly, and there has not been a comprehensive and rigorous field comparison of popular work zone merge control methods. Due to the cost and difficulties involved in field implementations, a majority of work zone mobility studies are based on computer simulations, particularly microscopic traffic simulations. Although computer simulations play such an important role in modeling work zone mobility, how to calibrate and validate simulation tools (i.e., car-following and lane-changing models) has not been thoroughly investigated. This is probably due to the lack of detailed field vehicle trajectory data. Another possible reason is that variable message signs and traffic control devices are widely used in work zones. Their impacts on driver behavior are complicated and are difficult to be incorporated into the calibration of computer simulation models.



	ME	RI	NH	MA	VT	CT
Structurally Deficient Bridges	14.8%	21.8%	14.6%	9.5%	9.2%	9.8%
Functionally Obsolete Bridges	18.1%	34.7%	17.8%	43.0%	23.9%	25.1%
Roads in Poor Condition	7.0%	41.0%	17.0%	19.0%	14.0%	41.0%

Figure 1 Bridge and Road Conditions in New England



	ME	RI	NH	MA	VT	CT
Structurally Deficient Bridges	356	167	355	487	251	413
Functionally Obsolete Bridges	436	266	435	2207	652	1059

Figure 2 Numbers of Structurally Deficient and Functionally Obsolete Bridges

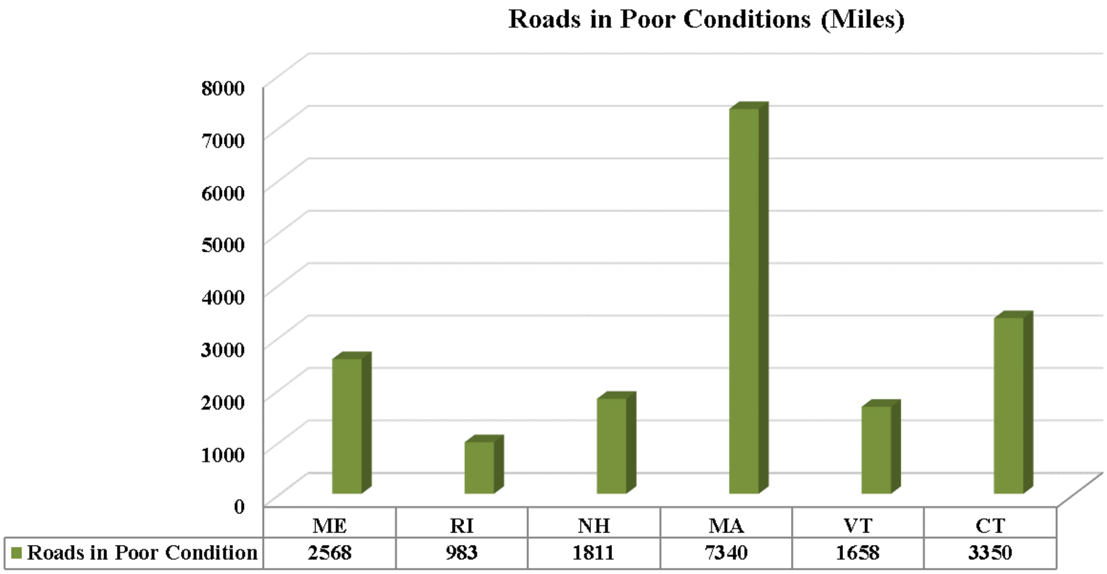


Figure 3 Roads in Poor Conditions in New England

1.2. Research Objectives

This research aims to improve the safety and mobility of highway work zones. Given the aforementioned limitations of existing work zone studies and the main contributing factors to work zone crashes, this study takes several innovative approaches that distinguish it from the previous research.

For the safety aspect of highway work zones, this research utilizes the Strategic Highway Research Program 2 (SHRP 2) Naturalistic Driving Study (NDS) data to gain an in-depth understanding of driver behavior in work zones. The NDS began in 2010 and is by far the largest coordinated safety program in the United States. It was designed specifically for collecting data (e.g., videos, vehicle trajectories) to understand driver performance and behavior immediately prior to crash and near crash events for improving traffic safety. It includes detailed driver characteristics, roadway, distance headway, speed, and acceleration information.

Another innovation is the development and application of a Virtual Reality (VR) driving simulator. Compared to traditional driving simulators using a projector/large curved screens, the VR-based driving simulator is much less expensive and can be easily set up. It provides participants with highly realistic driving experience and substantially improves the fidelity of the collected driving behavior data. In this research, the VR driving simulator is mainly used to evaluate drivers' responses to different work zone speed control strategies, as unsafe speed and large speed variations are major contributing factors to work zone crashes [9].

For highway work zone mobility, this research focuses on merge control strategies and adopts microscopic traffic simulation as the evaluation platform. A Smart Work Zone (SWZ) data set obtained from Massachusetts is used to validate and calibrate the developed simulation models. In addition to evaluating existing popular merge control strategies such as early merge and late merge, this research proposes a new strategy termed *New England Merge* (detailed in Chapter 6). Based on the results of extensive simulation runs, this new merge control method demonstrates superior mobility performance compared to early merge and late merge.

1.3. Report Organization

The rest of this report is organized as the followings:

- Chapter 2 provides an overview of the standard work zone Temporary Traffic Control Plans (TTCPs) adopted by state Departments of Transportation (DOTs). These include work zone layouts, warning signs and their placements, and traffic control strategies. In addition to traffic control practices, Chapter 2 presents a summary of key contributing factors to work zone crashes;

- Based on the description of standard TTCPs, Chapter 3 further provides a comprehensive and detailed review of work zone speed control and merge control strategies. With improving safety as its primary goal, speed control is typically designed to reduce average travel speed, number of speeders, and speed variation. Merge control is mainly for improving work zone mobility or throughput. However, it can also have a significant impact on safety. Based on the review, the existing speed and merge control methods are discussed and compared. In this chapter, performance metrics that are commonly used for evaluating work zone TTCPs are also reviewed;

- Chapter 4 presents the analysis results of the NDS and the SWZ data. The objectives of the NDS data analysis include understanding driver behavior immediately prior to crash and near-crash events in work zones, identifying major contributing factors to crashes and near crashes, and gaining insights into driver behavior in response to speed control strategies and potentially using the results for calibrating microscopic traffic simulation tools. The purpose of analyzing the SWZ data is solely to calibrate microscopic traffic simulation tools for modeling work zone merge control;

- Chapter 5 describes the efforts of the VR-based driving simulator development and application. Using the VR driving simulator, several work zone speed control strategies identified in Chapter 3 are evaluated under both daytime and nighttime conditions. In addition, a survey is conducted to understand how participants perceive the VR driving simulator and the speed reduction effectiveness of commonly used control strategies;

- Chapter 6 focuses on the evaluation of the work zone merge control strategies identified in Chapter 3. The mobility impacts of merge controls are evaluated using VISSIM microscopic traffic simulation. Based on the simulated vehicle trajectory data, the safety impacts of merge control methods are also analyzed using the Surrogate Safety Assessment Model (SSAM) developed by the Federal Highway Administration (FHWA); and

- Chapter 7 summarizes the entire study.

2. Work Zone Traffic Control Background

Chapter 2 provides an overview of the current work zone traffic control practices adopted by state Departments of Transportation (DOTs). Relevant work zone traffic control elements (see Figure 4 through Figure 8) such as warning signs and their placements, and traffic control strategies are given particular attention and a subsection is dedicated to each of them. In addition to traffic control practices, Chapter 2 also presents a summary of key contributing factors to work zone crashes based on historical data.

Given so many states, it would be overwhelming to provide a detailed review of their work zone control practices one by one. Therefore, this chapter focuses on Connecticut, New York, New Hampshire, Massachusetts, Vermont, Maine, Indiana and Virginia. Other relevant documents such as National Cooperative Highway Research Program (NCHRP) reports are also included in the review.

Although many states have their own work zone traffic control manuals, these manuals are mostly based on Chapter 6 of the Manual on Uniform Traffic Control Devices (MUTCD) [*10*], which defines work zones as an area from the initial advance warning sign to the location where traffic is no longer affected. Figure 4 illustrates the following typical components of a work zone defined in the MUTCD.

- Advance warning area;
- Transition area;
- Activity area (consisting of buffer area and work area); and
- Termination area (including buffer area and downstream taper).

Figure 5 through Figure 8 show the components of temporary traffic control zones defined by some state DOTs, including CTDOT [*11*], MassDOT [*12*], Indiana DOT [*13*] and New York State DOT (NYSDOT) [*14*]. In Sections 2.1 through 2.4, the current work zone traffic control practices adopted by different state DOTs are compared to those in the MUTCD in more detail.

The number and types of traffic control devices used in a work zone is often determined by the work duration. In general, the longer a work duration is, the more traffic control devices will be needed. For this research, intermediate- and long-term stationary work durations as defined below by several state DOTs are considered. Temporary traffic control requirements for these types of operations can be found in [*11*,*12*,*13*,*14*]

- *Intermediate-Term Stationary Work Duration*: Work that takes more than one day and up to three consecutive days, or night time work that lasts more than one hour; and

- *Long-Term Stationary Work Duration*: Work that takes more than three consecutive days.

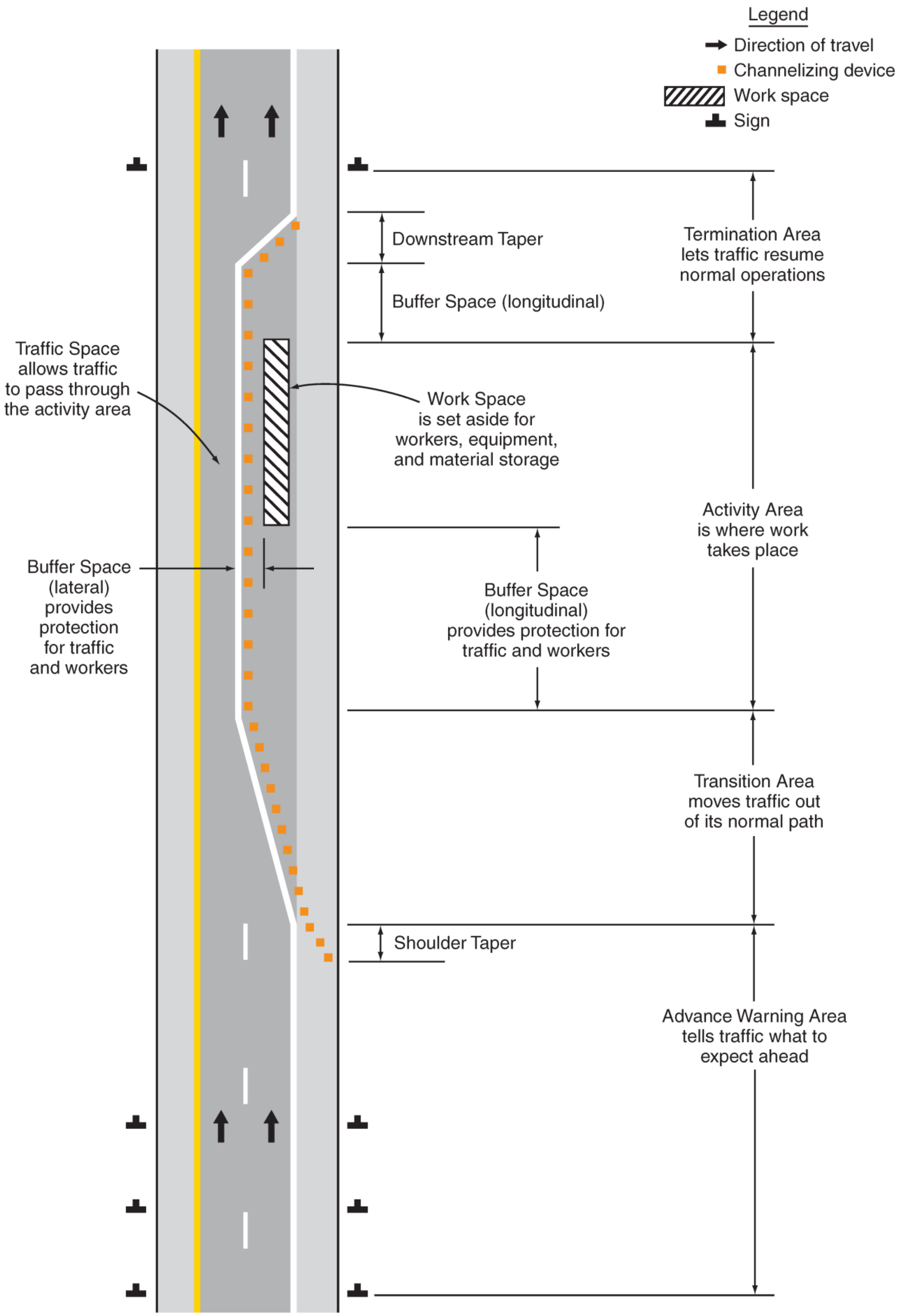


Figure 4 Typical Components of a Work Zone [*10*]

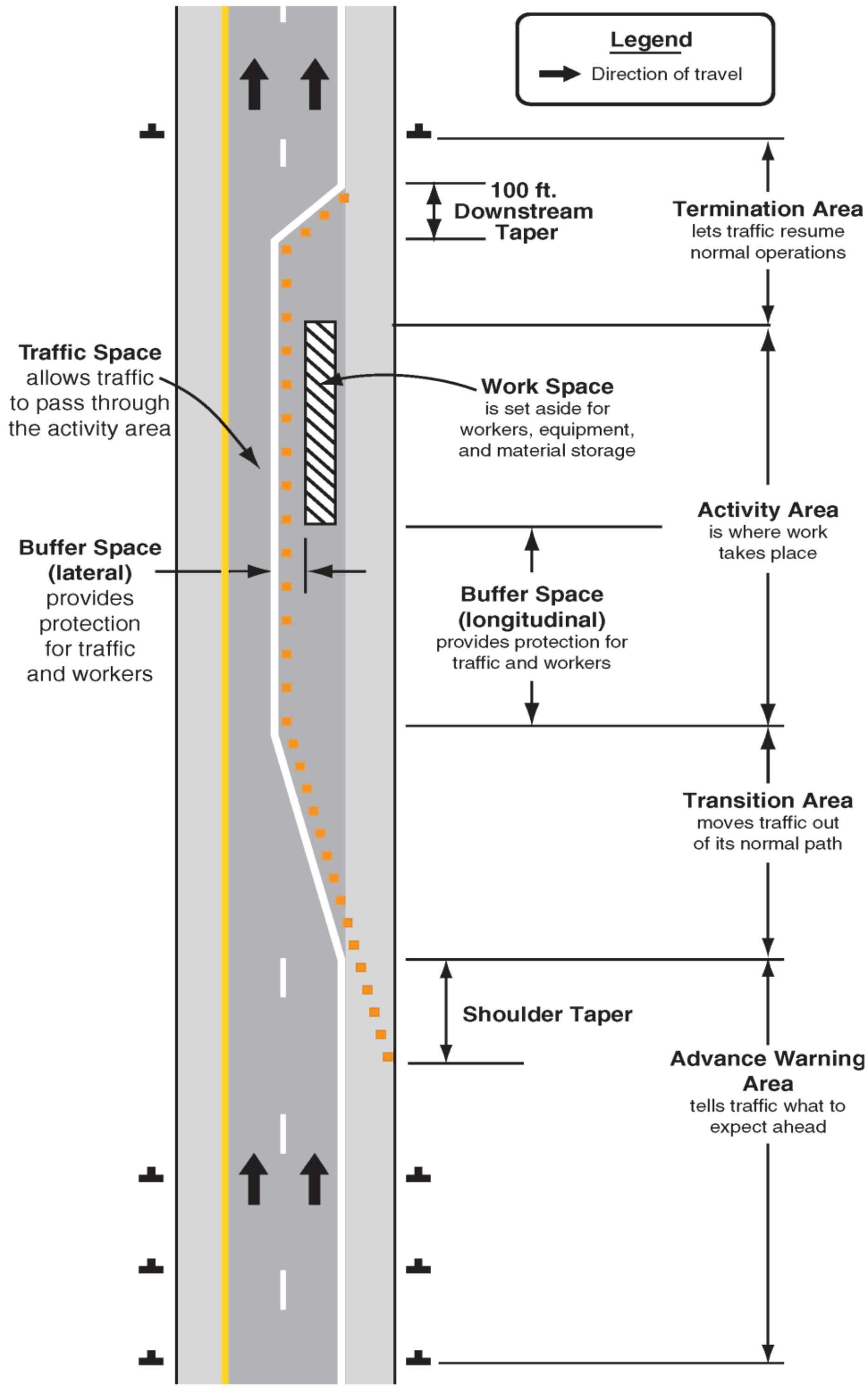


Figure 5 Components of a Temporary Traffic Control Zone in Connecticut [*11*]

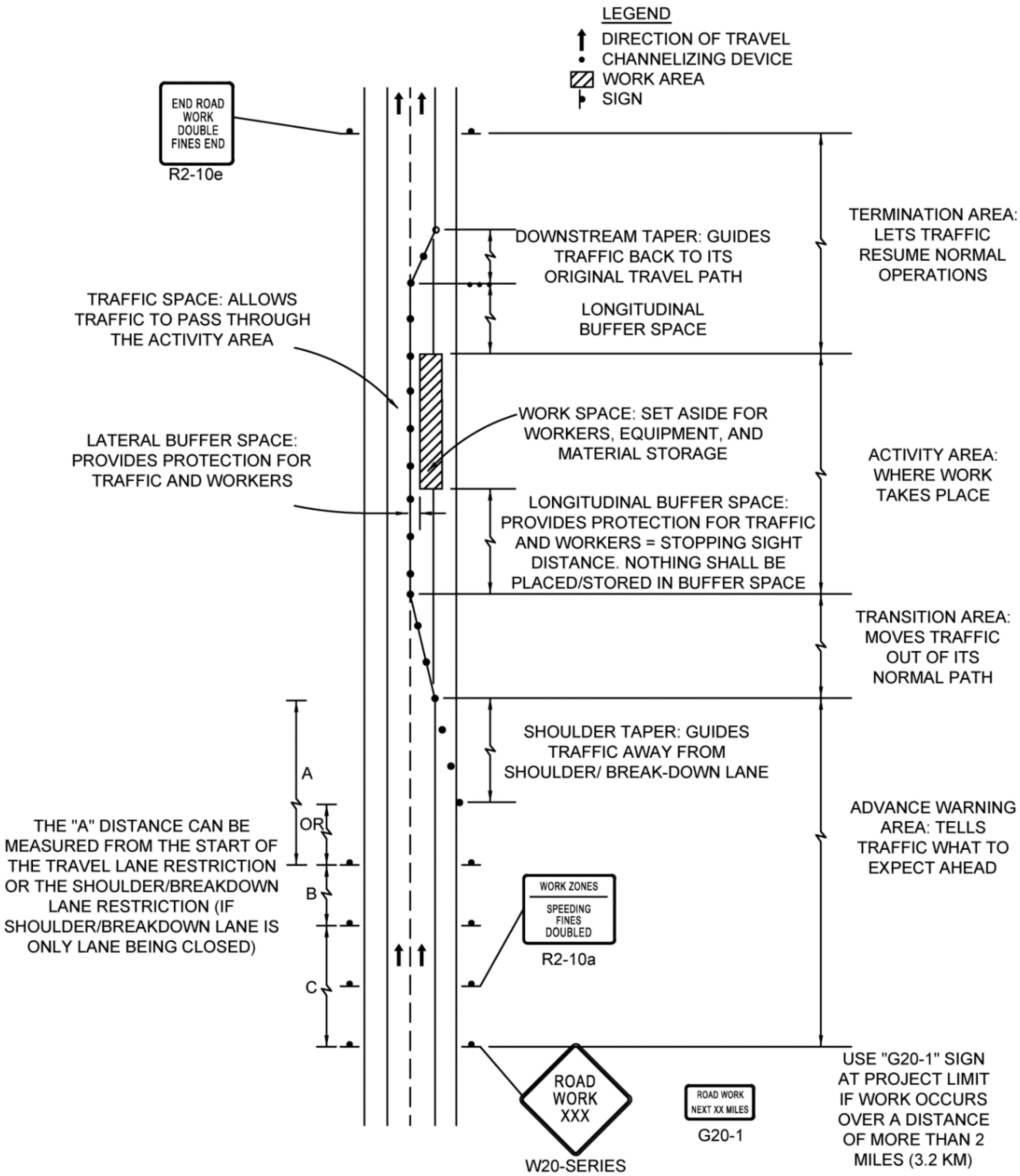


Figure 6 Components of a Temporary Traffic Control Zone in Massachusetts [*12*]

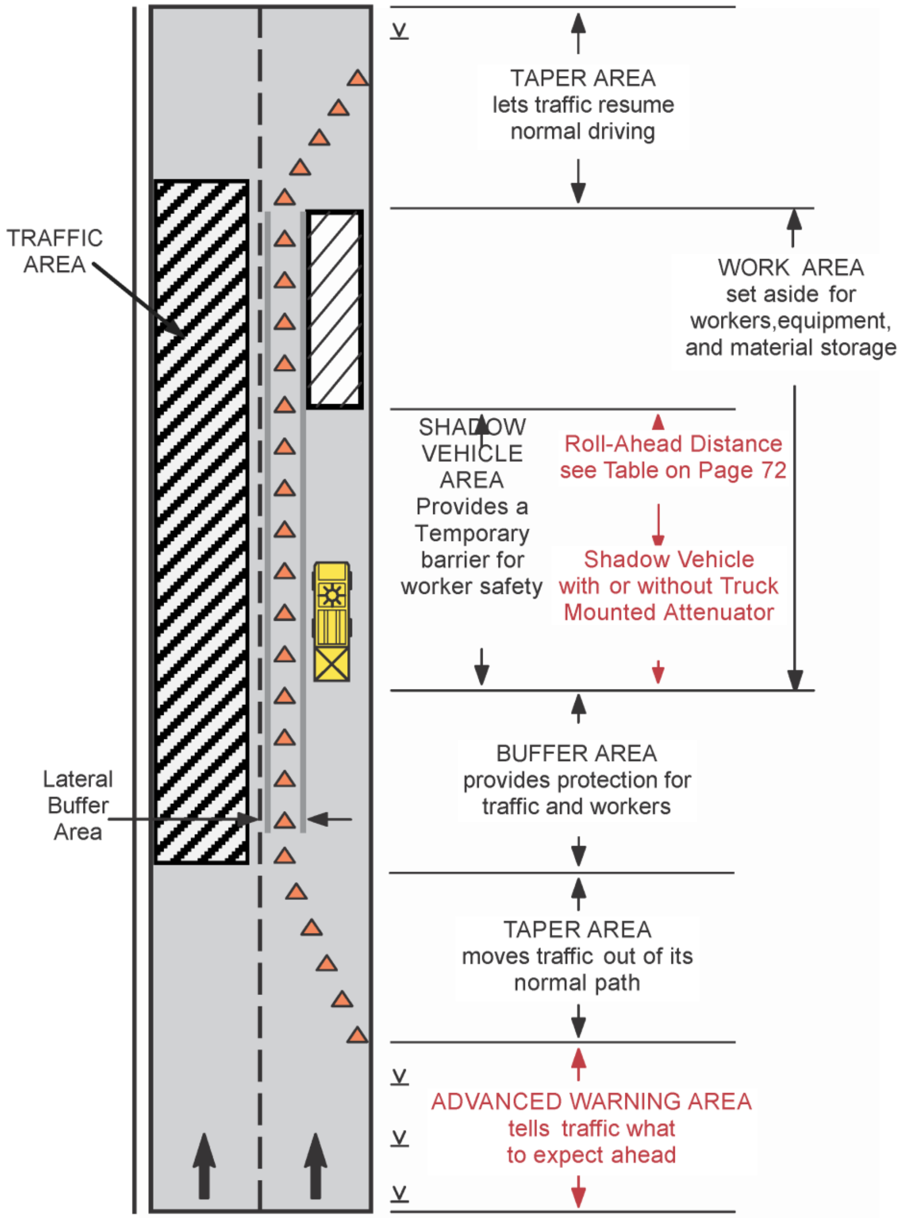


Figure 7 Components of a Temporary Traffic Control Zone in Indiana [*13*]

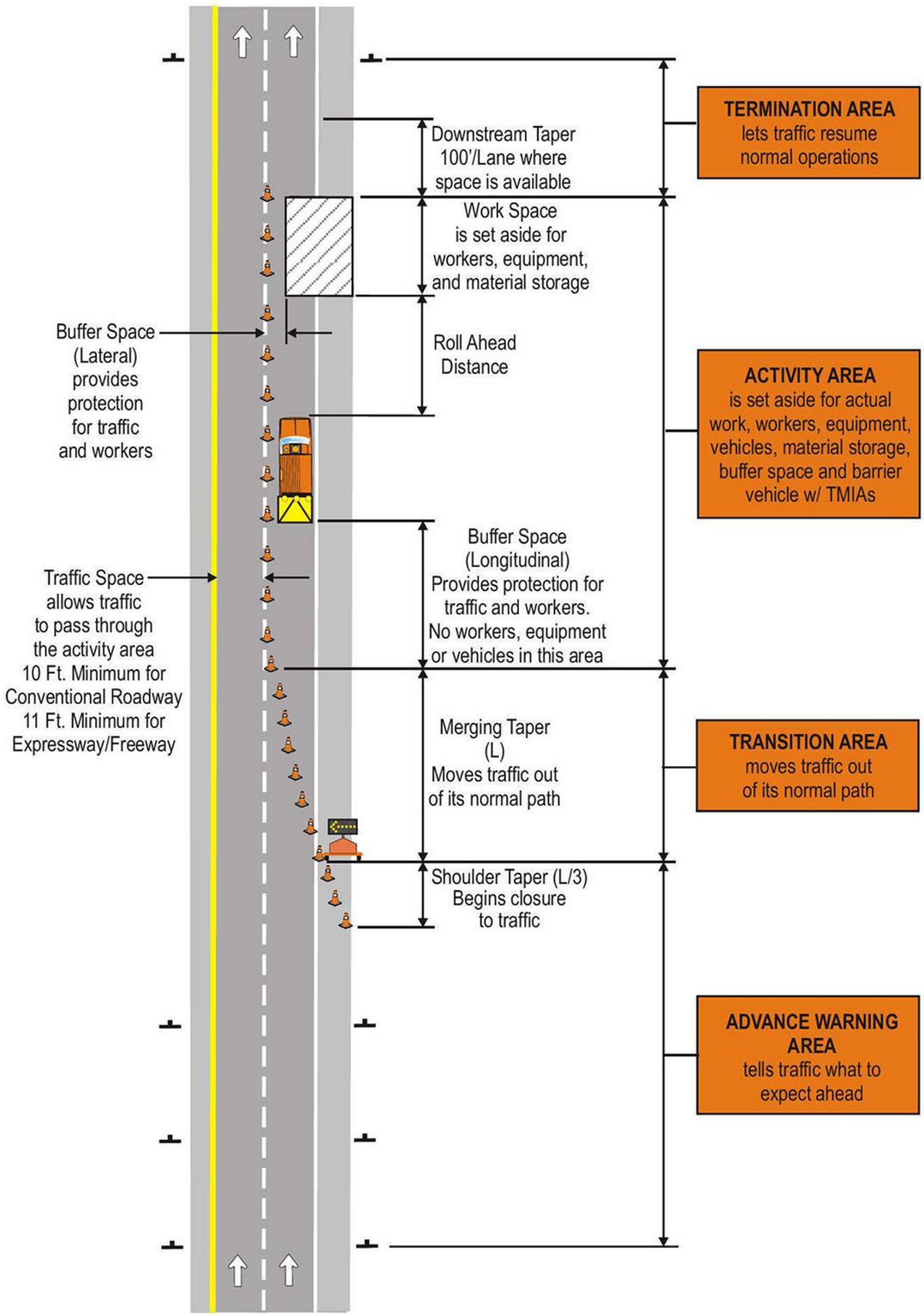


Figure 8 Components of Work Zone Traffic Control Area in New York State [*14*]

2.1. Advance Warning Signs

Table 2 Summary of Advance Warning Sign Spacing Stipulated by MUTCD & Various State DOTs

Road Type	Distance Between Signs (feet)		
	A	B	C
MUTCD [*10*]			
Urban (low speed)*	100	100	100
Urban (high speed)*	350	350	350
Rural	500	500	500
Expressway/Freeway	1,000	1,500	2,640
Connecticut [*11*]			
Urban (low speed)*	100	100	100
Urban (high speed)*	350	350	350
Rural	500	500	500
Expressway/Freeway	1,000	1,500	2,640
New York State[*14*]			
Urban (30 MPH or Less)	100	100	100
Urban (35- 40 MPH)	200	200	200
Urban (45 MPH or Greater)	350	350	350
Rural	500	500	500
Expressway/Freeway	1,000	1,500	2,600
New Hampshire [*15*]			
Urban (low speed)*	100	100	100
Urban (high speed)*	350	350	350
Rural	500	500	500
Expressway/Freeway	1,000	1,500	2,640
Massachusetts [*12*]			
Local or low Volume Roadways	350	350	350
Most Other Roadways	500	500	500
Freeways or Expressways	1,000	1,500	2,640
Vermont [*16*] & Maine [*17*]			
Urban (30 MPH or Less)	100	100	100
Urban (35- 40 MPH	200	200	200
Urban (45 MPH or Greater)	350	350	350
Rural	500	500	500
Expressway/Freeway	1,000	1,500	2,600
Indiana [*13*]			
25-30 mph	100	100	100
35-40 mph	350	350	350
45-55 mph	500	500	500
Multilane Divided 50 mph or Higher	1,000	1,600	2,640
Expressway/Freeway	1,000	1,600	2,640
Virginia [*18*]			
Urban (low speed)*	100	100	100
Urban (high speed)*	350	350	350
Rural	500	500	500
Expressway/Freeway	1,000	1,500	2,640

* Speed category to be determined by highway agency

Setting up advance warning signs is a three-stage process as shown in Figure 9. The initial sign alerts drivers that there is a work zone ahead (see SIGN #3). The second sign tells drivers the nature of road closure, for instance right lane closed, left lane closed, median work, and shoulder work. The third sign (i.e., SIGN #1) is placed before the merging taper and informs drivers what action needs to be taken while entering a work zone. Figure 9 is obtained from the New York State DOT Traffic Sign Manual [*14*]. The MUTCD recommends a minimum 1,000-foot distance between advance warning signs on expressway/freeways. Table 2 lists the distances for other roadways recommended by MUTCD and some state DOTs.

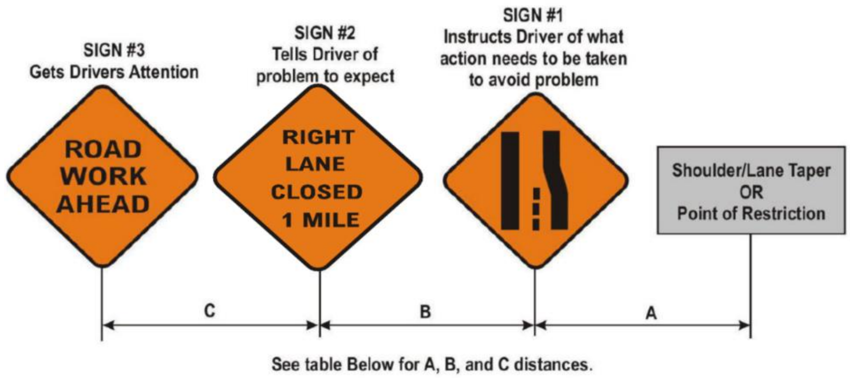


Figure 9 Three-Step Process for Setting up Advance Warning Signs [*14*]

2.2. Taper and Buffer Lengths

The following five types of roadway tapers are commonly used in work zone temporary traffic control:

1) *Merging Taper*: When a travel lane is closed and vehicles in that lane have to merge into other lanes;
2) *Shifting Taper*: When there is no reduction in the number of lanes and all lanes are shifted simultaneously to the left or right;
3) *Shoulder Taper*: This happens when the shoulder is closed. It is similar to the merging taper. However, vehicles do not have to change lanes since all travel lanes are open;
4) *Downstream Taper:* It is at the end of a work zone and serves as the transition area between the work zone and normal roadway segment; and
5) *One-lane*, *Two-way Taper*: When one lane of a two-lane (one in each direction) roadway is closed and vehicles from the two directions are discharged alternately using the remaining lane.

Since this research focuses on work zones on major highways, only relevant types of roadway tapers are reviewed. Table 3 summarizes the merging taper length criteria for lane widths ranging from 10 to 12 feet as specified in the MUTCD and by some state DOTs. Table 4 provides a summary of the shifting and shoulder taper lengths. The MUTCD and many state DOTS also provide recommendations on the buffer space length, which ensures the safety of a work zone. The recommended buffer area lengths are presented in Table 5.

Table 3 Summary of Merging Taper Length Criteria Stipulated by MUTCD & Various State DOTs

Speed Limit (mph)	Lane Width (feet)			Maximum Spacing of Devices (feet)
	10	**11**	**12**	
MUTCD [*10*], Massachusetts [*12*], New Hampshire [*15*],Vermont [*16*] & Maine [*17*]				
40 or less	$L = WS^2/60$	$L = WS^2/60$	$L = WS^2/60$	Speed Limit Equivalent
45 or more	L = WS	L = WS	L = WS	Speed Limit Equivalent
Connecticut [*11*]				
25	105	115	125	25
35	205	225	245	35
45	450	495	540	45
55	550	605	660	55
65	650	715	780	65
New York State [*14*]				
25	120	120	140	25
30	160	180	180	30
35	220	240	260	35
40	280	300	320	40
45	460	500	540	45
50	500	560	600	50
55	560	620	660	55
65	660	720	780	65
Indiana [*13*]				
20	$L = WS^2/60$	$L = WS^2/60$	160	40
25	$L = WS^2/60$	$L = WS^2/60$	160	40
30	$L = WS^2/60$	$L = WS^2/60$	200	40
35	$L = WS^2/60$	$L = WS^2/60$	280	40
40	$L = WS^2/60$	$L = WS^2/60$	320	40
45	L = WS	L = WS	560	80
50	L = WS	L = WS	600	80
55	L = WS	L = WS	680	80
60	L = WS	L = WS	720	120
65	L = WS	L = WS	800	120
70	L = WS	L = WS	840	120
Virginia [*18*]				
25	105	115	125	25
40	270	295	295	35
45	450	495	540	45
55	550	605	660	55
65	650	715	780	65

L = Taper length in feet,
W = Width of offset in feet, and
S = Posted speed limit, off peak 85th percentile speed prior to work starting or the anticipated operating speed in mph.

Table 4 Summary of Shifting & Shoulder Taper Length Criteria Stipulated by MUTCD & Various State DOTs

Type of Taper	Merging Taper	Shifting Taper	Shoulder Taper
MUTCD [*10*]	L	0.5L	0.33L
CT [*11*]	L	$\begin{cases} 0.5L \text{ when } S < 50 \text{ mph} \\ L \text{ when } S > 50 \text{ mph} \end{cases}$	0.33L
NY [*14*]	L	0.5L	0.33L
NH [*15*]	L	0.5L	0.33L
MA [*12*]	L	0.5L	0.33L
VT [*16*]	L	0.5L	0.33L
ME [*17*]	L	0.5L	0.33L
IN* [*13*]	$\begin{cases} 160 \text{ ft when } 20 \geq S \leq 25 \\ 200 \text{ ft when } S = 30 \\ 280 \text{ ft when } S = 35 \\ 320 \text{ ft when } S = 40 \\ 560 \text{ ft when } S = 45 \\ 600 \text{ ft when } S = 50 \\ 680 \text{ ft when } S = 55 \\ 720 \text{ ft when } S = 60 \\ 800 \text{ ft when } S = 65 \\ 840 \text{ ft when } S = 70 \end{cases}$	$\begin{cases} 80 \text{ ft when } 20 \geq S \leq 30 \\ 120 \text{ ft when } 35 \geq S \leq 40 \\ 200 \text{ ft when } 45 \geq S \leq 50 \\ 240 \text{ ft when } 55 \geq S \leq 60 \\ 280 \text{ ft when } 65 \geq S \leq 70 \end{cases}$	$\begin{cases} 80 \text{ ft when } 20 \geq S \leq 25 \\ 120 \text{ ft when } S = 30 \\ 160 \text{ ft when } 35 \geq S \leq 40 \\ 280 \text{ ft when } S = 45 \\ 320 \text{ ft when } S = 50 \\ 360 \text{ ft when } 55 \geq S \leq 60 \\ 400 \text{ ft when } S = 65 \\ 440 \text{ ft when } S = 70 \end{cases}$
VA [*18*]	L (See Table 3)	0.5L	0.33L

*All taper lengths are specified for lane width (offset width) = 12 ft.

Table 5 Summary of Length of Longitudinal Buffer Space Stipulated by MUTCD & Various State DOTs

Speed (mph)	Distance (ft.)								
	MUTCD Table 6C-2 [*10*]	**CT [*11*]**	**NY [*14*]**	**NH [*15*]**	**MA [*12*]**	**VT [*16*]**	**ME [*17*]**	**IN [*13*]**	**VA [*18*]**
20	115	115	115	115	115	115	115	120	115
25	155	155	155	155	155	155	155	160	165
30	200	200	200	200	200	200	200	200	200
35	250	250	250	250	250	250	250	280	250
40	305	305	305	305	305	305	305	320	325
45	360	360	360	360	360	360	360	360	360
50	425	425	425	425	425	425	425	440	425
55	495	495	495	495	495	495	495	520	530
60	570	570	570	570	570	570	570	600	600
65	645	645	645	645	645	645	645	680	645
70	730	730	730	730	730	730	730	760	730

Note: use posted speed limit if 85^{th} percentile speed is unknown

2.3. Travel Lane Width

The NYSDOT mandates that the minimum travel lane width for all freeways and/or expressways is 11 feet. For all other roadways, the minimum lane width is 10 feet [*19*]. In the State of New York, the recommended minimum offset (clearance) from the edge of the travel lane to traffic barriers is 2 feet [*20*]. Travel lanes that are 12 feet wide with an offset of 2 feet to barriers is the most desired situation. However, this may not be available under some circumstances. In such cases, factors that determine acceptable travel lane width include [*21*]: traffic volume, heavy-vehicle volume, lateral constraint, speed, horizontal curvature, duration of lane constriction, one-way or two-way roadway, and number of lanes.

Also, travel lanes that are less than 10 feet wide are not recommended for multilane highways/expressways. Table 6 provides the recommended travel lane widths by undivided and divided highways [*21*].

Table 6 Example Framework for Selecting One-Way Traveled Way Widths [*21*]

		Metric				**U.S Customary**			
		Traveled way width (m)				**Traveled way width (ft.)**			
Facility type		Undivided highway		Divided Highway		Undivided highway		Divided Highway	
Lanes per direction		One	Two	One	Two	One	Two	One	Two
Traveled way Edge conditions	Constraint along neither traveled way edge	3.0 [1]	6.0 [2.3]	3.3	6.6 [3]	10 [1]	20 [2.3]	11	22 [3]
	Constraint along one traveled way edge	3.3 [1]	6.3 [2.3]	3.6	6.9 [3]	11 [1]	21 [2.3]	12	23 [3]
	Constraint along both traveled way edge	3.6 [1]	6.6 [2.3]	3.9	7.2 [3]	12 [1]	22 [2.3]	13	24 [3]

Notes:

1. Values apply only when all of the following conditions are met: low truck volumes, all curve radii equal or exceed 555 m (1,820 ft.); and anticipated 85^{th}-percentile speeds are less than or equal to 80 km/h (50 mph). If any of the three conditions is not met, add 0.3 m (1 ft.) to the base value.

2. Values apply only to roadways carrying moderate truck volumes where all curve radii equal or exceed 555 m (1,820 ft.). If either condition is not met, add 0.3 m (1 ft.) to the base value.

3. Values shown apply to two-lane, one-way traveled ways. For constricted two-way traveled ways, consider separation of opposing directions using (a) additional traveled way width, (b) channelizing devices, or (c) a traffic barrier.

4. To use this exhibit, first determine the traveled way edge conditions. “Constraint” refers to the presence of an imposing feature, such as a feature those results in “shying away” at the edge of the traveled way. Temporary barriers are a common constraint feature. Next, identify the type of facility (undivided or divided) approaching the work zone. Using this information and the number of travel lanes through the work zone, determine the base (i.e., unadjusted) value within the appropriate cell. Superscripted numerals indicate the note numbers that should be referenced to determine appropriate adjustment, if any, to the base value.

5. For traveled ways with edge constraint, the distances indicated are measured to the face of the constraining features (i.e., the offset is included in the tabulated or adjusted dimension). Values lower that those obtained from this method may be appropriate for very low exposure (i.e., traffic volume, constricted lane segment length, and duration of operation).

2.4. General Work Zone Control Strategies

The National Cooperative Highway Research Program (NCHRP) Report 581 [*20*] provides a summary of the advantages and disadvantages of basic work zone design strategies. These advantages and disadvantages are presented in Table 7.

Table 7 Summary of Work Zone Control Strategies [*20*]

Strategy	Summary	Advantages	Disadvantages
Alternating one-way operation	Mitigates for full or intermittent closure of lanes. Used primarily with two-lane facilities.	Low agency cost and low non transportation impacts; flexible, several variations available.	Requires stopping of traffic; reduces capacity.
Detour	Reroutes traffic onto other existing facilities.	Flexible; cost varies depending on improvements to detour route; in some cases, only TTC needed.	Usually reduces capacity; service and infrastructure on existing roads may be degraded; may need agreement of another agency.
Diversion	Provides a temporary roadway adjacent to construction.	Separates traffic from construction; reduced impact on traffic.	Cost may be substantial, especially if temporary grade separation of hydraulic structure involved; right-of-way often required
Full road closure	Closes the facility to traffic for a specified (limited) duration.	Generally also involves expedited construction; separates traffic from construction.	Some form of mitigation is needed (detour, diversion, etc.); potentially significant traffic impacts.
Intermittent closure	Stops traffic for a short period.	Flexible and low agency cost.	Useful only for activities that can be completed in short time; requires stopping traffic.
Lane closure	Closes one or more travel lanes.	Maintains service; fairly low agency cost if temporary barriers are omitted.	Reduces capacity; may involve traffic close to active work.
Lane constriction	Reduces traveled way width.	Maximizes number of travel lanes.	Traveled way width is less than desirable; may involve traffic close to active work.
Median crossover	Maintains two-way traffic on one roadway of a normally divided highway.	Separates traffic from construction; right-of-way not required.	Reduced capacity; not consistent with approach roadway; relatively costly; interchanges need special attention.
Use of shoulder	Uses shoulder as a travel lane.	Fairly low cost, depending on shoulder preparation.	Displaces traditional refuge for disabled vehicles; debilitates shoulder pavement structure; cross slopes may be problematic.

Another NCHRP Report 500 [*22*] also provides a wide range of strategies for improving work zone safety that cover engineering, enforcement and education. These strategies are listed in Table 8 and are classified as proven (P), tried (T) and experimental (E). A detailed description of these strategies can be found in section V of the NCHRP report. Several of these strategies also have sub-strategies.

Table 8 Summary of Strategies to Improve Work Zone Safety [*22*]

Objectives	Strategies
Reduce the number, duration, and impact of work zones	• Improve maintenance and construction practices (P) • Utilize full-time roadway closure for construction operations (T) • Utilize time-related contract provisions (P) • Use nighttime road work (P) • Use demand management programs to reduce volumes through work zones (P) • Design future work zone capacity into new or reconstructed highways (T)
Improve work zone traffic control devices	• Implement ITS strategies to improve safety (E) • Improve visibility of work zone traffic control devices (T) • Improve visibility of work zone personnel and vehicles (varies) • Reduce flaggers' exposure to traffic (T)
Improve work zone design practices	• Establish work zone design guidance (T) • Implement measures to reduce work space intrusions (and limit consequences of intrusions) (T) • Improve work zone safety for pedestrians, bicyclists, motorcyclists, and heavy-truck drivers (T)
Improve driver compliance with work zone traffic controls	• Enhance enforcement of traffic laws in work zones (T) • Improve credibility of signs (E) • Improve application of increased driver penalties in work zones (T)
Increase knowledge and awareness of work zones	• Disseminate work zone safety information to road users (T) • Provide work zone training programs and manuals for designers and field staff (T)
Develop procedures to effectively manage work zones	• Develop or enhance agency-level work zone crash data systems (T) • Improve coordination, planning, and scheduling of work activities (T) • Use incentives to create and operate safer work zones (T) • Implement work zone quality assurance procedures (i.e., safety inspections or audits) (T)

2.5. Work Zone Crash Characteristics

Work zones significantly increase crash risk [*23*,*24*] on highways. According to a 2014 FHWA report [*25*], most fatal work zone crashes occurred on roads with a speed limit of greater than 50 mph. This report also presents the most common types of crashes by work zone area as shown in Figure 10. As can be seen, rear-end collisions and collisions with fixed objects are the two most common crash types in work zones. To avoid rear-end collisions, it is important to ensure that all drivers travel at approximately the same speed in addition to reducing the average travel speed in work zones. For reducing the number of collisions with fixed objects, it would be interesting to investigate the safety impacts of travel lane width, barrier and drum offsets (i.e., placement of barriers and drums), and driver distraction.

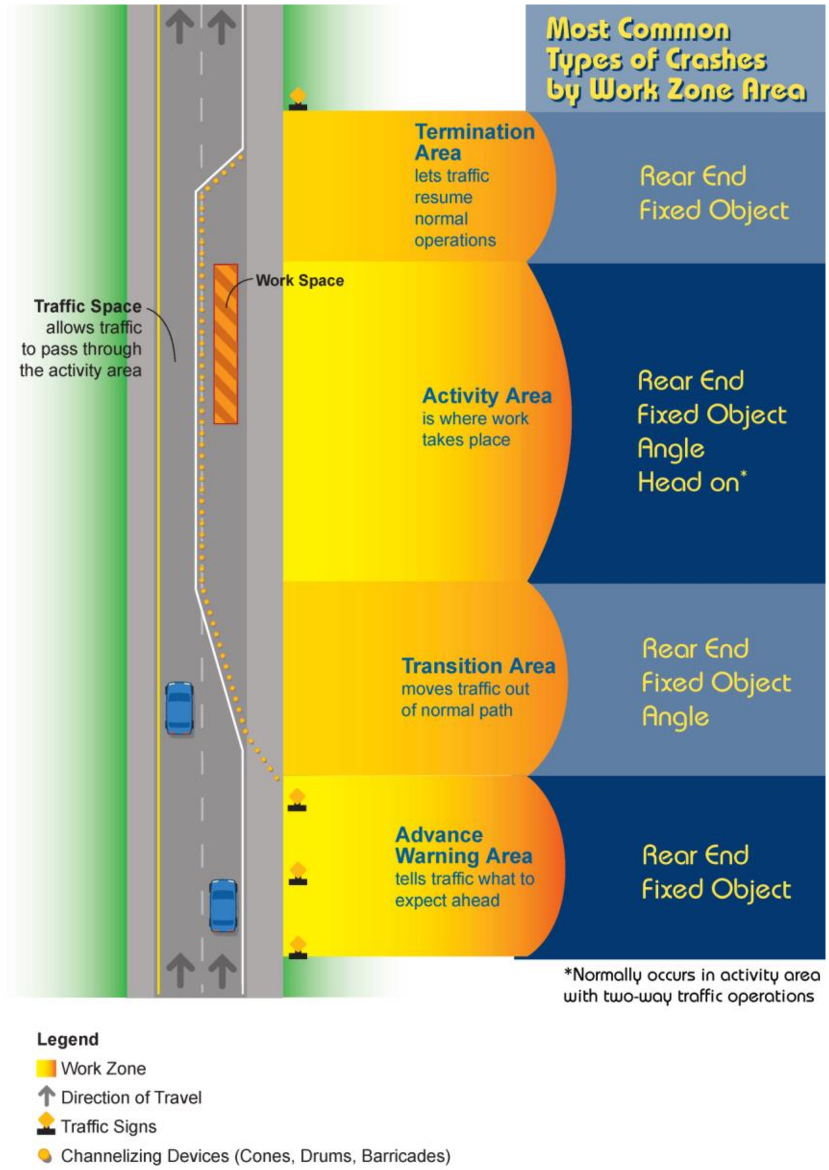


Figure 10 Most Common Types of Crashes by Work Zone Area [*25*]

Similar to the above FHWA research, a study by Garber and Zhao [*26*] found that the most common type of crashes in work zones is rear-end crash and work zone related accidents are mainly caused by speed variances. In their study, the locations of 1,484 work zone accidents are categorized into areas shown in Figure 11. The location analysis results suggest that more crashes occurred in work zone activity areas than in non-work activity areas. Gerber and Zhao also found that more sideswipe collisions occurred in transition areas than in advance warning areas. This seems to suggest that last-minute lane changes are more dangerous than early merges.

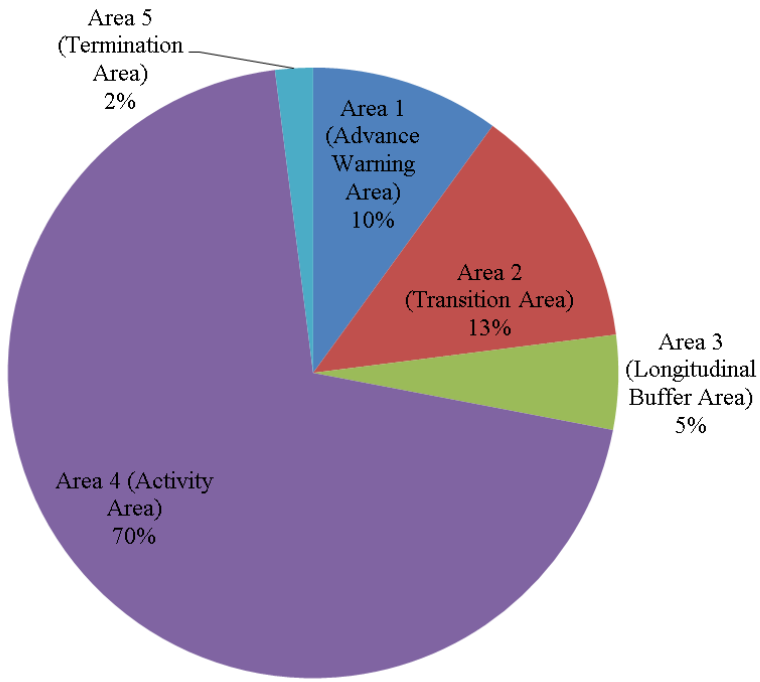


Figure 11 Location Distribution for All Work Zone Crashes

Another study by Garber and Woo [*27*] identified prevalent work zone crash characteristics and evaluated traffic control devices commonly used in urban work zones. They found that angle, side-swipe, and rear-end crashes were the most common types of crashes reported in work zones. Work zone crashes were more likely to involve multiple vehicles compared to non-work zone crashes. Environmental factors did not seem to play a major role in increasing crash risk in work zones.

Table 9 Crashes and Work in Progress [*28*]

Work in Progress	**Injury Severity Level**		**All Crashes**
	Property Damage Only	**Injury**	
Yes	74.2%	25.8%	62
No	82.9%	17.1%	41
	Location in Work Zone		
	Approach	**Taper**	**Activity Area**
Yes	22.6%	11.3%	66.1%
No	22.0%	26.8%	48.8%
	Manner of Collision		
	Rear-end	**Sideswipe**	**Object**
Yes	69.4%	21.0%	3.2%
No	36.6%	31.7%	24.4%

Raub et al. [*28*] found that driver distraction is a major contributor to rear-end crashes. In their study, 110 work zone crashes in Illinois were analyzed. Of the 110 crashes, 103 crashes were a direct result of work zones and the remaining 7 were not attributed to work zones. The result revealed that work zones caused drivers to slow down unnecessarily and even stop in approaching areas. They also found that speed was not a major contributor to crashes within the work zone itself (especially in the activity area). The study stated that approximately 40% of all work zone crashes occurred when there were no work activities going on. 60% of work zone incidents occurred when work was in progress and activity within the work zone was the prime distraction factor. Table 9 describes the severity of the work zone crashes when work was in progress.

Also, GPS devices and smartphones were found to be major causes of driver distraction in work zones. Raub et al. [*28*] emphasized the significant negative impacts of improper merge behavior in the approach area of work zone, and drivers approaching queues at high speeds. Table 10 and Table 11 adopted from Raub et al. [*28*] show the contributing factors for collisions in work zones. These results are also supported by the study conducted by MaineDOT [*9*].

Table 10 External Roadway Elements Contributing to Crashes [*28*]

Contributing Elements[1]	All Crashes		Location in Work Zone			
	Number	Percentage Of Crashes	Approach	Taper	Work Area	Exit
Traffic	13	11%	6	0	7	0
Activity	14	14%	0	2	12	0
Construction	5	4%	1	1	3	0
Obstructed View	7	6%	0	3	4	0
Traffic Control Devices (TCD) Problem	6	5%	0	1	4	1
Pavement	6	5%	0	0	6	0
Narrow Lanes	14	14%	1	5	8	0
No Escape	27	24%	4	6	17	0
Other	22	19%	9	4	9	0
Total	**114**		**21**	**22**	**70**	**1**

[1] Police could check one or more contributing elements

Table 11 Contributing Driver Actions to Crashes [*28*]

Driver Actions[1]	All Crashes		Location in Work Zone			
	Number	Percentage Of Crashes	Approach	Taper	Work Area	Exit
Sudden Slowing or Stopping	38	25%	7	4	27	0
Driving Outside	9	6%	5	2	2	0
Improper Lane Change	13	9%	3	5	4	1
Failure to Yield	19	13%	1	11	7	0
Exceed Speed	5	3%	1	1	3	0
Exit Behavior	1	1%	0	1	0	0
Following Too Closely	25	15%	6	1	18	0
Improper Approach	2	1%	2	0	0	0
Distraction Inside the Vehicle	17	11%	6	2	10	0
Alcohol/Drugs	1	1%	0	0	1	0
Vehicle Defect	3	2%	0	1	2	0
Other	19	13%	3	0	15	0
Total	**152**		**34**	**28**	**89**	**1**

[1] Police could check one or more contributing elements

Raub et al. [*28*] also stressed the importance of videotaping vehicles to study driver behavior while they approach a work zone. Five categories are employed to classify driver merge behaviors and are shown below. Table 12 shows the relative frequencies for different merging and through vehicle behaviors observed in their study. As the traffic volume increases, the percentage for late merge significantly increases as well.

- Early merge: early enough that the normal traffic is not affected (e.g., slowed down),
- Mid merge: merge into the middle of a queue in the open lane but is at least 50 meters before the taper,
- Late merge: merge right before or into the merging taper,
- Forcing merge: two or more vehicles trying to merge into the same gap in the open lane, and
- Using shoulder: passing other vehicles using the shoulder.

Table 12 Driver Behavior Classification [*28*]

Behavior Type	IL 120-1st Visit	IL 120-2nd Visit	Interstate94	Dundee Rd
Merging Vehicles				
Est. Merging Volume (%)	19.9%	16.5%	47.8%	30.3%
a. Early	48.7%	55.6%	53.7%	17.1%
b. Mid Merge	41.7%	29.0%	5.8%	12.2%
c. Late Merge	9.2%	14.5%	40.3%	65.8%
d. Forcing Merge	0.4%	0.9%	0.2%	4.9%
e. Using Shoulder	0.0%	0.0%	0.0%	0.0%
Through Lane				
a. Normal Behavior	98.2%	97.1%	90.9%	94.6%
b. Vigilante	0.6%	2.9%	2.7%	1.8%
c. Failure to Yield	1.2%	0.0%	6.4%	3.3%
d. Stopping in Lane	0.0%	0.0%	0.0%	0.3%
e. Rapid Approaching	0.9%	4.8%	4.9%	0.3%
Flow (vph)	1300	1300	1800	1800

* Percent of all vehicles approaching merge

Muttart et al. [*29*] conducted a driving simulation study to investigate work zone safety. They created 32 work zones that were tested by 38 participants. These work zones covered cell phone, no cell phone, and hands-free cell phone scenarios. Their results show that cell phone use may substantially increase crash risk in the work activity area.

Chambless et al. [*30*] analyzed work zone crash data collected from the states of Alabama, Michigan and Tennessee. Their study indicates that 4.3% of work zone crashes occurred due to speeding. Most work zone crashes occurred in the speed range of 45 to 55 miles per hour. Driving Under the Influence (DUI) accounted for 3.8% of work zone related crashes. Misjudging stopping distance and following too closely were the most commonly observed causes for crashes in work zones as indicated in their study.

Walker and Upchurch [*31*] suggested the following six countermeasures to reduce work zone crashes. They did not consider the effect of modern technologies such as collision avoidance systems to reduce work zone crashes. Driver distraction due to on-board navigation devices was also neglected in their study.

- Work zone speed limits
- Police presence

- Speed limit enforcement
- Public education
- Sign credibility
- Temporary pavement markings

The advantages and disadvantages of nighttime work were discussed in NCHRP report 581 [*21*] and are summarized in Table 13. Further, NCHRP Report 627 [*32*] used data from California, North Carolina, Ohio and Washington and concluded that overall, nightime work activities did not significantly increase the crash risk than daytime work activities. Additionally, nighttime crashes were not necessarily more severe than daytime crashes. The report stated that low traffic volumes during night resulted in much less crashes over the work zone duration. It finally concluded that it is safer to carry out nighttime operations in work zones because of reduced crash costs.

Table 13 Advantages and Disadvantages of Nighttime Work [*21*]

Advantages	Disadvantages
• Lower traffic volumes and lower traffic impacts • Lower impacts to commercial activity	• Higher agency cost • Higher safety risks • Disrupts normal social patterns of workforce • Noise • Possible compromise in construction quality

Rami et al. [*33*] used the Florida Crash Records Database for years 2002, 2003, and 2004 to study work zone safety. According to the results of their statistical models, roadway geometry (such as vertical and horizontal alignment), weather condition, age, gender, lighting condition, residence code, and driving under the influence of alcohol and/or drugs are all significant contributing factors to freeway work zone crashes. Straight level road segments were found to have a higher single-vehicle crash risk than straight upgrade/downgrade, curve level and curve upgrade/downgrade segments. Rami et al. explained that drivers tend to be more cautious on horizontal and vertical curves. The authors found that drivers are less likely to get involved in crashes when it is raining. Again, they attributed this to more cautious driving in inclement weather conditions.

Some other conclusions drawn from the study by Rami et al. [*33*] are: good lighting should be provided in and near the work activity area so that drivers can see warning signs clearly and take appropriate actions; truck drivers should be extremely careful in work zones, especially those with lane closure and narrow lanes. A low speed limit could help to improve the safety for truck drivers in work zones; driver distraction and aggressive driving frequently occur in work zones. Therefore, additional law enforcement is needed in work zones.

A study conducted by Bai and Li [*34*] examined 157 fatal work zone crashes between 1992 and 2004. They conducted statistical analysis of these work zone crashes to identify key risk factors and studied their characteristics. Human errors such as distracted driving, disregarding traffic control devices and warnings were identified as the prime causes of fatal crashes. Weather conditions did not significantly increase driver risk. Roadway geometry and inefficient traffic control devices were found to increase driver risk.

Morgan et al. [*35*] conducted a driving simulation based study of driver responses to urban highway work zone control configurations. The first configuration was the existing control and the second one had a reduced merging taper length. The two configurations were evaluated by 21 drivers with and without a lead vehicle. Data such as speed, braking, travel path, and collision frequency was recorded. For the reduced taper length configuration, drivers tended to drive significantly closer to the edge of the work activity area, suggesting that reducing taper length increases the risk to both drivers and workers. This is primarily due to the mismatch between driver anticipation and shortened transition distance. This risk for work zones with short tapers may be mitigated by encouraging early merge.

Figure 12 Visual In-Vehicle Display Installed in the Simulator [*36*]

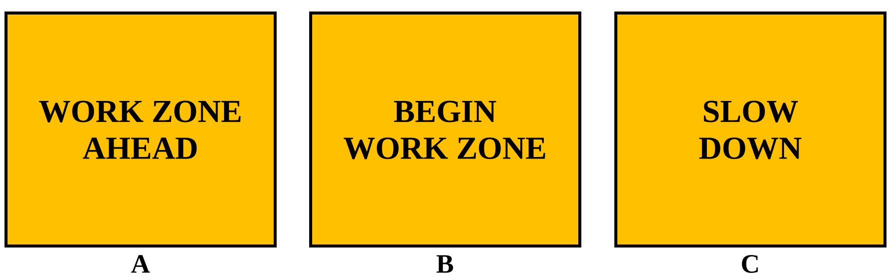


Figure 13 Visual Warnings Presented in the Simulator

Whitmire et al. [*36*] also studied work zone safety using driving simulator. Three work zone configurations were considered. The first configuration used only traditional signage. The second configuration employed an additional visual in-vehicle warning system. The third configuration considered an auditory in-vehicle warning system in addition to the signs in the first configuration. Figure 12 shows the visual in-vehicle display that was installed on the dashboard. A “SLOW DOWN” message was displayed when the “Work Zone Ahead” sign was within the line of sight and auditory warnings were issued. The messages that were used to provide visual warnings are shown in Figure 13. The text of the message was in black with an orange background that mimics a work zone sign. The study results indicate that adding in-vehicle warnings led to better driver compliance to the work zone speed limit compared to traditional signage only scenarios.

2.6. Summary

This chapter provides some background information about work zone traffic control, including work zone layout, placement of warning signs, and lengths of various work zone sections. A comparison of the work zone control practices adopted by state DOTs and the recommended settings in the MUTCD suggests that there are no significant differences between them. Many studies have been conducted to explore strategies to improve work zone mobility and safety, and some of the findings are presented in Section 2.4. A more detailed and comprehensive review specifically focused on speed and merge controls is provided in Chapter 3. This chapter also includes a brief overview of work zone crash characteristics, which suggests that rear-end and angle crashes with other vehicles/fixed objects are the most common types of work zone crashes. These crash characteristics confirm that it is important to further look into strategies for work zone speed and merge controls.

3. WORK ZONE TEMPORARY TRAFFIC CONTROL PLANS (TTCPS)

Work zones often have disproportionately high percentages of rear-end and angel crashes. Rear-end crashes are usually caused by following too closely and large speed variations due to stop-and-go traffic, while angle crashes are typically associated with unsafe merge behaviors. In addition, distracted driving is another major contributor to both rear-end and angle crashes.

Among all work zone Temporary Traffic Control Plans (TTCPs) for improving safety and mobility, speed and merge controls appear to be the most widely considered. This chapter begins with a comprehensive review of speed and merge control strategies that are commonly used by practitioners and popular among researchers. Based on the review, these TTCPs are compared and discussed in detail. Finally, some promising TTCPs are selected for further evaluations in Chapters 6 and 7.

3.1. Review of Work Zone TTCPs

3.1.1. TTCPs for Speed Control

Common work zone speed control strategies include law enforcement, flagging, radar speed sign (dynamic speed display), temporary rumble strips, transverse paint strips, lane width reduction, Portable Changeable Message Sign (PCMS), speed photo-radar enforcement, and variable speed limit. Sometimes one speed control strategy is given two different names (e.g., speed trailer and radar speed sign). The remaining of this subsection provides a detailed review and comparison of these methods.

Ullman and Riesland [*37*] surveyed work zone speed control methods used in Texas and identified factors that may affect their effectiveness. The found law enforcement and flaggers to be the most effective methods for controlling speed in work zones. Three types of law enforcement were often used in Texas, which are circulating patrols, stationary patrols, and police officer standing by a patrol vehicle. Among the three law enforcement methods, circulating patrols appear to be the least effective. However, they are the most popular and are often used in long-term work zones. Flaggers are commonly used and are almost as effective as law enforcement in reducing speed in work zones. The authors found that traditional static speed limit signs (not variable speed limit signs), although widely used in work zones, have little impacts on work zone traffic speeds. The authors also reviewed changeable message signs, rumble strips, transverse paint stripes, reduced lane widths, and radar transmissions. These methods had limited uses in Texas and they were found to be less effective than either law enforcement or flaggers.

Noel et al. [*38*] evaluated four multilane freeway work zone speed control strategies: (1) a flagger who follows the procedure outlined in the Manual On Uniform Traffic Control Devices (MUTCD), (2) an MUTCD flagger who uses hand signals to slow down drivers, (3) a police car with lights and radar on, and (4) a uniformed police officer. These strategies were tested in the field for about two weeks. The authors found that all four strategies can effectively reduce speeds in work zones, particularly the two law enforcement strategies (i.e., the last two strategies). This finding is consistent with what Ullman and Riesland concluded [*37*]. The authors also pointed out that although the law enforcement strategies are more effective, they typically require a lot of coordination efforts and are more expensive to implement. Additionally, flaggers were found [*39*] to be able to effectively reduce the chance for vehicles to follow too closely, in addition to reducing speeding.

Hajbabaie et al. [*40*] also evaluated four work zone speed control techniques, which are speed feedback trailer, police car, the speed feedback trailer plus police car, and automated Speed Photo-radar Enforcement (SPE). These techniques were all found to be effective and can reduce vehicle speeds by 6 to 8 mph.

Ullman et al. [*41*] reviewed safety concerns regarding work zones on high-volume and high-speed roadways in Texas. The identified problems include excessive speeds before and within work zones, aggressive braking and lane-changing (queue jumping) upstream of and within traffic queues, and lane straddling. The authors recommended testing the following strategies to address the identified issues: (1) real-time remote speed enforcement system, (2) portable traffic management systems, and (3) late merge to address queue jumping (see Figure 14). In addition to late merge, the authors also discussed an Indiana lane merge concept (see Figure 15) for addressing queue jumping in work zones. This Indiana lane merge concept is essentially a dynamic early merge strategy. It detects the end of the queue in real time and advises drivers to merge upstream of the queue.

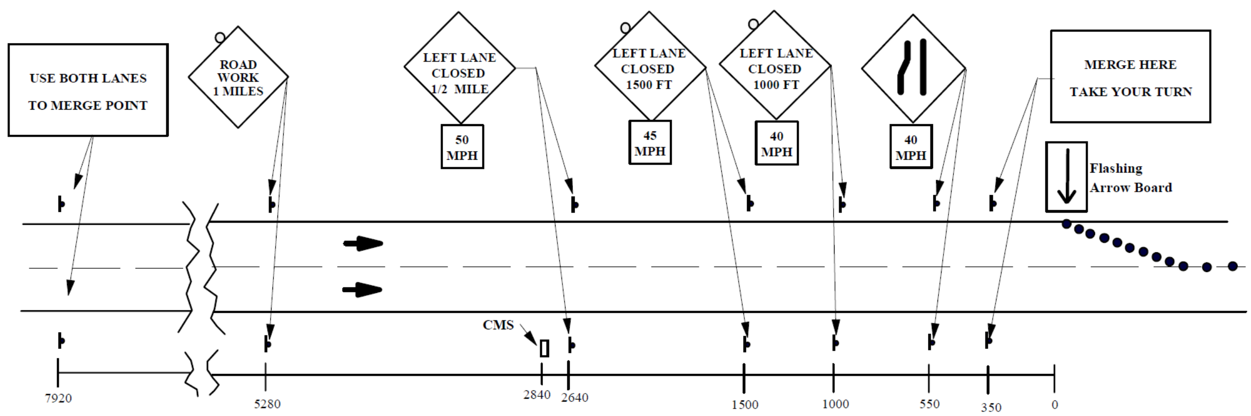


Figure 14 Work zone late merge [*42*]

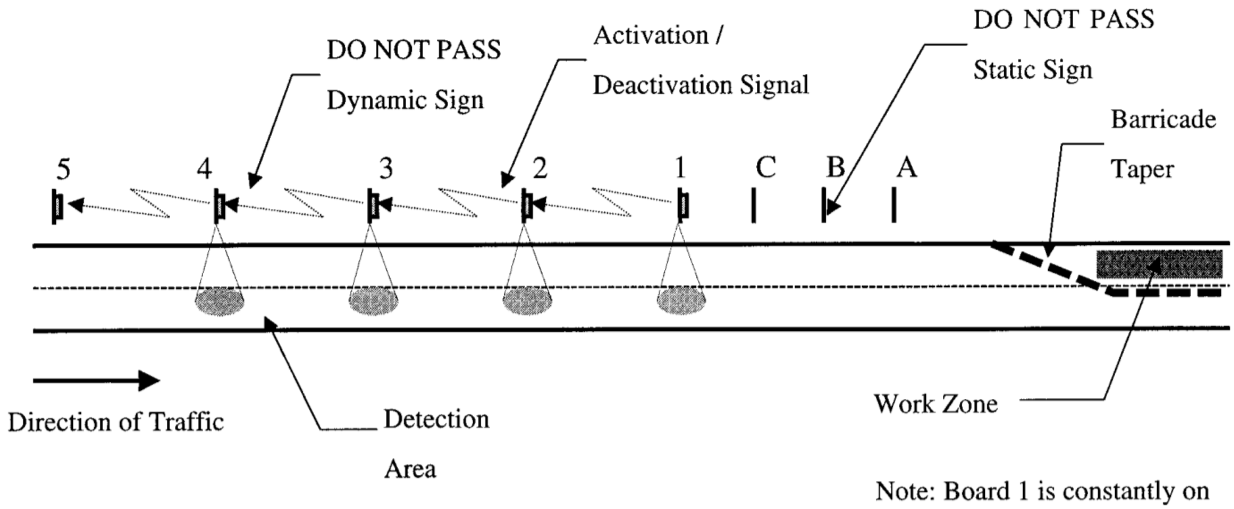


Figure 15 Indiana lane merge concept [*43*]

Reddy et al. [*44*] conducted a field evaluation of the speed reduction effects of temporary rumble strips. Speed data was collected from work zones with and without temporary rumble strips. They concluded that installing temporary rumble strips upstream of work zones can help to reduce vehicle speeds.

Li et al. [*45*] compared three Portable Changeable Message Sign (PCMS) settings on work zone speed reduction: (1) PCMS turned on, (2) PCMS deployed but turned off, and (3) no PCMS deployed. The found that these three settings were able to reduce travel speed over a 500 ft distance by 4.7 mph, 3.3 mph, and 1.9 mph, respectively. Later on in a separate study, Li and Bai [*46*] investigate the impact of PCMS location on work zone speed reduction. They concluded that the best location for PCMS is between 556 and 575 ft downstream of the MUTCD W20-1 sign.

Yang and Lu [*47*] conducted a Variable Speed Limit (VSL) study for work zone traffic operations. It applies a macroscopic model to predict traffic states in the next time horizon and estimate the corresponding optimal speed limits. The VSL approach was evaluated using VISSIM simulation and demonstrated potential to significantly reduce speed variance and improve traffic operation efficiency. VSL has also been field tested [*48*] on a six-mile work zone on I-80 in Utah. The collected data shows that speed variation in general has been reduced. The authors emphasize that it is important for the VSL to reflect true traffic conditions in order to build trust among drivers and increase compliance.

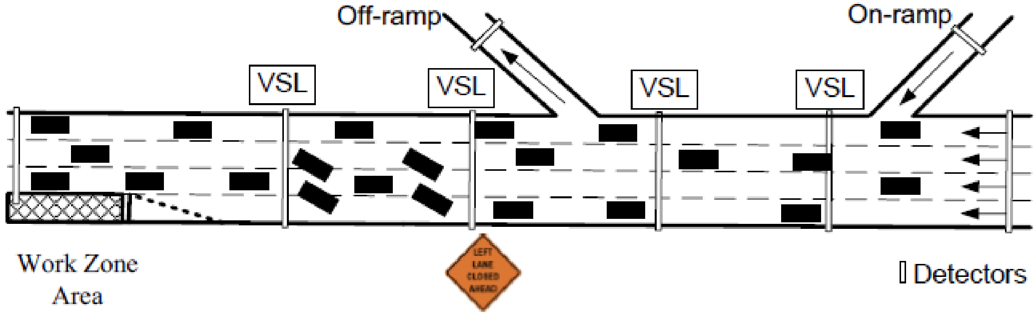


Figure 16 Illustration of VSL for work zone operations [*47*]

Kwon et al. [*49*] field tested a single VSL sign. The system was designed to reduce upstream traffic speed to be the same as the downstream traffic. In other words, it is to narrow down the gap between upstream and downstream traffic speeds. Some positive results were reported in this study. Intuitively, the effectiveness of such a VSL system will be affected by the number and locations of VSL signs, which were not thoroughly considered in this field test.

Fudala and Fontaine [*50*] also attempted to evaluate VSL in the field. Due to changing site conditions and problems with the VSL control algorithm, their field test did not generate any conclusive results. The authors further resorted to microscopic simulation to evaluate the impacts of VSL on traffic operations and safety (based on surrogate safety measures). They concluded that VSL works better when the demand is not significantly greater than the capacity. Although the VSL idea for work zone speed management conceptually is reasonable and promising, its effectiveness depends heavily on a number of issues (e.g., number and locations of VSL signs, the ability to generate reasonable speed limits, and traffic conditions).

Lyles et al. [*51*] tested VSL in the field but reported minor improvements. Due to congestion, they did not observe any speed reduction impacts. On the other hand, the authors observed increased average speeds and decreased travel time through the test site. No significant or consistent impacts on the 85^{th} percentile speed and speed variance were observed, although the authors did find reductions in the percentage of speeders. Additionally, an empirical review of crash data shows that the VSL implementation did not seem to cause increases in crash risk.

Chang and Kang [*52*] investigated how VSL control and dynamic merge control can affect work zone mobility and safety both separately and jointly. They found each of these methods performs better than its static counterpart. Additionally, the joint method outperforms each of the two methods in terms of throughput and speed variance.

Medina et al. [*53*] studied the effects of automated speed photo–radar enforcement (SPE) on vehicle speed downstream (1.5 miles) of a work zone. Field data suggests that SPE was able to reduce downstream speed by 1.1 to 3.8 mph for cars and by 0.8 to 5.3 mph for trucks. SPE also reduced speeding cars by 2.9% to 28.6% and speeding trucks by 4.2% to 48.3%. They compared SPE with the following strategies: speed feedback trailer, police car with lights on/off, and speed feedback trailer plus police car with lights on/off. The speed feedback trailer plus police vehicle with lights off strategy demonstrated some downstream speed reduction effects, which are less significant compared to the effects of the SPE. The effects of other strategies were found to be insignificant.

Miller et al. [*54*] conducted an empirical analysis of factors that may influence work zone speeds during night time. A regression analysis showed that presence of police enforcement, high percentage of semi-trucks, and high traffic volumes are positively associated with mean speed reductions in work zones. On the other hand, factors such as number of open lanes, original (before having the work zone) speed limit greater than 60 mph, distance between work zone speed limit sign and the first cone/barrel in the taper, and progression of time through the night are negatively associated with speed reductions. They also found that before midnight and queued vehicles helped to reduce the vehicle speed standard deviation. Additionally, more open lanes, more speed limit signs, high percentages of personal vehicles, and high traffic volumes tend to increase the speed standard deviation.

Debnath et al. [*55*] investigated factors that may influence work zone vehicle speeds by surveying drivers. The most influential factors ranked by drivers include: visible presence of workers, visible presence of police, and speed feedback trailers, which is consistently with many other studies reviewed in this research. The least effective methods are static signs, traffic cones, etc. The detailed survey questions are provided in Table 14 below. It is worth noting that compared to revealed preference surveys, stated preference survey results may not always accurately reflect respondents'/drivers' true behavior in work zones.

Table 14 Ranking of work zone speed reduction strategies [*55*]

Rank	Speed Control Method	Mean Rating	Stdev of Rating
1	Presence of workers on road	4.59	0.62
2	Visible police presence	4.51	0.87
3	Speed feedback displays	4.17	0.92
4	High visibility clothing for workers	4.04	0.89
5	Presence of workers behind barriers	4.00	0.92
6	Reduced speed limits	3.98	0.95
7	Flashing amber lights	3.96	0.93
8	Double demerits points for speeding	3.88	1.20
9	"Reduce Speed" signs	3.77	0.94
10	Increased fines for speeding in work zones	3.77	1.20
11	"Roadwork Speed Limits are Enforced" signs	3.59	1.10
12	Traffic cones	3.53	0.94

Cruzado and Donnell [*56*] studied the speed reduction effects of dynamic speed display signs (i.e., speed feedback trailers) in transition zones of two-lane rural highways (not work zones). The transition zones consist of a high-speed segment followed by a low-speed segment. From before-during-after observations, the dynamic speed display signs were able to reduce free-flow traffic speeds by 6.4 mph on average. However, once these signs are removed, they observed an average increase in speed by 6.6 mph.

Another study [*57*] also evaluated the effects of speed feedback trailers. They field tested some improved speed feedback trailers (e.g., increased message size, added flashing lights, multiple trailers) in two work zones. Regression results of the collected data indicate that increasing message size and adding flashing lights contributed to speed reductions and less speeding activities. The level of the impact depends on vehicle type and time of day (e.g., daytime and nighttime). The authors recommended using multiple speed feedback trailers to achieve further speed reductions.

Chen et al. [*58*] compared speed feedback trailers with law enforcements for speed control in work zones. The found that speed trailers had minor impacts on speed reduction during daytime, but more significant impacts on speed reduction and reducing speeding during nighttime. Although speed trailers appeared to be effective, the authors observed decreasing effects over time, which probably was due to drivers becoming familiar with this strategy. Law enforcements are effective during both daytime and nighttime, but are associated with high operating costs. The authors concluded that a combination of speed trailers and law enforcements may result in cost-effective work zone speed management.

In another study [*59*], four work zone speed management methods were compared based on field data: (1) a Uniformed Traffic Officer (UTO) and a police car with blue lights on during the entire time when a work zone is active; (2) targeted police enforcements when a work zone is active; (3) a Radar Speed Feedback Sign (RSFS) that posts the speed limit and the detected speeds; and (4) combination of UTO and RSFS. As shown in Figure 17 and Figure 18, other than the targeted police enforcement, the remaining three strategies were very effective in reducing both speeding and number of speeders. This conclusion in general is consistent with the findings in Chen et al. [*58*]. Given the high cost of having a UTO present all the time, a more cost-effective strategy could be the combination of targeted police enforcement and RSFS. Using the RSFS data, police officers can be strategically or dynamically deployed to different work zones.

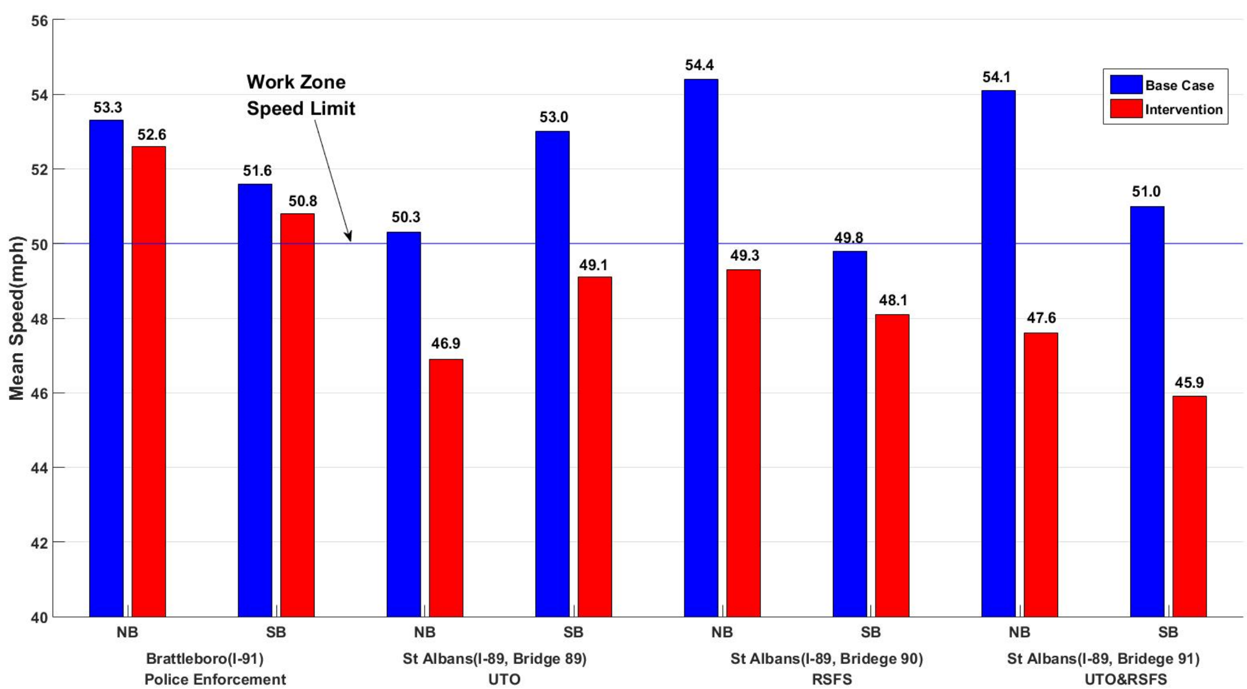


Figure 17 Mean speeds before and after the interventions by method [*59*]

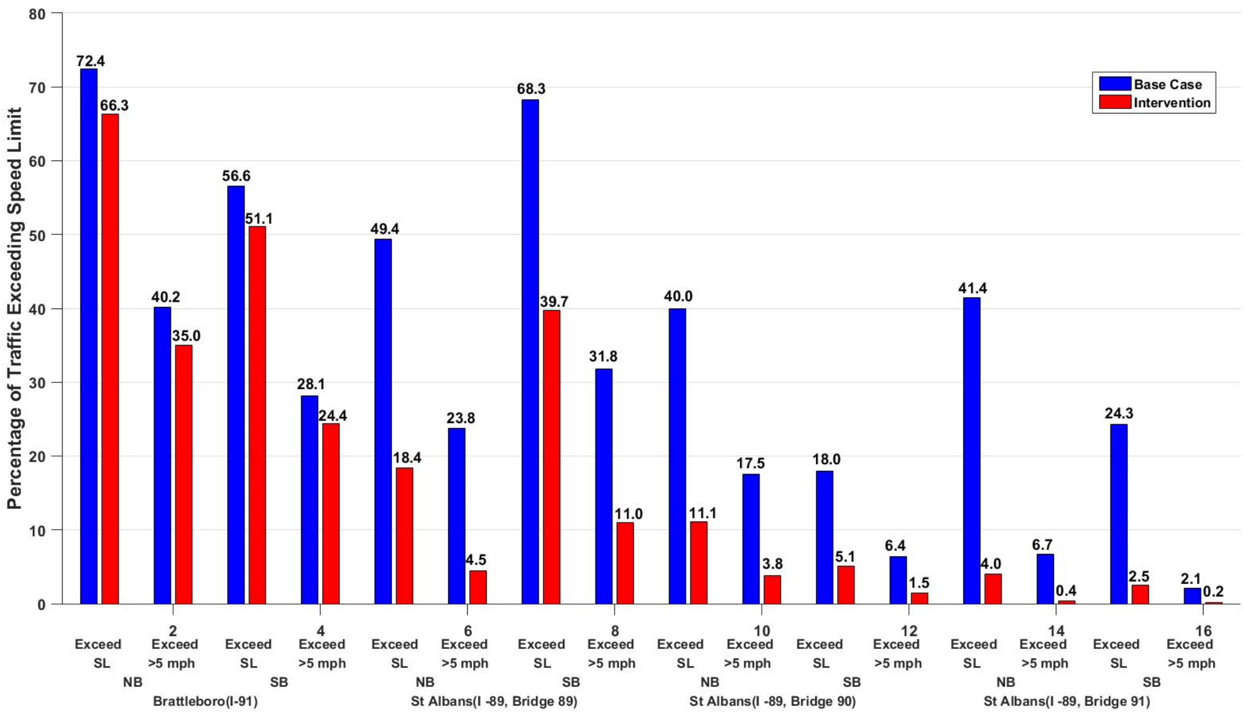


Figure 18 Percentage of traffic exceeding the speed limit by speed management methods [*59*]

Morris et al. [*60*] studied the impacts of four strategies on driver attention and speed: no control at all, police speed enforcement, SPE, and SPE + speed feedback trailer. They conducted driving simulations and concluded that overall SPE without speed trailer does not seems to significantly improve driver attention in work zones compared to other strategies. One exception is that drivers looked less frequently at secondary task display in the SPE + speed trailer case than other strategies when downstream of work zones. On the other hand, the authors found age to be a significant factor that influences driver attention and speed. Young and old drivers appeared to be more likely to exceed the speed limit and have varying responsiveness to different speed enforcements. Middle-aged drivers followed the speed control the best and consistently regardless of the type of speed enforcement.

Roberts and Smaglik [*61*] modified the speed feedback trailer by alternatively displaying vehicle speed and a monetary fine message. The addition of the monetary fine message did not have any significant impacts on the average travel speed. However, it was able to reduce the number of vehicles traveling at least 15 mph above the speed limit by 50%. Some other researchers [*62*] proposed to integrate CMS with radar speed detector. The integrated CMS system displays messages that are conditional on the detected speed.

Oregon [*63*] introduced SPE in 2007 on non-interstate highways. A study was conducted to investigate its safety impacts based on field implementation data. The authors found that during the SPE enforcement period, on average the percentage of speeding vehicles was reduced by around 24% at the speed data collection point. However, this reduction appeared to be strictly dependent on the SPE enforcement. The reduction effect disappeared after the SPE equipment was removed. Benekohal et al. [*64*] also found SPE to be effective in reducing speeds. They observed similar absence of speed reduction effects when the SPE is removed.

Allpress and Leland [*65*] conducted a field test of two strategies to reduce speeds from 100 to 50 km/h in a work zone shown in Figure 19. The two strategies are illustrated in Figure 20. The traffic cones are placed evenly in one case and unevenly (with decreasing intervals) in the other one. Both strategies were found to be very effective in reducing vehicle speed, particularly the uneven one. Also, both methods reduced the number of dangerous speeding (defined as traveling at least 20 km/h over the speed limit) by over 50%.

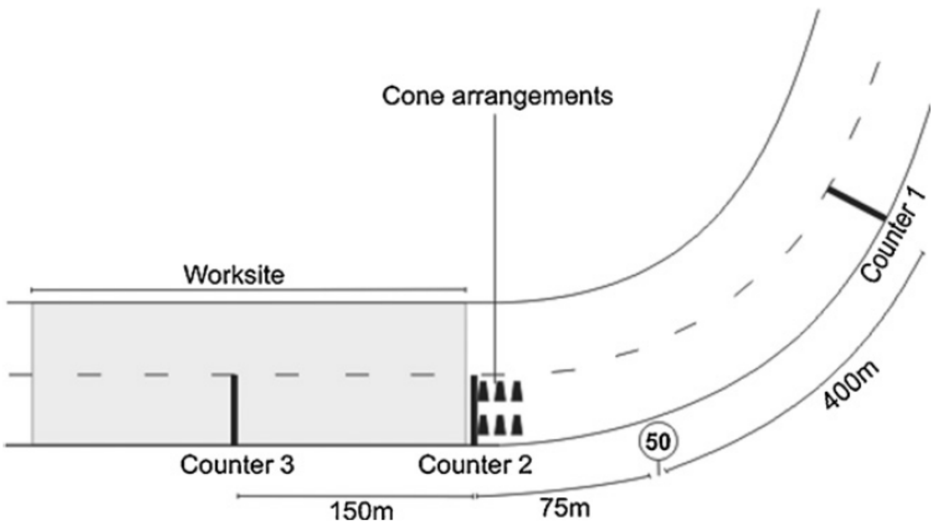


Figure 19 Work zone layout [*65*]

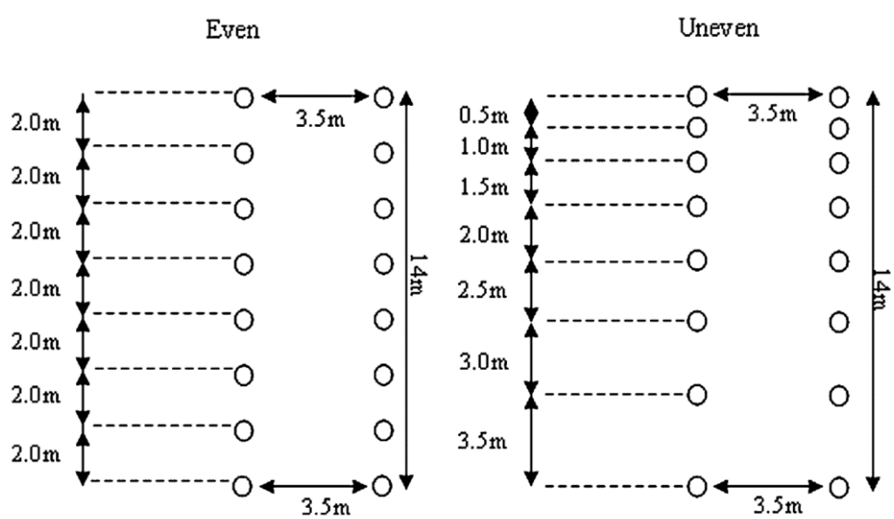


Figure 20 Cone layout plan [*65*]

Savolainen et al. [*66*] investigated the speed reduction impacts of removable rumble strips. Speed data was measured 5,500 ft and 600 ft upstream of work zones with and without temporary rumble strips. Speeds and percentages of speeding at 5,500 ft did not exhibit significant variations across from different types of work zones. Based on the speed data collected at 600 ft, the temporary rumble strips were able to reduce speed by more than 8 mph. The authors suggested that temporary rumble strips would be more effective when multiple sets of them are placed close to the work zone.

A study funded by the National Road Administrations of Norway, Sweden, The United Kingdom, Belgium/Flanders, Germany, and Ireland [*67*] reviewed work zone speed management strategies. The methods identified in their study include regulatory speed limit signs, speed monitoring displays, variable message signs, flaggers, rumble stripes, narrow lanes, optical speed bars, police enforcements, SPE, and drone/decoy radar. In their review, they found studies suggesting that narrow lanes (sometimes with tubular markers) can effectively reduce vehicle speeds [*68*,*69*]. However, some other researchers argued that narrow lanes may lead to driver discomfort and increase collision risk especially for large vehicles [*70*] (e.g., trucks).

Shaw et al. [*71*] provided a comprehensive review of work zone speed management strategies. Some of these strategies have not been mentioned previously, including speed feedback trailer that also shows speeding vehicles' license numbers, chicanes, tractor-trailer-type mobile barrier systems, gateway assemblies, optical speed bars, chevron pavement markings, sequential and synchronized warning lights, pilot vehicles, pace vehicles, and rolling closures.

Bham and Mohammadi [*72*] conducted a study that consists of an objective field evaluation and two subjective surveys regarding work zone speed management. The impacts of three scenarios are compared: lane closure, lane width reduction, and construction activity. It was found that construction activity reduced passenger car and truck speeds by 3.5 and 2.2 mph, respectively, compared to no construction. For all three methods, only the narrow lane (through adding tubular markers) scenario was able to keep the average speed under the posted speed limit. Narrow lane in combination of construction reduced the speeds of cars and trucks by 8.5 and 11.1 mph, respectively. For narrow lane without construction, the corresponding numbers were 4.0 and 8.1 mph, respectively. Also, the authors found a lower speed limit compliance rate when the speed limit was 60 mph rather than 50 mph.

The authors [*72*] also surveyed different state DOTs' work zone speed management practices and drivers. Based on the DOT survey, most respondents agreed that police patrol is very effective in reducing speed, while only 25% of them found regulatory signs to be effective. The driver survey results indicate that drivers tend to follow their own perceived safe speeds in the absence of police enforcements. Many respondents suggested that work zone speed limits should be set in accordance with the traffic conditions. When a work zone is congested, 92% of the surveyed car drivers and all truck drivers suggested a reduced speed limit is needed. On the other hand, 92% of car drivers and 73% of truck drivers would prefer a relatively high posted speed limit during light traffic conditions. Over 90% of drivers reported that they would reduce speeds when there are active construction activities. The subjective survey results well support the objective evaluation findings.

3.1.2. TTCPs for Merge Control

Tarko et al. [*73*] proposed an Indiana Merge Lane System (IMLS), which uses a sequence of "*DO NOT PASS*" signs that can be activated /deactivated depending on traffic to create a no passing zone of varying length. The purpose of the no passing zone is to encourage drivers to switch to the open lane(s) upstream of the end of the dynamically changing queue to improve safety and efficiency. The authors conducted both simulation and field studies of the proposed IMLS. The results show that IMLS can significantly reduce the number of late merges, which are often dangerous, and the travel time of the open lane. However, the authors noticed a slight reduction in capacity at the merge point during the field observations, which requires further research and field tests.

McCoy et al. [*74*] compared IMLS, Late Merge (LM), and Nevada Department of Road (NDOR) merge based on field data. They concluded that LM and ILMS generate higher capacities and less numbers of traffic conflicts than NDOR. The authors also interviewed drivers regarding their opinions about different merge control methods. Some truck drivers were skeptical about the level of compliance with the "*DO NOT PASS*" signs used in ILMS. They suggested that law enforcements are needed to ensure the successful implementation of ILMS. As for LM, some truck drivers complained about vehicles in the closed lane cutting into the open lane in front of them. Other truck drivers challenged whether it is reasonable to have a single merge point. Finally, the authors recommended that LM should be made traffic responsive and additional research is needed to identify threshold values (e.g., flow, density) to turn LM on and off. McCoy and Pesti [*75*] later proposed a Dynamic Late Merge (DLM) control concept. Kang et al. [*76*] compared NDOR (or conventional merge without control) control with DLM based on field data. The results suggest that DLM outperformed the conventional merge control in terms of throughput. However, they also acknowledged that DLM without proper traffic warning signs may generate excessive traffic conflicts.

Table 15 Thresholds used in DLM methods [*78*]

State	Maryland (Kang et al. [*76*])		Minnesota (Taavola et al. [*77*])		Kansas (Meyer [*79*])	
Work Zone type	2 lanes reduced to 1 lane		2 lanes reduced to 1 lane		3 lanes reduced to 1 lane	
Parameter	Occupancy		Speed and volume		Speed	
Threshold	Activation	Deactivation	Activation	Deactivation	Activation	Deactivation
	Any sensor> 15%	All sensors < 5%	Sensor < 30 mph	Based on volume but the criteria are unclear	Upstream lane 2 < 35 mph and upstream all lanes < 46 mph	Upstream lane 2 > 40 mph and upstream all lanes > 51 mph
Evaluation Method	Field Test		Field Test		Simulation	

Kang and Chang [*78*] proposed a Lane-Based Dynamic Merge (LBDM). It is different from the traditional Dynamic Late Merge (DLM) that considers a static threshold value (see examples in Table 15) to switch between early merge and late merge. The authors argued that DLM based on simple and static thresholds does not perform well under dynamically changing traffic conditions. In their paper, a lane-based algorithm that takes into account speed, flow, and capacity was proposed to determine when to use early merge and late merge. Simulation results suggest that the LBDM outperformed DLM in terms of throughput. However, it generated higher speed variations. Therefore, the authors recommended that LBDM be used in conjunction with VSL.

Meyer [*79*] conducted a field study to compare early merge and late merge. He concluded that late merge did not show significant improvements over the baseline early merge control. An overlapped speed scheme is used to switch between early and late merges in this study. When the average speed goes down below 46.6 mph, the system is switched from early merge to late merge. When the average speed increases above 51.3 mph, late merge is replaced by early merge. The author concluded that such an overlapped strategy can avoid oscillation between early merge and late merge. He also recommended that density be used instead of speed as the threshold parameter.

Shrock [*80*] compared work zones with and without an upstream "*STATE LAW MERGE NOW*" warning sign based on field tests. Two measures of effectiveness were considered in this study, which are percentage of vehicles that remain in the closed lane and number of conflicts in the merge area. It was found that the additional warning sign did not affect the percentage of vehicles that remained in the closed lane. For the right-lane closure case, the author found that the sign significantly reduced the number of conflicts in the merge area.

Ramadan and Sisiopiku [*81*] investigated four work zone merge strategies under peak and off-peak traffic conditions: late merge, early merge, mainline merge metering (i.e., adding a meter to the close lane), and temporary ramp metering. They found that the mainline merge metering generated the least number of lane changes, higher average speeds, and lower traffic densities under peak traffic conditions. On the other hand, it resulted in the highest CO emissions. Under off-peak conditions, late merge control appeared to be the best control strategy in terms of all measures of effectiveness except for density.

Tarko and Venugopal [*82*] evaluated the safety and capacity performance of the Indiana Lane Merge System (ILMS), which is a dynamic work zone merge control that encourages drivers to merge upstream of the lane closure point or end of the queue. Spreadsheet tools were developed to analyze the safety and capacity performance of ILMS under various conditions. They concluded that ILMS should be used under low to medium traffic conditions (AADT less than 50,000 vehicles/day for a 2-lane highway with 1 lane closed).

Late merge encourages drivers to stay in their lanes and take turns to merge when approaching the lane closure point. Based on late merge, Idewu and Wolshon [*83*] proposed a joint merge concept and tested it in the field. Different from the traditional late merge, joint merge includes a two-sided taper at the merge point so that vehicles in both approaching lanes have to change lane. It assigns the same priority to both approaching lanes (as opposed to a higher priority to the open lane in late merge). The joint merge and conventional merge (i.e., no control) were tested using the same work zone. The results show that the merge speeds and throughputs of both control strategies were about the same with the input volume ranging from 600 to 1,200 vehicles per hour. The authors did observe more cautious merge maneuvers and balanced lane volumes with the joint merge.

Weng et al. [*84*] applied the classification and regression tree to model vehicle merge behaviors at work zones. They found that distance to the work zone, time to collision with the lead vehicle, and current speed may affect drivers' merge decisions. This study did not specifically address merge strategies such as early merge or late merge. However, the findings may be useful for developing more accurate lane-changing models in work zone merge areas.

Tympakianaki et al. [*85*] proposed an interesting but controversial real-time signalized merge control on highway mainline to maximize work zone throughput and reduce delay. They investigated the impacts of the traffic signal location on merge control efficiency, and proposed a learning/adaptive fine-tuning (AFT) algorithm to calibrate the control parameters. Microscopic simulations were used to demonstrate the benefits of this new control method. As shown in Figure 21 below, traffic signals can be installed on all lanes or selected lanes (e.g., excluding the reserved HOV lane).

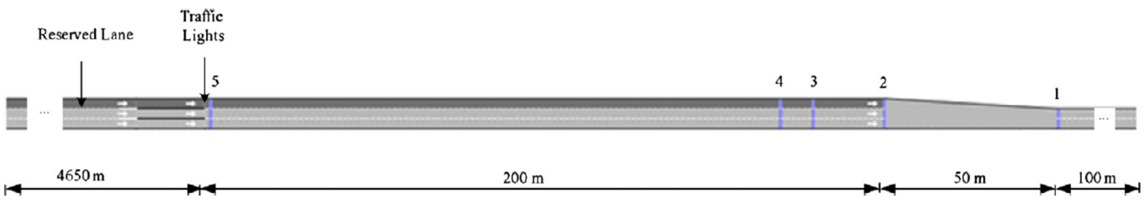


Figure 21 Signalized control for highway work zones [*85*]

Kurker et al. [*86*] conducted VISSIM simulations of early merge, late merge, and signalized merge strategies. They also analyzed the safety performances of these strategies using SSAM and concluded that early merge is suitable for low traffic demand, late merge is better for low to moderate demand, and signalized merge is preferred for high traffic demand. They also conducted field observations at a Houston site with early merge signs. For uncongested traffic conditions, most drivers complied with the early merge sign well. However, more drivers were found to ignore the early merge sign when the traffic became congested.

Wei et al. [*87*] integrated DLM with the ramp meter concept and named it as Dynamic Merge Metering Traffic Control System (DMM-Tracs). A portable traffic signal controller is added to the lane(s) to be closed (not to those open lanes as in [*85*]). The signal heads are controlled using either a fixed cycle or ramp meter mode (i.e., 1 or 2 vehicles per green interval). Based on upstream traffic conditions, the signal control parameters are dynamically adjusted. Based on VISSIM simulations, the authors recommended that for 2-lane highway reduced to 1 lane case, the threshold value for turning on the DMM-Tracs is 1,600 vph. For 3-lane highway reduced to 2 lanes case, the corresponding threshold is 4,750 vph. Although this DMM-Tracs strategy seems interesting, a potential issue is that the queue in the closed lane will cause congestion upstream. If the end of the queue is considered as a lane drop point, this strategy may be equivalent to simply shifting the work zone upstream.

Pesti et al. [*88*] also conducted VISSIM simulations to evaluate the performance of DLM. They mentioned that early merge in general works well during light traffic conditions. When traffic gets congested, queues can form easily. In this case, enforcing early merge may cause drivers in both open lane(s) and closed lane(s) to be upset and behave aggressively. Drivers in the closed lane(s) who have passed the end of the queue will find it difficult to merge into the open lane(s). This often happens since some drivers may ignore the early merge sign. Also, the queue may frequently extend beyond the early merge sign. On the other hand, drivers in the open lane(s) will get upset when they see vehicles in the closed lane(s) pass them and try to merge downstream. The authors recommended speed threshold values for switching between early and late merges (see Table 16). However, no details were provided in terms of how these values were obtained. In a separate study based on field observations, Pesti et al. [*89*] found late merge to be more beneficial than the NDOR merge in terms of safety, efficiency, and throughput. The field data suggested that the full potential of late merge were not achieved due to noncompliance of the late merge signs by some drivers. Hallmark [*90*] studied driver behaviors that may affect work zone traffic operations and safety based on data collected from a freeway over a 6-day period. They observed 30 queue jumpings and 51 lane straddling, which further led to dangerous behaviors such as forced merge, late merge, and late forced merge. These behaviors are less likely to occur during late merge compared to early merge.

Table 16 Thresholds for early merge and late merge [*88*]

Speed Thresholds*	Early Merge	Late Merge
To Enter	>=40 mph	<= 35 mph
To Exit	< 35 mph	> 40 mph

* speed thresholds for a 2-lane highway reduced to 1 lane scenario with a 65 mph posted speed limit

Harb et al. [*91*] field tested two Simplified Dynamic Lane Merging Systems (SDLMS) and compared them with conventional work zone merge control. They found early SDLMS was able to generate higher throughput values than conventional merge and late merge, which is different from what Pesti et al. [*89*] concluded. The SDLMS control is turned on if the average speed over a 2-minute time interval is below 50 mph and will remain on for at least 5 minutes. When testing the early SDLMS, the PCMS displays "*DO NOT PASS*" followed by "*MERGE HERE*". While for the late SDLMS, the PCMS displays "*STAY IN YOUR LANE*" followed by "*MERGE AHEAD*". The throughputs observed from two work zones on I-95 are summarized in Table 17. The results seem to suggest that late SDLMS does not perform well under moderate traffic volumes.

Table 17 Summary of throughput results (vehicle/hour) [*91*]

Control	Mean	Standard Deviation	Min	Max
Conventional	881	120	624	1092
Early SDLMS	970	135	696	1272
Late SDLMS	896	111	696	1092

Since merge behavior plays a critical role in work zone mobility and safety, Long et al. [*92*] conducted a driving simulation study to investigate how drivers respond to different work zone signage configurations. They compared MUTCD merge signs with Missouri alternate merge signs. They simulated both right and left lane closures. Based on the data collected from 75 driving simulation participants, no significant differences were found between the MUTCD and Missouri merge signs.

Beacher et al. [*93*] conducted a systematic review of static early, dynamic early, static late (see Figure 23), and dynamic late merges. A typical example of dynamic early merge is the Indiana Lane Merge System (ILMS) as show in Figure 22, which uses "*DO NOT PASS WHEN FLASHING*" signs (equipped with queue detectors) and prohibits queue jumping. When queue is detected next to a sign, the flashing lights on the adjacent upstream sign will be activated to prohibit passing and encourage vehicles to merge. The ILMS has also been referred to as the Michigan Lane Merge Traffic Control System (LMTCS) by some researchers from the Wayne State University [*94*].

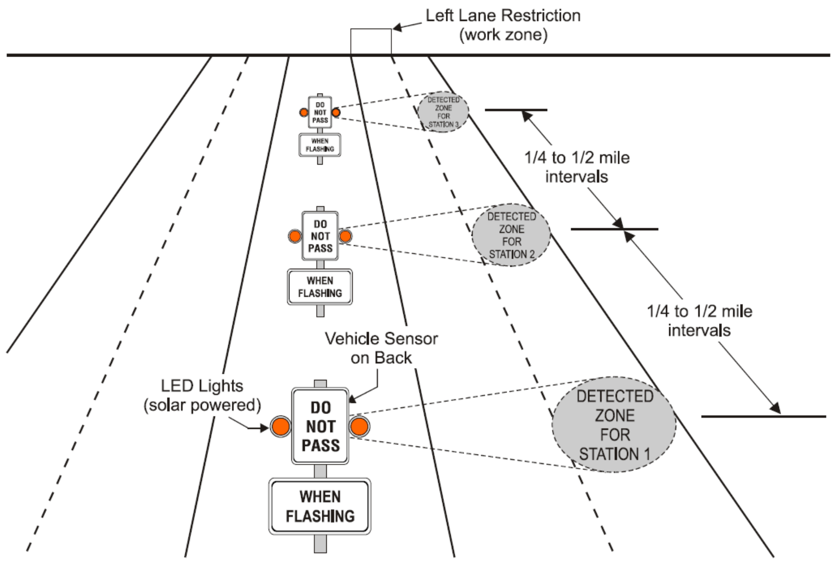


Figure 22 Indiana Lane Merge System (ILMS) [*93*]

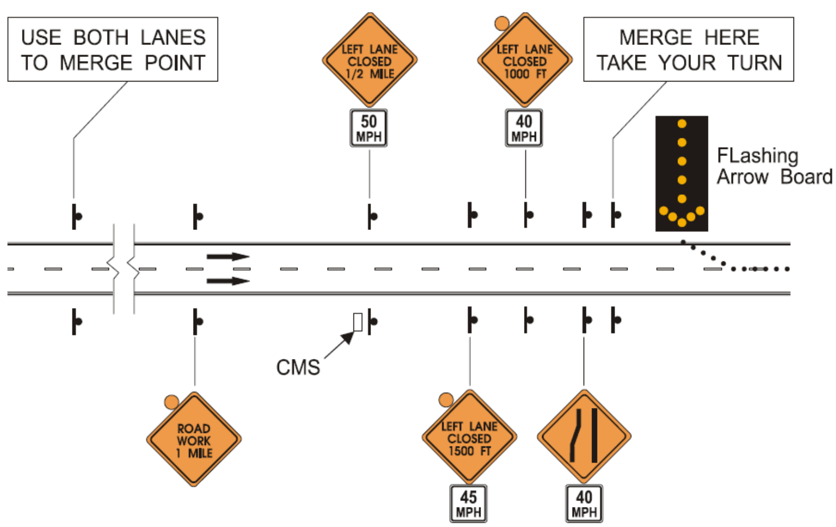


Figure 23 PennDOT late merge concept [*93*]

Beacher et al. [*93*] found mixed conclusions about the four merge methods in their review: The Wayne State study [*94*] found that ILMS was able to increase speed and decrease delay and aggressive driving behaviors. It did not generate any significant capacity benefits. A Nebraska study [*74*] found ILMS to generate less forced merges and slightly improved capacity (from 1,460 to 1,540 vphpl) than the standard MUTCD merge. A Purdue University study [*82*] suggested that ILMS decreased capacity by 5%, which was attributed to drivers' unfamiliarity with ILMS. It is important to note that the data in these studies were collected under different conditions. Beacher et al. [*93*] also mentioned that these studies were conducted at different congestion levels. The above review findings are further summarized in Table 18 below.

Table 18 Summary of work zone merge control performances [*93*]

MOE	MUTCD Merge	Late Merge		Early Merge	
		Static	Dynamic	Static	Dynamic
Capacity (pcph)	1,460 [*74*] 1,320 [*82*]	1,730 [*74*]	1,820 [*75*]	--	Conflicting results: Decreased by 5% ([*82*]) Increased to 1,540 ([*74*])
Forced Merges	20/hour [*74*]	Decreased 75% [*74*]	--	Decreased [*95*]	1/day [*74*]
Lane Distribution	--	Volume increased 30% in closed lane [*74*]	--	Volume increased 12.4% in open lane [*95*]	Volume increased 20% in open lane [*74*]
Mean Speed (vs. MUTCD)	--	Decreased 7 mph (uncongested) and 32 mph (congested) [*74*]	--	Decreased 16.1 mph (uncongested) [*95*]	Decreased 2 mph (uncongested) [*74*]
Queue Length	--	Decreased 50% [*74*] Decreased 23% [*96*]	--	--	--

It is worth noting that many studies on merge strategies are based on microscopic simulation, mostly VISSIM simulation. Although simulation plays an important role in evaluating merge control methods. Very few studies investigated simulation model development and calibration specifically for work zones. Nemeth and Rouphail [*97*] developed a microscopic model for simulating freeway lane closure. When making merge decisions, this model can take into consideration the information from traffic control devices, personal preference for early/late merge (obtained from a driver survey), and the availability of safe gaps. It is also able to consider the blocking of traffic signs by large vehicles. Although the authors concluded that satisfactory results were obtained from the model, it was not validated using detailed field data.

3.2. Metrics for Evaluating Work Zone TTCPs

To quantify how work zones impact travelers, residents, businesses and workers, many metrics (performance measures) have been proposed. Some metrics describe the impacts of a specific work zone (project-level metrics), whereas others measure the impacts of a set of work zones (agency program-level metrics) [*98*]. These work zone performance metrics can be broadly categorized into safety and mobility & operational measures. Commonly used work zone safety performance metrics include [*99*]:

- Crash frequency (i.e., total, by injury severity)
- Percentages of crashes in various categories (e.g., severities, types of collisions, and contributing factors)
- Crash rate (i.e., per million-vehicle-miles)
- Crash costs

- Service patrol dispatch frequency
- Fire department dispatch frequency
- Speeds
- Speeding citation frequency
- Inspection scores
- Worker fatalities and injuries
- Work zone intrusion frequency

Popular work zone mobility & operational performance metrics include [*99*]:

- Delay per vehicle
- Queue length
- Duration of queue
- Volume/capacity ratio
- Level-of-service
- Volume (throughput)
- % time at free-flow speed
- % work zones meeting expectations for traffic flow
- User complaints

In this study, diving simulation and microscopic traffic simulation are used to evaluate work zone TTCPs. Since most of the above-referenced safe metrics can only be obtained from field observations, the following four metrics are adopted for safety performance evaluation: speed, speed variation, number of conflicts by type, and average Time to Collision (TTC). Among them speed and speed variations are used in the driving simulation result analysis, and number of conflicts and TTC are used in the microscopic traffic simulation result analysis.

As for mobility performance, microscopic traffic simulation tools can generate very detailed outputs for calculating most of the above-referenced mobility metrics. Including all these metrics can make the result analysis too overwhelming. Therefore, only the following key metrics are used for work zone mobility performance evaluation in Chapter 6: delay per vehicle, queue length, and volume/throughput.

3.3. Discussion and Recommendations

3.3.1. Summary of Speed Control TTCPs

Based on the review, it is found that:

- Various forms of law enforcements [*37,38,55,72*] are probably the most effective speed control strategies. However, they are usually expensive to implement;
- Flaggers are almost as effective as law enforcements [*37,38*]. This strategy is relatively less expensive and easier to implement than law enforcements. Some researchers [*55,72*] found that active construction activities and presence of workers will encourage drivers to

reduce speeds, which supports the argument that flaggers are effective in reducing work zone speed;

- Automated speed photo-radar enforcement (SPE) [*40,53,63,64*] and dynamic speed display [*55,56,57,59*] are considered as effective as law enforcements. Some researchers [*57*] recommended using multiple dynamic speed display signs in a work zone. Chen et al. [*58*] found that the effects of dynamic speed display may decrease over time due to drivers being familiar with it. They recommended that this strategy be used in conjunction with law enforcements. Morris et al [*60*] found that SPE with speed display is more effective than SPE alone in improving driver attention;
- Field tests of temporary rumble strips [*44,66*] show that they are effective in reducing vehicle speeds in work zones. Savolainen et al. [*66*] recommended that multiple sets of rumble strips should be installed close to the beginning of a work zone to increase their effectiveness. However, other researchers concluded that they are ineffective [*37*];
- Mixed results [*47,51*] are reported regarding the speed reduction impacts of VSL. The effects of VSL on speed reduction depends on many factors such as locations of VSL signs and algorithms to determine the optimal speed limits [*50*];
- Mixed speed reduction impacts of PCMS [*37,45*] are reported;
- Static traffic signs are found to be ineffective in reducing speed [*37,55,72*];
- Mixed results about traffic cones are reported [*55,65*]; and
- Narrow lanes are found to be less effective than law enforcements and flaggers by some researchers [*37*]. Others concluded that narrow lanes may lead to driver discomfort and increase collision risk especially for large vehicles [*70*]. However, some studies found narrow lanes [*68,69,72*] can effectively reduce speeds in work zones.

3.3.2. Summary of Merge Control TTCPs

Four major categories of merge control have been identified, which are: (1) no control (also referred to as NDOR control, (2) early merge (including static and dynamic), (3) late merge (including static and dynamic), and (4) signalized control (for both the closed lane only and for all lanes). The pros and cons of these methods are summarized below:

- Early merge is found to be able to reduce risky late merge behaviors and improve the travel speed in the open lane [*73*]. There is no general consensus regarding its impacts on capacity [*73,74,82,94*]. It is recommended that adequate law enforcements should be provided to ensure drivers follow the "*DO NOT PASS*" sign. Kurker et al. [*86*] noted that the compliance rate of early merge drops as congestion builds up. This may subsequently affect the mobility and safety performance of early merge;
- Meyer [*79*] found that late merge does not necessarily provide higher capacity than early merge. He recommended a set of overlapped speed threshold values to switch between early and late merges to avoid oscillation. This overlapped strategy is also considered by Kang et al. [*76*];
- It is generally agreed that early merge performs better under light traffic conditions [*82,86,88*], late merge is better for moderate to high traffic conditions, and signalized merge is better for oversaturated conditions. Ramadan and Sisiopiku [*81*] found late merge to outperform early merge under off-peak conditions as well based on simulations.

In another field study, Harb et al [*91*] found early merge to generate higher throughputs than late merge under uncongested conditions. To fully benefit from the potential of late merge, Pesti et al. [*89*] suggested that efforts should be taken to familiarize drivers of the "*TAKE TURN*" to merge rule;

- If early merge is not properly set up/operated either due to inadequate sign coverage/law enforcement, low compliance rate, or queue spills back beyond no passing signs, aggressive driving behaviors such as queue jumping, lane straddling, forced merge, and late merge may happen, which are extremely dangerous. Late merge can better address these issues along the approach to the merge point. However, at the merge point the take-turn-to-merge rule may create both risky short gaps (due to limited merge distance) and inefficient large gaps (due to the slow movement/acceleration of heavy vehicles) that affect safety and throughput; and
- Two forms of signalized merge have been proposed. The first one is to add traffic signals to both closed and open lanes [*85*] and the other one only adds a signal to the closed lane [*87*]. Although signalized control seems to be able to well handle high traffic volumes during congested conditions, both methods may generate safety risk and confusion among drivers and have not been widely implemented in practice;

4. ANALYSIS OF NATURALISTIC DRIVING STUDY (NDS) AND SMART WORK ZONE (SWZ) DATA

This chapter presents the analysis results of the Naturalistic Driving Study (NDS) data and the Smart Work Zone (SWZ) data. The NDS data analysis aims to understand driver behavior immediately prior to work zone crash and near-crash events, identify significant crash contributing factors, gain insights into driver behavior in response to speed control strategies, and potentially use the results for calibrating microscopic traffic simulation tools. The SWZ data analysis is solely to identify useful information for calibrating microscopic traffic simulation tools.

4.1. Analysis of Naturalistic Driving Study (NDS) Data

4.1.1. Background

The NDS was funded through the Transportation Research Board (TRB) Strategic Highway Research Program 2 (SHRP 2). This study installed radar, GPS, and video cameras in over 3,400 participants' vehicles to collect behavioral data continuously for more than one year in a naturalistic setting. It was designed specifically to collect data to understand driver performance and behavior immediately prior to crash and near-crash events. The collected data includes:

- Driver characteristics such as vision test results, demographic information, and physical and psychological characteristics;
- Lighting, weather, roadway surface condition, traffic control, and driver eye glance;
- Video data showing forward and rear roadway views, driver views, snapshots of passenger seats. From the video data, work zone and variable message sign data may be obtained;
- Vehicle characteristics (e.g., year, make, and model), vehicle lateral and longitudinal accelerations, gas pedal position, lane offset, turn signal use, brake application, distances to front vehicles, and distance changing rates; and
- Horizontal curvature (e.g., radius and length), grade and super elevation, lane width and type, shoulder type, intersection location and control, and locations of speed limit signs, median, and rumble strip.

The NDS data covers various weather, time, roadway, driver, and vehicle conditions. This massive multiyear data collection project was completed in 2013 and generated 5.4 million trip files in six states (Indiana, Pennsylvania, Florida, New York, North Carolina, and Washington). Some of these states are similar to New England in terms of weather, topography, and driver population. Based on this data set, this research aims to answer the following questions:

- How do drivers react to traffic control devices, advance warning signs, pavement markings, speed limit signs, radar speed signs, variable message signs, and presence of police officers or highway patrol vehicles? An advantage of using the NDS data is that one can observe driver behavior changes over time and distance. For example, drivers may slow down when they see a radar speed sign showing that "Speed limit is 45 mph and your speed is 60 mph". However, they may accelerate to 60 mph soon after they pass the sign. This information is important for determining the best locations for radar speed signs;

- What are the major causes of driver distraction in work zones? The answer to this question is particularly important, since driver inattention/distraction was the most important driver offense in work zones based on the 2010 MaineDOT data;
- In cases of lane closure, when do drivers change lanes and what factors may affect this decision. The answer to this question can help us understand the "failure to yield right of way" offense [9] in work zones;
- What control devices and signs can help maintain a safe distance between vehicles? and
- How do factors such as fog, sun glare, pavement conditions, number of lanes, lane width, and concrete barriers vs. traffic cones affect driver lateral and longitudinal behavior?

4.1.2. Description of NDS Data

This research considers crash and near-crash events/trips in work (construction) zones on Interstate/Bypass/Divided Highway with no traffic signals. These interstate and divided highways all had 1-2 open lanes in each direction in the work activity area. These work zones involved either lane or shoulder closure. In addition to crash and near-crash events, this research also analyzes additional "Balanced-Sample Baseline" and "Additional Baseline" epochs, given that these epochs also occurred in work (construction) zones that meet the above criteria. From the qualified work zones, the following time series data has been requested:

- Forward camera video
- Front RADAR data (longitudinal and lateral range and relative speed, object ID) for all objects identified by the RADAR
- Subject ID and vehicle ID
- Accelerations of both x-axis and y-axis
- Lane position offset
- Vehicle speed (network and GPS)
- Time stamp
- Seatbelt usage
- Lane width
- All head related attributes
- ABS activation, electronic stability control, and traction control
- Pedal (both brake and acceleration position)
- Steering wheel position
- Vehicle characteristics (i.e., make, model, year)
- Driver demographics (i.e., age, gender, education, income, and visual and cognitive tests)

For each crash/near-crash event, the above attributes are obtained. For non-crash and near-crash epochs/trips, time series data one mile before the work zone and 0.25 miles after the work zone is requested. For epochs involving crashes, time series data one mile before the work zone until where the event occurred is requested. Based on the requested NDS data, driver behavior and crash characteristics have been analyzed and are presented in Sections 4.1.3 and 4.1.4.

4.1.3. Driver Behavior Data Analysis

The initial plan of this research includes analyzing driver behavior in response to TTCPs using the NDS data. A review of the received NDS videos suggests that the contents of roadside signs (e.g., static signs, PCMS) are barely legible, making it difficult to perform the intended driver behavior analysis. Another problem is that there are inadequate observations from the same work zone (i.e., with the same or similar TTCP settings). Since almost every trip has a different TTCP set up, it is difficult to establish meaningful relationships between driver behavior and work zone traffic control elements. Nevertheless, the research team did try to analyze the driver speed and acceleration behavior. The results however did not lead to definite conclusions.

4.1.4. Crash Data Analysis

This section focuses on analyzing driver behavior immediately prior to work zone crash and near-crash events, and identifying significant crash contributing factors. As shown in Table 19, the entire NDS data set includes 7 crashes and 28 near crashes in work zones. In addition to crashes and near crashes, 253 regular trips from the same set of work zones are also obtained.

Table 19 Summary of requested NDS crash data

Event Type	Count	Percent
Crash	7	2%
Near-Crash	28	10%
Additional Baseline	96	33%
Balanced-Sample Baseline	157	55%
Total	288	100%

<u>*Driver Behavior*</u>

Table 20 summarizes how drivers behaved before the crash and near-crash events occurred. Many people may think speeding is the most important contributor to work zone crashes. However, as the data in Table 20 suggests, the main causes for near-crash events were distracted driving, fatigue driving and other unsafe maneuvers. For crash events, the main reasons were distracted driving and speeding. The findings from the NDS data is supported by a study conducted by the Maine Department of Transportation (MaineDOT) [*9*], which suggests that the top four risk factors for work zone related crashes in Maine during 2010 were:

- Driver inattention/distraction (183 crashes)
- Following too closely (89 crashes)
- Illegal and unsafe speed (58 crashes)

- Failure to yield right of way (50 crashes)

Table 20 Summary of driver behavior prior to crash/near-crash

Driver Behavior	Near-crash		Crash	
	Count	Percent	Count	Percent
Aggressive driving, specific, directed menacing actions	1	4%	--	--
Apparent unfamiliarity with roadway	1	4%	1	14%
Cutting in, too close behind other vehicle	1	4%	--	--
Distracted	**5**	**18%**	**2**	**29%**
Drowsy, sleepy, asleep, fatigued	**2**	**7%**	--	--
Exceeded safe speed but not speed limit	1	4%	--	--
Exceeded speed limit	1	4%	**2**	**29%**
None	**13**	**46%**	1	14%
Passing on right	1	4%	--	--
Speeding or other unsafe actions in work zone	**2**	**7%**	1	14%

Different from the Maine data set, the NDS data also suggests that fatigue driving was a major contributor to near crashes. Another interesting finding from the NDS data is that 46% of the drivers' behavior was "*None*" prior to a near-crash event, meaning the incident was caused by other vehicles, not the subject vehicle. These near crashes are singled out and further analyzed in Table 21. It can be seen that all these near-crash events were caused by either slow-moving traffic/sudden slowdown of lead vehicle or unsafe merging maneuver of vehicle in adjacent lane.

The analysis of crash and near-crash events suggests that efforts to improve work zone safety should focus on the following topics: (1) generating smooth traffic with similar speeds and avoiding stop-and-go situations; (2) adopting strategies to eliminate driver distraction; and (3) taking proper control actions to ensure that vehicles merge efficiently and in an orderly manner. Among them, topic (3) is also strongly related to work zone mobility. In this research, topics (1) and (2) are addressed in Chapter 5 by utilizing a VR driving simulator, and topic (3) is addressed in Chapter 6 based on VISSIM microscopic traffic simulation.

Incident Type and Nature

Table 22 and Table 23 summarize the natures and types of crash and near-crash events, respectively. As can be seen in Table 22, the collision type distributions for crashes and near crashes are clearly different. Most crash events are single-vehicle conflicts, while most near crashes are either conflicts with lead vehicles or with vehicles in adjacent lanes. Since there are only 7 crashes but 28 near crashes, the collision type distribution for near-crash events might be more representative of work zone crashes. In terms of incident type (see Table 23), there are three main types of collisions/near collisions: rear-end, road departure, and sideswipe. This suggests that:

Table 21 Summary of near-crash events with "None" driver behavior

ID	Event Nature	Pre-Incident Maneuver	Narrative
1	Conflict with a lead vehicle	Going straight, constant speed	Driver distraction and slow traffic ahead
2	Conflict with vehicle in adjacent lane	Changing lanes	Unsafe merge of vehicle in adjacent lane
3	Conflict with a lead vehicle	Going straight, constant speed	Driver distraction and slow traffic ahead
4	Conflict with vehicle in adjacent lane	Going straight, constant speed	Unsafe merge of vehicle in adjacent lane (which moved in front of the subject vehicle at a slower speed)
5	Conflict with a lead vehicle	Going straight, constant speed	Rapid deceleration of lead vehicle
6	Conflict with vehicle in adjacent lane	Going straight, accelerating	Unsafe merge of vehicle in adjacent lane
7	Conflict with vehicle in adjacent lane	Going straight, accelerating	Unsafe merge of vehicle in adjacent lane
8	Conflict with a lead vehicle	Changing lanes	Sudden and rapid deceleration of lead vehicle
9	Conflict with vehicle in adjacent lane	Going straight, constant speed	Unsafe merge of vehicle in adjacent lane
10	Conflict with a lead vehicle	Decelerating in traffic lane	Rapid deceleration of lead vehicle and slow traffic ahead
11	Conflict with a lead vehicle	Going straight, constant speed	Lead vehicle slowed down when passing a parked construction vehicle. The subject vehicle did not expect the deceleration.
12	Conflict with a lead vehicle	Going straight, accelerating	stop and go traffic and slow reaction of the subject vehicle
13	Conflict with merging vehicle	Merging	Slow traffic ahead

- It is important to provide an adequate lane width in work zones when possible. In this way, if drivers make a mistake, they will still have chances to correct it;
- It is important for drivers to exercise extreme caution in merge and diverge areas, and avoid last-minute merge maneuvers. Clear traffic signs should be set up at proper locations to give drivers sufficient time to digest the guidance information. This is particularly important during nighttime work zone activities; and
- Compared to speeding, sudden deceleration (due to stop-and-go traffic or merging vehicle) seems to be a more dangerous crash contributing factor, particularly to rear-end crashes. Based on the descriptions of crash and near-crash events in the NDS data set, the following strategies may be considered to address the rear-end crash risk: (1) using proper traffic signs and control devices (e.g., radar speed sign) to alert drivers and prevent distracted driving from happening; and (2) providing dynamic merge guidance (e.g., late merge, early merge) based on real-time traffic to prevent last-minute risky merge maneuvers.

Table 22 Summary of incident nature

Crash	Count	Percent	Near Crash	Count	Percent
Conflict with a lead vehicle	1	14%	Conflict with a following vehicle	1	4%
Conflict with obstacle/object in roadway	2	29%	**Conflict with a lead vehicle**	**17**	**61%**
Conflict with vehicle in adjacent lane	1	14%	Conflict with merging vehicle	2	7%
Single vehicle conflict	**3**	**43%**	Conflict with obstacle/object in roadway	1	4%
--	--	--	**Conflict with vehicle in adjacent lane**	**7**	**25%**

Table 23 Summary of incident type

Crash	Count	Percent	Near Crash	Count	Percent
Other	2	29%	Other	1	4%
Rear-end, striking	1	14%	Rear-end, striking	23	82%
Road departure (left or right)	3	43%	Rear-end, struck	1	4%
Sideswipe, same direction (left or right)	1	14%	Sideswipe, same direction (left or right)	3	11%

Incident Location

The NDS data in Table 24 suggests that overall about one third of the crashes/near crashes occurred in areas related to work zones, while the remaining of them occurred directly in work zones.

Table 24 Summary of incident location

Location	Crash		Near Crash		All	
	Count	Percent	Count	Percent	Count	Percent
Construction Zone (occurred in zone)	4	57%	20	71%	24	69%
Construction zone-related (occurred in approach or otherwise related to zone)	3	43%	8	29%	11	31%

Traffic Density

Table 25 and Table 26 show the traffic densities for the crash, near-crash, and baseline events. As shown in Table 25, most of the crash and near-crash events occurred when the traffic was in Level of Service (LOS) B (43%), while the baseline events (Table 26) data suggests that about 35% of the trips occurred in LOS B. This seems to suggest that LOS B is more dangerous than other LOS conditions. By comparing the data in Table 25 and Table 26 for different LOS, similar conclusions can be drawn for LOS C and D. When traffic is in those LOS, crash and near-crash events are more likely to occur. In particular, as the LOS became worse, the chance for crashes or near-crashes to occur also increased. Such findings are not surprising given the frequent stop-and-go traffic, short gaps, much restricted maneuverability, and probably more aggressive behaviors in these conditions due to drivers being frustrated when stuck in traffic.

Table 25 Summary of traffic density for crash and near-crash events

Density	Crash		Near-crash		All	
	Count	**Percent**	**Count**	**Percent**	**Count**	**Percent**
LOS A1: Free flow, no lead traffic	2	29%	--	--	2	6%
LOS A2: Free flow, leading traffic present	2	29%	3	11%	5	14%
LOS B: Flow with some restrictions	2	29%	13	46%	15	43%
LOS C: Stable flow, maneuverability and speed are more restricted	1	14%	6	21%	7	20%
LOS D: Unstable flow - temporary restrictions substantially slow driver	--	--	5	18%	5	14%
LOS F: Forced traffic flow condition with low speeds and traffic volumes that are below capacity	--	--	1	4%	1	3%

Table 26 Summary of traffic density for baseline events

Density	Count	Percent
LOS A1: Free flow, no lead traffic	45	18%
LOS A2: Free flow, leading traffic present	97	38%
LOS B: Flow with some restrictions	88	35%
LOS C: Stable flow, maneuverability and speed are more restricted	13	5%
LOS D: Unstable flow - temporary restrictions substantially slow driver	5	2%
LOS E: Flow is unstable, vehicles are unable to pass, temporary stoppages, etc.	5	2%

Lighting and Weather Conditions

The lighting data in Table 27 suggests that overall the chance for crash and near-crash events to occur was higher in dark & lighted and dusk conditions. An interesting phenomenon is that dark and unlighted condition did not seem to significantly increase the chance of crash and near-crash events. A possible explanation is that lighted road segments are often in urban areas with more traffic, while unlighted segments are typically in suburban or rural areas with less traffic (i.e., less risk exposure).

The weather data in Table 28 shows weak evidence that mist/light rain and raining conditions both contribute to higher probabilities of work zone crashes/near-crashes compared to other types of weather. This is probably because mist and rain may blur mirrors and windshield, increasing the crash risk involved in car-following and merge maneuvers. Due to the relatively small sample size, the NDS data set does not contain any crash/near-crash events in fog condition. Therefore, the impact of fog on work zone crashes may be better assessed when more data is available.

Table 27 Summary of lighting conditions

Lighting	Crash/Near-crash		Baseline	
	Count	**Percent**	**Count**	**Percent**
Darkness & lighted	7	20%	15	4%
Darkness & not lighted	3	9%	27	10%
Dawn	0	0%	2	1%
Daylight	23	66%	202	82%
Dusk	2	6%	7	3%

Table 28 Summary of weather conditions

Weather	Crash/Near-crash		Baseline	
	Count	**Percent**	**Count**	**Percent**
Fog	0	0%	1	1%
Mist/Light Rain	2	6%	7	1%
No Adverse Conditions	31	89%	235	94%
Raining	2	6%	10	4%

4.2. Analysis of Smart Work Zone Data

Smart Work Zone (SWZ) data from MassDOT is also obtained and analyzed in this research. The goal is to use the SWZ data to calibrate the VISSIM simulation tool for work zone mobility analysis. The SWZ data consists of speed, occupancy, and volume data at 1-minute interval for each lane before, within, and after a work zone.

This research begins with a work zone on I-195 in Swansea, MA. It is on a highway segment with 3 lanes reduced to 2 lanes and has a lane shift. The observed traffic volume distribution among the two open lanes are compared against the VISSIM simulation results. The SWZ data suggests that the traffic flows of the two open lanes are clearly unbalanced. For the eastbound and westbound traffic, their lane flow distribution patterns are different as well. Although VISSIM generates unbalanced flows for the two open lanes, the observed and simulated lane flow distribution trends do not match well. One explanation is that some subtle differences between eastbound and westbound work zones such as pavement conditions, TTCPs, and lateral clearances may have significant impacts on drivers' lane choices. Such subtle differences are not reflected in the VISSIM network and their impacts are not captured in the VISSIM car-following and lane-changing models either.

Since the research team does not have the full knowledge of how the TTCP (e.g., traffic signs, control devices, law enforcement) was set up during the SWZ data collection periods, it is difficult to precisely replicate the observed flow patterns using simulations. Even with the detailed work zone configuration data, microscopic traffic simulation tools such as VISSIM cannot take all of them into full consideration. Therefore, we decide not to further pursue this calibration effort using the SWZ data. In the future, it would be helpful to collect detailed work zone configuration data and video data covering an entire work zone to fully capture how the work zone operates. The comprehensive data will allow for accurate and detailed simulation model calibration.

4.3. Summary

This chapter analyzes the NDS and SWZ data. The NDS data analysis results suggest that the main causes for crash and near-crash events in work zones are distracted driving, fatigue driving, speeding, and other unsafe maneuvers. This finding is consistent with the results of a MaineDOT study [*9*], but different from the common belief that speeding is the most important crash contributing factor in work zones.

The NDS results show that the most common types of work zone crashes are rear-end, road departure, and sideswipe, suggesting the importance of work zone speed control, merge control, and prevention of distracted driving. Analyzing the traffic operation conditions when work zone crash and near-crash events occurred shows that crash risk is significantly higher during LOS B, C, and D (see definitions in Table 26). This supports the opinion that speeding is not the most significant crash risk factor for work zones. A more critical crash risk factor probably is large speed variation, which can often be observed during congestion and stop-and-go traffic.

A limitation of the NDS data set is that it does not contain enough samples for the same or similar work zone settings. The lack of samples makes it difficult to single out a particular work zone traffic control element, and draw meaningful conclusions about its impacts on driver behavior. However, the research team still believes that the NDS data can be invaluable for work zone safety study. With the developments in image processing techniques (e.g., convolutional neural networks), the huge NDS video data may be processed more quickly and accurately, and be extracted and categorized into groups based on key traffic operation characteristics (e.g., presence of police vehicles). This will allow us to identify enough samples to single out the impacts of a particular TTCP element. Given the existing limitation of the NDS data for driver behavior research, the proposed VR driving simulator seems to be a feasible alternative for the moment.

The effort of using SWZ data to calibrate VISSIM simulation tool is unsuccessful. This seems to suggest that there are factors other than work zone layout (e.g., right lane closed, left lane closed, lane shift) that affects work zone throughput and volume distribution by lane. These factors could be pavement conditions, law enforcement, lateral clearance, variable message signs, etc. Such factors are not explicitly considered in existing microscopic simulation tools. More research is needed in quantifying the impacts of such factors based on either field data (e.g., video data showing vehicle trajectories) or driving behavior data generated by high-fidelity driving simulators. The findings in this area are very important for calibrating traffic simulation tools.

5. TTCPs for Work Zone Speed Control

Many previous work zone safety studies are based on crash reports filled out by police officers. Statistical models are then developed to establish connections between crash frequency/injury severity and explanatory factors. Some recent studies have adopted driving simulation [*100,101*] to collect time series data to investigate how drivers behave throughout a highway work zone. Such an approach is helpful for understanding the various causes (e.g., distracted driving) of work zone crashes and the benefits of different combinations of safety countermeasures. It also allows safety analysts to study near-crash events, which are not captured in work zone crash reports.

This study develops an innovative driving simulation framework based on Virtual Reality (VR) to study the safety performance of various work zone TTCPs. Compared to traditional driving simulators (see Figure 24) consisting of a projector/large curved screen, VR-based driving simulators (see Figure 25) are much less expensive and can be easily set up. It provides participants with highly realistic driving experience.

Figure 24 Traditional driving simulator [*102*]

Figure 25 VR based driving simulator

Since one of the main objectives of this research is to identify effective work zone speed reduction strategies, this VR driving simulation study develops several scenarios to model how drivers control their speeds when passing through a highway work zone in response to various TTCPs. Based on a comprehensive review of existing TTCPs for highway work zone speed control (see Section 3.1.1.), three speed control strategies are identified and six driving simulation scenarios are created in the VR environment. These strategies are tested under both daytime and nighttime conditions.

This chapter consists of three main components. First, an overview of the proposed work zone speed control strategies and how they are created in the VR environment are described. Second, the VR driving simulation results are presented and analyzed. Third, conclusions and discussion are provided.

5.1. VR Driving Simulation Scenarios and Study Design

Based on a comprehensive review of work zone TTCPs, the following three speed control strategies are identified: (1) Radar Speed Feedback Sign (RSFS); (2) tubular marker; and (3) narrow lane. Law enforcement is not selected in this VR driving simulation study, since it is already well recognized that law enforcement is very effective in reducing work zone speed. A main problem with this strategy is the implementation cost and the amount of coordination work required. Based on the three selected strategies, this study further develops the following six work zones (driving simulation scenarios):

- ***Work Zone 1*** considers a series of RSFS that are distributed evenly throughout a work zone. The distance between two adjacent RSFS is about 335 meters (1,100 ft);
- ***Work Zone 2*** uses tubular markers that are evenly spaced for speed control. The distance between two adjacent tubular markers is 10 meters (33 ft);
- ***Work Zone 3*** also uses evenly distributed RSFS. However, the distance between two adjacent RSFS is increased to 550 meters (about 1,800 ft);
- ***Work Zone 4*** is similar to *Work Zone* 2 but uses a reduced distance between two tubular markers. The new distance is set to 5 meter (about 16 ft);
- ***Work Zone 5*** is based on *Work Zone* 4. The only difference is that the original tubular markers are replaced by some wider tubular markers; and
- ***Work Zone 6*** uses the narrow lane strategy. It reduces the existing lane width from 3.66 meters (12 ft) down to 3.35 meters (11 ft). In the previous 5 work zones, a lane width of 3.66 meters (12 ft) is used.

Figure 26 shows the overall layout of the work zone investigated in the driving simulation study. The work activity area is separated from the open lane by concrete barriers. The speed control devices (i.e., tubular markers, RSFS) discussed in the above six scenarios are deployed throughout the work zone (see Figure 26 below). Among them, the tubular markers are only deployed along the yellow pavement marking, while the RSFS are deployed on both sides of the open travel lane. Each participant is asked to drive through a warm-up segment to allow them to become familiar with the VR driving simulator. After the warm-up segment, each participant is then asked to conduct two tests. The two tests consist of the same six work zones (corresponding to the above six scenarios). The first test is during daytime, while the second one is during nighttime. At the end of the driving simulation, each participant is asked to complete a survey regarding her/his opinions on work zone speed control strategies and the VR driving simulator.

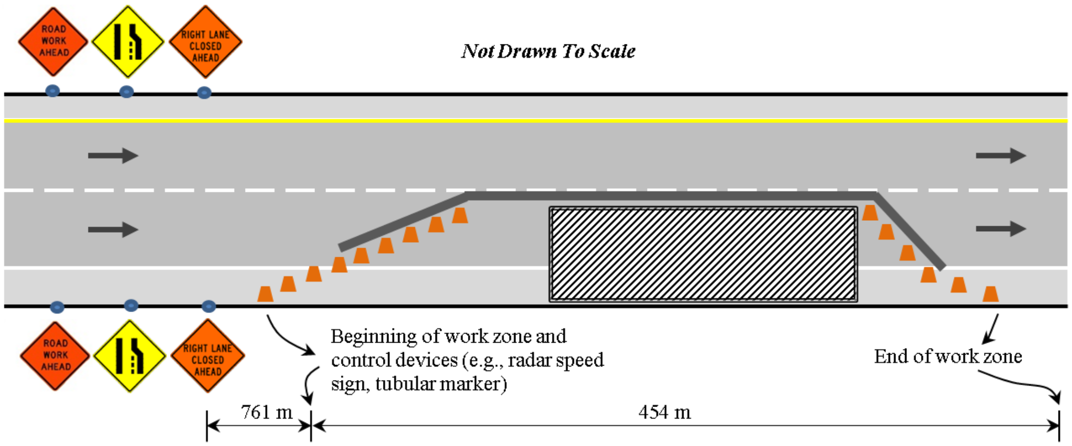
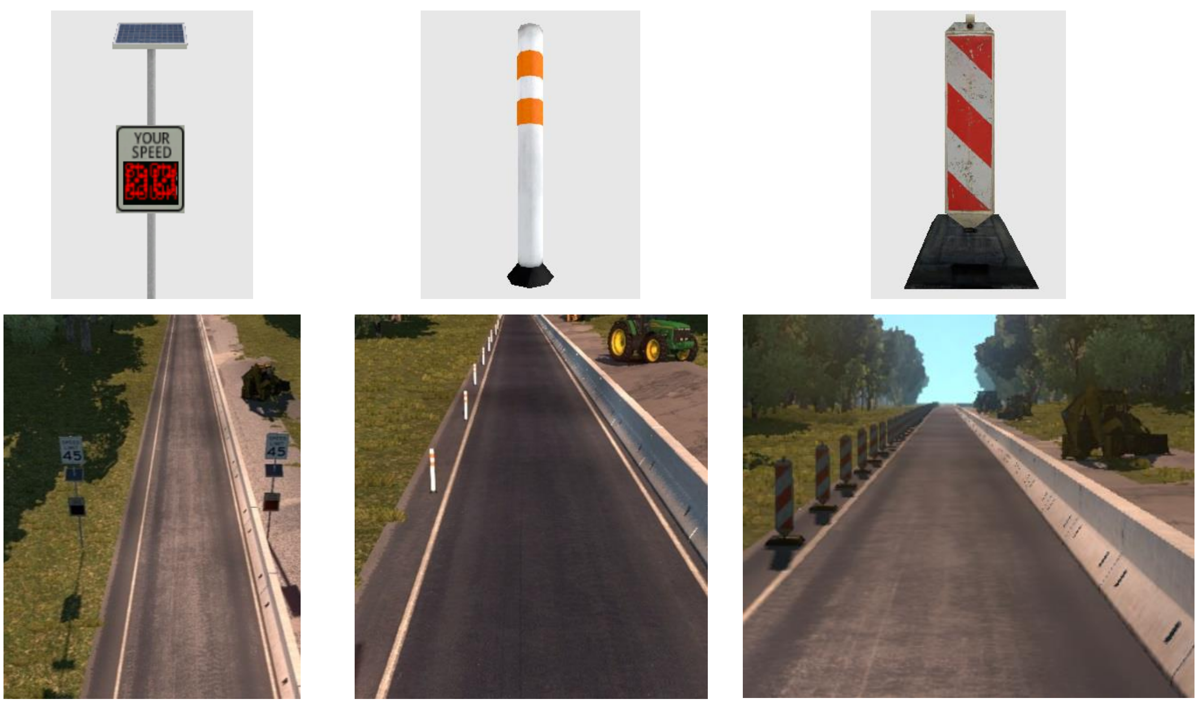


Figure 26 Work zone layout

To further illustrate how the selected speed control strategies look like and how they are coded, Figure 27 provides some screenshots of the developed VR driving simulation scenarios.



(a) RSFS (b) tubular marker (c) wide tubular maker

Figure 27 Screenshots of VR simulation scenes

5.2. VR Driving Simulation Results Analysis

This research recruits 27 male and 19 female drivers for the driving simulation study. These participants are between 18 and 41 years old. Therefore, the sample in this study is slightly biased towards young and male drivers. The following subsections summarize the driving simulation results.

5.2.1. Simulation Results

Figure 28 and Figure 29 show the speeds profiles of all drivers during daytime and nighttime, respectively. The speed profiles in these figures start shortly from the "*RIGHT LANE CLOSED AHEAD*" sign and stop at the end of the work zone (see Figure 26) covering approximately 1,000 meters. Two vertical lines are included in each subfigure of Figure 28 and Figure 29 to show where the work activity area begins and ends.

From the individual speed profiles in Figure 28 and Figure 29, it is not easy to see the overall trend of how speed changes. Therefore, the average speeds of all drivers at various locations are calculated and presented in Figure 30. The corresponding speed standard deviations are shown in Figure 31. It can be seen from these two figures that:

- The result for the 6th work zone suggests that the narrow lane strategy can reduce traffic speed in a consistent and gradual manner. If the work zone considered in this study is longer, one may be able to see the average speed stabilizes for a while before it goes up (drivers often accelerate when they are about to leave the work zone). This probably is because drivers need some time to realize that the lane is narrower and to take actions gradually, while drivers typically require less time to react to Radar Speed Feedback Signs (RSFS). Figure 31 shows that narrow lanes in general result in lower speed variations in day time than in night time. However, they may lead to large speed variations towards the end of the work zone irrespective of the time of day, increasing the risk of read-end crashes. Although narrow lanes appear to be effective in reducing work zone traffic speed, they may cause driver discomfort and should be considered with caution. One suggestion is to use pavement marking to create a false narrow lane impression without reducing the physical lane width. If a driver makes a lane departure mistake, she/he can still have a reasonable amount of time to correct it;
- Work Zones 2, 4 and 5 all use tubular markers. The main difference between Work Zones 2 and 4 is that 4 considers a shorter interval, and the difference between Work Zones 4 and 5 is that 5 uses a wider tubular maker. The average speed results show that during daytime Work Zones 4 and 5 (i.e., shorter interval) lead to larger speed reductions, while Work Zone 2 (i.e., longer interval) produces more speed reductions during nighttime. Dense tubular markers with a shorter interval may generate guidance effect to drivers during nighttime, increasing the visibility of upcoming road geometry and causing drivers to go faster (see Figure 32) than in the sparse tubular markers case (i.e., Work Zone 2). Figure 31 shows that Work Zone 2 leads to overall smaller speed variations among drivers than Work Zones 4 and 5 throughout the work activity area. However, for the same driver Work Zone 2 (see Figure 30) exhibit larger speed changes particularly during nightime. Overall, Work Zone 5 is recommended among the three; and

- The results for Work Zones 1 and 3 show that RSFS generates relatively consistent speed reduction effects during both daytime and nighttime. A potential issue with RSFS is that it may cause drivers to switch between acceleration (past a RSFS) and deceleration (before a RSFS) and generate speed waves as in Work Zones 1 (daytime) and 3 (both nighttime and daytime). Such a speed variation over distance for the same driver (different from the speed variation among drivers at various locations) may also be an important contributor to rear-end crashes. Compared to Work Zone 1, Work Zone 3 results in smaller differences (see Figure 30) among speed at lane closure point, minimum speed in work activity area, and speed at work zone end point. Figure 31 suggests that Work Zone 3 generates overall smaller between-driver speed variations particularly during daytime. From a pure speed reduction perspective, Work Zone 1 appears to be better. From speed harmonization standpoint, Work Zone 3 is also a good choice. In this research, only RSFS density is considered as a control variable. In future studies, it would be interesting to investigate RSFS location as a control variable and try to identify specific optimal locations for RSFS.

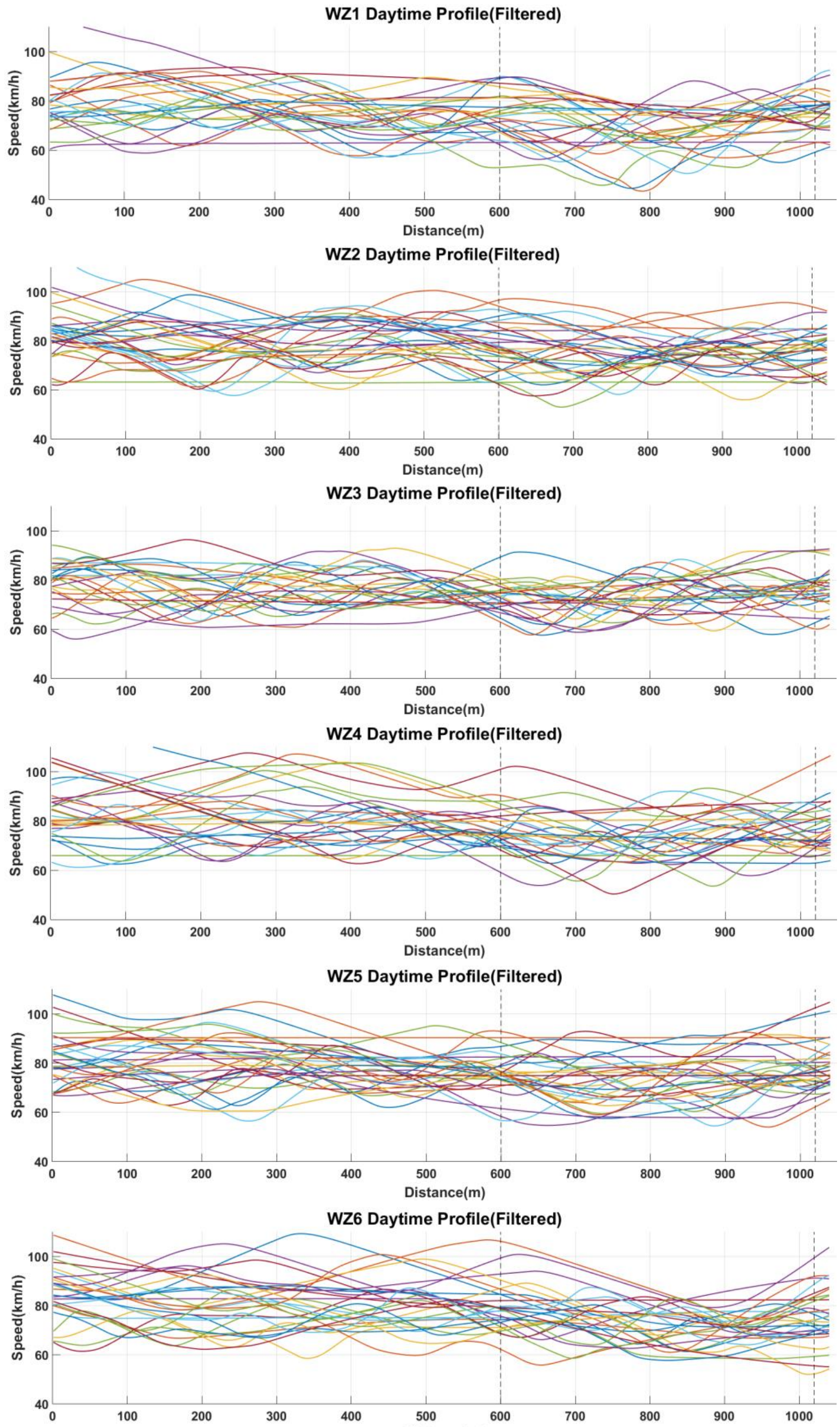


Figure 28 Daytime speed profiles

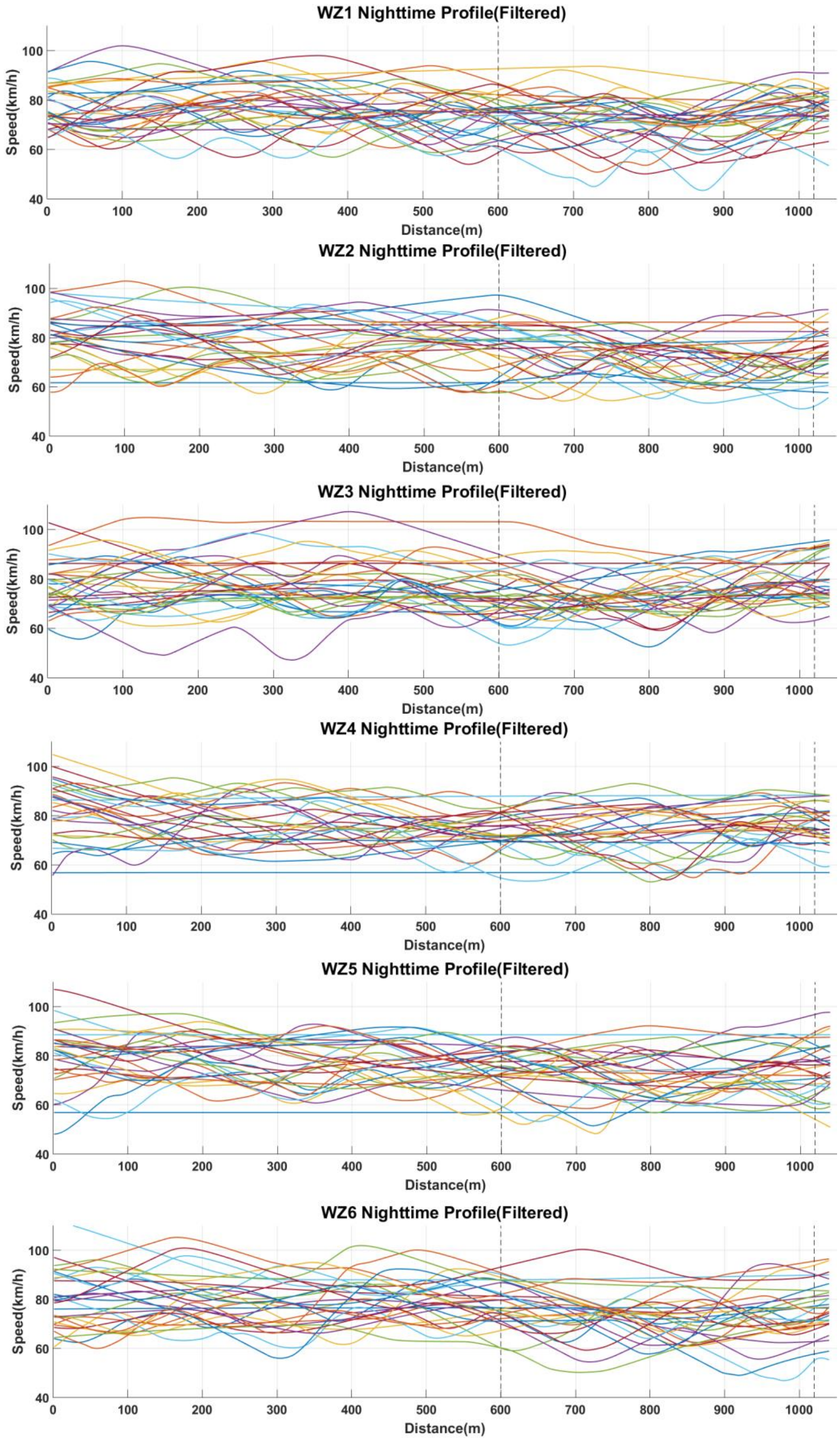


Figure 29 Nighttime speed profiles

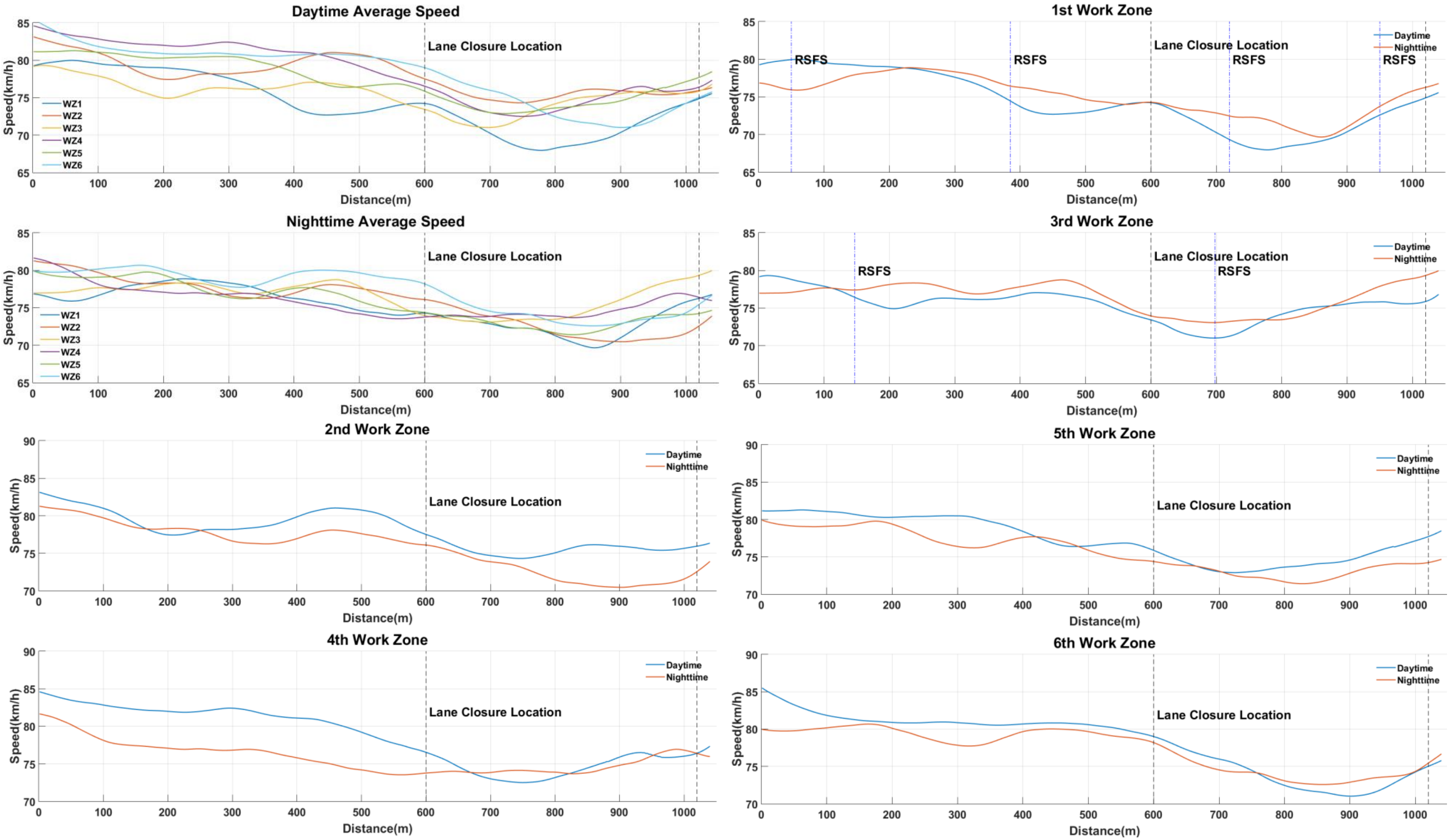


Figure 30 Average speed profiles

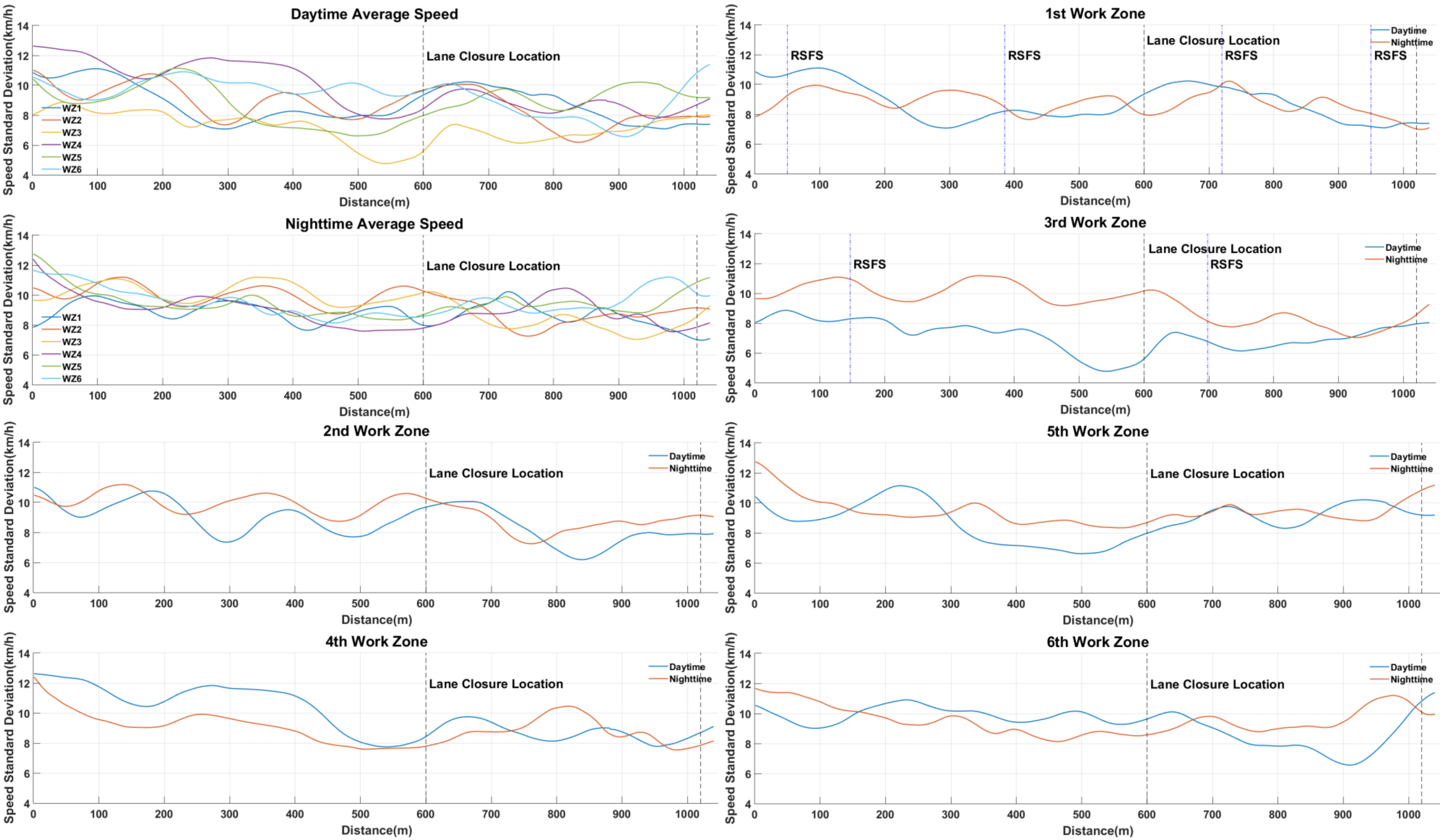


Figure 31 Speed variation comparison

(a) Work Zone 2

(b) Work Zone 4

(c) Work Zone 5

Figure 32 Comparison of Work Zones

5.2.2. Survey Results

The participant survey results are presented in Table 29, which suggest that participants in general are familiar with highway work zones and are conservative and safe drivers. Most of them think that the VR driving simulator provides realistic driving experience and the corresponding average rating is 7.0 out of 10 (with 10 being very realistic). We ask participants who give low ratings to this question and find that the main reasons for their low ratings are related to the steering wheel and gas and brake pedals, which do not give them realistic force feedback. Since this research uses a motion simulator, most participants are satisfied with the kinematic changes in speed and acceleration when accelerating and decelerating.

For Question #5 in Table 29, speed photo enforcement receives the highest rating among the six speed control strategies. Radar speed sign, flagger, and transverse rumble strip are given approximately the same rating and they are all considered effective in reducing traffic speed. An interesting finding is that overall participant felt that tubular markers are less effective compared to the previously mentioned four speed control strategies. Our initial thought is that adding tubular markers would give drivers the impression of narrow lanes and traveling at a speed that is higher than the actual speed. The survey results seem to suggest that most participants do not feel the same way. Variable Message Sign (VMS) is also considered to be less effective than radar speed sign, flagger, transverse rumble strip, and speed photo enforcement. This is probably because most drivers think VMS is mainly for disseminating real-time traffic and guidance information rather than traffic control and speed enforcement.

Table 29 Driving simulation participant survey result

#	Question (On a scale of 0 to 10)	Min	Mean	Max	Stdev
1	How do you rate your familiarity with driving through highway work zones (0~not familiar, 10~very familiar)	1.0	7.1	10.0	2.6
2	Do you consider yourself an aggressive driver (0~not at all, 10~definitely yes)	0.0	4.6	10.0	2.3
3	Are you often involved in distracted driving (0~not at all, 10~very often)	0.0	3.7	10.0	2.6
4	Your experience with the VR driving simulator (0~no realistic at all, 10~very realistic)	3.0	7.0	10.0	1.8
5	Your opinion about the effectiveness of the following speed control strategies (0~not effective, 10~very effective)				
	a). radar speed display sign	0.0	7.7	10.0	2.6
	b). flagger	0.0	7.7	10.0	2.6
	c). transverse rumble strip	0.0	7.8	10.0	2.4
	d). tubular markers	0.0	6.5	10.0	2.7
	e). speed photo enforcement	1.0	8.2	10.0	2.0
	f). variable message sign	0.0	6.8	10.0	2.6
6	What other work zone speed control strategies would you recommend? (optional question)	For this optional question, 27 participants provided answers and 22 of them recommended presence of law enforcements.			

5.3. VR Driving Simulation Conclusions and Discussion

This driving simulation study develops an innovative Virtual Reality (VR) driving simulator to model driver behavior in highway work zones. Three speed control strategies are considered: (1) Radar Speed Display Sign (RSFS), (2) tubular markers, and (3) narrow lane. Based on these control strategies, six work zones are developed and tested under daytime and nighttime conditions by 46 participants. The driving simulation results suggest that densely spaced RSFS (i.e., Work Zone 1) is the most effective strategy to reduce work zone traffic speed, which is consistent with the survey results. However, the RSFS strategy may potentially increase individual drivers' speed variations over distance due to their heterogeneous responses to RSFS. The speed reduction effect of tubular markers (Work Zones 2, 4, and 5) is less significant compared to Work Zone 1. An advantage of using tubular makers is that they seem to result in less speed variations for individual drivers throughout the work activity area. The narrow lane strategy is able to result in consistent speed reductions, since drivers tend to be more cautious when the lane becomes narrow. The collected trajectory data also suggests that different drivers may have very different perception of the safety risk caused by narrow lanes, which leads to larger speed variations among drivers compared to other speed control strategies considered in this study. Finally, Work Zones 1 and 5 are recommended for further investigations due to their speed reduction and speed harmonization performance, respectively.

The survey results in general are in line with the driving simulation results. Most participants consider RSFS and law enforcement to be very effective work zone speed control strategies. Among RSFS, flagger, transverse rumble strip, tubular markers, speed photo enforcement, and variable message sign, tubular markers are considered to be the least effective speed control method. This is different from what the result in Figure 30 suggests. A potential explanation is that drivers are affected by tubular markers without clearly realizing it. Additional data to be collected in the future may help confirm this conjecture.

Since the application of VR technology in driving simulation is relatively new, the experience learned in this study can be of use to other traffic safety researchers who are also interested in exploring this revolutionary technology. The review of work zone speed control strategies, the virtual reality driving simulation results, and the survey will help traffic engineers and safety analysts understand the safety impacts of different work zone speed control strategies and identify the best ones to suit their specific work zone safety needs.

Artificial intelligence vehicles are not included in this simulation study and drivers make speed choices based on their own perceptions of driving conditions. This is to avoid the potential impacts of slow-moving artificial intelligence vehicles on participants' speeds. Such a restriction can be relaxed in future studies. Combinations of different strategies are not considered in this study either. It would be interesting to see how tubular maker combined with narrow lane and transverse rumble strip can affect traffic speed.

6. TTCPs for Work Zone Merge Control

Four of the merge control (early, late, conventional, and signalized) strategies reviewed in Chapter 3 are further evaluated in this chapter by a microscopic traffic simulation tool, VISSIM. The VR based driving simulator is for evaluating the safety performance of work zone speed control TTCPs, while the microscopic traffic simulations are primarily to evaluate how different merge control TTCPs affect work zone mobility.

As discussed in Chapter 3, merge control may also affect work zone safety. For example, if early merge is not properly set up/operated either due to inadequate sign coverage/law enforcement, low compliance rate, or queue spilling back beyond no passing signs, aggressive driving behaviors such as queue jumping, lane straddling, and forced merge may happen, which are extremely dangerous. To investigate the safety impacts of the identified merge controls, vehicle trajectories generated by VISSIM are further analyzed using the Surrogate Safety Assessment Model (SSAM) developed by the FHWA [*103*].

In addition to the four merge controls reviewed in Chapter 3, this study proposes a new merge control strategy based on the idea of ramp metering. This new strategy is named the New England Merge (NEM). It is evaluated using VISSIM and SSAM as well. The results are compared to those of the previous four merge control methods.

Ideally, the simulation study should include all common types of work zones, for example, right/left-lane closure, right/left-shoulder closure, and lane shift. However, existing microscopic simulation tools such as VISSIM and Aimsun are not able to capture the driver behavior differences between right-lane closure and left-lane closure. Also, these simulation tools cannot model the impacts of shoulder closure, unless users customize these tools with their own traffic flow models. Therefore, only two simulation scenarios are considered in this research (1) two-lane highway with the right lane closed; and (2) three-lane highway with the right-most lane closed. Various traffic flow scenarios are considered to investigate how these merge control strategies perform under low to high traffic volumes.

6.1. New England Merge (NEM) Control

When reviewing work zone merge control methods in Chapter 3, early merge, late merge, and signalized merge are found to be popular among practitioners and researchers. However, these methods all have limitations as summarized below:

- Early merge requires strict law enforcements. Otherwise, the compliance rate of early merge will drop as congestion builds up and subsequently may lead to aggressive driving behaviors such as queue jumping, lane straddling, and forced merge. Also, early merge usually generates longer queues than conventional no control and late merge;
- Late merge in general does not generate the aggressive behaviors as early merge does. However, at the merge point the take-turn-to-merge rule may create both risky short gaps

(due to limited merge distance) and inefficient large gaps (due to the slow movement/acceleration of heavy vehicles) that affect both safety and throughput;

- Two forms of signalized merge have been proposed. The first one is to add traffic signals to both closed and open lanes and the other one only adds a signal to the closed lane. The second method essentially moves the lane drop point upstream and theoretically does not improve work zone merge operations. Both methods may generate confusion among drivers, as it is atypical to see signals on highways. Additionally, signal control most likely will generate stop-and-go traffic and is often associated with high rear-end crash risk. Therefore, they have not been widely implemented in practice; and
- It is generally agreed that early merge performs better under light traffic conditions, late merge is better for moderate to high traffic conditions, and signalized merge is better for oversaturated conditions. There is no consensus in terms of exactly when to use a particular control. In addition, switching from one control to another may cause short-term chaos.

Due to the above limitations, a new merge control method named New England Merge (NEM) is proposed. In the NEM, the approach to a work zone (i.e., the advance warning area and segments upstream of it) is divided into a meter zone followed by a merge zone. Vehicles approaching the work zone are instructed to increase their time gaps upon entering the meter zone. Specifically, each vehicle needs to increase the front time gap to twice the safe time gap needed for the corresponding speed. The meter zone is used to provide sufficient distances for vehicles to adjust their gaps and lane change is prohibited in this zone. While increasing the time gaps, vehicles are also advised to adjust their positions so that they travel near the middle point of two consecutive vehicles in the adjacent conflicting lane. Towards the end of the meter zone, if vehicles in both lanes are projected onto a single virtual lane, all the resultant time gaps are expected to be close to but greater than the minimum safe time gap required.

As mentioned before, a merge zone is introduced between the meter zone and the merge point. Lane changes are allowed in the merge zone. When vehicles leave the meter zone and enter this merge zone, they take turns to merge.

The proposed NEM has the following potential benefits: (1) different from early merge, late merge, and signalized merge, the NEM is designed to handle all travel demand conditions. There is no need to transition from one merge control to another control, and there is no need to worry about the potential chaos caused by the transition; (2) early merge requires all vehicles to form one line. This may generate high-speed and low-density flow at the merge point due to the platoon dispersion effect. Late merge may lead to high-density but low-speed flow at the merge point, especially in congested conditions. Both scenarios do not seem to help with maximizing the throughput. Theoretically, the NEM control is able to form high-density and relatively high-speed flow at the merge point; and (3) introducing the meter zone may allow drivers enough reaction time and distance to adjust their relative positions, contributing to safe and orderly merges.

Many modern vehicles are now equipped with the Adaptive Cruise Control (ACC) technology, which makes the implementation of the NEM control fairly straightforward. In the future, connected vehicles will further improve the feasibility and applicability of this new strategy.

Even without the ACC and connected vehicles, The NEM control can still be readily implemented with proper law enforcements and roadside signs. For example, tubular makers can be set up for drivers to estimate and maintain distance gaps; variable message signs can be set up to provide guidance information (i.e., recommended time/distance gap) based on real-time traffic; and drivers can use vehicles in the adjacent lane as a reference to maintain distance gap and adjust positions.

The proposed NEM can potentially increase throughput and reduce aggressive driving behaviors. It is expected to generate queue lengths that are comparable to those from late merge, but shorter than those generated by early merge. In Sections 6.3 and 6.4, the NEM control is thoroughly evaluated and compared with the other four merge control methods. In the following subsection, the Wiedemann 99 car-following model is described, based on which the technical detail of the proposed NEM is introduced.

6.1.1. Wiedemann 99 Car-Following Model

The Wiedemann 99 car-following model is developed for modeling highway traffic. It serves as the basis for the development of the NEM model. The Wiedemann 99 car-following model is outlined in Equations (1) through (4):

$$sdxc = L + CC0 \tag{1}$$
$$dxc = sdxc + CC1 * v \tag{2}$$
$$dxo = dxc + CC2 \tag{3}$$
$$dxf = dxo + CC3 * dv - CC4 \tag{4}$$

where,

$sdxc$ = minimum closing standstill distance,
L = length of lead vehicle,
$CC0$ = standstill distance (desired distance between lead and following vehicles when their speeds are both equal to 0),
dxc = following distance,
$CC1$ = headway time (desired time in seconds between lead and following vehicles),
v = subject vehicle speed if it is slower than the lead vehicle, otherwise v is equal to the lead vehicle speed,
dxo = minimum opening distance. When the distance between lead and subject vehicles is smaller than dxo, the subject vehicle should begin to decelerate,
$CC2$ = following variation (additional distance beyond the following distance that a vehicle requires),
dxf = threshold distance between lead and subject vehicles. It determines if the subject vehicle is under the "following" state. When the subject vehicle enters the "following" state ($dx < dxf$), the safe distance between lead and following vehicles is dxo. This means the acceleration of the following vehicle will oscillate around 0 when $dx = dxo$,
$CC3$ = threshold for entering "following" state, and
$CC4$ = negative speed difference during the following process.

6.1.2. Control of Vehicles in the Open Lane

Based on the NEM control, in the meter zone all vehicles in the open lane are required to increase their gaps with lead vehicles. In this way, vehicles in the closed lane can move into the large gaps in the open lane during the merge zone without courtesy stops or slowing down. The following Equations (5) through (7) describe how the gaps are increased among vehicles in the open lane:

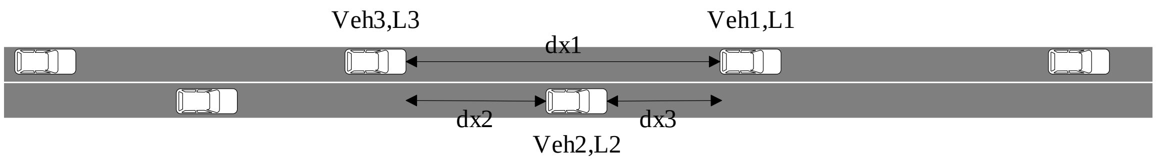


Figure 33 How Gaps are increased in the Meter Zone

$$dx1 = dx2 + L2 + dx3 \qquad (5)$$

Given Figure 33, it is necessary for Equation (5) to hold to ensure safety when vehicles in the closed lane (the right lane) merge left. In Equation (5), $L2$ is the length of the vehicle in the closed lane. Based on Equations (1) through (3), Equation (5) can be rewritten as Equation (6). Note that vehicle length (L) is omitted here since $dx1$ measures the distance between the rear bumper of the lead vehicle and the front bumper of the following vehicle. Similarly, $dx2$ and $dx3$ are further expanded and represented by Equation (7).

$$dx1 = CC0 + CC1\_MZ * v + CC2 \qquad (6)$$
$$dx2 = dx3 = CC0 + CC1\_def * v + CC2 \qquad (7)$$

Where v is set to 20.1 m/s based on typical work zone speed limit of 45 mph, $CC0$ = 1.5 m and $CC2$ = 4 m based on VISSIM default setting, and $CC1\_def$ = 1.7 sec based on a study by Yang et al. [*104*]. According to Equations (5) through (7), the headway time for vehicles in the open lane in meter zone ($CC1\_MZ$) should be set using Equation (8). In this research, we use 3.9 sec for $CC1\_MZ$ in VISSIM.

$$CC1\_MZ \geq \frac{L2+CC0+CC1\_def*20.1*2+CC2}{20.1} = 3.81 \text{ sec} \qquad (8)$$

6.1.3. Control of Vehicles in the Closed Lane

To maximize work zone throughput, vehicles in the closed lane should also adjust their positions in the meter zone and try to maintain equal longitudinal gaps with the two adjacent vehicles in the open lane. Depending on the location of a vehicle in the closed lane, it will end up with being one of the following two conditions:

Condition 1: $dx4 > dx3$ and there is no lead vehicle between Veh1 and the subject vehicle

Figure 34 illustrates what condition 1 looks like. Under this condition, there are four additional cases. In each case, the longitudinal acceleration of a subject vehicle in the closed lane is determined by Equations (9) through (12), where vs is the speed of the subject vehicle and acc is the longitudinal acceleration of the subject vehicle.

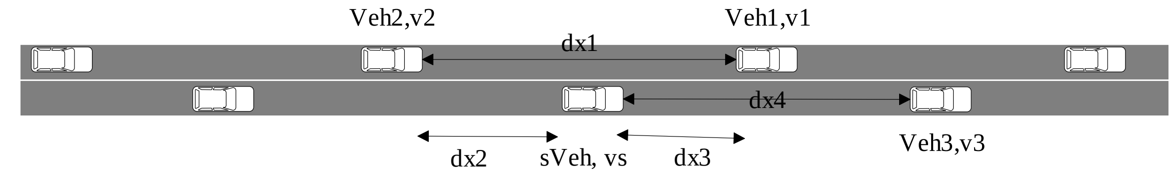


Figure 34 No Lead Vehicle between Veh1 and the Subject Vehicle

a) $dx3 > dx2$ and $vs > \frac{v1+v2}{2} + 3$:

$$acc = \max(-\sqrt[2]{dx2}\ ,\ \frac{v1+v2}{2} - vs) \qquad (9)$$

When $\frac{v1+v2}{2} + 3 \geq vs > \frac{v1+v2}{2}$, the subject vehicle's acceleration is determined based on the Wiedemann 99 car-following model using parameter $CC1 = 1.7$.

b) $dx3 > dx2$ and $vs \leq (v1 + v2)/2$:

$$acc = \min(\sqrt[2]{dx3 - dx2}\ ,\ 2) \qquad (10)$$

c) $dx3 < dx2$ and $vs < (v1 + v2)/2$:

$$acc = \min(-\sqrt[2]{\frac{(dx2-dx3)}{2}}\ ,\ \frac{v1+v2}{2} - vs) \qquad (11)$$

d) $dx3 < dx2$ and $vs \geq (v1 + v2)/2$:

$$acc = \max(-\sqrt[2]{dx2 - dx3}\ ,\ -2) \qquad (12)$$

Condition 2: $dx4 < dx3$ there is a lead vehicle Veh3 between Veh1 and the subject vehicle

Figure 35 shows what condition 2 looks like. The corresponding longitudinal acceleration of vehicles in the closed lane are determined by the following methods:

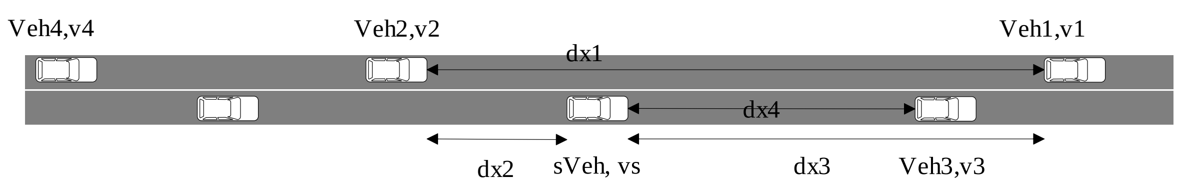


Figure 35 Has a Lead Vehicle between Veh1 and the Subject Vehicle

a) $dx2 + dx4 \geq 2 * dxo$ (with $CC1$ = 1.7 sec): In this case, the subject vehicle's acceleration is simply determined based on the Wiedemann 99 car-following model using parameter $CC1 = 1.7$; and

b) $dx2 + dx4 < 2 * dxo$ (with $CC1\_def$ = 1.7 sec): The subject vehicle's acceleration is again calculated based on the Wiedemann 99 car-following model by setting $CC1$ to 10. By using such a large $CC1$ value, the subject vehicle will decelerate until it becomes the first vehicle between Veh4 and Veh2 in the closed lane.

6.2. Simulation Configurations

6.2.1. Scenarios

As shown below, five merge control methods are evaluated based on the following two types of work zones: (1) Type I - *two-lane highways with the right-lane closed*; and (2) Type II - *three-lane highways with the right-most lane closed*. For Type I work zones, traffic volumes ranging from 1,000 vph to 2,000 vph with an increment of 100 vph are considered. For Type II work zones, the traffic input ranges from 2,200 vph to 4,000 vph with the same increment. A 3% heavy vehicle is assumed for all simulations conducted in this research.

1. Late Merge (LM)
2. Conventional Merge (CM) without control
3. Early Merge (EM)
4. Signalized Merge (SM)
5. NEM

Under EM, right-lane vehicles are assumed to merge to the left lane when they are >=1,600 ft away from the merge point. For CM, vehicles are assumed to merge between [1,000 ft, 1,600 ft) from the merge point. LM is defined as vehicles merging when they are < 1,000 ft from the merge point. Note that EM, LM, and CM each consists of several scenarios. For example, scenarios that require vehicles to merge at 1,000 ft, 1,200 ft, and 1,400 ft are all considered as CM.

For SM control, vehicles are not allowed to change lanes when they are within 500 ft of the merge point. For Type I work zones, a two-phase control with a cycle of 60s is considered to alternately discharge vehicles in the two lanes. Each phase has 26s of green, 3s of yellow and 1s of all red. For Type II work zones, the signal control plan is slightly different. In this case, there is no signal head for the left-most lane, which means vehicles in the left-most lane can go freely all the time, but cannot change lanes upstream of the merge point. The middle and right lanes are controlled in the same way as in Type I work zones.

During a preliminary VISSIM simulation study, it is found that VISSIM tends to result in long queues in the closed lane and continuously moving traffic in the open lane as shown in Figure 36. This is particular true when the input traffic volume is high. In practice, some vehicles in the closed lane will behave increasingly aggressively and force themselves into the open lane as they are getting closer to the merge point. This forced merge behavior will generate shockwaves in the open lane and cause all lanes to have approximately the same speed. Also, this will decrease the chance for vehicles to wait until the merge point to change lanes, which is the situation illustrated in Figure 36.

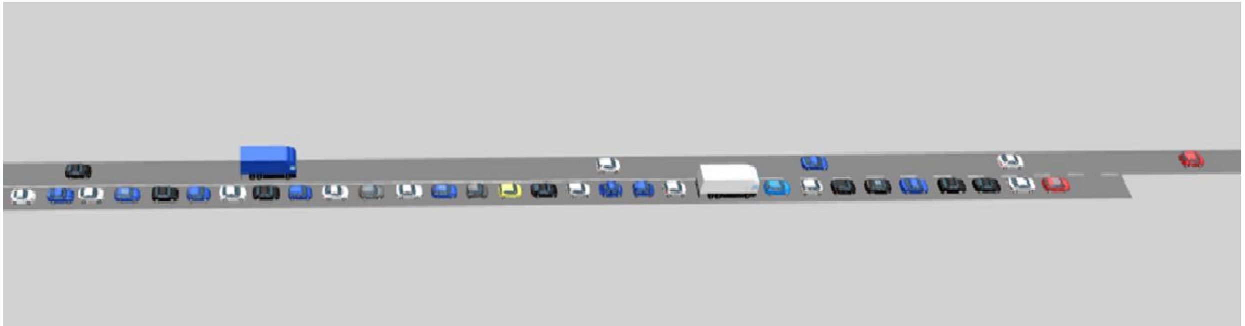


Figure 36 Unrealistic flow pattern

The issue illustrated in Figure 36 may generate inaccurate results especially for the previously defined LM at a distance of 200 ft (denoted as LM-200), since for LM-200 vehicles in both lanes are expected to take turns to merge when they are 200 ft away from the merge point. This is clearly not the case in Figure 36. Therefore, an additional LM strategy called LM-New is included, which uses the "conflict area" tool provided in VISSIM to model traffic operations at the merge point.

It is worth noting that in the previously defined EM, CM, LM, and SM, the "static routing decision" in VISSIM is used so that vehicles know ahead of time which lane is closed. Additional distance information (e.g., 1,000 ft, 2,000 ft) is provided to advise drivers where to begin to merge left. Drivers may not be able to merge precisely at the suggested distance due to lack of safe gaps. If the traffic is congested, some drivers may have to continue and wait until the merge point to change lanes. If a driver is very conservative, the scenario in Figure 36 can happen. For SM, the distance advisory information is irrelevant, since vehicles are controlled by signals and cannot change lanes upstream of the signal heads. For the LM-New control, the "conflict area" tool is used and the two conflicting lanes are given the same priority. This can generate results that mimic the "take turns to merge" operations. However, the default "conflict area" tool does not allow users to change (e.g., reduce) drivers' aggressiveness, and the throughput result for LM-New control is clearly overestimated based on the default "conflict area" tool. Nevertheless, this method is still included as a benchmark to be compared with the proposed NEM control. For NEM, lane changes at the merge point are handled in the same way as in EM, CM, and LM.

6.2.2. Parameters and Performance Measures

Yang et al. [*104*] found that two parameters significantly affect VISSIM work zone simulation results and provided some recommended values shown in Table 30. For other parameters, default values in VISSIM are used. For each combination of input volume and merge control strategy, the simulation is repeated 30 times with different random seed numbers. Each simulation run is 3000s long. The first 900s are used as the warm-up period and only data from 901s to 2700s is used to calculate model performance.

Table 30 Parameters used in VISSIM

	Merge distance > 800 ft	Merge distance <= 800 ft
Min headway (ft)	17.21	11
Headway time (s)	1.7	1.2

To compare the performances of the merge control strategies, three Measures of Effective (MOEs) are considered in this research, which are defined below. The evaluation results are reported for Types I and II work zones separately.

- *Throughput*: total number of vehicles that are able to pass the lane closure point;
- *Average Delay per Vehicle*: average delay per vehicle for vehicles that have exited the network; and
- *Queue Length*: mean travel time for all vehicles that have exited the network.

6.3. Type I Work Zone Simulation Results

6.3.1. Average Delay per Vehicle

Figure 37 shows the average delay per vehicle results for Type I work zones under EM, CM, and LM control. The horizontal axis denotes the merge distance and the vertical axis is for the average delay per vehicle. A total of 3,960 simulation runs have been conducted to generate the results in Figure 37. The following can be observed from the results:

- When the vehicle input is less than 1,200 vph, the difference in terms of average delay among various merge distances is marginal;
- As the merge distance increases (i.e., merge earlier), in general the average delay per vehicle decreases with a few exceptions. For example, when the input volume is 1,700 vph, the average delay increases slightly as the merge distance goes up from 2,000 ft to 2,200 ft. This might be explained by the fact that average delay is calculated based only on data from vehicles that have exited the network. If the data for vehicles still in the network is also considered, such a minor variation in average delay may be gone; and
- When the vehicle input is greater than 1,400 vph, the average delay curves for all merge distances go up sharply. This results seem reasonable, as the capacity for Type I work zones is typically around 1,400 vph.

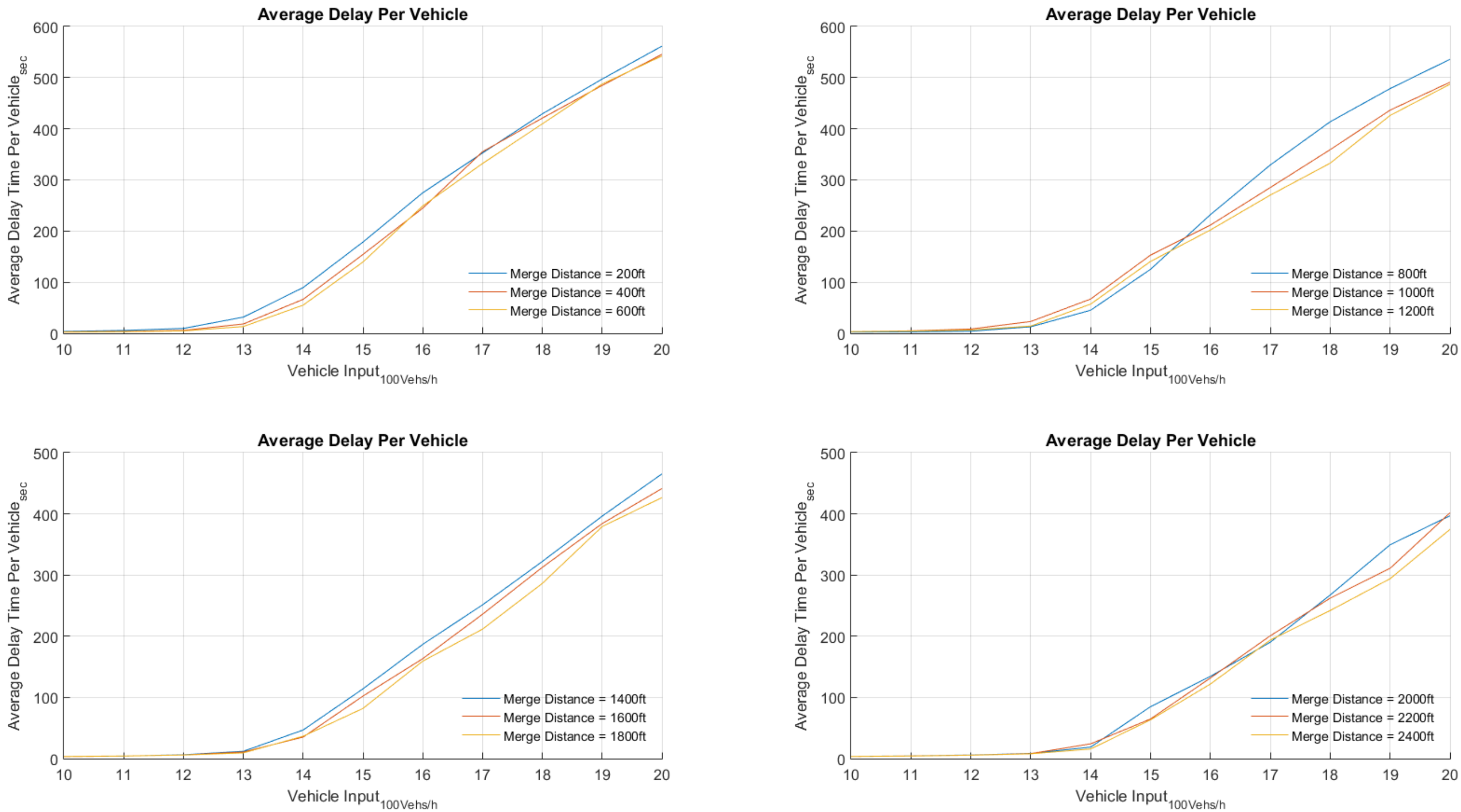


Figure 37 EM, CM, and LM average delay results for Type I work zone

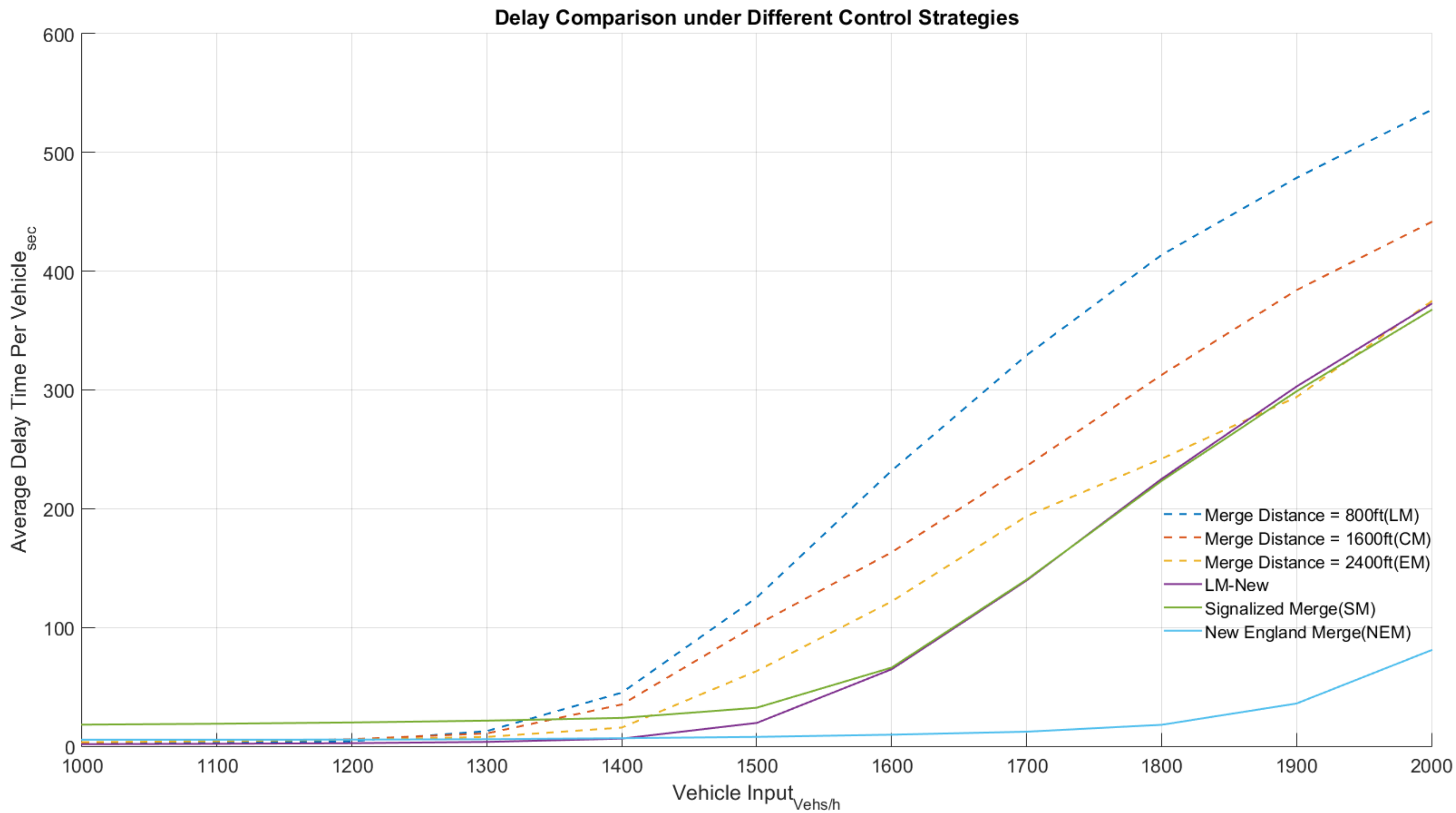


Figure 38 Comparison of all average delay results for Type I work zone

Figure 38 compares the average delay results of all merge control methods considered in this research. Since EM, CM, and LM all consist of a range of merge distances, only one representative merge distance is selected for each of them to avoid cluttering the figure. In Figure 38, 800 ft is selected for LM, 1,600 ft is for CM, and 2,400 ft is for EM. The results in Figure 38 suggest that:

- Overall, when the input volume is lower than 1,200 vph, it is better to consider methods other than the SM control. As the input volume goes beyond approximately 1,430 vph, it is always better to use the SM control than EM, CM, and LM. This suggests that when the volume is low to medium, the benefits of SM is not enough to offset the control delay introduced by it. When the input volume is too high, it is less efficient to rely on drivers to negotiate the right of way to merge compared to SM. This finding is consistent with the data reported in the 2006 MassDOT Work Zone Management Manual [*105*], which suggests that the capacity for a two-lane highway work zone with one lane closed is around 1,340 vph. When the volume is approaching capacity, it might be worthwhile to introduce unconventional control strategies such as SM;
- EM performs better than CM and LM, suggesting that in general it is better to merge as earlier as possible. When the volume is beyond 1,800 vph, the EM performance is even comparable with LM-New and SM. This again is due to the phenomenon described in Figure 36. The high-speed continuous flow in the left lane contributes to an overall low average delay for EM (note that the average delay is calculated based on vehicles that have exited the network), which is unrealistic in practices. Therefore, this does not mean for extremely heavy traffic, EM is still as good as SM;
- When the volume is less than 1,400 vph, there is negligible difference between LM-New and NEM. As the volume increases beyond 1,400 vph, the delay of LM-New goes up significantly and is much larger than the delay of NEM. As described before, LM-New utilizes the "conflict area" tool in VISSIM to model merge behavior. When the volume is relatively low, vehicles can negotiate among themselves and merge at high travel speeds. For high volume cases under LM-New, vehicles will merge at low travel speeds due to the stop-and-go traffic, while NEM can allow vehicles to travel and merge at high speeds in the meter and merge zones; and
- Under all volume conditions, NEM outperforms SM. This suggests that it is beneficial to introduce a meter zone before the merge point, which can allow vehicles to merge at high speeds and effectively reduce delay. On the other hand, NEM seems to generate higher delays than EM, CM, and LM when the volume is less than 1,200 vph. This is probably because there are enough safe gaps in this case for vehicles to merge at high speeds even without NEM. The additional constraints introduced by NEM will unnecessarily slow the overall traffic down.

6.3.2. Throughput

Figure 39 shows the throughput results for Type I work zones with EM, CM, and LM control. It can be seen that:

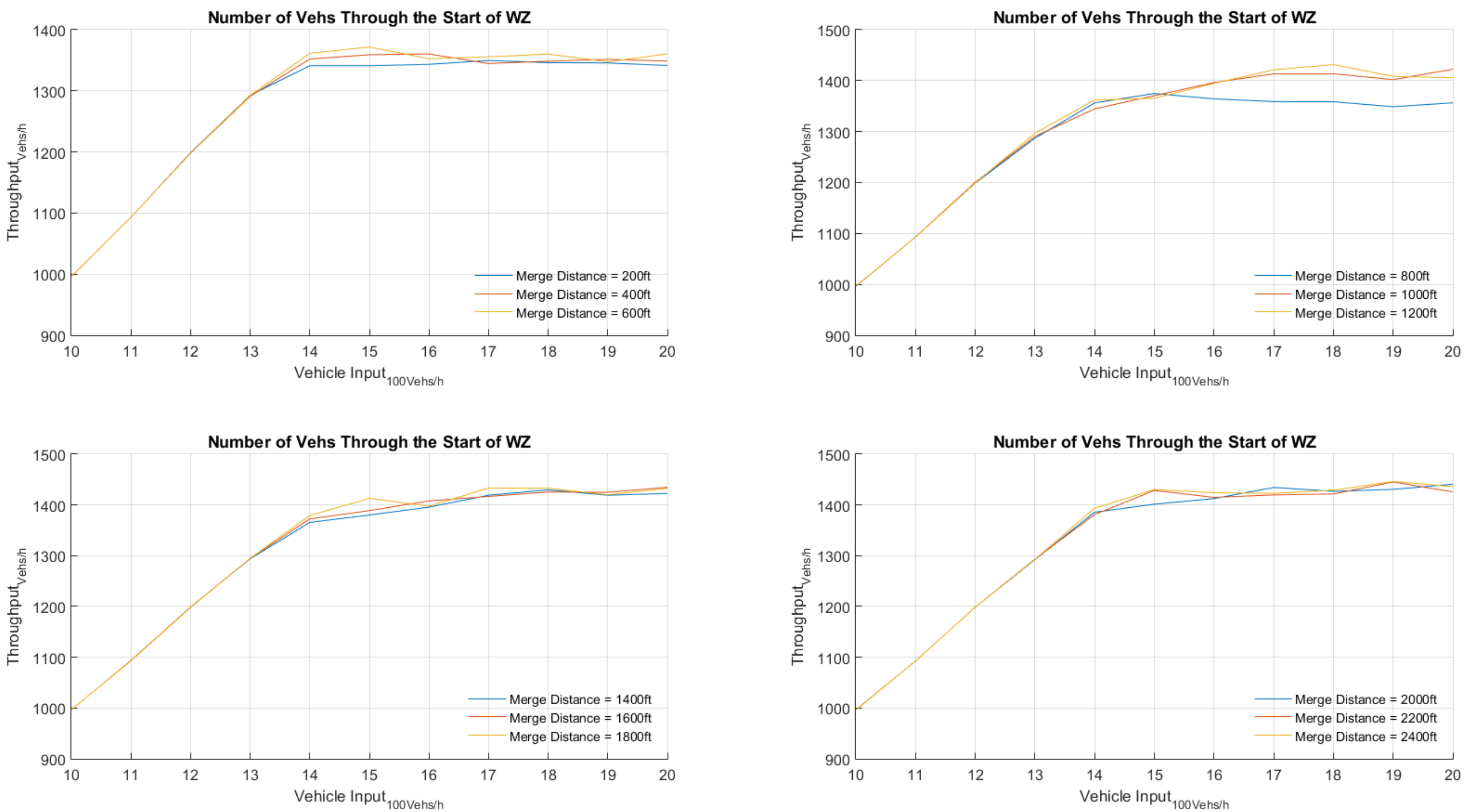


Figure 39 EM, CM, and LM throughput results for Type I work zone

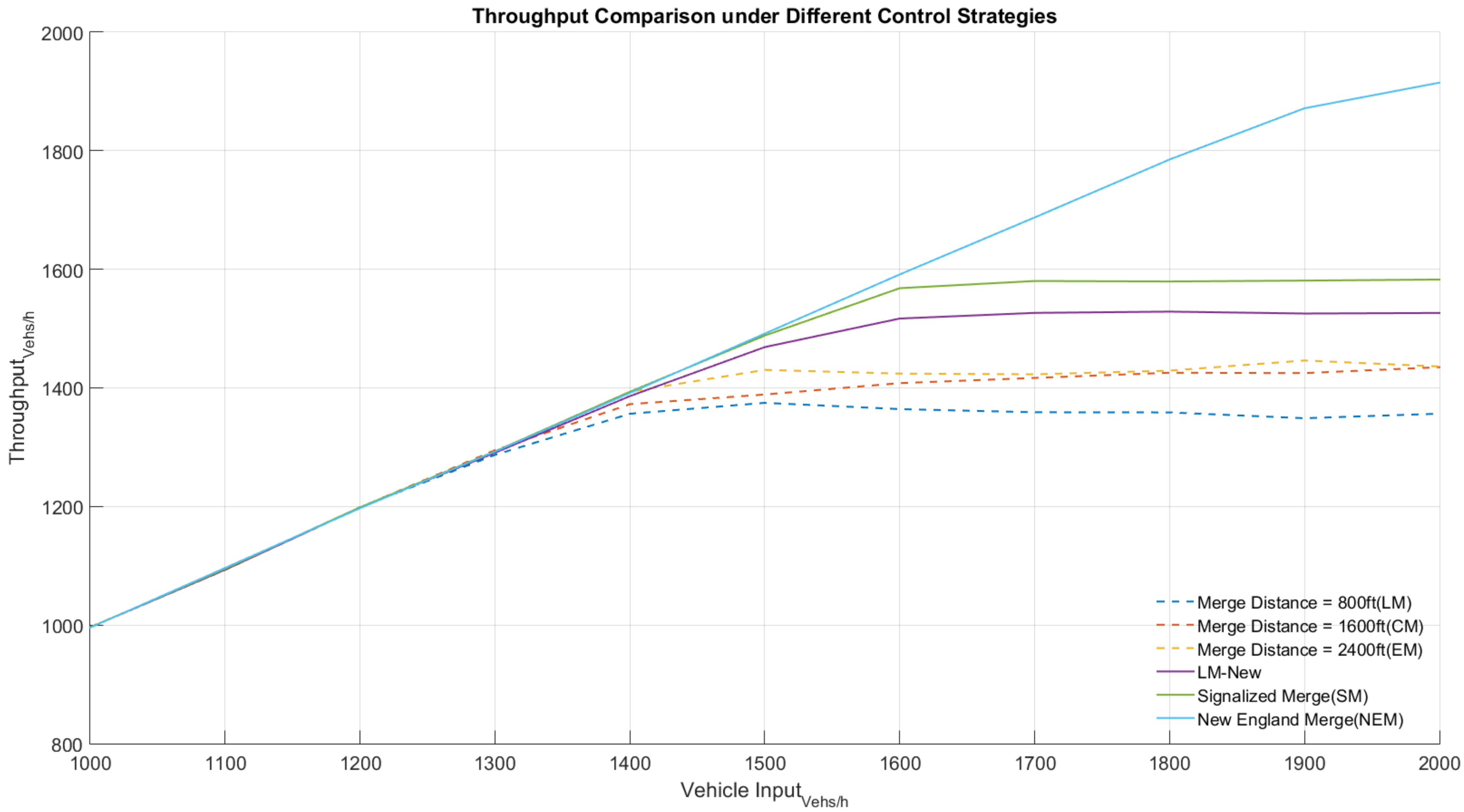


Figure 40 Comparison of throughput results for Type I work zone

- For low traffic volumes (less than 1,300 vph), there is no major difference between the three merge control methods (i.e., throughput is not affected by the merge distance);
- As the input volume increases, it is clear that EM and CM generate higher throughputs than LM (defined as merge distance <1,000 ft). The maximum throughput generated by LM is about 1,350 vph. While for CM and EM, the maximum throughput is well above 1,400 vph; and
- When the input flow is at 1,400 vph. Comparing the four subfigures in Figure 39 clearly suggests that increasing the merge distance (i.e., from LM to EM) helps to improve throughput. At this flow level, the 200-ft merge distance generates a throughput of about 1,340 vph, the 1,200-ft merge distance leads to a throughput of approximately 1,360 vph, while the 2,400-ft merge distance produces a throughput of almost 1,400 vph.

Figure 40 presents a comparison of all merge control strategies in terms of throughput. The following observations are made based on the results:

- When the input volume is less than 1,200 vph, all merge control methods provide approximately the same throughput, which is equal to the input flow. Considering the significantly higher average delay from the SM in this case, it is better to adopt the remaining methods;
- When the input volume is greater than 1,500 vph, the throughputs of SM and NEM are clearly higher than the remaining merge control methods. Additionally, the average delay of NEM is lower than all other methods. Therefore, it is better to use NEM control in this case; and
- When the input volume increases from 1,200 vph to 1,500 vph, the results in Figure 40 suggest that the throughput benefits of using EM and CM over LM become increasingly clear. The delay results in Figure 38 also suggest that EM is a better option than CM and LM in this flow range. However, a close examination of the simulation animations suggests that the best choice might not be EM or CM. The simulation animations show that in this flow range many vehicles in the right lane cannot find a suitable gap upstream and have to wait until the merge point to change lanes. This makes EM essentially LM. Since LM adopts a different set of VISSIM parameters (see Table 30), vehicles become more aggressive when getting closer to the merge point. Therefore, the continuous flow in the left lane (see Figure 36) is more likely to be interrupted, leading to a lower throughput but more realistic flow pattern than EM and CM. In conclusion, the better average delay and throughput performances of EM than LM should be interpreted with caution, unless EM is strictly enforced.

6.3.3. Queue Length

Figure 41 shows the queue length results for EM, CM, and LM, which are consistent with the throughput results in Figure 39. Overall, increasing the merge distance (i.e., merge earlier) results in slightly shorter queue lengths. This observation can be explained by the larger throughputs for EM in Figure 39. However, it contradicts with the fact that LM uses both lanes until the merge point, while EM only utilizes one lane. Theoretically, EM will double the queue length compared to LM for the same number of vehicles. This is because in this research right-lane vehicles are suggested to merge at specified static locations. In some cases, they may not be able to find a safe gap at the specified location and will have to continue downstream. Such cases become more frequent as the input volume increases. Therefore, the EM control considered here does not reflect a perfectly enforced and implemented EM case with extensive sensors and advisory signs. The queue lengths from EM are underestimated by the simulation results and should be interpreted with caution.

Figure 42 compares the queue lengths of all merge control methods. It can be seen that:

- When the input volume is less than 1,300 vph, SM always generates longer queues than EM, CM, and LM, showing that SM is not suitable until the input flow is approaching the capacity;
- When the input volume is less than 1,200 vph, the queue length differences among most methods, except for SM, are almost negligible; and
- NEM generates the shortest queue lengths under almost all flow conditions, which are much shorter than the results from LM-New and SM for high input flows.

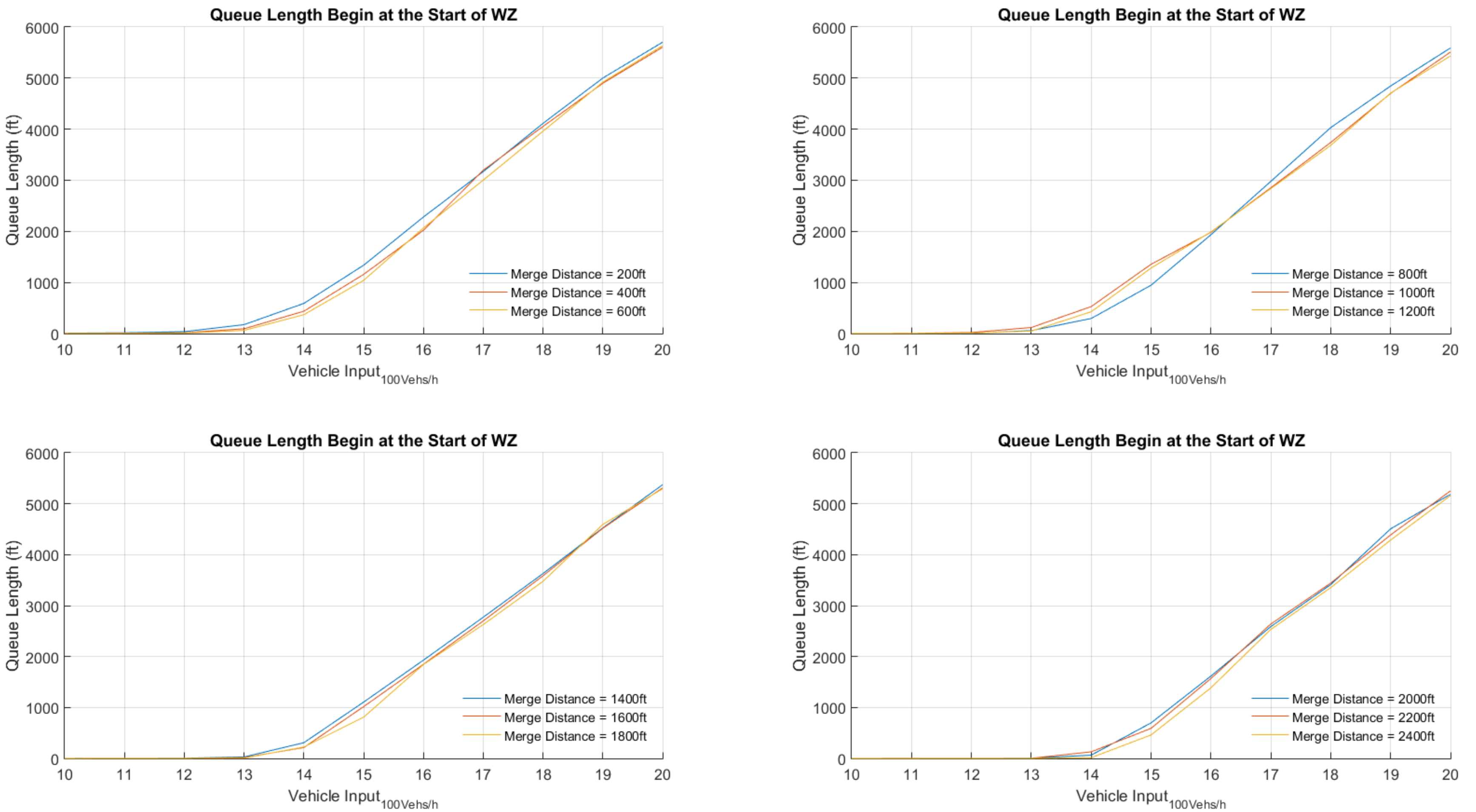


Figure 41 EM, CM, and LM queue length results for Type I work zone

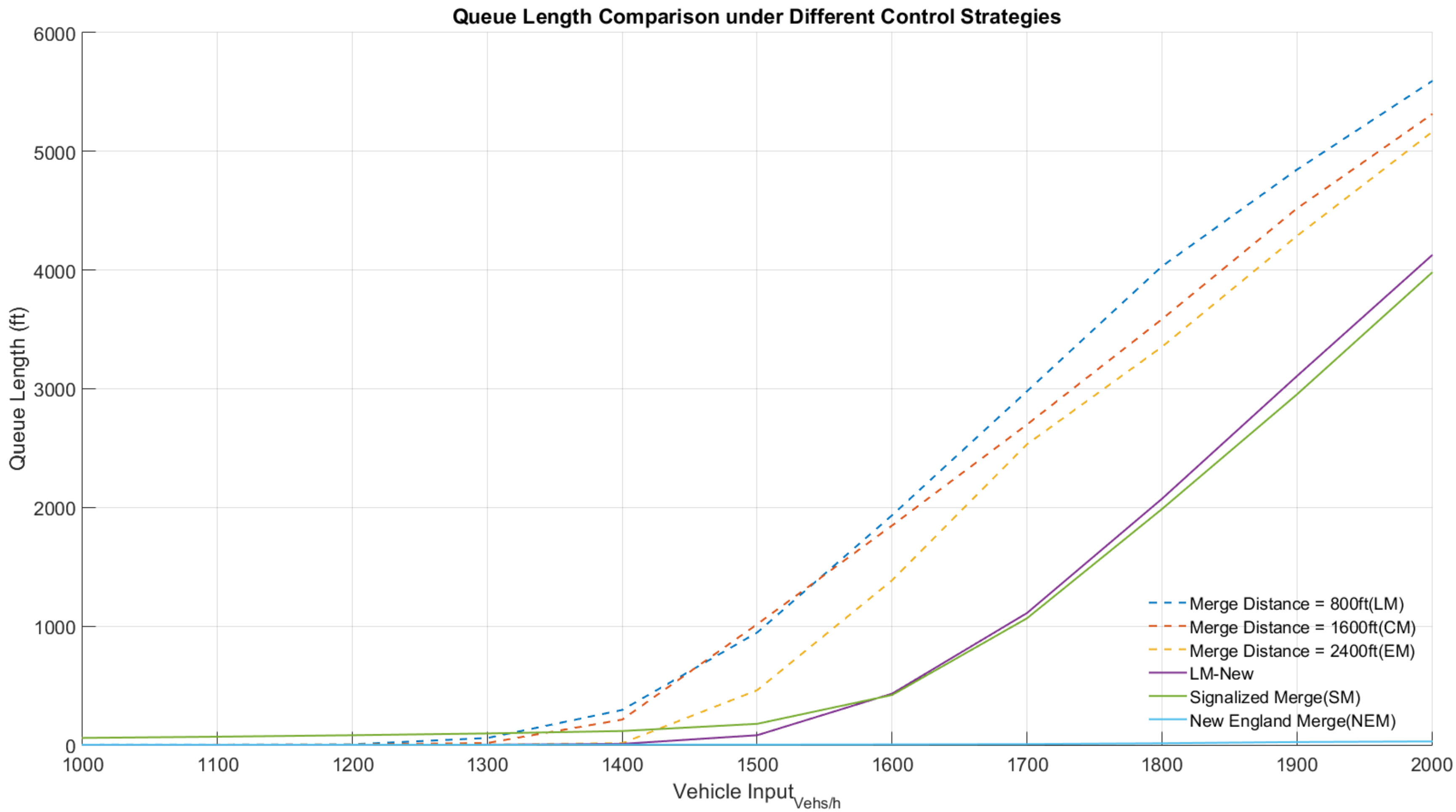


Figure 42 Comparison of queue length results for Type I work zone

6.3.4. Density

To address the issue described in Figure 36 and generate more realistic simulation results, this research experiments with a set of modified EM, CM, and LM strategies. These new strategies utilize a simple priority rule to require vehicles in the open lane to yield to right-lane vehicles approaching the merge point. More specifically, when there is a standing queue of over 20 vehicles in the closed lane (right lane) at the merge point, vehicles within 300 ft of the merge point in the open lane (left/middle lane in this study) should stop for 20 s and let vehicles in the closed lane to merge and continue.

To find out how the proposed priority rule merge strategy works, this research develops a tool to visualize how traffic density in the merge area changes over time and distance. The density maps for input volume = 1,400 vph without and with priority rule are shown in Figure 43 and Figure 44, respectively. These figures show that the priority rule control can help to equalize the traffic densities of the open and closed lanes (particularly for the LM and CM cases), which is one typically sees/expects in real life work zone traffic operations. The density results for a more congested case (volume = 2,000 vph) are presented in Figure 45 and Figure 46, in which similar trends as in the 1,400 vph case are observed. The density maps suggest that additional work is needed in the future to develop custom microscopic simulation tools for modeling work zone merge behavior.

6.4. Type II Work Zone Simulation Results

6.4.1. Average Delay per Vehicle

Figure 47 shows the average delay results for Type II work zones with EM, CM, and LM control. A total of 6,840 simulation runs have been performed to generate the results in Figure 47. The following can be observed from the results:

- For EM and CM under the same input flow, the average delay decreases as the merge distance increases. This trend is consistent with the EM and CM results for Type I work zones; and
- For the Type I work zone average delay results, LM generates the highest average delays. While for Type II work zones, the results in Figure 47 show that LM results in the lowest average delays. A close look at the LM simulations suggests that this is due to the more aggressive parameters (see Table 30) used for LM. For Type I work zones, there is only one open lane. The aggressive drivers in the right lane will frequently interrupt the left open lane traffic, causing negative impact on both average delay and throughput. For Type II work zones, there are two open lanes. The middle lane is still negatively impacted by aggressive drivers from the right lane. However, the throughput of the left-most lane can significantly benefit from the aggressive driver behaviors (e.g., high-speed vehicles merge from the middle lane to the left-most lane. This helps to fill large gaps and generate short time headways). Additional simulations suggest that the negative impacts here are often outweighed by the benefits for Type II work zones.

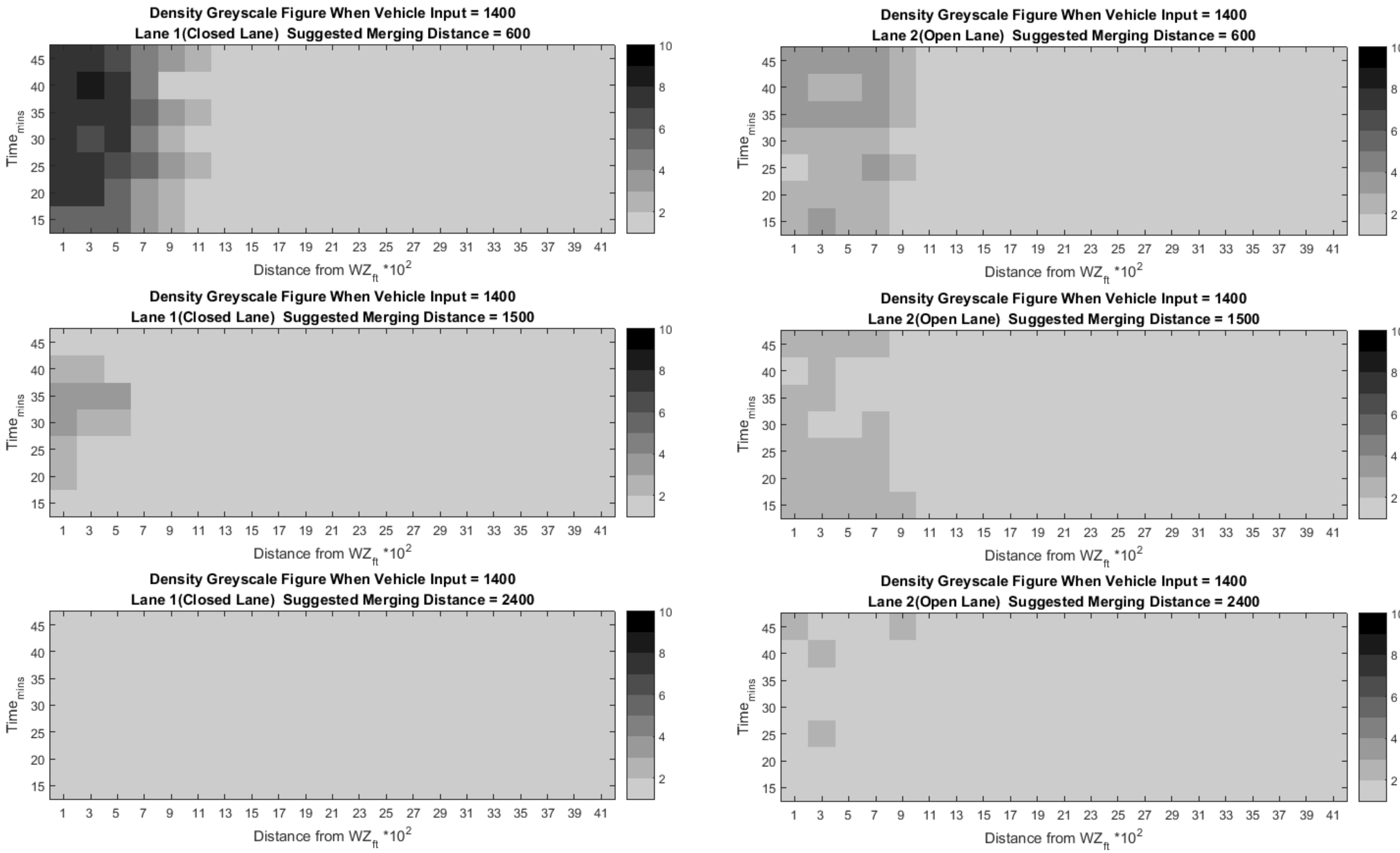


Figure 43 Density map for Type I work zone without priority (Volume = 1,400 vph)

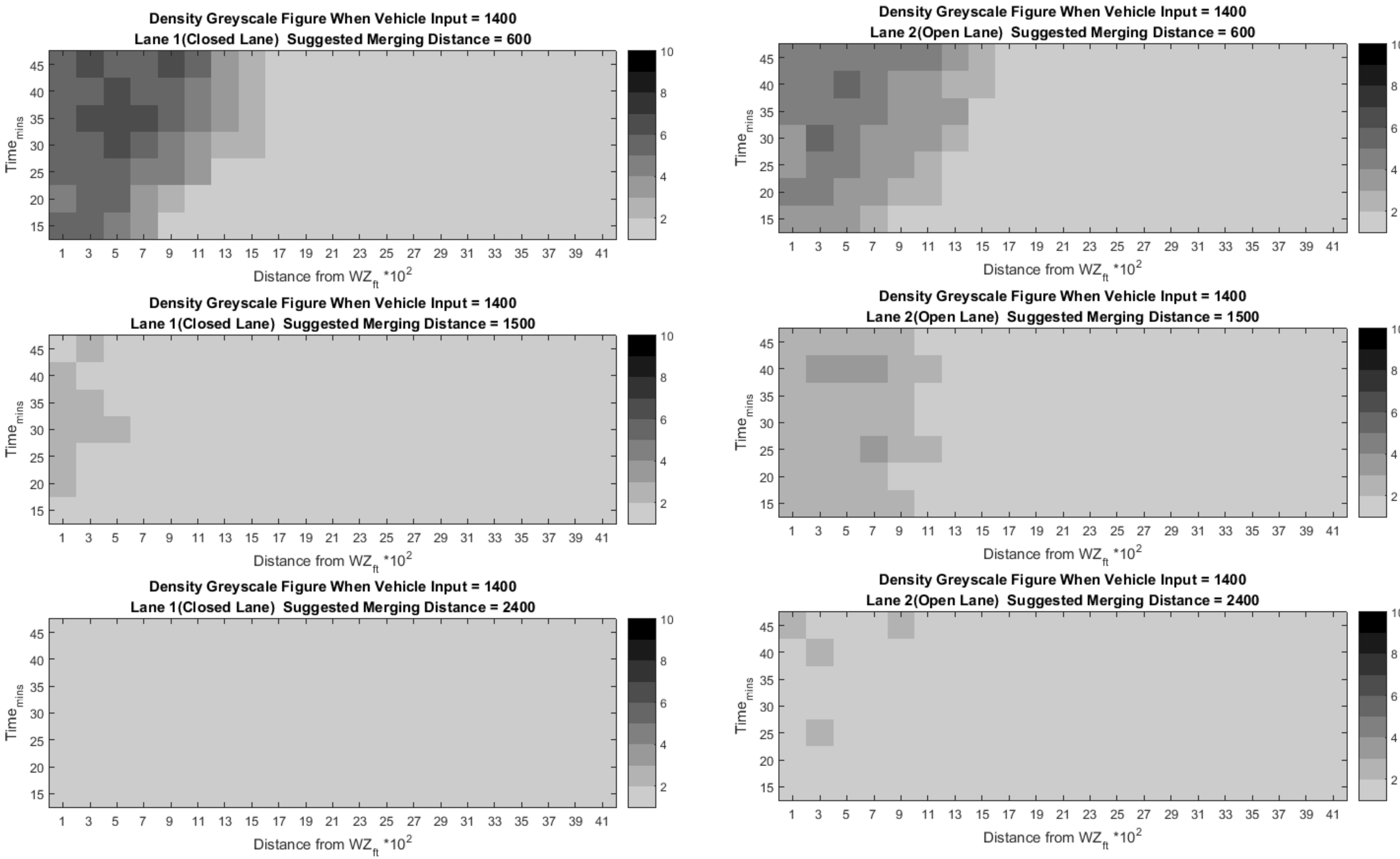


Figure 44 Density map for Type I work zone with priority (Volume = 1,400 vph)

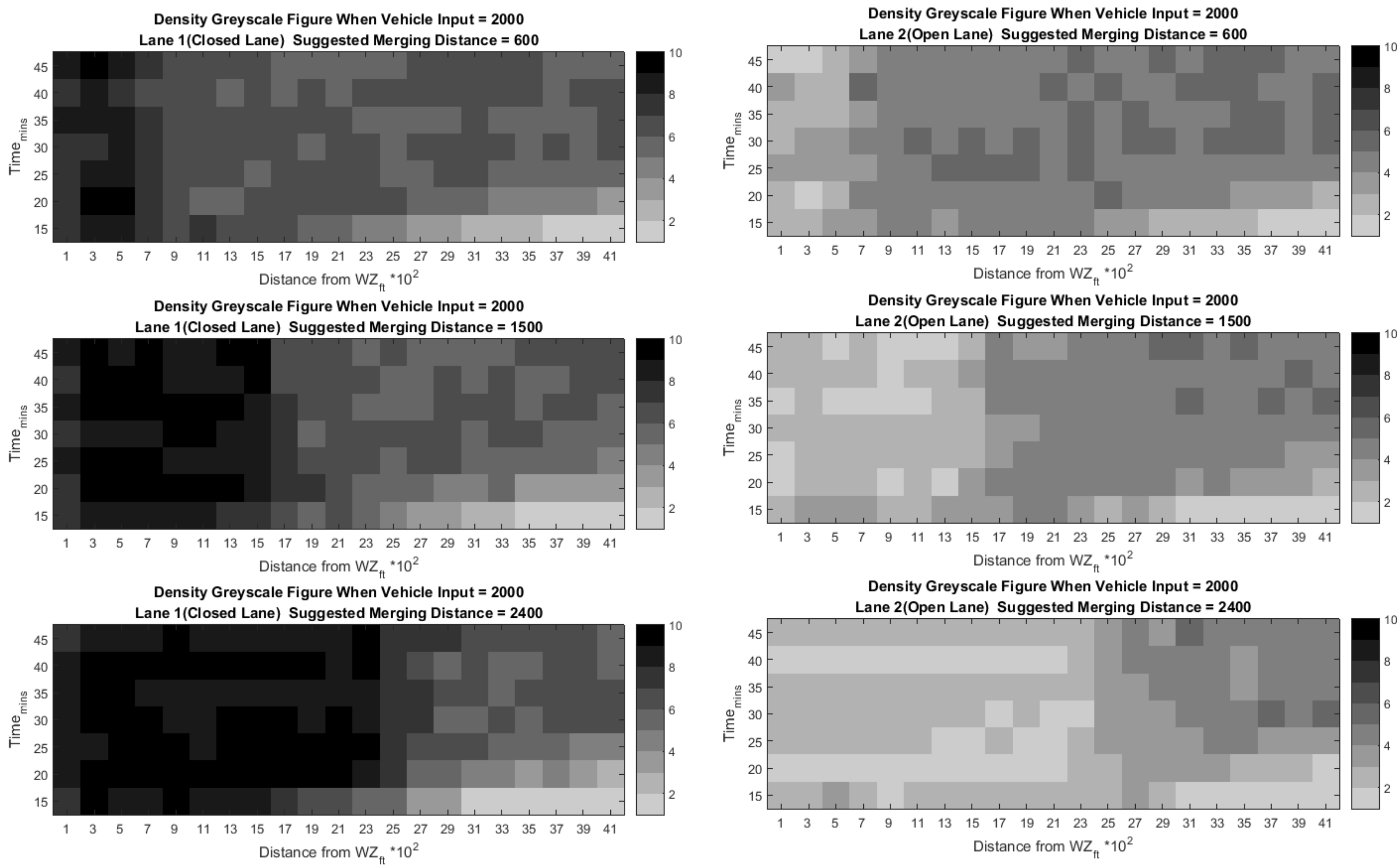


Figure 45 Density map for Type I work zone without priority (Volume = 2,000 vph)

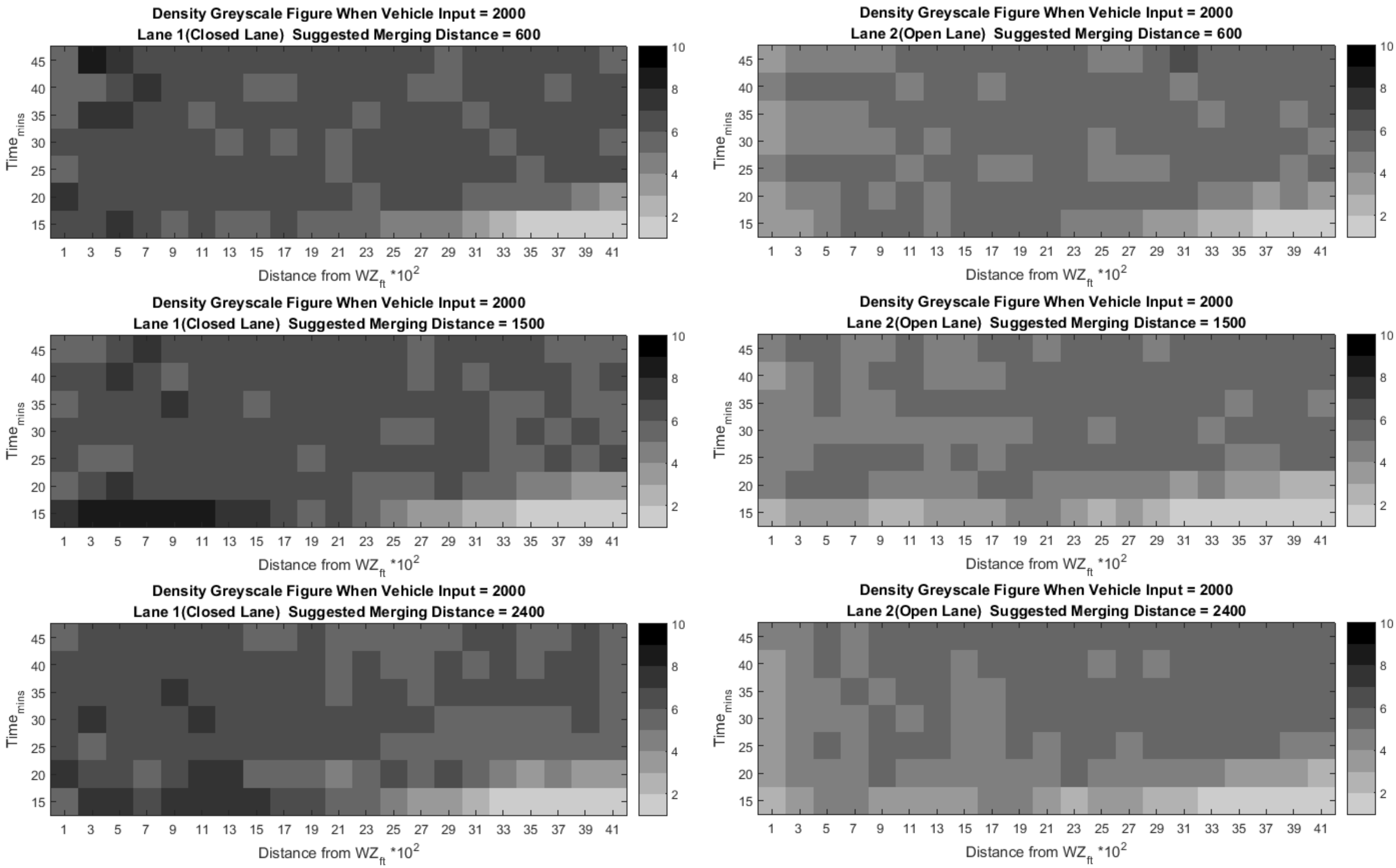


Figure 46 Density map for Type I work zone with priority (Volume = 2,000 vph)

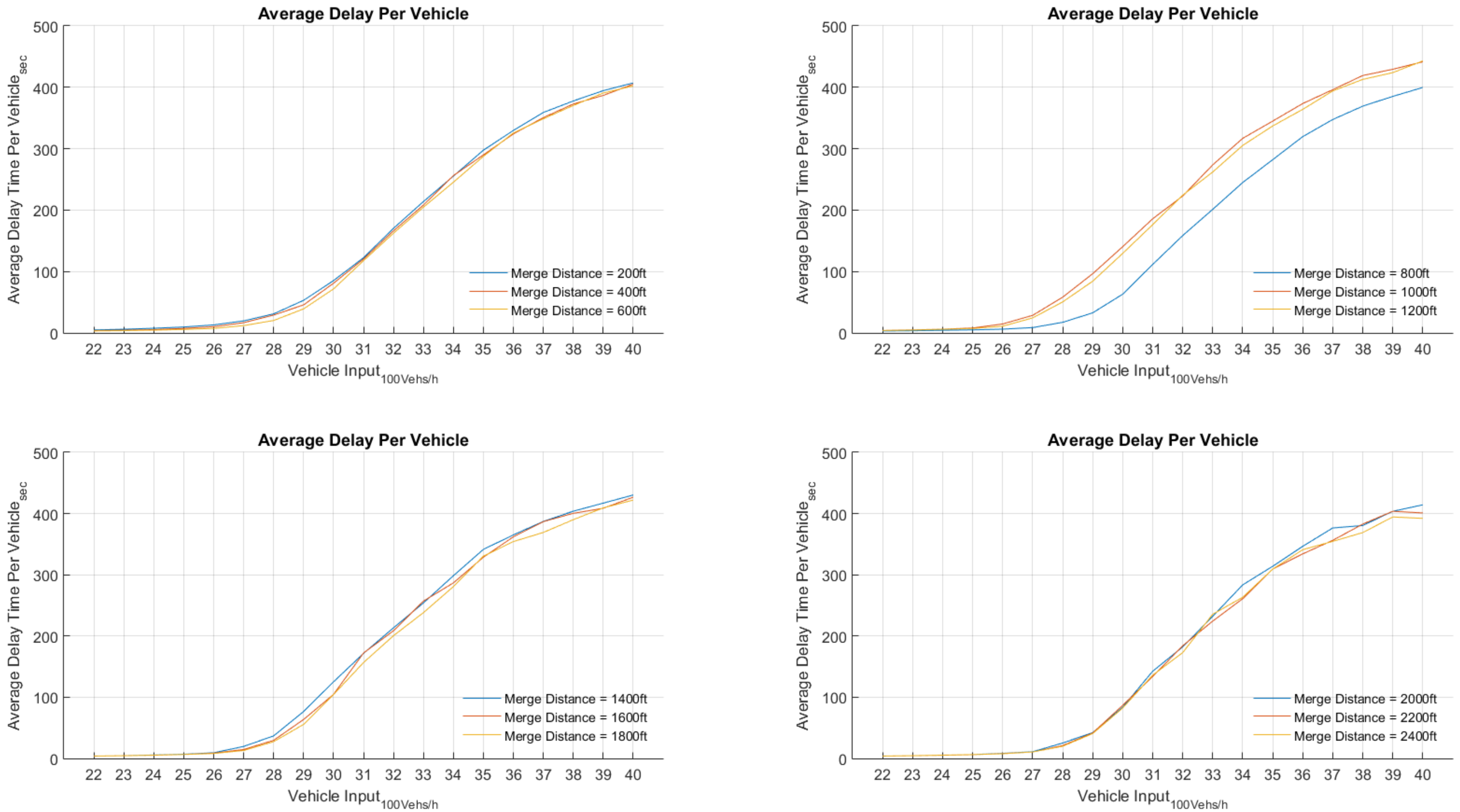


Figure 47 EM, CM, and LM average delay results for Type II work zone

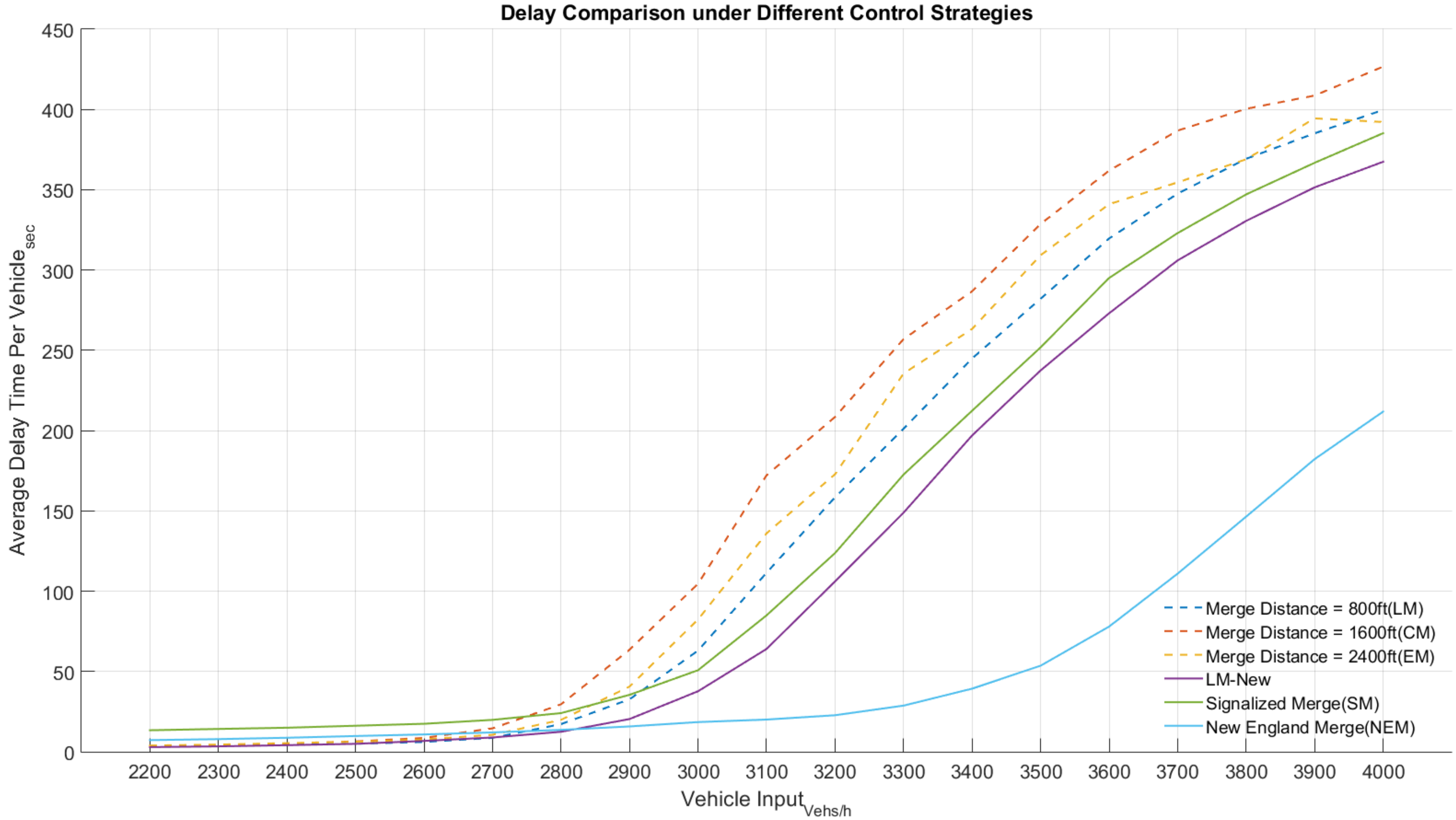


Figure 48 Comparison of average delay results for Type II work zone

Figure 48 compares all merge strategies in terms of average delay. The results suggest that:

- Overall, when the input volume is lower than 2,600 vph, it is better to consider control methods other than SM and NEM. When the input volume goes beyond approximately 2,900 vph, the benefits of using SM and NEM become clear. Similar findings are obtained from the results for Type I work zones. Again, this finding is consistent with the data included in the 2006 MassDOT Work Zone Management Manual [*105*], which suggests that the capacity for a three-lane highway work zone with one lane closed is around 2,980 vph. When the input volume is close to capacity, methods such as EM, CM, and LM usually do not work well; and
- When the volume is less than 2,700 vph, NEM generates higher delay than EM, CM, and LM. However, it outperforms SM under all flow conditions. Similar trends are also observed in the Type I work zone delay results.

6.4.2. Throughput

Figure 49 shows the throughput results for Type II work zones with EM, CM, and LM control. The following observations are made:

- For low traffic volumes (less than 2,600 vph), there is no difference among the three methods and the throughput is equal to the vehicle input;
- In general, as the merge distance increases, the throughput also goes up gradually and eventually stabilizes at 2,800 vph. However, there is a discontinuity (a significant throughput drop) between LM and CM (i.e., between 800 ft and 1,000 ft). This is caused by the different parameters used in LM and CM and the discussion in Section 6.4.1 also applies here. Since both CM and EM use the same set of VISSIM parameters, the transition from CM to EM is fairly smooth; and
- The maximum throughput achieved by LM is over 2,900 vph, while the maximum throughput for EM and CM is approximately 2,800 vph. The significant difference here also suggests the importance of properly selecting VISSIM parameters and collecting field data to calibrate them.

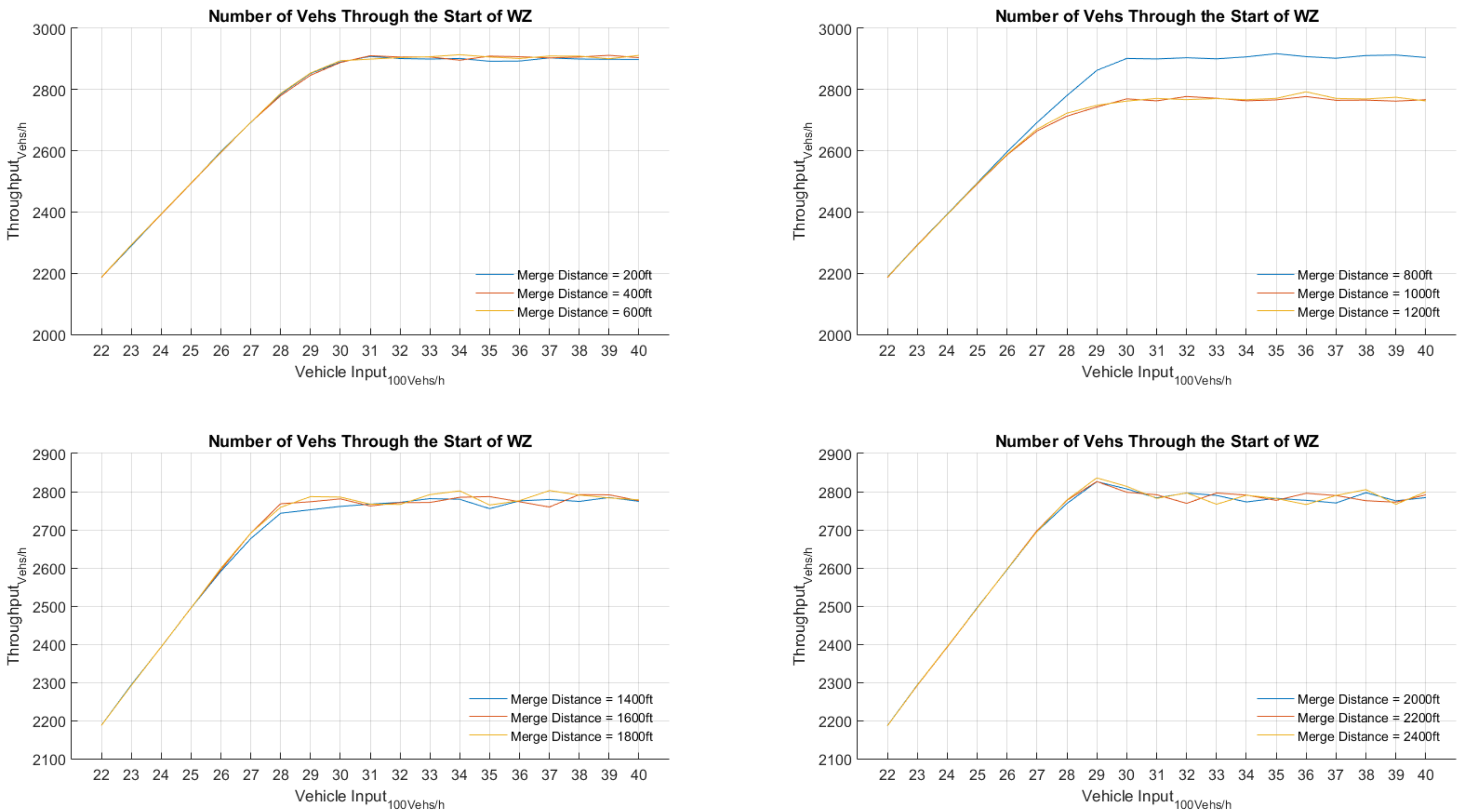


Figure 49 EM, CM, and LM throughput results for Type II work zone

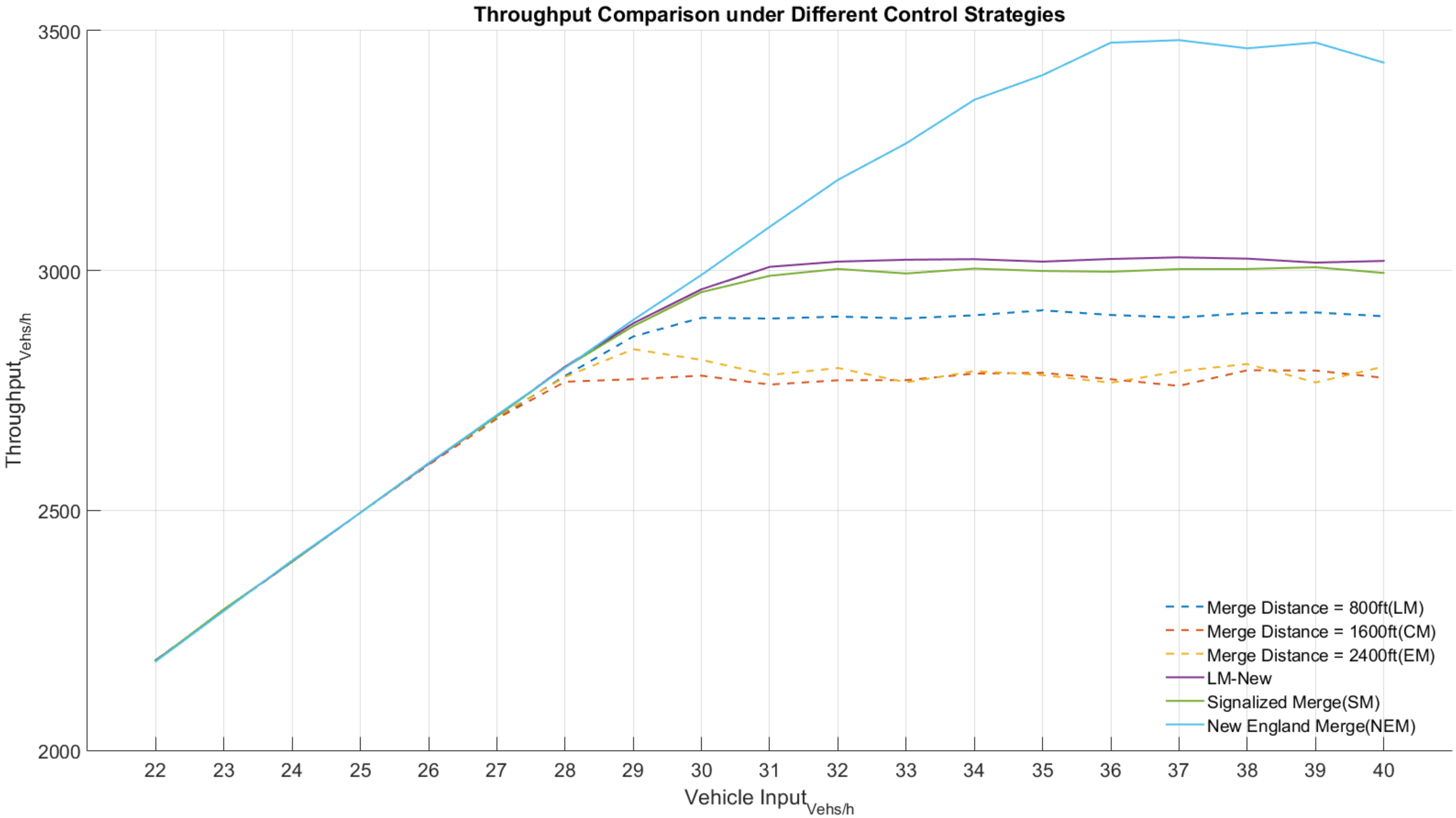


Figure 50 Comparison of throughput results for Type II work zone

Figure 50 compares all strategies in terms of throughput. Again, to avoid cluttering the figure, 800 ft, 1,600 ft, and 2,400 ft are selected to represent LM, CM, and EM, respectively. The results suggest that:

- When the input volume is less than 2,600 vph, all methods provide approximately the same throughput;
- Between 2,600 and 2,800 vph, SM, LM-New, and NEM begin to show clear advantages over the LM, EM, and CM methods. As mentioned before, LM-New tends to overestimate the throughput due to the limitation of the VISSIM "conflict area" tool. It is still included as a benchmark to show how well some other methods can perform;
- When the input flow is over 2,800 vph, SM, LM-New, and NEM significantly outperform the remaining methods, particularly EM and CM; and
- The maximum throughput generated by SM stabilizes at 3,000 vph, while the proposed NEM can reach almost 3,500 vph. Both SM and NEM merge controls use the same set of VISSM parameters. This significant throughput difference between them suggests that NEM is a very promising method.

6.4.3. Queue Length

Figure 51 shows the queue length results for EM, CM, and LM. The trend here is very different from the one for Type I work zones. The shorter queue lengths for LM are due to its more aggressive parameters. Unlike in Type I work zones, Type II work zones have two open lanes. The aggressive parameters for LM encourage vehicles in the middle lane to change to the left-most lane. Since vehicles in these two lanes have approximately the same speed, these lane changes will increase the throughput of the left-most lane (by filling large gaps and forming high-density and high-speed flows) and consequently the overall throughput. Higher throughputs typically lead to shorter queue lengths. While for Type I work zones, there is only one open lane. The aggressive parameters will only increase the chance for slow-moving vehicles in the right-most lane to interrupt the traffic in the left lane, reducing the overall throughput.

Figure 52 shows the queue length results for all methods. It can be seen that:

- Before the input volume reaches 2,900 vph, SM still generates significantly longer queues than LM, CM, and EM due to the control delay. When the input volume is greater than 2,900 vph, SM clearly outperforms those methods; and
- When the flow is less than, 2,600 vph, the queue length difference among NEM, CM, LM, and EM control methods is negligible. For higher input volumes, NEM consistently generates the shortest queue length.

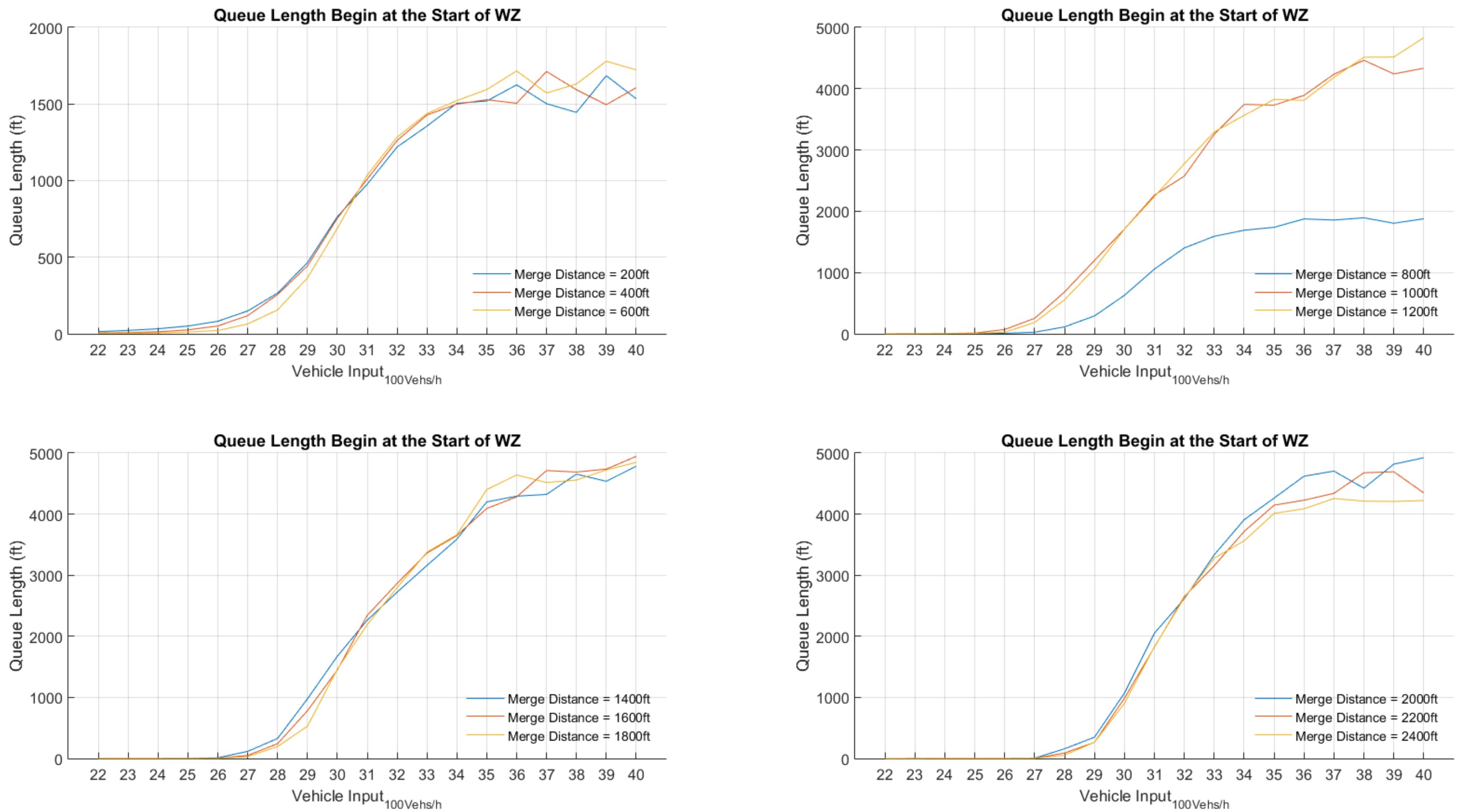


Figure 51 EM, CM, and LM queue length results for Type II work zone

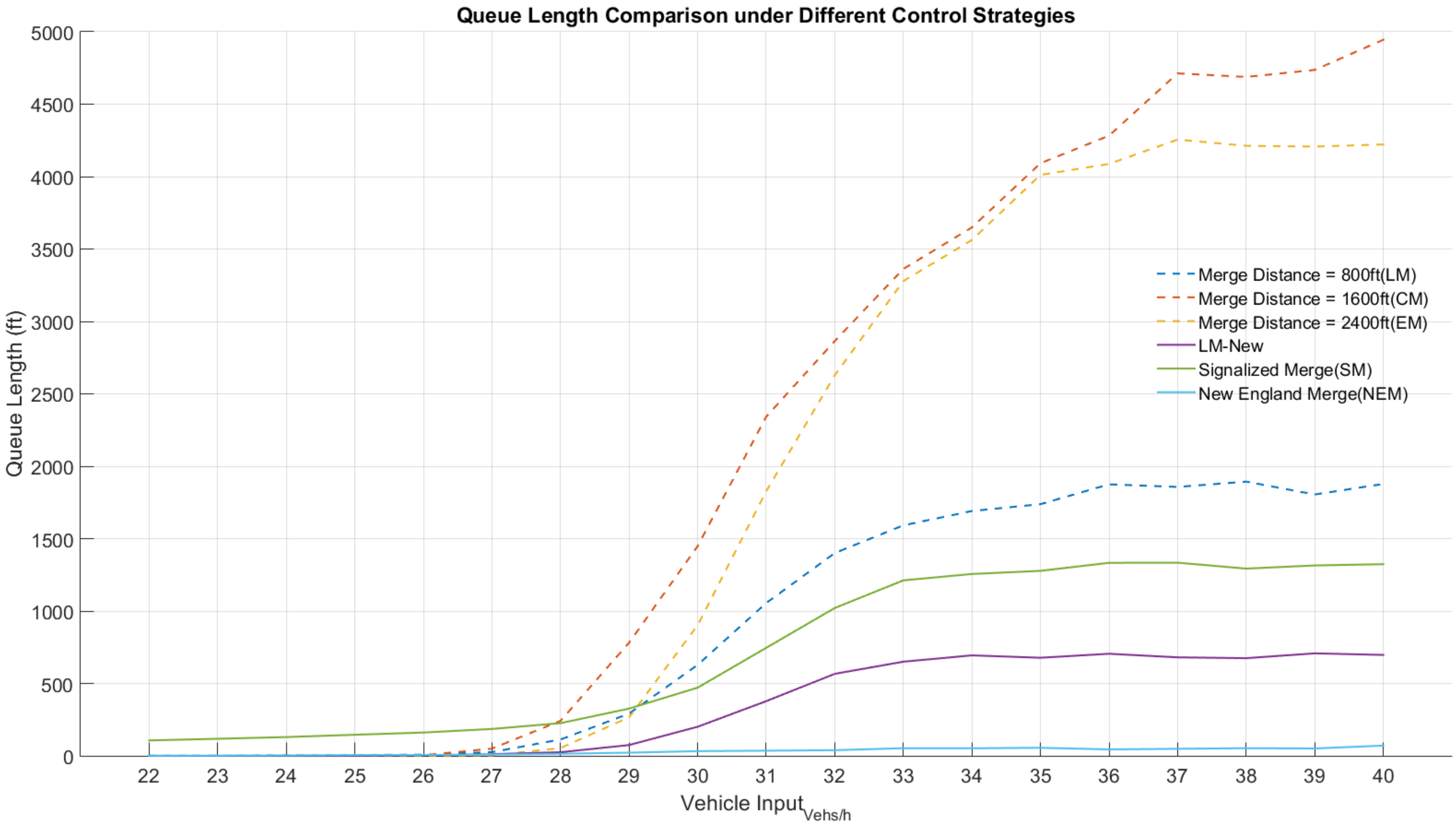


Figure 52 Comparison of queue length results for Type II work zone

6.4.4. Density

Using the density tool developed for VISSIM (see Section 6.3.4), the density maps for input volume = 2,800 vph without and with priority rule are shown in Figure 53 and Figure 54, respectively. The density results for a more congested case (volume = 3,800 vph) are presented in Figure 55 and Figure 56. Similar trends are observed in both traffic demand conditions, suggesting that the priority rule control can help to equalize the traffic densities of the open and closed lanes, although the changes for Type II work zones are less obvious compared to those for Type I work zones in Figure 43 through Figure 46.

6.5. Safety Analysis based on SSAM

Based on the vehicle trajectories simulated by VISSIM, this section further analyzes the safety performance of various work zone merge strategies. The analysis is based on the Surrogate Safety Assessment Model (SSAM) developed by the Federal Highway Administration (FHWA), and the results are organized by work zone types.

SSAM takes the trajectories of individual vehicles from VISSIM microscopic traffic simulator as the input. It then calculates the angle of approach (conflict angle) between two vehicles and the potential conflict severity. The conflict angle determines conflict type, which is classified as rear-end conflict if ||Conflict Angle|| < 30°, crossing conflict if ||Conflict Angle|| > 85°, and otherwise lane-changing conflict [*106*]. The conflict severity is determined mainly based on the Time to Collision (TTC) between conflicting vehicles. Note that SSAM is not able to model single-vehicle crashes.

As described in Section 2.5, a significant portion of work zone crashes are attributed to unsafe merge maneuvers. By adopting appropriate merge control strategies for different traffic flow conditions, traffic safety and efficiency at work zones may be improved [*107*]. To confirm this, six merge control strategies are evaluated using SSAM, which are:

- Early Merge (EM) with a merge distance of 2,400 ft;
- Conventional Merge (CM) with a merge distance of 1,600 ft;
- Late Merge (LM) with a merge distance of 800 ft;
- New late merge (LM-New) based on the VISSIM “conflict area” tool;
- Signalized Merge (SM); and
- New England Merge (NEM)

In addition to different merge strategies, three input traffic demand levels are considered in the SSAM analysis, which are 1,000 vph, 1,500 vph, and 2,000 vph for Type I work zones and 2,400, 3,200, and 4,000 vph for Type II work zones.

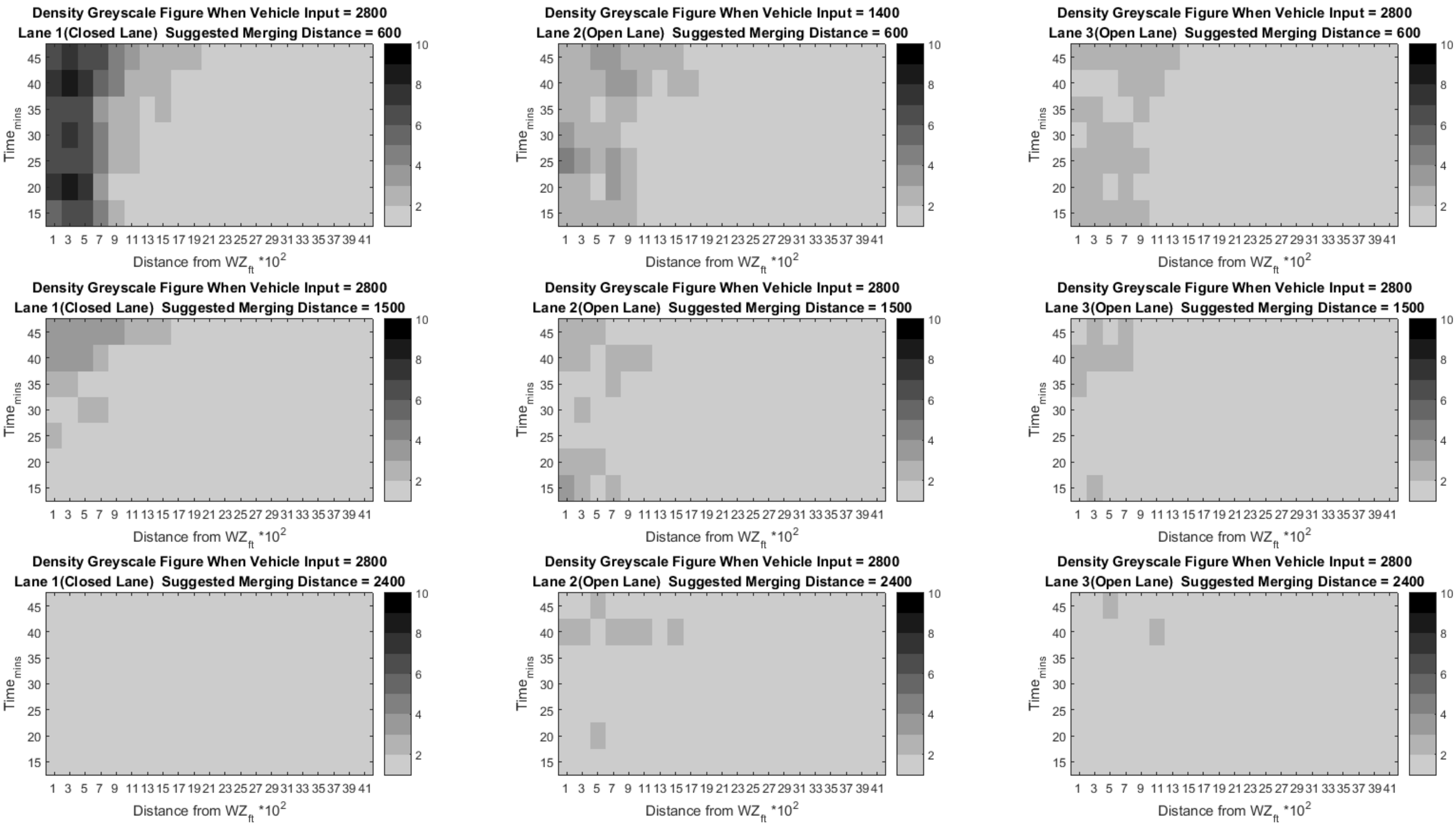


Figure 53 Density map for Type II work zone without priority (Volume = 2,800 vph)

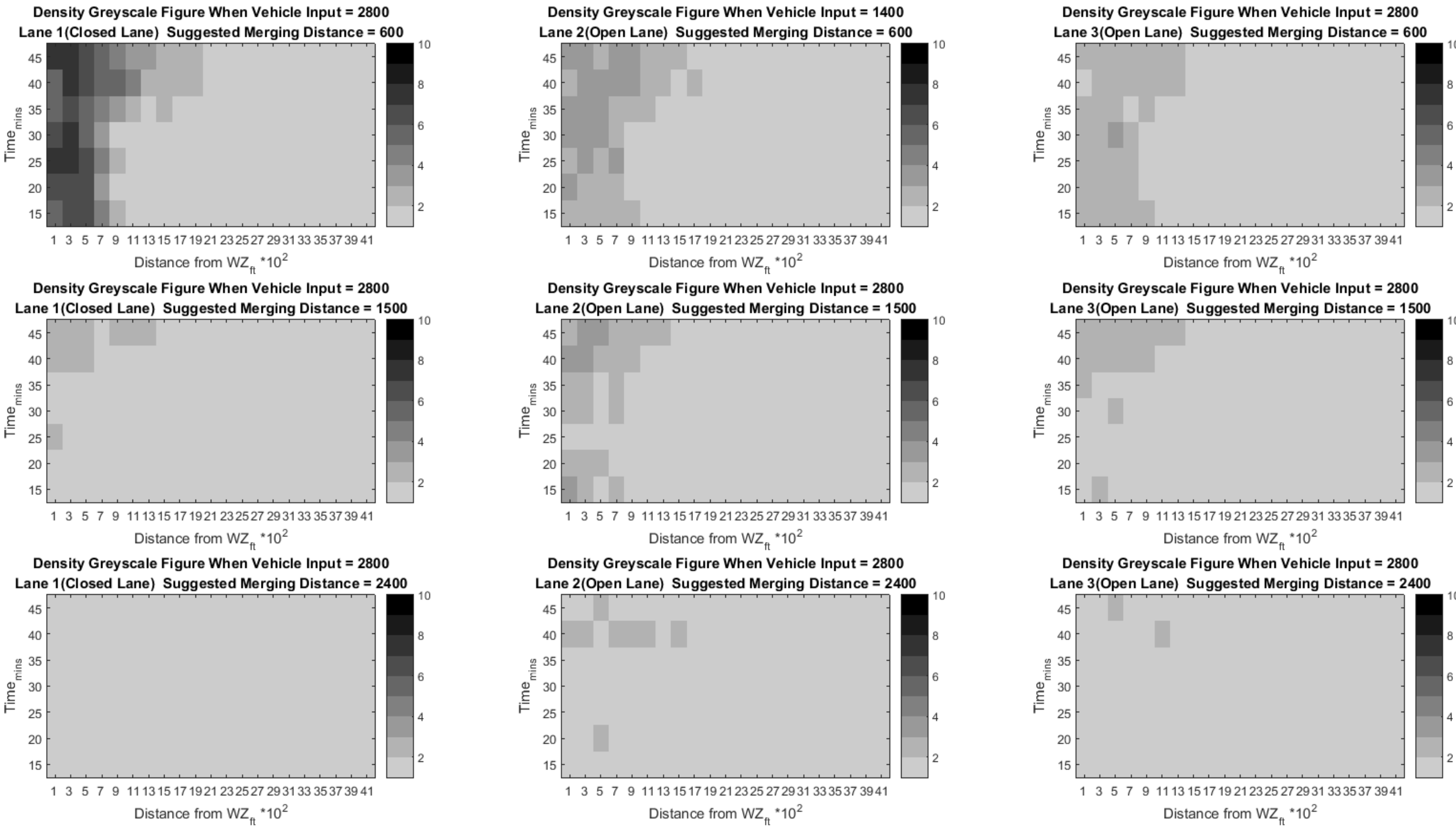


Figure 54 Density map for Type II work zone with priority (Volume = 2,800 vph)

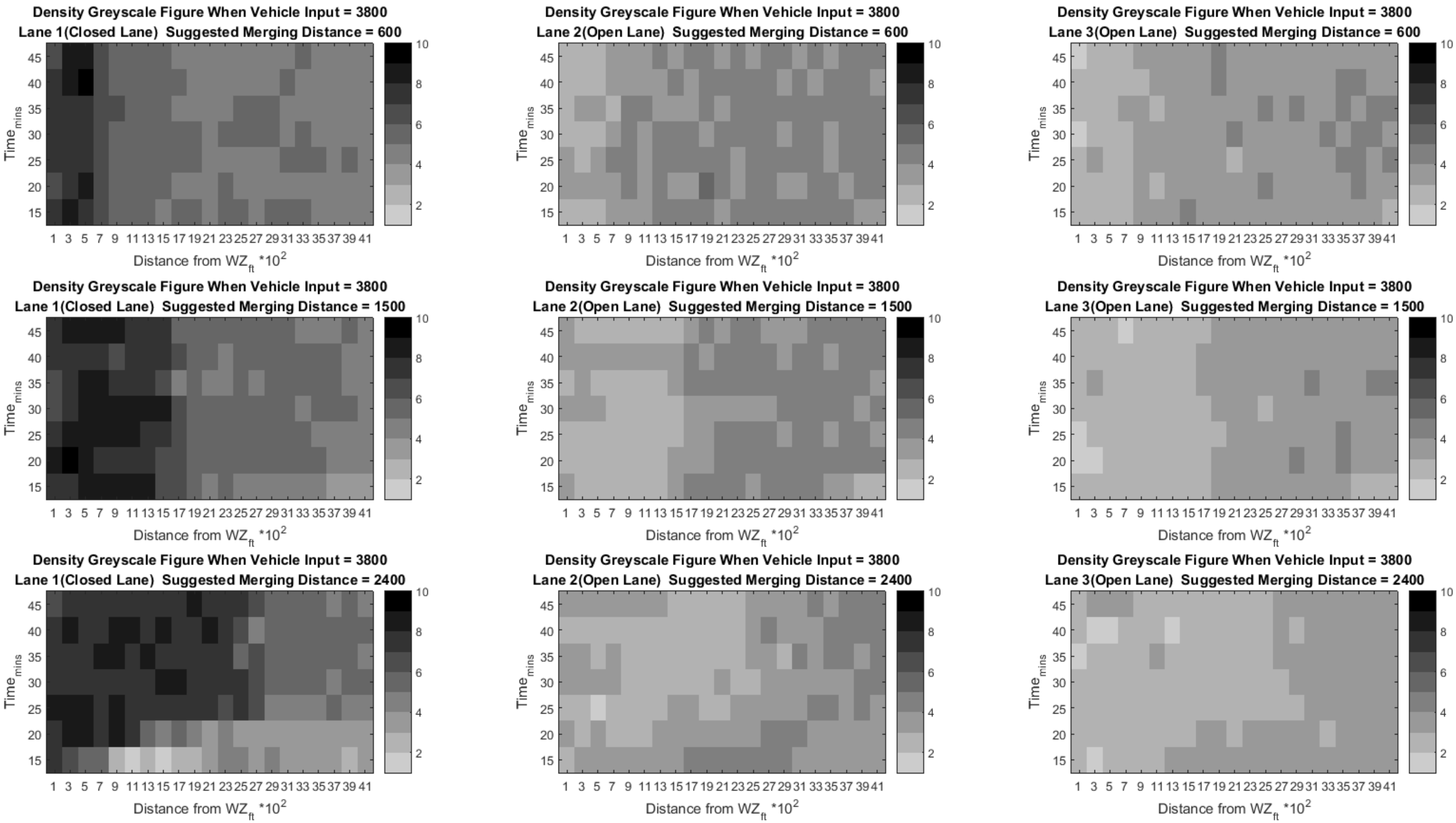


Figure 55 Density map for Type II work zone without priority (Volume = 3,800 vph)

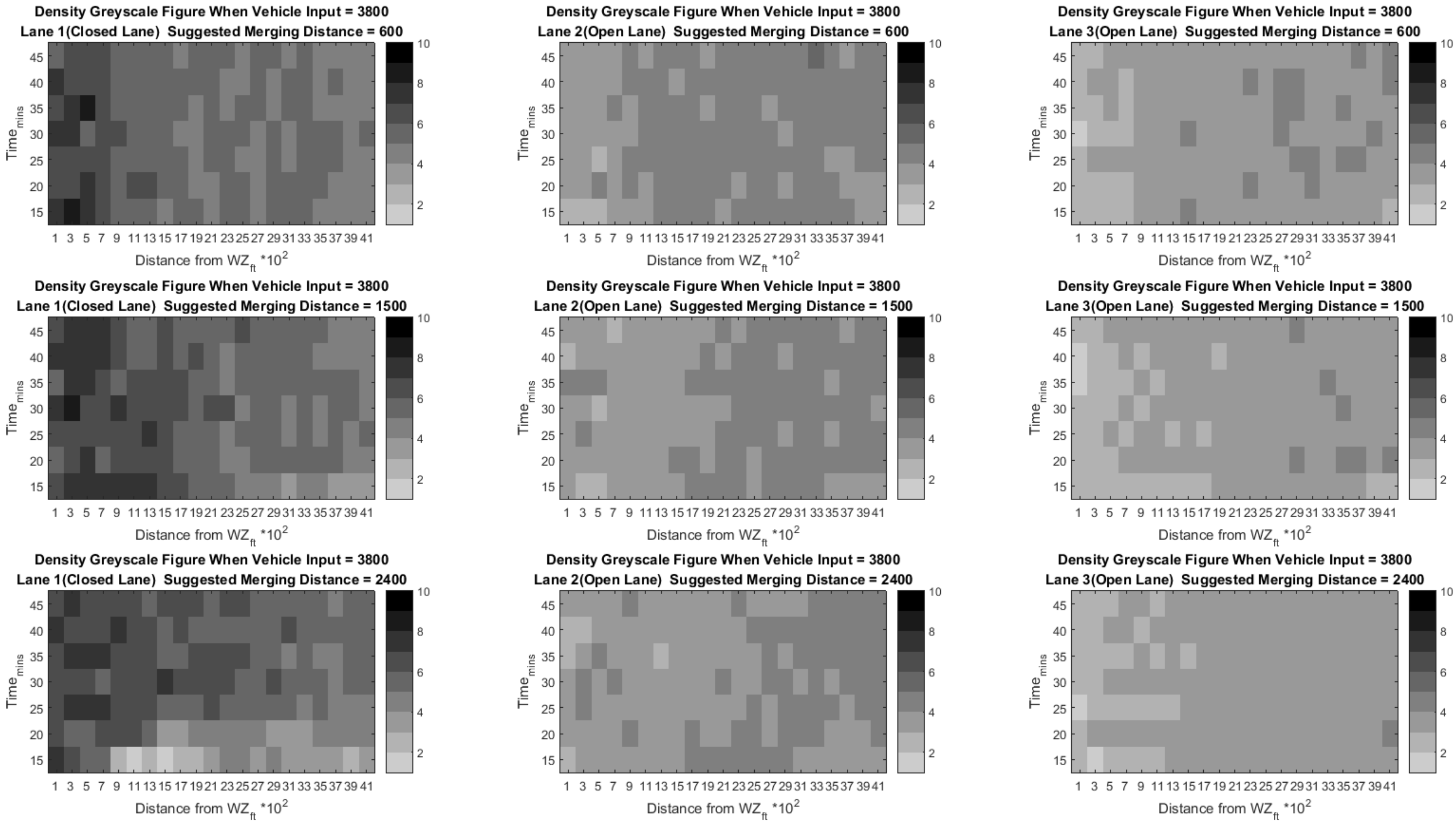


Figure 56 Density map for Type II work zone with priority (Volume = 3,800 vph)

6.5.1. Type I Work Zone

Table 31 SSAM results for Type I work zones

Merge Control Method & Input Volume	Total conflicts (a+b)	Rear-end conflicts (a)	Lane-change conflict (b)	TTC
LM-New				
1,000 vph	42	42	0	0.11
1,500 vph	646	643	3	0.70
2,000 vph	13,406	13,383	23	1.15
LM				
1,000 vph	3	2	1	0.81
1,500 vph	2,140	2,108	32	1.15
2,000 vph	15,987	15,918	69	1.19
CM				
1,000 vph	3	3	0	0.89
1,500 vph	784	768	17	1.17
2,000 vph	11,435	11,354	81	1.20
EM				
1,000 vph	3	2	1	0.72
1,500 vph	905	898	8	1.24
2,000 vph	8,689	8,618	71	1.20
NEM				
1,000 vph	18	17	1	0.51
1,500 vph	16	15	1	0.68
2,000 vph	4,156	4,136	20	1.14
SM				
1,000 vph	65	65	0	1.17
1,500 vph	290	289	1	1.14
2,000 vph	10,760	10,733	27	1.21

The SSAM evaluation results for Type I work zones (two-lane highway with one lane closed) are shown in Table 31, including total number of conflicts, number of rear-end conflicts, number of lane-change conflicts, and TTC. The number of conflicts results are also illustrated in Figure 57 through Figure 59. The following observations regarding the numbers of conflicts are made:

- As the input volume increases, the numbers of conflicts of different merge control types all increase drastically;
- Compared to rear-end conflicts, the numbers of lane-change conflicts are almost negligible under all traffic flow conditions;
- At the 1,500 and 2,000 vph input flow levels, NEM generates the lowest numbers of total conflicts, and EM generates the second lowest numbers of total conflicts. Although SM

is able to generate satisfying throughput performance (see Figure 40), it also leads to significantly high rear-end risk;

- Both NEM and SM result in higher numbers of conflicts than LM, CM, and EM at the 1,000 vph flow level. This suggests that NEM and SM are unsuitable when the input volume is low and it is better to let drivers decide the best merge maneuvers;
- LM-New is introduced to show the maximum throughput that LM may achieve. As shown in Figure 40, LM-New generates lower maximum throughputs than SM under congested conditions (e.g., flow greater than 1,500 vph). The data in Table 31 suggests that LM-New also underperforms SM in terms of total number conflicts under congested conditions; and
- Overall, the number of conflicts results show that NEM is the best merge control strategy under moderate to congested traffic conditions.

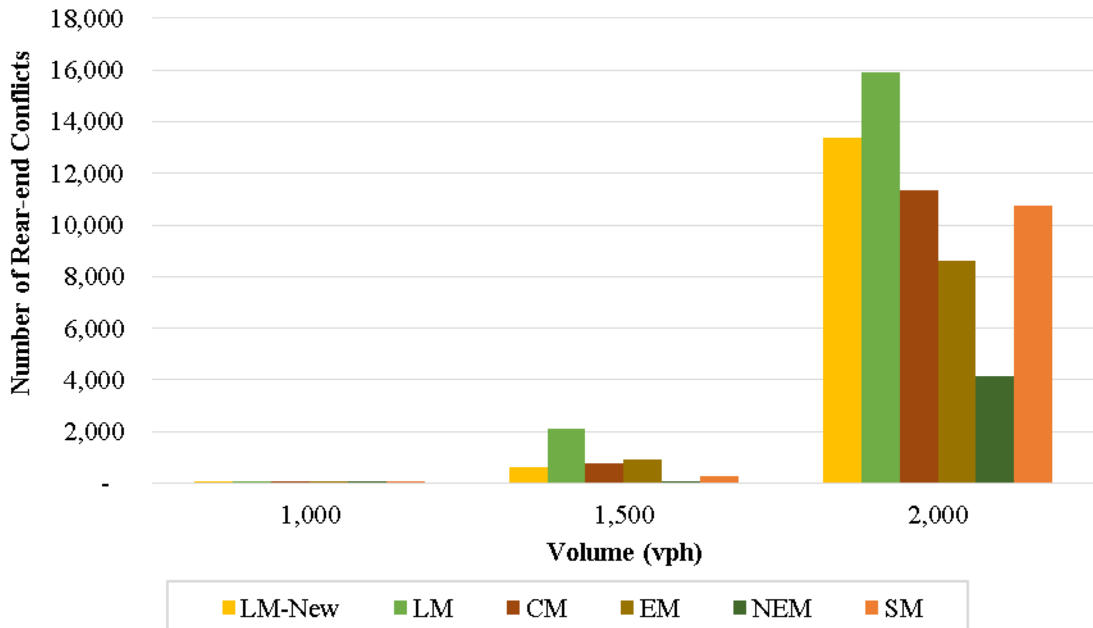


Figure 57 Number of rear-end conflicts for Type I work zones

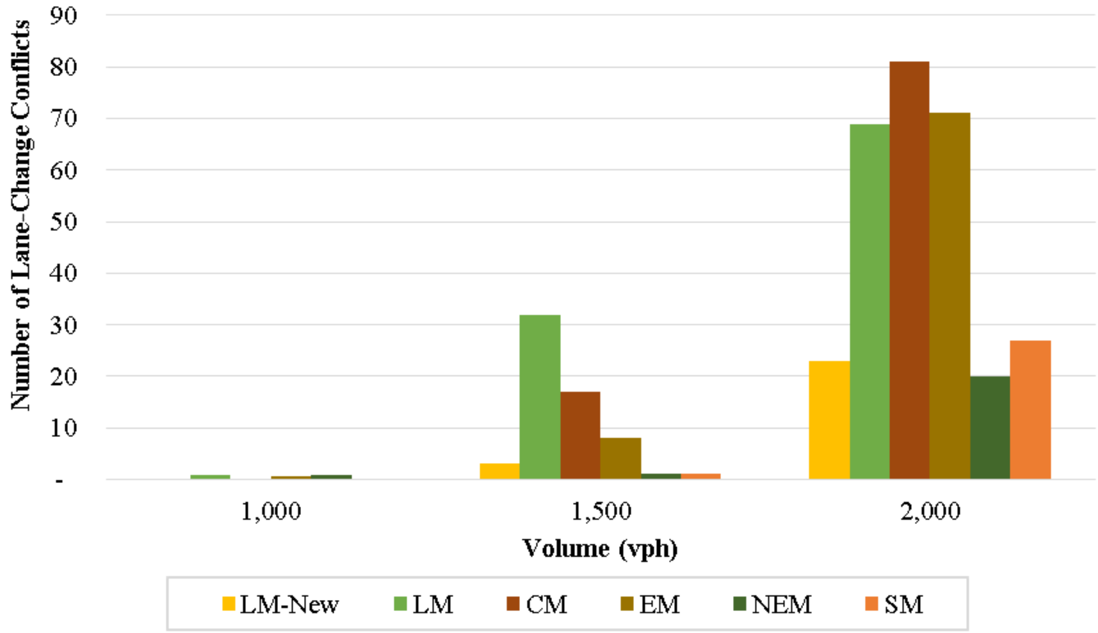


Figure 58 Number of lane-change conflicts for Type I work zones

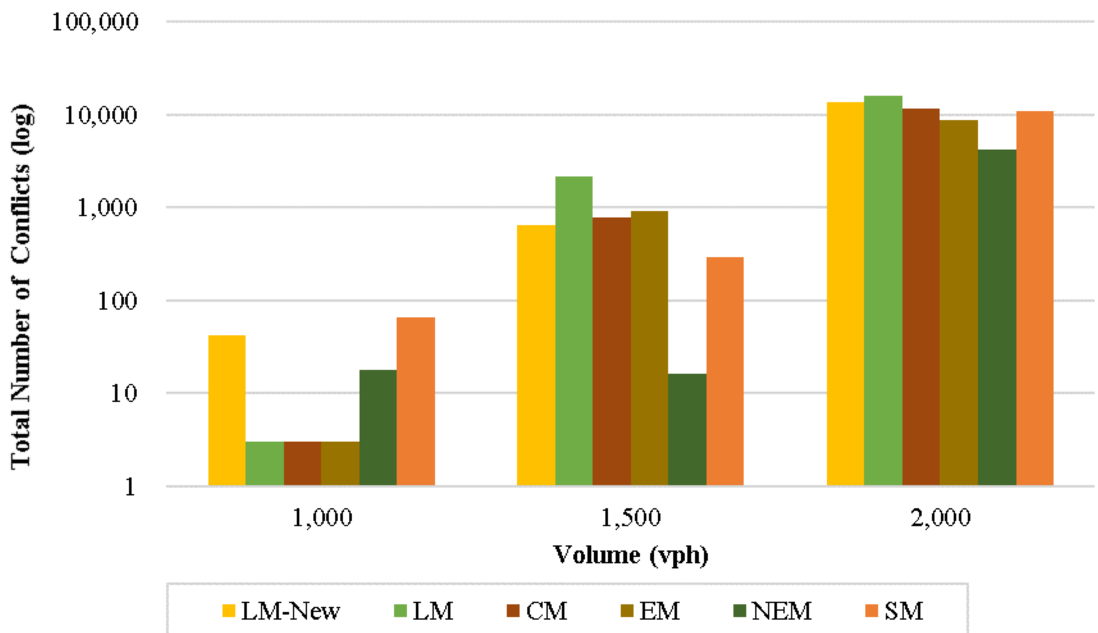


Figure 59 Number of all conflicts for Type I work zones

Another important safety measure, Time to Collision (TTC), is defined as the minimum time-to-collision value estimated during a conflict. This estimate is based on the current locations, speeds, and trajectories of two vehicles at a given instant [*106*], and low TTC values indicate more severe crashes (not necessarily more crashes). The TTC results in Figure 60 show that:

- On average LM-New and NEM generate lower TTC values than the remaining methods, particularly when the input volume is less than 1,500 vph;
- When the input volume is at 2,000 vph, all methods perform about the same in terms of TTC;
- The TTC results for SM are almost the same for all flow levels;
- In general, as the input volume increases, the average TTC also increases. This is probably because vehicles travel at higher speeds during lower volume cases, and result in smaller TTC values; and
- Although the TTC performances of NEM are not the best, considering its very low numbers of conflicts, it is still a very competitive and promising method for work zone merge control.

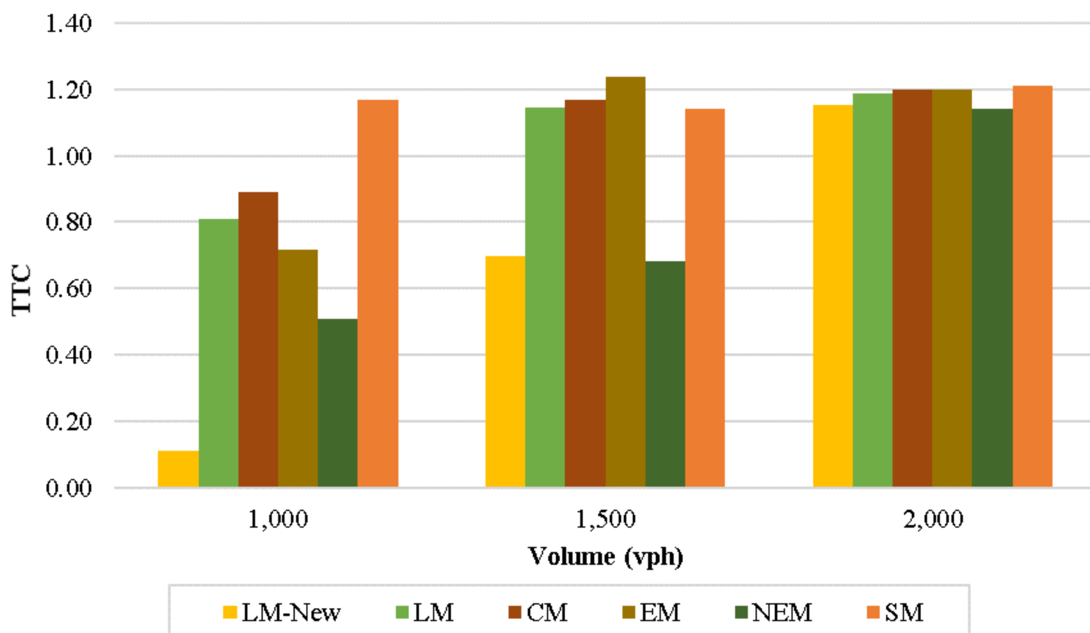


Figure 60 TTC results for Type I work zones

In addition to number of conflicts and TTC, merge control strategies also affect how conflicts are distributed [*106*]. As shown in Figure 61, the Type I work zone in this study is divided into 13 cells and each cell is 300 ft long. Cell 0 (see horizontal axis) represents the road segment 600 ft downstream of the merge point and Cell 2 denotes the lane closure location. In each cell, the blue column is for rear-end conflicts and the maroon one is for lane-change conflicts. For cells without any columns, there are no conflicts of any types in them.

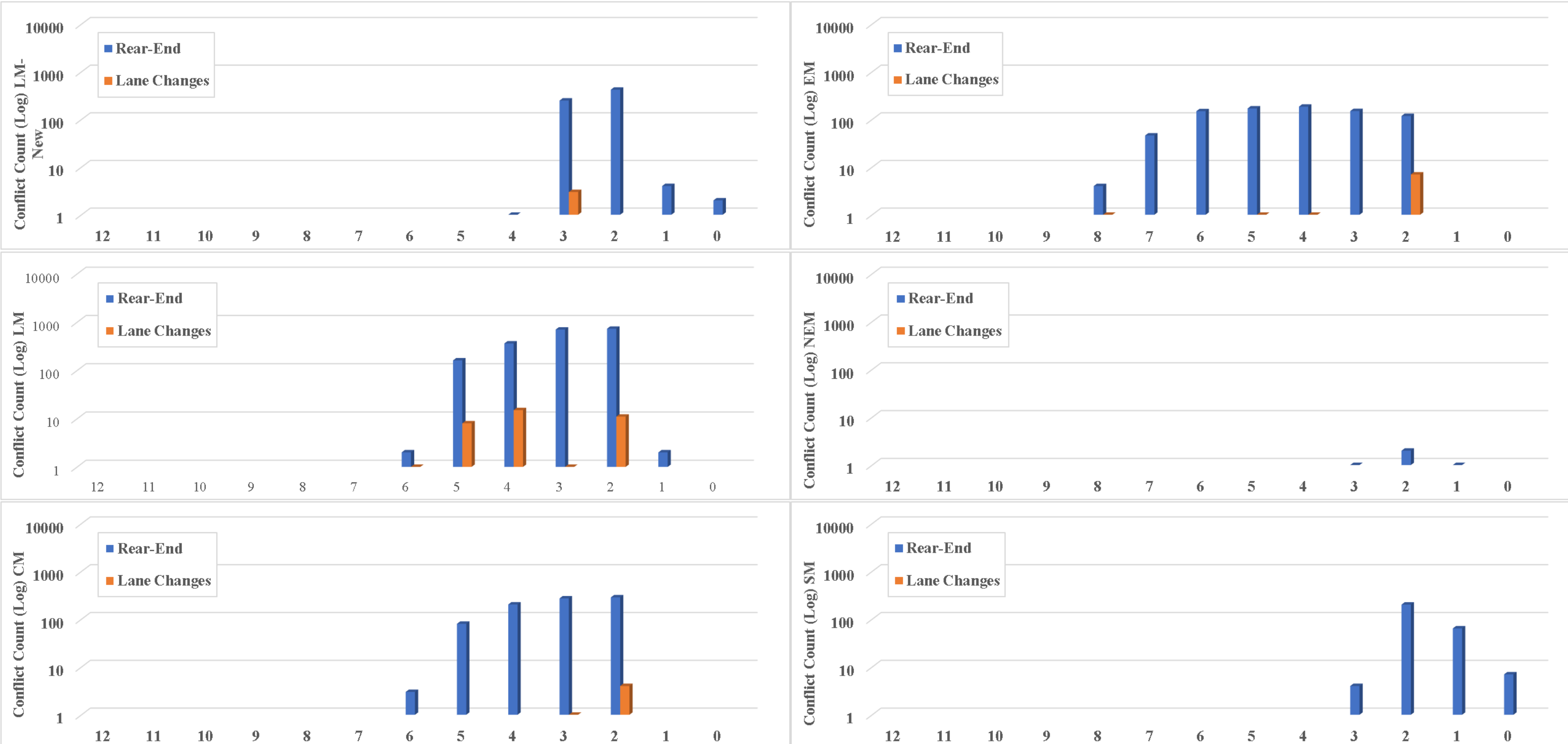


Figure 61 Distribution of conflicts for Type I work zones at 1,500 vph

6.5.2. Type II Work Zone

Table 32 SSAM results for Type II work zones

Merge Control Method & Input Volume	Total conflicts (a+b)	Rear-end conflicts (a)	Lane-change conflict (b)	TTC
LM-New				
2,400 vph	189	171	18	0.35
3,200 vph	5,659	5,537	122	1.08
4,000 vph	18,144	17,999	146	1.23
LM				
2,400 vph	43	30	12	0.93
3,200 vph	6,072	5,891	181	1.20
4,000 vph	17,403	17,205	199	1.25
CM				
2,400 vph	25	14	11	0.70
3,200 vph	6,233	6,084	150	1.22
4,000 vph	17,446	17,291	155	1.25
EM				
2,400 vph	24	14	10	0.63
3,200 vph	6,156	6,022	134	1.22
4,000 vph	15,757	15,611	146	1.25
NEM				
2,400 vph	41	23	18	0.32
3,200 vph	245	174	72	0.58
4,000 vph	11,899	11,606	294	1.28
SM				
2,400 vph	209	202	7	1.12
3,200 vph	5,473	5,330	143	1.10
4,000 vph	18,603	18,412	192	1.22

The SSAM results for Type II work zones (three-lane highway with the right-most lane closed) are shown in Table 32. The number of conflicts results are also illustrated in Figure 62 through Figure 64. The following observations regarding number of conflicts are made:

- Overall, NEM results in the lowest total number of conflicts at 3,200 and 4,000 vph. At 2,400 vph, NEM generates more conflicts than CM and EM;
- NEM leads to the highest number of lane-change conflicts at 4,000 vph, although this is much smaller than the number of rear-end conflicts. The large number of lane-change conflicts for NEM is partially due to its much higher throughput at this input flow than other merge methods. As shown in Figure 50, the throughput for NEM at 4,000 vph is almost 500 vph higher than the second best performing method; and

- At low to medium input traffic levels, NEM results in smaller TTCs than other methods, but also smaller numbers of conflicts. When the input flow is at 4,000 vph, NEM generates a larger TTC and a smaller number of total conflicts, suggesting that it is more suitable for congested traffic conditions.

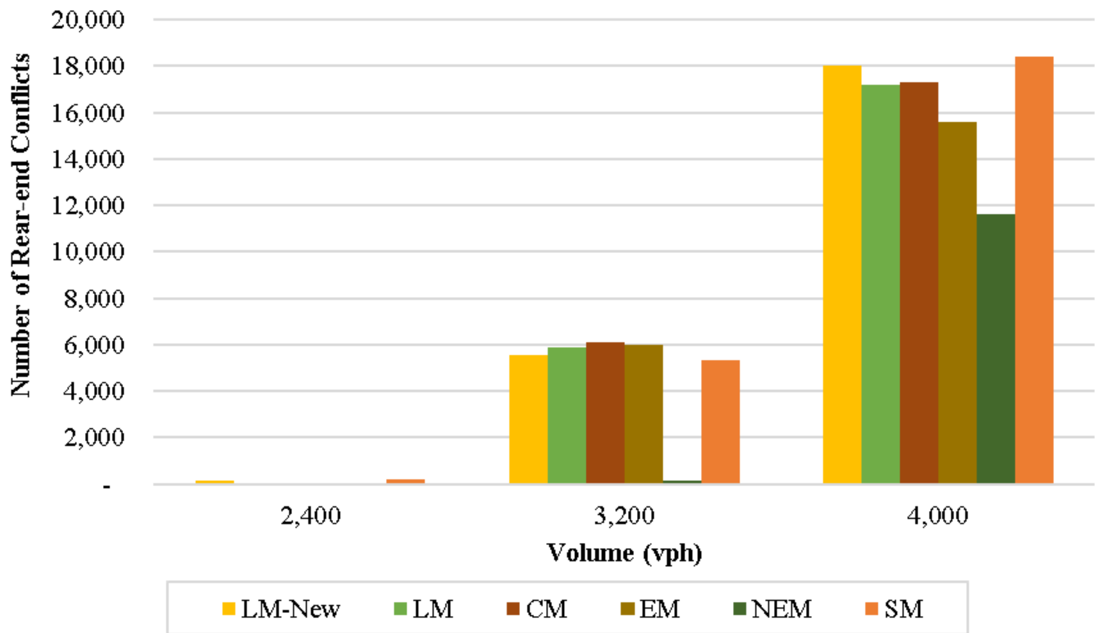


Figure 62 Number of rear-end conflicts for Type II work zones

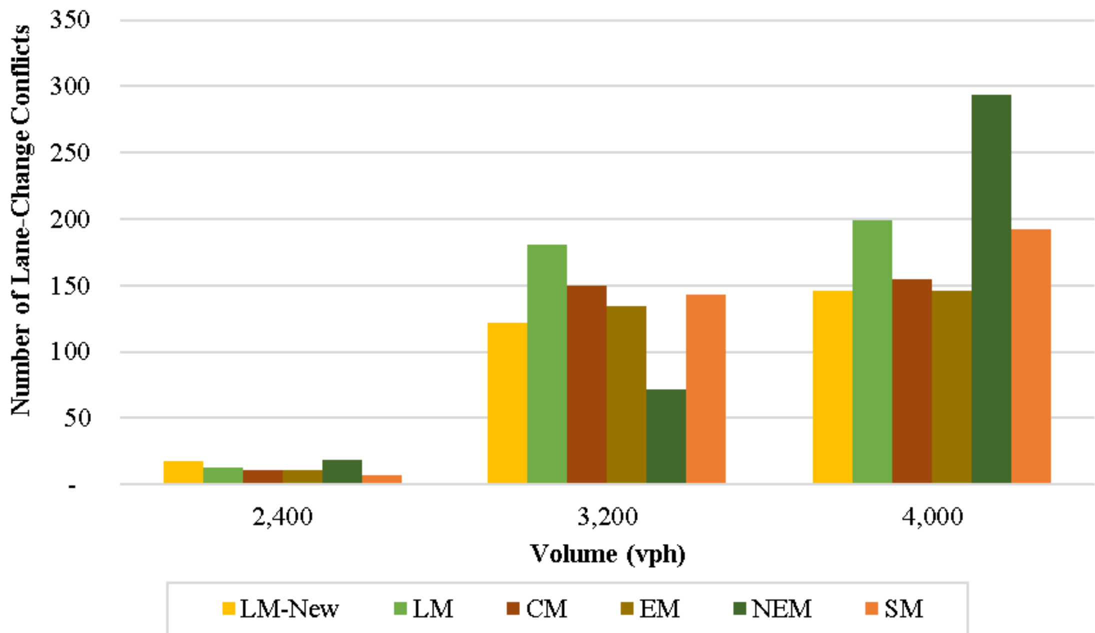


Figure 63 Number of lane-change conflicts for Type II work zones

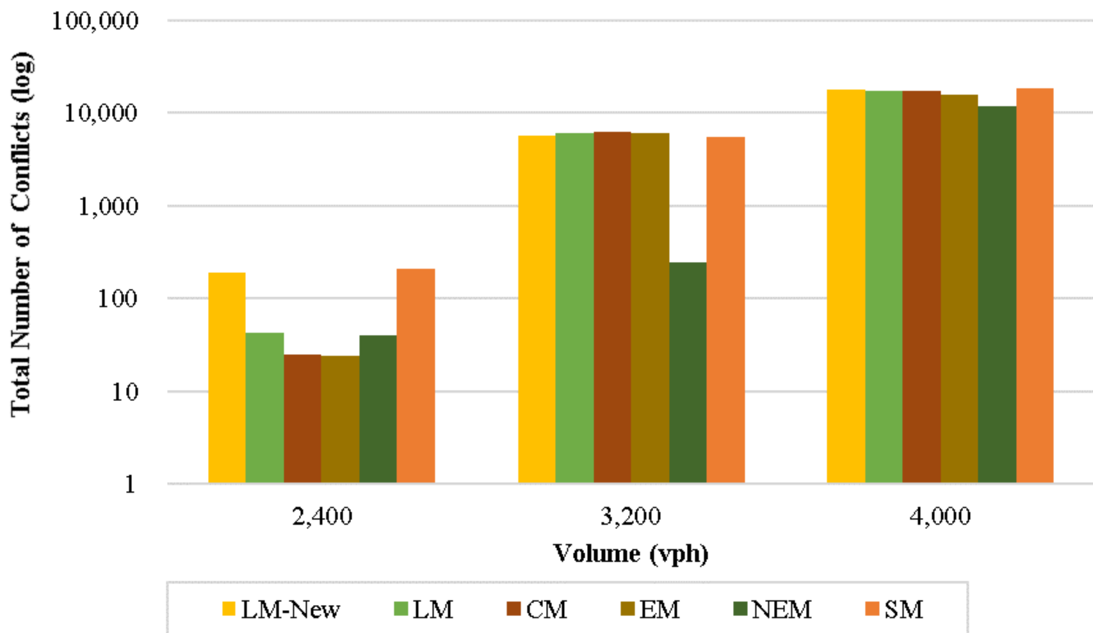


Figure 64 Number of all conflicts for Type II work zones

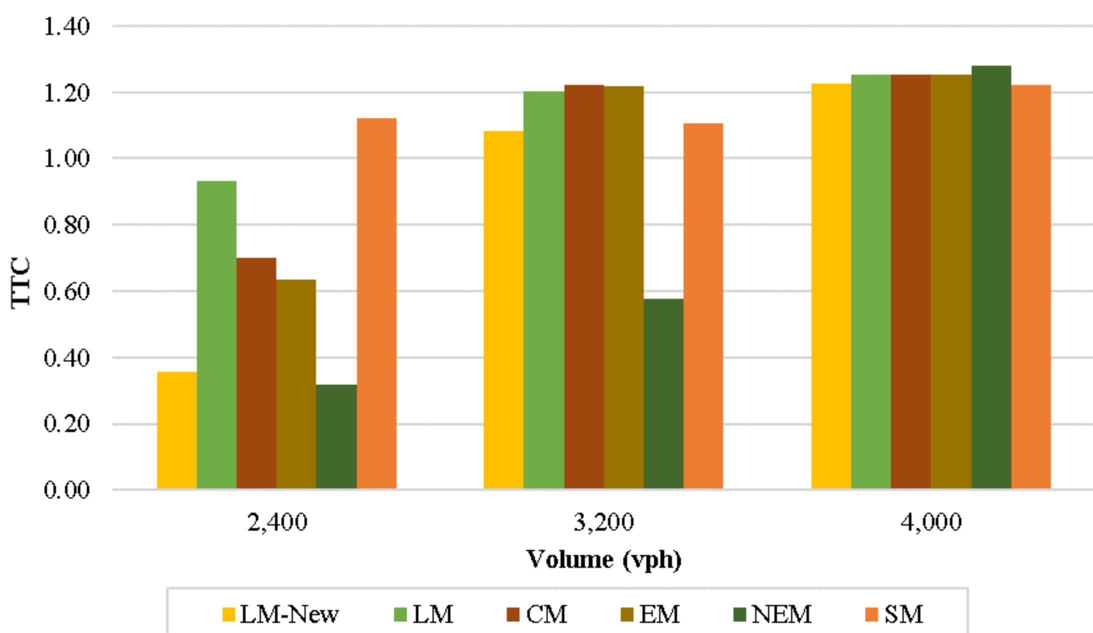


Figure 65 TTC results for Type II work zones

A conflict distribution analysis is also performed for Type II work zones. As shown in Figure 66, the Type II work zone in this study is divided into 24 cells and each cell is 300 ft long. Using 24 cells instead of 13 as in the previous subsection is to cover a longer distance. Again, Cell 0 (see horizontal axis) represents the road segment 600 ft downstream of the merge point and Cell 2 denotes the lane closure location. For NEM control, Cell 16 is the beginning point where lane changes are prohibited. In each cell, the blue column is for rear-end conflicts and the maroon one is for lane-change conflicts. For cells without any columns, there are no conflicts of any types in them. It can be seen that:

- NEM generates the least amount of conflicts and most of them occur before Cell 16. Clearly the meter zone pushes the queue start point upstream. At the merge point, NEM results in a much lower number of conflicts than other methods;
- LM-New, LM and SM all generate significant numbers of conflicts even after the merge point. For NEM, there are no conflicts beyond the merge point; and
- The large number of conflicts near Cell 17 for NEM is probably caused by vehicles trying to switch to the left-most lane, which is not interrupted by the merging traffic at the merge point and is therefore more attractive. In Type I work zones, such a lane does not exist and this is why we do not see a large number of conflicts near Cell 17. To reduce the amount of conflicts near Cell 17, an extended no-lane-change zone may be set up before the meter zone to prohibit lane changes between the middle lane and the left-most lane.

6.5.3. Conclusions

The SSAM results for both Type I and Type II work zones are presented and discussed in this section. Overall, the SSAM results suggest that as the input volume increases, the total numbers of conflicts also increase for each merge control method, but the average severities of conflicts in general tend to decrease (as manifested by the increased TTCs) probably due to reduced travel speeds as an effect of congestion. Compared to rear-end conflicts, the number of lane-change conflicts is almost negligible for both Types I and II work zones.

For Type I work zones, NEM generates the lowest number of conflicts for heavily congested traffic conditions (e.g., 2,000 vph), but produces one of the highest numbers of conflicts for relatively low traffic volumes (e.g., 1,000 vph). The TTC results show that NEM generates significantly lower TTC values at 1,000 and 1,500 vph than most other methods, but comparable TTC values at 2,000 vph with other methods. This suggests that NEM is better for oversaturated traffic conditions in terms of both safety and average delay (see Figure 38), but not for low traffic inputs. Such a conclusion also applies to Type II work zones. For Type II work zones, an interesting phenomenon is that NEM results in significant numbers of rear-end and lane-change conflicts upstream of the meter zone. This is because for Type II work zones the left-most lane is not affected by the merging traffic at the lane closure point, and is more attractive to vehicles approaching the meter zone. This generates many lane changes before the meter zone, contributing to many lane-change and rear-end conflicts.

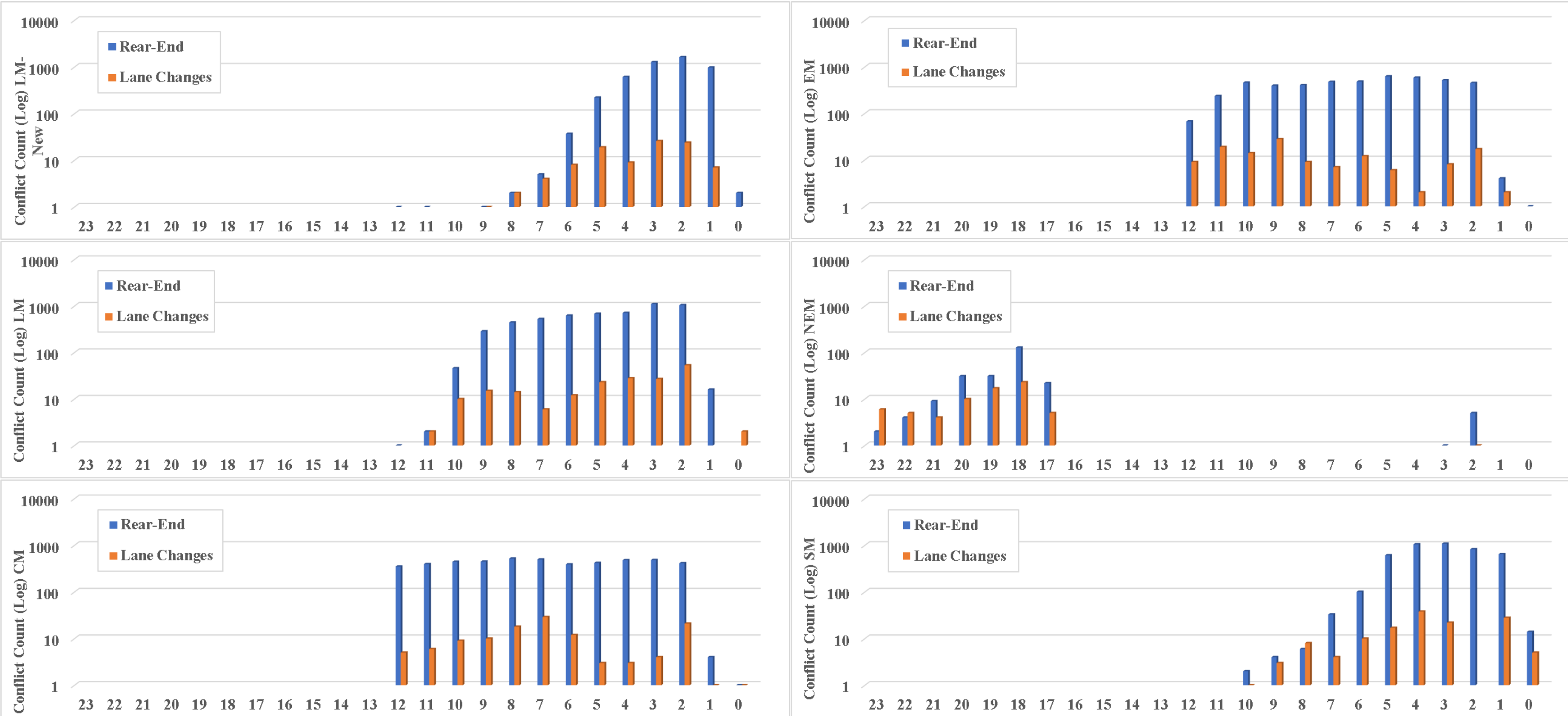


Figure 66 Distribution of conflicts for Type II work zones at 3,200 vph

6.6. Discussion and Recommendations

To thoroughly investigate the impacts of merge control on work zone mobility, Aimsun simulations are also conducted to evaluate EM, CM, LM, and SM control. Based on the default car-following and lane-changing parameters in Aimsun, the issue of large speed gaps between the open and closed lanes in VISSIM (see Figure 36) is not seen during Aimsun simulations. Further investigations of the Aimsun result suggest that default Aimsun parameters often lead to overestimated work zone throughputs. For Type I work zones, the simulated throughput by Aimsun can go beyond 2,000 vph regardless of the merge control type and merge distance. To address this issue, the research team modified the default Aimsun parameters to bring the simulated throughput for CM down to approximately 1,450 vph [*105*]. However, this caused the large speed gaps issue observed in VISSIM to also occur in Aimsun. Given that both simulation tools are not specifically designed to model work zone merge control and have some limitations, the research team decided to focus on only one tool (i.e., VISSIM) and try to address the limitations by customizing it (See Section 6.2).

Based on the VISSIM simulations conducted in this research and the comprehensive literature review, the following recommendations regarding work zone merge control are provided. Note that the recommendations are not simply made based on the simulation results, as VISSIM does not have a specific module for modeling work zone merge maneuvers and cannot take all practical impact factors into consideration. For example, drivers in the open lane may choose to yield to a vehicle in the closed lane as it gets very close to the merge point or after it has been waiting for a gap for too long. Also, vehicles in the closed lane may intentionally keep a large gap with the lead vehicle, which will allow them to accelerate to the open-lane speed and merge safely. Based on the simulation results and some practical considerations, the recommendations for Type I work zone merge control are:

- When the input volume is less than 1,300 vph, LM, EM, CM, and NEM all perform better than SM in terms of average delay and queue length. Taking safety into consideration, CM might be better;
- When the input volume is greater than 1,500 vph, SM and NEM appear to be always better than LM, CM, and EM in terms of almost all measures considered and can be used if they are properly implemented without confusing drivers. Given the confusion that SM may introduce, NEM is recommended in this case;
- When the input volume is between 1,300 vph and 1,500 vph, among LM, EM, and CM it might be better to use LM from a practical standpoint, although EM under this situation appears to generate the highest throughput, lowest average delay, and shortest queue length based on the simulation results. Utilizing a single lane (i.e., EM) instead of all available lanes in practice will lead to long queues, causing traffic to spread to upstream ramps or even surface streets. Additionally, an empty lane next to a long queue may increase driver noncompliance of the no-passing sign of EM, leading to aggressive driving behaviors such as lane straddling, queue jumping, and forced late merge. When the traffic volume is high and there is no proper law enforcement, EM is likely to essentially become LM; and

- When the volume is between 1,300 vph and 1,500 vph, NEM is preferred over the above LM considering its much lower number of potential conflicts and higher throughput.

For Type II work zone merge control:

- When the input volume is less than 2,700 vph, LM, EM, and CM all perform better than SM in terms of average delay and queue length, but not throughput. Taking implementation feasibility and safety into consideration, LM is recommended for this case;
- When the input volume is greater than 3,000 vph, SM and NEM should be considered and NEM is more preferred due to its better performance; and
- When the input volume is between 2,700 vph and 3,000 vph, among EM, CM, and LM it again might be better to use LM from a practical standpoint. When SM and NEM are also considered, NEM is recommended over LM.

7. DISCUSSION AND SUMMARY

This research focuses on two critical factors that influence the mobility and safety of highway work zones: speed control and merge control. Among them, speed control is investigated using the Naturalistic Driving Study (NDS) data and an innovative Virtual Reality (VR) driving simulator. For merge control, VISSIM and SSAM tools are used to evaluate various merge control strategies, including a New England Merge (NEM) proposed in this research. Additionally, a comprehensive review of existing speed and merge control methods is conducted.

This report describes what the research team has accomplished in the areas listed below. Some of the findings are summarized briefly in this Chapter. More detailed summaries and recommendations are provided at the ends of individual chapters or subsections.

- Review and development of Temporary Traffic Control Plans (TTCPs) for work zone speed control and merge control
- Analysis of NDS data
- Analysis of SWZ data
- Development of VR-based driving simulator and VR driving simulation study to evaluate the speed reduction effects of various TTCPs
- VISSIM microscopic simulation analysis of work zone merge control strategies in terms of mobility performance
- SSAM analysis of the safety performance of work zone merge control strategies

The review of TTCPs for work zone speed control shows that various forms of law enforcements are still the most effective but expensive means of controlling speed in work zones. Mixed speed reduction performances are reported for narrow lanes. One concern about narrow lanes is that they may cause driver discomfort and leave drivers small chances to correct mistakes (e.g., lane departure due to distraction) made. Dynamic speed display is also found to be effective in reducing vehicle speed and is less expensive to implement compared to law enforcements. It is recommended that this strategy be utilized together with law enforcements. Dynamic speed display signs are often equipped with traffic sensors. They can be used to post speed limits based on real-time traffic conditions and collect speed violation data. Based on the real-time and historical speed violation records from work zones, adaptive schedules can be developed for law enforcements to target most problematic work zones or time periods.

The review of merge control methods identifies four major strategies: no control, static/dynamic early merge, static/dynamic late merge, and signalized merge. Early merge is considered to be able to result in high-speed flow in the open lane and reduce risky last-minute merge maneuvers. However, there is no consensus regarding its impact on throughput and its success depends heavily on proper law enforcements. Congestion can often degrade the compliance with the "*DO NOT PASS*" sign of early merge, which may potentially lead to unsafe behaviors such as queue jumping, lane straddling, and forced merge. Late merge requires vehicles to take turn and merge at the merge point. It does not have the previously mentioned issues associated with early merge. However, merging at the last minute may create unsafe short gaps. It is generally believed that early merge is better for uncongested conditions, late merge is more suitable for congested traffic, and signalized merge is better for extremely heavy traffic. However, this conclusion has not been verified by rigorous field studies, and mixed results regarding the throughputs of early merge and late merge have been reported. Although the concept of signalized merge is interesting, it has not been implemented in the field yet partially due to the potential confusion caused by introducing traffic signals on a highway.

This study aims to use the NDS and SWZ data for analyzing driver behavior in work zones, calibrating microscopic traffic simulators, and understanding the detailed characteristics of crash and near-crash events in highway work zones. Due to the lack of observations from the same (or similar) work zones, it is found that the NDS data obtained for this study is insufficient for analyzing driver behavior in work zones. The analysis of NDS crash data suggests that distraction is the most important endogenous factors contributing to work zone crashes and near crashes followed by fatigue driving and speeding. Stop-and-go traffic, sudden slowdown of lead vehicle, and unsafe merge maneuvers of vehicles in adjacent lanes are identified as top exogenous factors. These findings confirm the importance of proper speed and merge control for improving work zone safety. The NDS crash data also suggests that when the traffic flow is in levels of service B, C, and D (see Table 25), crash and near crash events are more likely to happen.

This research also attempts to use SWZ data for calibrating microscopic traffic simulators. Due to the lack of full knowledge about how the TTCP (e.g., traffic signs, control devices, law enforcements) was set up during the SWZ data collection periods, it is difficult to precisely replicate the observed traffic flow patterns using VISSIM simulation. Even with detailed work zone configuration data, microscopic traffic simulation tools such as VISSIM cannot take all of them into full consideration. Therefore, the research team decides not to further pursue this calibration effort using the SWZ data. In the future, it would be helpful to collect video data covering an entire work zone to fully capture its traffic operations. The detailed video data will allow for accurate and detailed simulation model calibration.

To evaluate work zone speed control strategies, this research proposes and develops an innovative VR-based driving simulator. Based on three speed control strategies, six work zone scenarios are developed and tested under daytime and nighttime conditions. In addition, a survey is conducted to see how drivers value different speed control strategies. Both the VR simulation and the questionnaire results show that radar speed sign/dynamic speed display can effectively reduce traffic speed in work zones. Since the application of VR technology in driving simulation is relatively new, the experience learned in this study can be of use to other traffic safety researchers who are also interested in exploring this revolutionary technology.

This research proposes a New England Merge (NEM), in which the approach to a work zone is divided into a meter zone followed by a merge zone. Vehicles approaching the work zone are instructed to increase their front time gaps in the meter zone. The meter zone is used to provide an adequate distance for vehicles to adjust their gaps and lane change is prohibited in this zone. While increasing the time gaps, vehicles are also advised to adjust their positions so that they travel near the middle point of two consecutive vehicles in the adjacent conflicting lane. Lane changes are allowed in the merge zone. When vehicles leave the meter zone and enter this merge zone, they take turns to merge. VISSIM is used to evaluate the mobility performances of various merge control methods, including NEM. Two types of work zones are simulated: (1) Type I: two-lane highway with one lane closed, and (2) Type II: three-lane highway with the right-most lane closed. The simulation results show that NEM performs significantly better than no control, early merge, and late merge under medium to extremely heavy traffic conditions. It also consistently outperforms signalized merge under all flow conditions.

During this research, it is noted that commercial microscopic traffic simulators such as VISSIM and Aimsun cannot accurately model work zones using default parameters. Research is needed in both understanding driver behavior in work zones in response to various control instructions and developing specific lane-changing models for work zones to simulate behaviors such as take turns to merge and courtesy yielding of drivers in the open lane.

The SSAM tool developed by the FHWA is also utilized in this research to analyze the safety performances of various merge control methods. It is found that the proposed NEM generates much less conflicts than the remaining methods at medium to high input flows for Type I work zones. For Type II work zones, NEM still produces the lowest numbers of rear-end conflicts under medium to high traffic conditions. However, it results in the highest number of lane-change conflicts for the heavy input flow condition, partially due to its significantly higher throughput (i.e., higher lane-change risk exposure) in this case. This phenomenon is also explained by the fact that vehicles try to change to the left-most lane at the beginning of the meter zone, since the left-most lane in Type II work zones are not affected by the merging traffic at the lane closure point.

Overall, this study has three main contributions to work zone safety and mobility research. It innovatively utilizes NDS data for analyzing work zone crash and near-crash events characteristics, and provides useful insights into how crashes occurred in highway work zones. It develops and applies a VR-based driving simulator for studying work zone speed control strategies. Last but not least, it proposes a New England Merge (NEM) method that demonstrates promising mobility and safety performance based on the VISSIM simulation and SSAM analysis results. The proposed NEM can be readily implemented when all vehicles are connected and automated. Even without connected and autonomous vehicles, this method is still practical given driver compliance and proper law enforcements, which are also required by the early merge and late merge strategies that have been field implemented.

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9. APPENDIX - SOURCE CODE FOR VISSIM DENSITY MAP TOOL

```
#import "C:\\Program Files\\PTV Vision\\PTV Vissim 8\\Exe\\VISSIM.exe" rename_namespace
("VISSIMLIB")

#include <string>
#include <iostream>
#include <iomanip>
#include <fstream>

using namespace std;
int vehinput = 500;
double TT[10];          // Traveltime
double No_Veh[10]; // Number of Vehicles
int Veh_TT_measurement_number = 1;
ofstream
output("C:\\Users\\Tianzhu_Ren\\Desktop\\Final_project0606\\Network_Total\\3to2_Nothing\\d
ata.txt", ios::trunc);
ofstream
density1("C:\\Users\\Tianzhu_Ren\\Desktop\\Final_project0606\\Network_Total\\3to2_Nothing\\
density1.txt", ios::trunc);
ofstream
density2("C:\\Users\\Tianzhu_Ren\\Desktop\\Final_project0606\\Network_Total\\3to2_Nothing\\
density2.txt", ios::trunc);
ofstream
density3("C:\\Users\\Tianzhu_Ren\\Desktop\\Final_project0606\\Network_Total\\3to2_Nothing\\
density3.txt", ios::trunc);

int lndst;
double queue[10];
double stopdelay[10];
double vehdelay[10];

double average(double *x, int len)
{
	double sum = 0;
	for (int i = 0; i < len; i++)
		sum += x[i];
	return sum / len;
}

int main(int argc, char* argv[])
```

```
{
	// initialize COM
	CoInitialize(NULL);
	{
		// create Vissim object
		VISSIMLIB::IVissimPtr Vissim;
		Vissim.CreateInstance("Vissim.Vissim");

		bstr_t Path_of_COM_example_network =
"C:\\Users\\Tianzhu_Ren\\Desktop\\Final_project0606\\Network_Total\\3to2_Nothing\\"; //
always use \\ at the end

		// Load a Vissim Network :
		bstr_t Filename = Path_of_COM_example_network + "network.inpx";
		cout << Filename << endl;
		bool flag_read_additionally = false; // you can read network(elements)
additionally, in this case set "flag_read_additionally" to true
		Vissim->LoadNet(Filename, flag_read_additionally);

		// Load a Layout :
		Filename = Path_of_COM_example_network + "network.layx";
		Vissim->LoadLayout(Filename);

		int Random_Seed = 42;
		Vissim->Graphics->CurrentNetworkWindow->PutAttValue("QuickMode", 1);
		Vissim->Simulation->PutAttValue("UseMaxSimSpeed", true);
		Vissim->Simulation->PutAttValue("SimPeriod", 2700);
		VISSIMLIB::IVehicleTravelTimeMeasurementPtr veh_tt_measure = Vissim-
>Net->VehicleTravelTimeMeasurements->GetItemByKey(1);
		VISSIMLIB::IDelayMeasurementPtr delay_measure = Vissim->Net-
>DelayMeasurements->GetItemByKey(1);
		VISSIMLIB::IQueueCounterPtr q_measure = Vissim->Net->QueueCounters-
>GetItemByKey(1);

		output.setf(ios::fixed, ios::floatfield);
		output.precision(3);
		density1.setf(ios::fixed, ios::floatfield);
		density1.precision(2);
		density2.setf(ios::fixed, ios::floatfield);
		density2.precision(2);
		density3.setf(ios::fixed, ios::floatfield);
		density3.precision(2);
		output << "Vehinput" << "     " << "LaneDist" << "  " << "StopTime" << " " <<
"TravelTime" << "      " << "Queue" << "       " << "No_Veh" << endl;

		int veh_number;
```

```
		double veh_position;
		double veh_speed;
		bstr_t veh_linklane;
		VISSIMLIB::IVehiclePtr Vehicle;
		int p;
		int mt;
		int num200;

		for (vehinput = 2200; vehinput <= 4000; vehinput = vehinput + 100) {
			for (lndst = 200; lndst <= 2500; lndst = lndst + 100) {
				double Num[21][3][181] = { 0.00 };
				double vcont[10] = { 0 };
				for (int i = 0; i <= 9; i++) {
					Vissim->Simulation->PutAttValue("RandSeed",
Random_Seed+i);
					Vissim->Simulation->PutAttValue("SimPeriod", 3000);
					Vissim->Net->VehicleInputs->GetItemByKey(1)-
>PutAttValue("Volume(1)", vehinput);
					Vissim->Net->Links->GetItemByKey(10000)-
>PutAttValue("LnChgDist", lndst);
					for (int t = 900; t <= 2700; t = t + 10)
					{
						mt = (t - 900)/10;
						Vissim->Simulation->PutAttValue("SimBreakAt",
t);

						Vissim->Simulation->RunContinuous();
						VISSIMLIB::IIteratorPtr Vehicles_Iterator =
Vissim->Net->Vehicles->GetIterator();
						num200 = 0;
						while (Vehicles_Iterator->GetValid())
						{
							Vehicle = Vehicles_Iterator->GetItem();
							veh_number = Vehicle-
>GetAttValue("No");

							veh_position = Vehicle-
>GetAttValue("Pos");

							veh_speed = Vehicle-
>GetAttValue("Speed");

							veh_linklane = Vehicle-
>GetAttValue("Lane");
							//density1 << veh_linklane << endl;
							//density1 << veh_position << endl;
							if (veh_linklane == bstr_t("1-1")) {
								if (6600 < veh_position &
veh_position < 7220) {
									if (veh_speed <= 2) {
```

```
num200++;
}
}
}

for (p = 0; p <= 20; p = p + 1)
{
if (veh_linklane == bstr_t("1-1")) {
if (7220 - 200 * (p + 1) <
veh_position & veh_position < 7220 - 200 * p) {
Num[p][0][mt] ++;
}
}
if (veh_linklane == bstr_t("1-2")) {
if (7220 - 200 * (p + 1) <
veh_position & veh_position < 7220 - 200 * p) {
Num[p][1][mt] ++;
}
}
if (veh_linklane == bstr_t("1-3")) {
if (7220 - 200 * (p + 1) <
veh_position & veh_position < 7220 - 200 * p) {
Num[p][2][mt] ++;
}
}
}
if (veh_position > 100) {
if (veh_speed < 2) {
vcont[i] += 10;
}
}
Vehicles_Iterator->Next();
}
Vehicles_Iterator->Reset();

if (mt % 3 == 0) {

if (num200 >= 25) {

Vissim->Net->PriorityRules-
>GetItemByKey(1)->PutAttValue("VehClasses",10);

}
else
{
Vissim->Net->PriorityRules-
```

```
>GetItemByKey(1)->PutAttValue("VehClasses",30);
                                    }

                                    }

                        }



                        Vissim->Simulation->RunContinuous();
                        TT[i] = veh_tt_measure-
>GetAttValue("TravTm(Current,Avg,All");
                        No_Veh[i] = veh_tt_measure-
>GetAttValue("Vehs(Current,Avg,All)");
                        queue[i] = q_measure-
>GetAttValue("QLen(Current,Avg)");
                    }
                        density1 << vehinput << "," << lndst << "," << endl;
                        density2 << vehinput << "," << lndst << "," << endl;
                        density3 << vehinput << "," << lndst << "," << endl;
                        for (int b = 0; b <= 180; b+=30) {
                            for (int q = 0; q <= 20; q++) {
                                density1 << Num[q][0][b] / 10 << ",";
                                density2 << Num[q][1][b] / 10 << ",";
                                density3 << Num[q][2][b] / 10 << ",";
                            }
                            density1 << endl;
                            density2 << endl;
                            density3 << endl;
                        }

                    output << vehinput << "        " << lndst << "          " <<
average(vcont, 10) << "        " << average(TT, 10) << "     " << average(queue, 10) << " " <<
average(No_Veh, 10) << endl;
                }
            }
            output.close();
        }
        CoUninitialize();
        return 0;
}
```