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Final Report

Evaluation of Traffic Control Options in Work Zones

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ABSTRACT

Lane closures for work zones along freeways produce bottlenecks. These bottlenecks are problematic due to loss of capacity and excessive lane changes, which impact the facility performance represented by operational level of service, emissions, and travel time. In addition, transportation agencies opt to nighttime scheduling of work zones which, in turn, has several operational, safety, and cost impacts. The issue persists because little is known about the impacts of available temporary traffic control strategies on operations at work zones, and associated emissions, travel time, and construction scheduling. This study utilized a comprehensive literature review, a national survey of practices, and microscopic simulation experiments to document and evaluate available traffic control strategies for work zone management. Using a corridor in Birmingham, AL as a testbed, the study quantified operational, environmental, and travel time reliability impacts of four temporary traffic control strategies for work zones. Also, a performance-based work zone scheduling approach was developed to provide decision support assistance for transportation agencies. The study provided evidence that the work zone length is insignificant with respect to facility level of service, environmental impacts, and delays. Additionally, the study concluded that late merge and mainline merge metering hold great promise and should be considered for implementation in place of the early merge approach commonly used in practice today.

EXECUTIVE SUMMARY

Maintenance and rehabilitation projects along freeway facilities typically mandate lane closures which often result in bottlenecks. Merging maneuvers at these bottlenecks have adverse impacts on traffic operations. Conventionally, transportation management plans are developed to address such impacts; however, such plans rely on conventional bottleneck merge control as stipulated in the Manual on Uniform Traffic Control Devices and overlook the relevant impacts on construction plans and schedules. Accordingly, agencies opt to schedule work zones during off-peak (nighttime) periods, which adversely impacts safety and productivity of workers. The issue persists because little is known about the performance of alternative bottleneck merge control strategies and their potential impacts on construction plans and schedules.

The purpose of this study was to identify alternative bottleneck merge control strategies with a potential to minimize congestion at interstates work zones and improve relevant construction practices. The study first performed a comprehensive literature and state-of-practice review to identify promising alternative merge control strategies with applications to work zones and document current practices. Then, the study employed microscopic simulation to quantify the impacts of four identified merge control strategies on operations, environment, safety, and construction planning and scheduling decisions. The results of the analysis provided clear evidence that work zone length is insignificant with respect to facility level of service, environmental impacts, and delays. Additionally, the study concluded that late merge and mainline merge metering hold great promise for implementation as alternates to early merge control that is currently the standard practice. In addition, the analysis showed that there are several feasible options for scheduling work zones during any period of day. This is an important finding as it will allow added flexibility for scheduling construction activities around the clock without compromising traffic flow quality. Furthermore, the study established a set of generalized performance indices, and proposed a combinatorial optimization approach to find the work zone setup with minimal impacts on facility performance.

The study is significant for its contribution to bridge an existing gap between work zone traffic control research and practice, and between transportation and construction engineering research related to work zone performance optimization. Additionally, this study contributes to the traffic microscopic simulation body of knowledge by providing practical provisions and creative approaches to simulate bottleneck merge control strategies in the popular microscopic simulation platform CORSIM, thus addressing existing limitations of the software. Overall, it is expected that the findings from this study will provide valuable guidance for transportation researchers and officials on traffic management strategies capable of optimizing construction work schedules while maintaining traffic flow quality at work zones, and associated costs.

CHAPTER 1
BACKGROUND

PROBLEM STATEMENT

In recent years, the focus of many states has shifted from building new highways to maintenance and rehabilitation, which gives rise to scheduled construction activities at work zones. Such activities often mandate lane closures to provide a work space which result in disruption of traffic upstream of merge locations (*1*). Earlier studies show that work zones represent the second largest cause of nonrecurring delay on principle arterials accounting for nearly 24% of all nonrecurring delay (*2*). Conventional traffic control plans are used to ease the merging process at work zone lane drop locations. Such plans normally work well when traffic demand is less than the capacity of the open lanes. However, when demand exceeds capacity, congestion develops, and the potential for collisions increases, especially when the congestion extends upstream beyond the advance lane closure signs (*3*). In addition, transportation agencies opt to schedule maintenance activities to off-peak hours, to reduce work zone impacts on traffic operations and safety. This practice, however, often lengthens project duration and increases maintenance-related costs as a result of repetitive setup, frequent cessation, and associated costs to nighttime operations (*4*).

Temporary traffic control (TTC) strategies are a tangible treatment to mitigate the impacts of work zones. Various TTC strategies exist, including both static and dynamic options. Determining the best TTC strategy dictates several decisions that intersect with construction phasing, staging, and choice of work scheduling periods. Even though temporary traffic control is an important component of work zone transportation management plans, little is known about the interaction between TTC strategies and construction schedules. This provides motivation to study and evaluate traffic control strategies at lane merge locations and their impacts on construction planning and scheduling decisions at work zone sites. Better understanding of such impacts would help transportation agencies and contractors to plan and schedule highway maintenance works with minimal disruption to traffic operations.

OBJECTIVES

This research investigated in depth the operational impacts of temporary traffic control strategies employed at work zone locations in order to facilitate the merging of vehicles into open lanes. Accordingly, the objectives of this research were set to:

1. Identify available TTC strategies, and understand the state-of-the-practice within State *Departments of Transportation* (DOTs);
2. Evaluate the operational, environmental, and travel time reliability impacts of identified TTC strategies; and
3. Develop an approach for performance-based work zone scheduling, that takes into consideration implemented TTC strategies.

The scope of the study was limited to TTC strategies for work zones at interstate highways. Using a section of I-65 in the Birmingham, Alabama region as test bed, the study investigated the impacts of work zone configurations, scheduling period and work zone length on facility performance in terms of density, emissions total, and delay per vehicle. The analysis considered 3-to-2 lane closures under various operational durations. While the findings of this study are transferable and applicable, with adjustments, to any jurisdiction, emphasis has been laid on driving behavior and operational characteristics in the Southeastern region of the United States.

SIGNIFICANCE AND IMPLICATIONS

This research bridges an existing gap between construction engineering research and transportation engineering research in an effort to make the construction scheduling decisions harmonized with the choice of a TTC strategy. In addition, this research contributes to the traffic simulation literature by providing new guidance on how to simulate lane closures and TTC techniques using *Corridor Simulation* (CORSIM) software. Another contribution is realized in the efforts to develop an approach for performance-based work zone scheduling. The results of this research benefit decision makers, engineers, and contractors towards making decisions that are aligned with all aspects of engineering involved.

ORGANIZATION OF THE REPORT

This report is organized in four chapters. The first chapter presents background information, the research problem, and objectives. The second chapter discusses the methods and research approach used to conduct this study. The third chapter presents study results along a thorough discussion and interpretation of results. Finally, the fourth chapter presents conclusions, recommendations, and suggestions for future research. Technology transfer efforts are documented in the Appendix to this report.

CHAPTER 2
RESEARCH APPROACH

INTRODUCTION

A three-step approach was used in order to meet the study objectives. First, a systematic literature review was conducted to identify documented practices for work zone TTC and work zone scheduling. Second, a national survey of practice was conducted to document the state-of-the-practice within the State *Departments of Transportation* (DOTs). Third, controlled experiments were designed and performed to evaluate the impacts of identified work zone TTC strategies in terms of operational efficiency, environmental impacts, and travel time reliability. The following sections describe the approach for each step.

APPROACH FOR LITERATURE REVIEW

The first step involved a systematic literature review to identify available TTCs for interstate work zones, and efforts used to investigate or assess their costs, benefits, and barriers to implementation, if any. Table 2-1 lists the main sources of literature that were searched. The search was conducted using relevant keywords including: bottlenecks; incident management; tapers; traffic congestion; traffic incidents; and work zone traffic control.

Table 2-1. Sources of literature

Database	Publisher
Academic OneFile	Gale (Cengage Learning)
Academic Search Premier	EBSCO Industries, Inc.
Civil Engineering Database (CEDB)	American Society of Civil Engineers
Compendex	Elsevier B.V.
Google Scholar	Google
Journal Archives	JISC
National Transportation Library	US DOT
ProQuest Dissertations and Theses	ProQuest
Science Direct	Elsevier B.V.
Scopus	Elsevier B.V.
Springer Link	Springer
Taylor & Francis Online	Taylor & Francis Group
Transport Research International Documentation (TRID) database	Transportation Research Board (TRB) of the National Academies of Sciences, Engineering, and Medicine

The study team excluded any articles that were not written in English, or with a geographic scope outside the United States. Some articles were indexed within several databases, and some studies were reported within several other articles. Accordingly, the study team did run a redundancy check to eliminate duplicate results by using the identified authors' names, article titles, publication year, reported project, and/or case study.

APPROACH FOR NATIONAL SURVEY OF PRACTICE

The second step was to conduct a national survey of practice using a questionnaire survey tool that was developed specifically for this purpose. The survey was designed according to the guidelines set forth in Appendix B of the ITE Manual of Transportation Engineering Studies (*5*). Privacy of respondents was assured by following federal and state laws, as well as by review and approval of the *Institutional Review Board* (IRB). The survey included multiple-choice questions that addressed agencies' practices for selecting temporary traffic control strategies, rationale and selection criteria, coordination with construction activities (if any), and agency-collected mobility and exposure *measures of effectiveness* (MOEs) for implemented strategies. This survey was furnished in both paper-based and electronic formats, and all State Departments of Transportation were invited to participate.

APPROACH FOR CONDUCTING THE CONTROLLED EXPERIMENT

Experiment Design and Study Site

The objective of this study was to investigate various possible configurations for an interstate work zone, in terms of temporary traffic control strategies, work scheduling periods, and work zone lengths. Setting up an actual work zone in the field and changing the configuration for several attempts is practically unfeasible and thus undesirable. Accordingly, the study investigators decided to design their experiment as a microscopic simulation study. A section of Interstate 65 (I-65) in central Alabama passing through the city of Birmingham in Jefferson County, AL was selected as the simulation case study testbed as shown in Figure 2-1**Error! Reference source not found.**.The study segment is approximately 14 miles in length and extends from exit 247 where it intersects Valleydale Road, to exit 261, where it intersects Interstate 20/59 (I-20/59). It typically has three 12-ft lanes per mainline direction, with auxiliary lanes added at ramps locations. The posted speed limit is 60 mph with an advisory speed limit of 45 mph on ramps.

Field data required for coding the study corridor in the simulation model were collected to accurately represent actual traffic and design characteristics of the study segment. In addition to road geometry conditions, traffic volumes were collected at the beginning and end of the study segment, as well as on on- and off-ramps. The *Annual Average Daily Traffic* (AADT) for this specific section was 122,510 veh/day. Analysis of 24-hour traffic distribution at the study location revealed that there are four distinct traffic periods during any given 24-hour period. Figure 2-2 illustrates these periods that typically occur during weekdays namely morning peak at 8:00AM, mid-day or lunch time at 12:00PM, afternoon peak at 5:00PM, and off-peak or nighttime at 3:00AM, with highest traffic occurring at 8:00AM, and lowest traffic occurring at 3:00AM. Additionally, available traffic data indicate that the traffic stream typically carries around 10% heavy vehicles throughout the day.

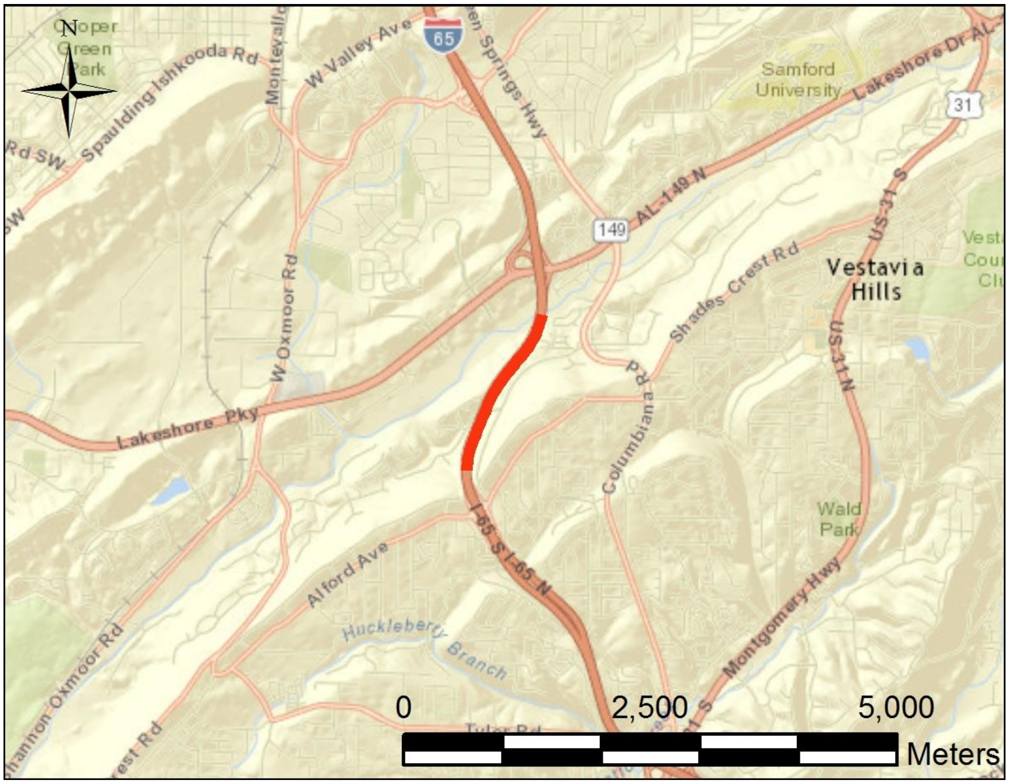

Figure 2-1. Study corridor

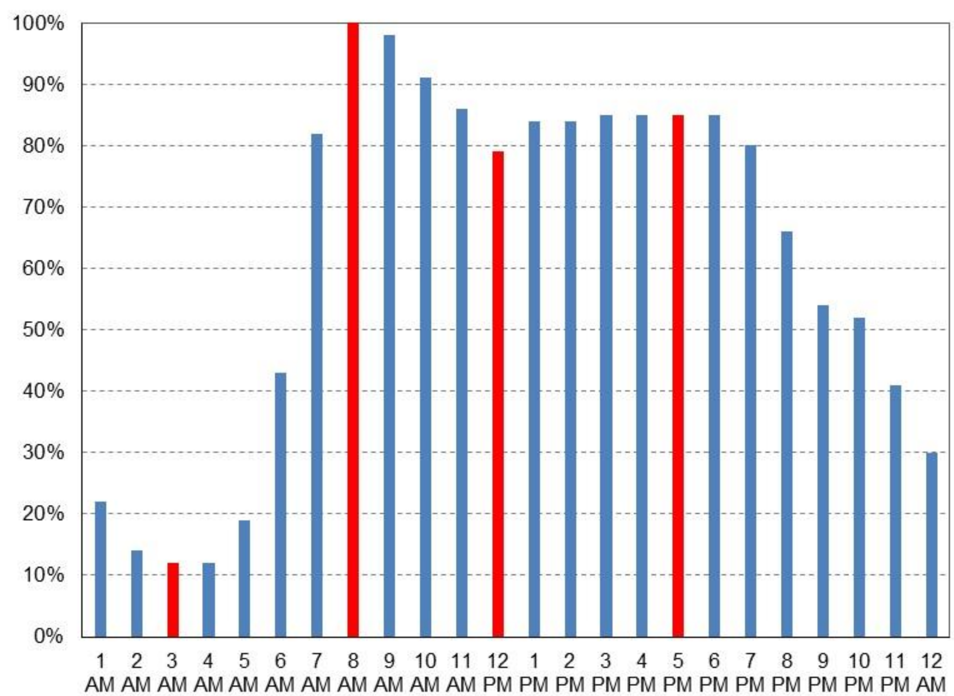

Figure 2-2. Typical 24-hour traffic distribution at I-65 N MP 257.7

Using geometric and traffic data and a microscopic simulation platform, base models were developed to simulate the prevailing traffic conditions at the study corridor during various periods of the day. Simulation models reflecting work zone operations were also developed, assuming a work zone setup with 3-to-2 lane drop on peak traffic direction. The roadway geometry, number of lanes closed, and location were fixed in this experiment. Factors considered were (a) work zone scheduling period, (b) the implemented merge control strategy (work zone configuration), and (c) work zone length.

As mentioned earlier, analysis of traffic flow patterns at the study site revealed four key periods of the day, namely morning peak period, mid-day peak period or lunch period, afternoon peak period, and off-peak or nighttime period. The *work scheduling period* was considered in this study as a categorical variable "P" with 4 levels corresponding to the identified periods. For the variable "P," possible values were "AM" for morning peak period, "MD" for mid-day peak period or lunch period, "PM" for afternoon peak period, and "NT" for off-peak period. Second, the *TTC strategy* was considered as a categorical variable "S" with four levels each representing the identified strategies. As for the variable "S," possible values are "EM" for early merge control, "LM" for Late merge control, "MM" for mainline merge metering, and "RM" for temporary ramp metering. Finally, the *work zone length* "L" represented five work zone length configurations as 500ft, 1000ft, 1500ft, 2000ft, and 2500ft.

As far as the experiment outcomes were concerned, three key MOEs were identified to represent the performance of each work zone setup, namely density, emissions total, and delay per vehicle. *Density* is the indicator for the highway level of service, while *emissions total* is a key indicator for the environmental impacts of the transportation system, and *delay* is a key indicator of travel time reliability and user satisfaction. This set up represents a multi-level three factor experiment with three outcomes. Table 2-2 illustrates the experiment design consisting of 80 runs for all possible combinations of the experiment factors S, L, and P. In addition, four control runs were added to represent the preconstruction, or baseline, conditions for the four considered periods.

Table 2-2. Experiment Design

Run	S	L	P
1	LM	500	AM
2	LM	500	MD
3	LM	500	PM
4	LM	500	NT
5	LM	1000	AM
6	LM	1000	MD
7	LM	1000	PM
8	LM	1000	NT
9	LM	1500	AM
10	LM	1500	MD
11	LM	1500	PM
12	LM	1500	NT
13	LM	2000	AM
14	LM	2000	MD
15	LM	2000	PM
16	LM	2000	NT
17	LM	2500	AM
18	LM	2500	MD
19	LM	2500	PM
20	LM	2500	NT
21	EM	500	AM
22	EM	500	MD
23	EM	500	PM
24	EM	500	NT
25	EM	1000	AM
26	EM	1000	MD
27	EM	1000	PM
28	EM	1000	NT
29	EM	1500	AM
30	EM	1500	MD
31	EM	1500	PM
32	EM	1500	NT
33	EM	2000	AM
34	EM	2000	MD
35	EM	2000	PM
36	EM	2000	NT
37	EM	2500	AM
38	EM	2500	MD
39	EM	2500	PM
40	EM	2500	NT

Run	S	L	P
41	MM	500	AM
42	MM	500	MD
43	MM	500	PM
44	MM	500	NT
45	MM	1000	AM
46	MM	1000	MD
47	MM	1000	PM
48	MM	1000	NT
49	MM	1500	AM
50	MM	1500	MD
51	MM	1500	PM
52	MM	1500	NT
53	MM	2000	AM
54	MM	2000	MD
55	MM	2000	PM
56	MM	2000	NT
57	MM	2500	AM
58	MM	2500	MD
59	MM	2500	PM
60	MM	2500	NT
61	RM	500	AM
62	RM	500	MD
63	RM	500	PM
64	RM	500	NT
65	RM	1000	AM
66	RM	1000	MD
67	RM	1000	PM
68	RM	1000	NT
69	RM	1500	AM
70	RM	1500	MD
71	RM	1500	PM
72	RM	1500	NT
73	RM	2000	AM
74	RM	2000	MD
75	RM	2000	PM
76	RM	2000	NT
77	RM	2500	AM
78	RM	2500	MD
79	RM	2500	PM
80	RM	2500	NT

Run	S	L	P
AM	N/A	N/A	AM
MD	N/A	N/A	AM
PM	N/A	N/A	AM
NT	N/A	N/A	AM

Note: S is merge control strategy; L is work zone length; and P is scheduling period

Microscopic Simulation Platform Selection

Testing the identified TTC strategies requires a high fidelity analysis tool that would closely mimic the individual movements of vehicles travelling through the study work zone. A microscopic traffic simulation modeling approach was selected for this project for its usefulness in analyzing key bottlenecks on roadway segments and corridors, where the movement of each individual vehicle needs to be represented to better understand the impact on roadway conditions, and for its capability of simulating all facility types (*6, 7*).

Many microscopic traffic simulation models are available in the market today, including AIMSUN, ARENA, CA4PRS, CORSIM, QUEWZ, QuickZone, and VISSIM (*1, 8-14*). Table 2-3 highlights the simulation platforms that were used by previous researchers in relevant research. Based on model capabilities and the needs of the current research, the CORSIM and VISSIM simulation models were identified as potential candidate simulation platforms for further consideration. Their capabilities were considered and are summarized in the following sections.

Table 2-3. Most widely used microscopic simulation platforms

Researcher	Scope	Platform
Lentzakis et al. (*10*)	Mainline metering/control	AIMSUN
Sun et al. (*13*)	Temporary Ramp Meter	VISSIM + FOT Video Data
Oner (*11*)	Temporary Ramp Meter	ARENA
Tympakianaki et al. (*14*)	Mainline metering/control	AIMSUN
Pesti et al. (*12*)	Dynamic Merge	VISSIM
Kurker et al. (*9*)	Early merge, late merge, signal merge	VISTA + CORSIM + VISSIM + SSAM
Wei et al. (*1*)	DLM with Merge Metering	VISSIM

Corridor-Microscopic Simulation Program (CORSIM)

CORSIM is the core simulation and modeling component of the *Traffic Software Integrated System* (TSIS) tool suite developed and sponsored by *Federal Highway Administration* (FHWA) (24). CORSIM is a micro-simulation model that models individual vehicle movements based on car-following and lane-changing theories on a second-by-second basis (time-step simulation) for the purpose of assessing traffic performance on a roadway network. CORSIM includes both NETSIM (for surface street simulation) and FRESIM (for freeway simulation). CORSIM is a stochastic model that incorporates random processes to model complex driver, vehicle, and traffic system behaviors and interactions.

CORSIM was developed over time and evolved through the merging of several simulation platforms into one model, which made CORSIM synonymous with its artificial barrier between arterial and interstate networks. This default may cause inaccuracies such as the "metering" of traffic on high-volume onramps or "backups" of traffic on high-volume off-ramps (*15*). However, this issue was addressed by Minnesota Department of Transportation (*16*) were they provided an approach to resolve interface nodes between freeways and surface streets.

VISSIM

VISSIM is the microscopic stochastic traffic simulator that is mostly used as a tool for the design of urban public transportation systems, but has shown capabilities of reproducing freeway traffic behaviors as well (*17*). VISSIM is a time-step and behavior-based simulation model, developed to model urban traffic by "Planung Transport Verkehr AG" of Karlsruhe, Germany based on the work of Wiedemann (*18*, *19*). It can analyze traffic operations under various constraints, including lane configuration, traffic composition, and traffic signals (*9*).

Comparison of CORSIM and VISSIM

Bloomberg and Dale (*20*) provided a detailed technical comparison of the two popular traffic simulation models CORSIM and VISSIM, and concluded that CORSIM and VISSIM are more similar than they are different. The biggest difference they observed was the variability of the models, which they suggested should be addressed by making multiple runs. One advantage of VISSIM over CORSIM is the capability of simulating dynamic merge concepts by using the *Vehicle Actuated Programming* (VAP) feature of VISSIM (*12*). Another comprehensive comparison between CORSIM and VISSIM was performed by Choa et al. (*15*) for freeway microscopic simulation. The following conclusions summarize the results of that comparison:

- CORSIM provided the shortest set-up time. VISSIM required about an additional day for model refinement.
- CORSIM use link-based routing which can result in inaccurate lane utilization for closely-spaced intersections. The path-based routing in VISSIM eliminates this problem.
- VISSIM provide three-dimensional animation with options for enhancing the visual setting. The CORSIM two-dimensional animation is more simplistic.
- Both platforms do not provide average control delay for each turn movement. However, CORSIM provides average control delay for each approach. Both report total delay by link.
- CORSIM has an artificial barrier between Surface Streets and Freeways that can cause inaccuracies, if left unaddressed by the user, such as the "metering" of traffic on high-volume onramps or "backups" of traffic on high-volume off-ramps.

Available literature resources indicate that there is no one microscopic simulation platform that can be used for simulating each and every scenario related to work zone operations. (*21*). However, an older study by Pulugurtha et al. (*22*) showed that work zones events could be simulated more effectively using CORSIM when compared to VISSIM, through the comprehensive freeway incident simulation procedure, which is available as a part of the FRESIM module. That procedure allows the user to simulate the work zone event by specifying various factors such as the longitudinal position of a freeway link at which the event has occurred, distance over which the effects last, and the duration of the event. The percentage of the traffic affected by the work zone on the adjacent lane can be pre-established. This technique mimics real time situations where the traffic is affected by the adjacent lane traffic behavior. On the other hand, VISSIM has no special provision to simulate freeway incidents and/or work-zones that close a lane; however, this can be manipulated by simulating a bus stop for a specified time. Despite that work-around, VISSIM does not have the ability to specify blockages or "rubber necking" on a lane specific basis or to simulate short-term and long-term interruptions to traffic as can be done using CORSIM software. Based on the documented advantages of CORSIM against VISSIM when studying freeway work zone traffic, a decision was made to use CORSIM as the microsimulation platform for this study.

CASE STUDY SIMULATION MODELING DETAILS

Base Model Development

The simulation model considered a hypothetical 3-to-2 work zone setup on the rightmost lane of the Northbound direction of I-65 beginning at MP 254.56 with workspace length ranging from 500 ft to 2,500 ft with 500 ft increments. However, for temporary ramp metering, a hypothetical work zone was setup on the leftmost lane beginning at MP 253.98. In addition, the simulation model was coded to account for a buffer space of 485 ft and a merging taper of 800 ft to satisfy the requirements of the *Manual on Uniform Traffic Control Devices* (MUTCD) (*23*). Simulation was performed for each of the identified traffic periods for a 2-hour duration. The selection of the 2-hour period covers an hour before and an hour after the previously identified four distinct traffic patterns. Accordingly, simulation was performed for the morning peak period occurring between 7:00 am and 9:00 am, the mid-day or lunch time period occurring between 11:00AM and 1:00PM, the afternoon peak period occurring between 4:00PM and 6:00PM, and the off-peak or nighttime period occurring between 2:00AM and 4:00AM.

Because CORSIM is a stochastic time-step microsimulation model, the *Output Processor* was configured to use the same *random number seeds* across all simulation runs. In addition, the Output Processor was configured to collect mean cumulative outputs and corresponding standard deviations from 84 scenarios that were run five times each with a total of 420 simulation runs. Manipulating CORSIM for simulating driving conditions in work zones has been extensively studied by other researchers, and seven parameters were identified along recommended values to setup CORSIM for work zone driving conditions independent of location or geometry (*21, 24-27*). These seven parameters are:

1. **Vehicle entry headway:** This is the method CORSIM will use to generate vehicles at entry nodes. A negative exponential distribution was used in this study, which can be achieved by setting CORSIM to use an Erlang Distribution with a = 1.
2. **Rubberneck factor:** The rubberneck factor, in a percentage, represents the reduction in capacity that results from the tendency of drivers at work zones who to slow down to see what is happening. Literature recommend that open lanes at work zones as well as a portion equal to work zone length of the closed lane(s) post work zones should be coded for rubber necking incidents with a factor of 20% to account for such phenomenon.
3. **Car following sensitivity multiplier:** CORSIM uses driver sensitivity to account for the car-following logic. Despite the fact that drivers tend to be more aggressive at work zones, literature recommends using the default car-following sensitivity multipliers.
4. **Mean start-up delay time:** This is a link-specific parameter that is used by the model to discharge vehicles from a ramp meter onto the freeway. The default value is 1.0 second, and literature recommends a value of 2.4 seconds when simulating work zone conditions.

5. **Time to complete lane-change maneuver:** This parameter specifies the time needed by a driver to complete a lane-change maneuver. The default value is 2.0 seconds, and a literature recommended using a value of 2.2 seconds when simulating work zones to account for the increased driver aggressiveness at work zones, which does not usually allow drivers to complete a lane change without getting some resistance from other drivers.
6. **Percent drivers yielding to merging vehicles:** This parameter specifies the percentage of drivers desiring to yield the right-of-way to lane-changing vehicles attempting to merge ahead of them. The default value is 20%, and literature recommended a value of 15% to account for work zone conditions (*26*).
7. **Minimum separation for generation of vehicles:** This parameter governs the maximum rate at which vehicles can be emitted onto the network. The default value of 1.6 seconds is appropriate for freeway operations; however, earlier studies proved that a value of 1.3 seconds will enhance the calibration of CORSIM for work zone conditions (*26*).

Model Calibration

This study followed the guidelines and methods stated by the FHWA Traffic Analysis Tool Box, Volumes III, IX, and IX (*21, 24, 25*) to setup and calibrate CORSIM. Base models were calibrated so that the simulated volumes and speeds would be within of 15% of actual volumes and speeds. Calibration data were collected from archived sources such asALDOT traffic data, and from field data collection. Speed and volume data were collected during the identified four traffic periods. The calibrated model produced traffic volumes and speeds within a range of ±10%, with slightly higher traffic volumes than actual facility, and slightly less speeds than actual speed, as illustrated by Figure 2-3**Error! Reference source not found.**.

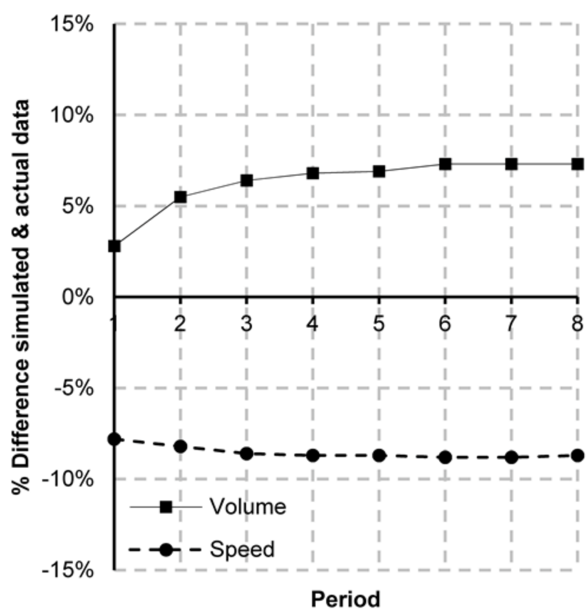

Figure 2-3. Speed and volume differentials for calibrated base model

Additionally, the floating vehicle technique was used to collect data relating to lane changing behavior as the time required to complete a lane change and the percentage of successful lane changes completed. The floating vehicle technique was conducted at active work zones along interstates in Jefferson County, AL.

Temporary Traffic Control Strategies Considered

Four TTC strategies were considered in this study namely (a) early merge control, (b) late merge control, (c) mainline merge metering strategies, and (c) temporary ramp metering. The following paragraphs offer an introduction of each strategy and explain how each strategy was modeled in CORSIM.

Late Merge Control

Late merge control strategy depends on urging drivers to remain in the lane(s) that are about to be blocked until they reach the beginning of the tapper. This strategy attempts to consume all available capacity to accommodate as many vehicles as possible. Simulation was performed using the CORSIM built-in Incident Management Algorithm, for the aforementioned hypothetical work zone configurations. Figure 2-4 provides a screen capture in CORSIM illustrating the microsimulation setup for late merge control.

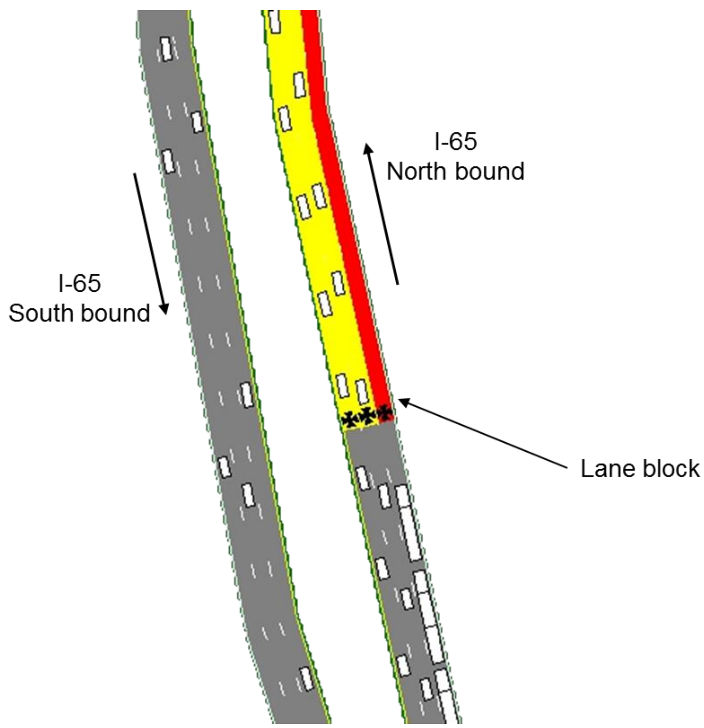

Figure 2-4. Work zone setup in CORSIM using late merge control

To account for the work zone presence, two incidents were coded. The first incident was a blockage on the rightmost lane starting from the beginning of simulation and extending to 2.5

hours to account for the warm-up time, and 20% rubbernecking-only on the middle lane and the left lane. To account for the traffic shockwave recovery, the second incident was coded on the segment following the work zone and with the same length with 20% rubbernecking-only on the rightmost lane.

Early Merge Control

Early merge control strategy depends on urging drivers to merge into open lane(s) as early as possible in a manner that minimizes lane changes near or at work zones. This strategy is usually used for lower volume facilities. Simulation was performed using CORSIM as a lane drop for the rightmost lane and a lane add following the work zone. In addition, rubbernecking-only incidents were coded along the work zone for open lanes to account for the speed reduction that occurs in work zones. Similar to late merge control, the model accounted for a buffer space; however, the merge taper was not accounted for as the model considered an early merge effective 5,800 ft upstream of work zone. This was coded by configuring the lane drop parameters in CORSIM. The distance of 5,800 ft accounts for merging signs placed 800 ft upstream of work zone and every 1,000 ft thereof. Figure 2-5 provides a screen capture in CORSIM illustrating the microsimulation setup for early merge control.

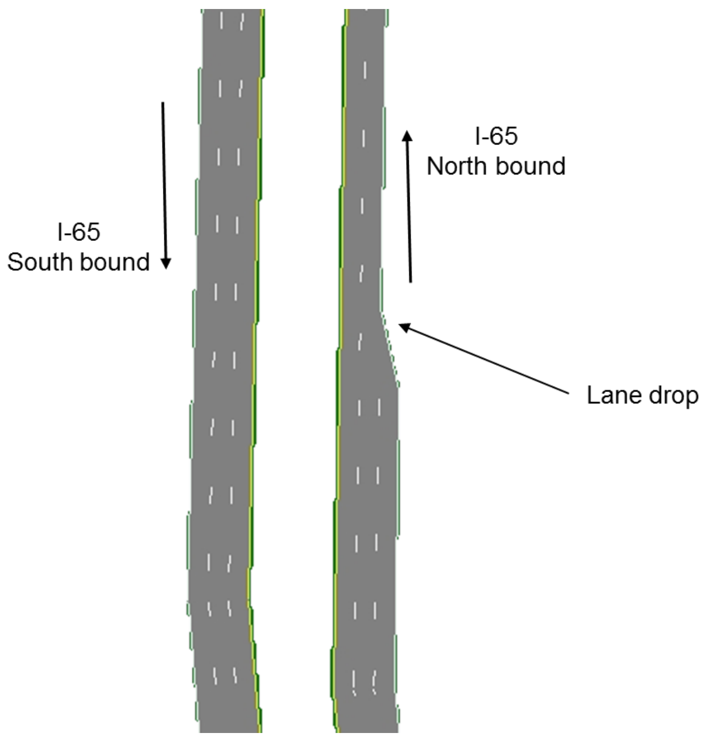

Figure 2-5. Work zone setup in CORSIM using early merge control

Mainline Merge Metering

Mainline merge metering incorporates a merge meter that functions in the same manner as a ramp meter but is installed on the mainline of the freeway lane that is about to be dropped and vehicles have to merge in the adjacent open lane(s). The simulation model was coded to account for a mainline meter upstream of the work zone buffer zone, with an acceleration/merge lane of 300 ft (*28*). The configured meter was a demand/capacity meter with capacity of 2,300 veh/hr/lane (*29*, *30*). The CORSIM demand/capacity metering algorithm performs an evaluation of current excess capacity, immediately downstream of the metered lane, at regular intervals, based on counts from the surveillance detectors on the freeway mainline (*31*). A maximum metering rate is calculated such that the capacity of this freeway section is not violated. This calculated metering rate is then applied like clock-time metering. A minimum metering rate of three green signals/60 seconds is applied to ensure that waiting vehicles are not trapped between the meter and the ramp connection to the freeway. The metering rate is also limited to headways that are greater than two seconds. Figure 2-6 provides a screen capture in CORSIM illustrating the microsimulation setup for mainline merge metering.

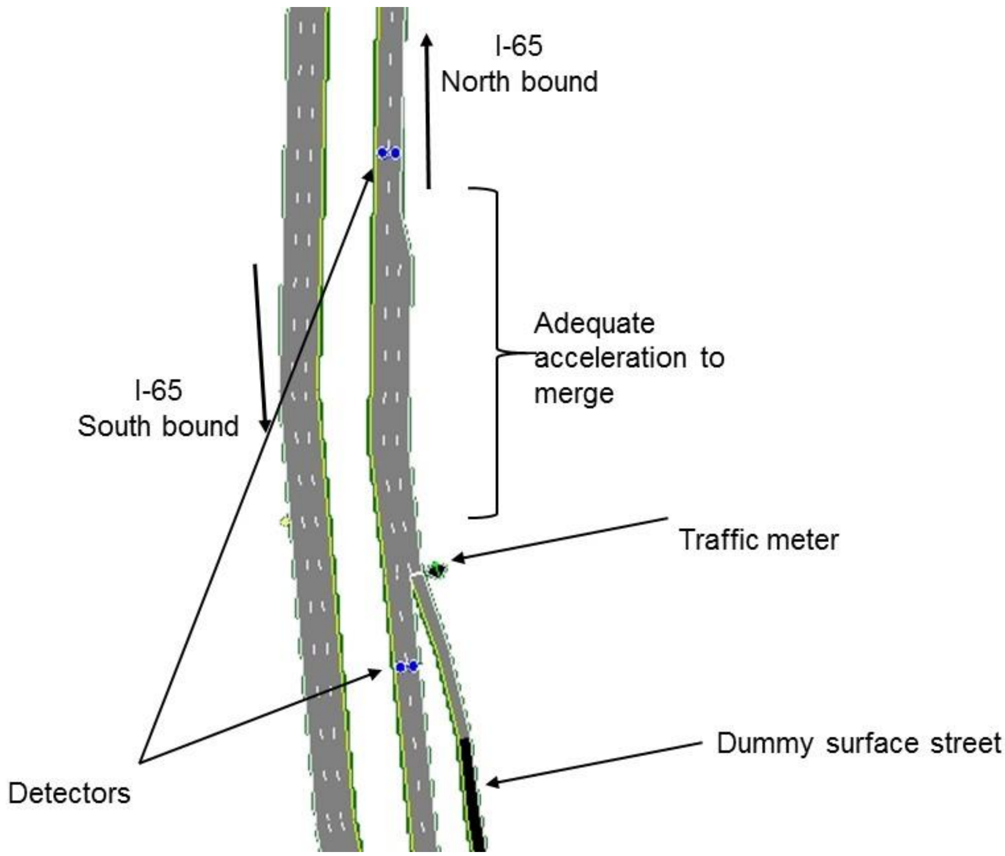

Figure 2-6. Work zone setup in CORSIM using mainline merge metering

Temporary Ramp Metering

Temporary ramp meters are installed at on-ramps where an on-ramp feeds an interstate work zone. The purpose of the temporary ramp meter is to regulate traffic going onto the interstate hence mitigating the mobility impacts of excessive merging in such sections. A hypothetical 3-to-2 work zone was modeled on the leftmost lane downstream from the subject on-ramp. A temporary ramp meter was installed with demand/capacity algorithm similar to the one modeled in the mainline metering strategy. Figure 2-7 provides a screen capture in CORSIM illustrating the microsimulation setup for temporary ramp metering.

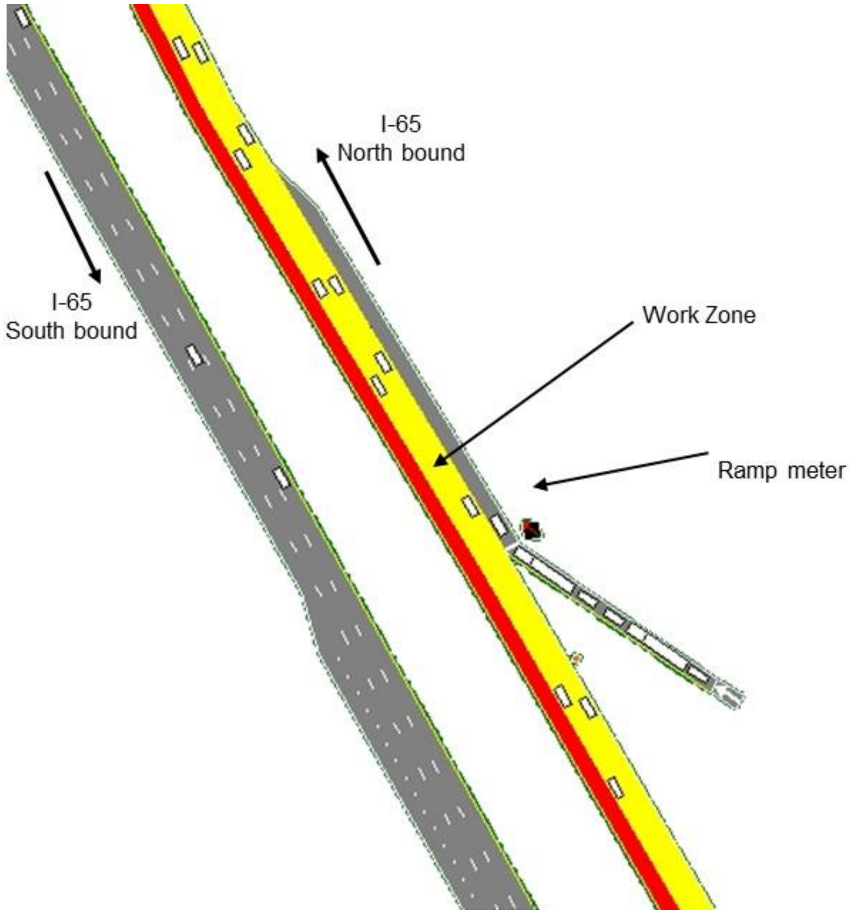

Figure 2-7. Work zone setup in CORSIM using temporary ramp metering

CHAPTER 3
FINDINGS AND APPLICATIONS

LITERATURE REVIEW FINDINGS

After a thorough search for relevant articles of literature, the study team identified nine articles that represent the latest research in bottlenecks merge control. Table 3-1 lists these articles along with the scope of work, and study approach. In addition to the MUTCD conventional merge control strategy, identified bottleneck merge control strategies fall into one of three categories, namely: (a) Early and late merge control; (b) Temporary ramp metering; and (c) Mainline merge metering. The findings of this literature review are summarized in the following subsections.

Table 3-1. Key articles for bottleneck merge control

Article	Scope	Approach
FHWA (*32*)	Policies and agency-level practices	Descriptive
Kurker et al. (*9*)	Early merge, late merge, signal merge	Microscopic traffic simulation
Lentzakis et al. (*10*)	Mainline metering/control	Microscopic traffic simulation
McCoy and Pesti (*3*)	Early merge, late merge, and dynamic late merge	Field test
Oner (*11*)	Temporary ramp metering	Process simulation
Pesti et al. (*12*)	Dynamic Merge	Microscopic traffic simulation
Sun et al. (*13*)	Temporary ramp metering	Microscopic traffic simulation
Tympakianaki et al. (*14*)	Mainline metering/control	Microscopic traffic simulation
Wei et al. (*1*)	Dynamic late merge and Merge metering	

Early and Late Merge Control Strategies

A widely accepted approach to manage work zone traffic is through the use of merge control techniques assisted with *Intelligent Transportation Systems* (ITS) technologies. McCoy and Pesti (*3*) identified two strategies used to control merging maneuvers at bottlenecks. The first strategy is "early merge control," which encourages drivers to merge into open lane(s) sooner than they would do, by providing advance signs, that is available with either static or dynamic configuration. Static early merge control provides notice(s) to merge at fixed distances, while dynamic early merge control provides such signs at variable distances based on real-time traffic conditions. The other approach is "late merge control," which encourages drivers to retain their lanes until they reach the lane closure taper. Late merge is sometimes referred to as "zipper merge" when associated with an alternating "zipper" fashion merge maneuver into the open lane (*32*). Again, there are static and dynamic configurations of late merge control. The dynamic configuration allows for switching between late merge control and conventional merge control according to traffic conditions.

McCoy and Pesti (*3*) studied several early and late merge strategies, and concluded that the dynamic late merge approach is the safest and most efficient strategy due to its responsiveness to actual traffic conditions. Also, Pesti et al. (*12*) performed a study to identify best bottleneck merge control strategies for work zones. Their conclusion favored dynamic merge control strategies for their traffic responsiveness. However, they recommended using dynamic merge control strategies only in the following configurations:

- 2 to 1 lane with single merge point
- 4 to 2 lanes with 2 merge points (each vehicle going through 1 merge point)
- 4 to 1 lane with 3 merge points (each vehicle going through 2 merge points)

Kurker et al. (*9*) used a combination of field observations, micro-simulation, and dynamic traffic assignment tools to develop a procedural guide for interstates work zone traffic control planning. Key elements of their research included determination of hours and days in which traffic demand is less than, equal to, or greater than the estimated work zone capacity. It also included consideration of traffic diversion to paths other than those passing through the work zone. Their main purpose was to suggest conditions for optimal use of early merge or late merge and to provide guidelines for use of signal-controlled merge operations. They concluded that early merge schemes are most suitable when traffic demand does not exceed work zone capacity. However, early merge schemes become highly problematic when traffic demand approaches or exceeds work zone capacity in which case late merge schemes provide the best available procedure as they are designed to use all available lane space prior to the work zone for queue storage. In addition, Beacher et al. (*33*) concluded that benefits from implementing late merge strategies may be limited where heavy vehicles constitute more than 20% of the traffic stream.

Temporary Ramp Metering Strategies

Ramp metering is an effective strategy for improving traffic flow along the mainline by controlling the rate of vehicles entering from the on-ramp into the mainline traffic (*5*). Ramp metering strategies are often utilized to balance demand and capacity, as well as improving safety on interstates (*34*). The documented mobility and productivity benefits of ramp meters motivated researchers to study the use of temporary ramp meters as an alternative to managing traffic on interstate work zones or incidents where there are on-ramps.

The earliest cited literature is a doctoral dissertation by Oner (*11*) where he investigated entrance ramp metering in interstates work zones via simulation. The simulation results indicated much shorter spill back queues from ramp metering signal back to arterials, and lower increase of the queue lengths from the interstate mainline rightmost lane merge area back to the ramp-metering signal.

Sun et al. (*13*) went a step further to evaluate deployed temporary ramp meters at seven work zones in Missouri. They extracted information about driver compliance, merging behavior, speed differentials, lane changing, and braking maneuvers from video-based field data. In addition, they utilized a calibrated simulation model to conduct mobility analysis and obtain total delays for under capacity, at capacity, and over capacity conditions. A limitation of the study is that all deployments considered were conducted during off-peak hours in an urban area, which raises questions about the applicability of their study findings during peak hours or in rural settings.

Mainline Merge Metering Strategies

"Mainline merge metering" strategies are built upon the same architecture as late merge control; however, a merge meter, similar to a conventional ramp meter, is installed at the tapper or point of merge to regulate the release of vehicles trying to merge into open lanes. Lentzakis et al. (*10*) developed a real-time merging traffic control scheme for work zone management aiming at throughput maximization when the arriving flow is greater than the work zone capacity. Their scheme employed the ALINEA ramp metering algorithm and was validated by microscopic simulation for a hypothetical work zone.

Continuing on that work, Tympakianaki et al. (*14*) evaluated real-time mainline merge metering control for work zones. They used a variant of the ALINEA ramp metering algorithm, to determine the appropriate distance between the merge area and the merge meter. They reported significant throughput maximization by avoiding capacity drop. Their results were restricted to a pre-set configuration of a hypothetical work zone where trucks were restricted to one lane and the work zone conditions were simulated as a geometric lane drop along other user-controlled parameters. This approach undermines the model integrity as to simulating real work zone conditions. In addition, there were no reported evidence of calibrating driver/vehicle behavior for work zone driving conditions.

Wei et al. (*1*) developed an approach for work zone bottleneck traffic control through integrating dynamic late merge, merge metering, and wireless communication technologies, for use at the merge taper of a work zone. They named their system as "*dynamic merge metering traffic control system*", which was evaluated using the microscopic simulation software VISSIM*. The study was limited to considering only traffic volumes for operating the merge metering signal, while disregarding other potential control parameters including speed, density and occupancy. In addition, the researchers were skeptical of their control algorithm, and recommended further development of the algorithm for controlling their system. Finally, yet importantly, the simulation runs for the merge metering method in the study by Wei et al. were performed using 30, 60, and 120 seconds signal cycles. No efforts for optimization were reported in consideration of operating speeds, traffic volumes, and traffic composition. This leaves the door open for further research to find out the optimum cycle length.

Effect of Bottleneck Merge Control Strategy on Construction Scheduling

Most applications of bottlenecks merge control strategies are for highway work zones. Accordingly, the intersection of bottlenecks merge control and construction scheduling operations had to be investigated to identify any practices that may influence the criteria for

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* ***V****erkehr* ***I****n* ***S****tädten –* ***SIM****ulationsmodell (VISSIM), which is* German for "Traffic in cities - simulation model"

selecting a bottleneck merge control strategy. Review of literature indicated that planning and construction are among key processes within current project delivery systems (*35*). In addition, available literature discuss the timing of construction planning and scheduling decisions rather than the type of such decisions; however, the types of decisions that need to be made are equally important and should not be overlooked.

Hardy and Wunderlich (*36*) grouped these decisions in three categories, namely scheduling; application; and *transportation management plan* (TMP). However, that conventional relationship between the three categories does not account for the impacts of developed TMPs and construction scheduling decisions. In addition, the study considers only a specific situation where scheduling decisions affect the TMP, which may not be the case for every project. TMPs are commonly developed at the bidding stage by the engineer and the contractor is forced to adopt. There have been some efforts on optimizing construction schedules; however, available literature overlooked the influence of bottleneck merge control strategies on construction planning and scheduling decisions.

Chien et al. (*37*) optimized construction scheduling and traffic control on partially closed two-lane two-way highways. They used a numerical method with the objective set to minimize the overall cost, while considering traffic flow variations over time. They formulated an objective function that considered work zone length, scheduling attributes, and traffic control parameters, considering real-time traffic demand. However, the method was flawed as a result of their effort to simplify the formulation of their objective function by considering user a constant average delay cost.

Recently, Morgado and Neves (*38*) developed a decision-making method for planning pavement maintenance and rehabilitation works, that integrates project cost, project duration, and user costs. Their computer-based method employed multiple weighted criteria to generate a set of feasible work zone schedules and layouts. Comparison of generated alternatives followed decision-maker's preferences and ignored user costs.

DISCUSSION OF LITERATURE REVIEW FINDINGS

The comprehensive review of available literature performed in this study indicated that there is no national reference that documents bottleneck merge control practices at work zones. In addition, available literature indicated that the major application for bottleneck merge control strategies is in highway work zones; however, there was no indication on how such practices may impact construction planning and scheduling decisions nor vice versa. Thus, there is a need to survey the state-of-the-practice regarding interstate traffic control strategies and to document any efforts that consider highway construction activities.

To address this issue, the authors performed a survey of DOTs current practices related to merge control strategies at work zone bottleneck. The details of this survey are discussed in CHAPTER 2 and the findings are summarized in the following section.

RESULTS OF THE SURVEY OF PRACTICE

A total of 27 State DOTs representatives provided responses to the state of practice survey over a 45-day period, representing a 54% response rate. Responses were received from the States of Alabama, California, Colorado, Illinois, Iowa, Michigan, Minnesota, Mississippi, Missouri, North Carolina, South Carolina, South Dakota, Utah, Vermont, West Virginia, Wisconsin, and Wyoming, in addition to 10 undisclosed States. The survey results and relevant discussion fall into one of the following four categories:

- Bottleneck merge control strategy
- Accelerated construction practices
- Construction planning and scheduling practices, and
- Monitoring, evaluation, and research efforts

The following sub-sections present the survey results and relevant discussions.

Bottleneck Merge Control Strategy

Survey participants were asked to state their agencies' lane closure and merge control strategies at work zones that are commonly used within their jurisdiction. Survey results indicated that most agencies prefer to schedule works during off-peak periods for projects that are constructed as a single segment or multiple segments (66% and 55% respectively). For agencies that opt to partially close a highway and implement a merge control strategy, responses indicated that static early merge control is the most common strategy by 57.14%, static late merge control ranked second by 21.43%, conventional merge control ranked third by 14.29%, and dynamic early and late merge control tied by 3.57% each, as illustrated by Figure 3-1. Responses also indicated that temporary ramp metering and main line merge metering are not used at all in practice.

Figure 3-2 illustrates the responses regarding the criteria or rationale for selecting a bottleneck merge control strategy. Common practice or earlier experience ranked first by 40.35%; favorable safety impacts ranked second by 19.30%; followed by agency policy (17.54%); favorable mobility impacts (4.04%); and cost effectiveness (8.77%). The survey results suggest that the driving factor for selecting the type of bottleneck merge control is common practice, while cost effectiveness is the least considered factor.

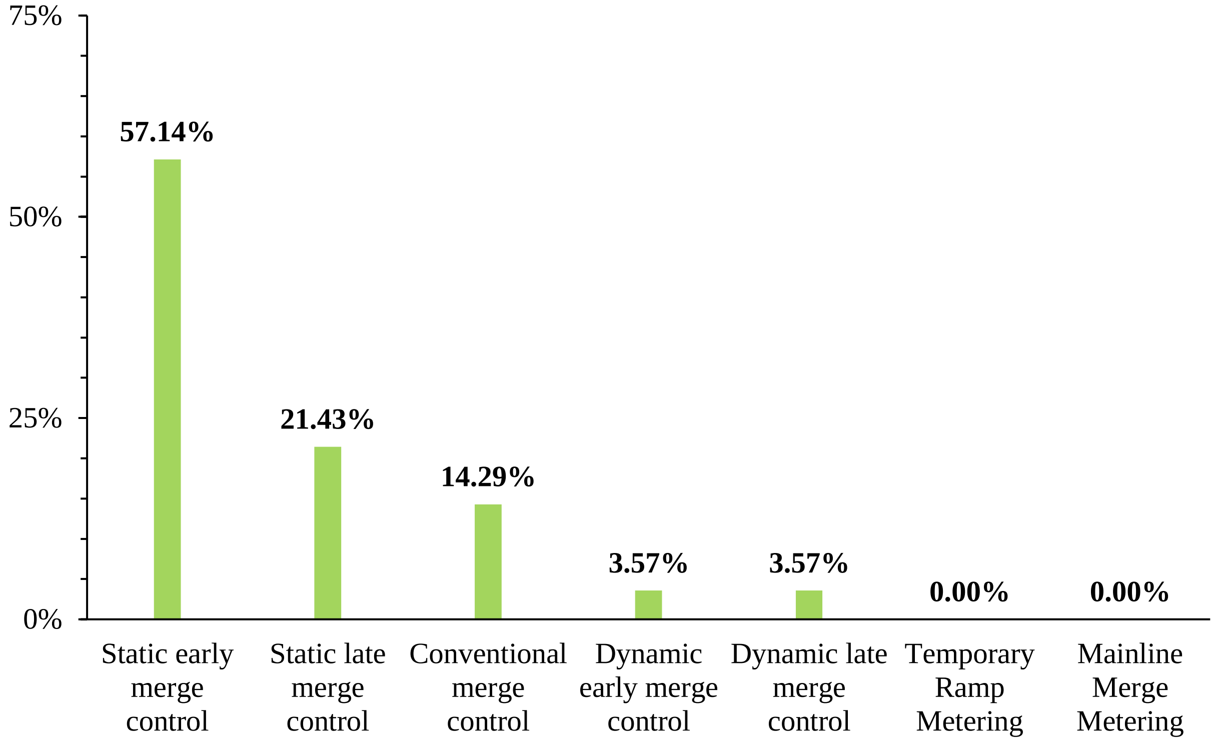

Figure 3-1. Selected bottleneck merge control strategy

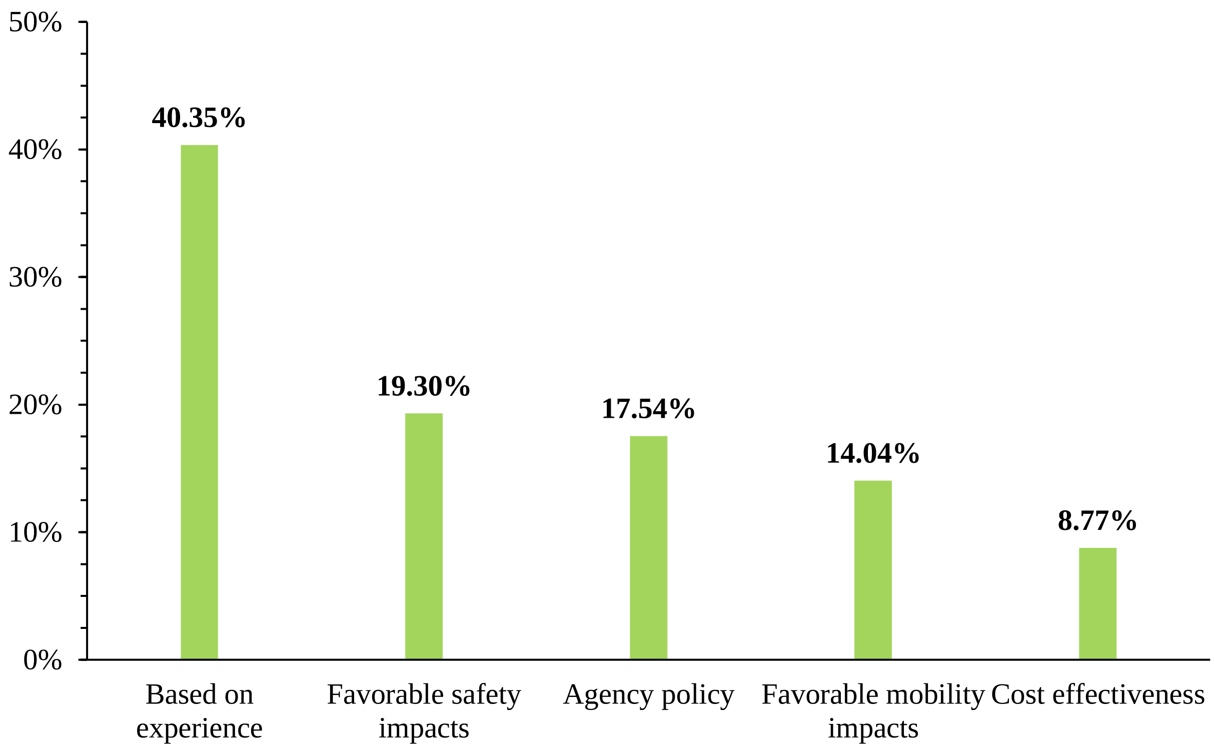

Figure 3-2. Rationale behind selection of bottleneck merge control strategies

Accelerated Construction Practices

Respondents were asked to indicate their agencies' practice regarding accelerated construction technologies, and their perception of the relation between such practices and the implemented merge control strategies. Results indicated that 66% of the DOTs responding to the survey are currently implementing or adopting accelerated construction practices, 10% are planning to implement such practices in the future, 14% are researching the concept of accelerated construction, and 10% are not interested in such practices at present. In addition, 79% of the respondents believe that accelerated construction practices are related or impacted by implemented bottleneck merge control strategies.

Construction Planning and Scheduling Practices

The survey also documented the respondents' professional perception of the probable impacts of implemented bottleneck merge control strategies on construction planning and scheduling decisions. Survey responses indicated that 48% of the participating DOTs allow the contractors to choose work zone or segment lengths within a pre-set range, 38% define a work zone or segment length within the contract documents, and 14% allow the contractor to choose the length based on a DOT approved construction plan and schedule. Ultimately, it is the DOTs decision when it comes to setting or choosing the work zone or segment lengths. In addition, the survey responses indicated that 69% of the DOTs develop bottleneck merge control plans driven by a given work zone length, on the other hand, 24% determine the work zone length driven by planned bottleneck merge control plan, and 7% of the DOTs do not correlate work zone or segment lengths to the implemented bottleneck merge control plan. As for how surveyed DOTs perceive the relation between implemented bottleneck merge control plans and construction duration, 48% of the DOTs determine construction durations based on past experience, 45% estimate durations based on site-specific traffic conditions and merge control plans, and 7% estimate durations based on the assumption of night-time, off-peak construction.

Monitoring, Evaluation, and Research Efforts

The survey of practice included three questions that tackled the agencies' efforts towards monitoring and evaluation of current practices, availability of relevant guidelines or manuals, and research efforts to improve current practices. Survey results indicated that the majority of the responding DOTs (25 respondents representing 92.6% of total) collect exposure and/or mobility MOEs. Table 3-2 documents DOTs efforts towards collecting and documenting MOEs for work zones and shows that there is little consistency among responding agencies on the type of MOEs collected. Most commonly used MOEs include % of days or nights when work activity occurs (45%); % work activity hours with 1, 2, 3 or more lanes closed (31%); average lane closure length (28%), and maximum queue length (28%).

In addition, 45% of the DOTs have established guidelines and/or manuals for work zone traffic control impacts, 31% have some guidelines and are in the process of improving or revising them, 10% have no guidelines and are interested in developing some, and 14% have no guidelines and believe they do not need any. Furthermore, survey results indicate that 31% of the DOTs have an established policy to meet the requirements of the work zone safety and mobility rule, 38% are performing modest research efforts to meet such requirements, and 21% are constantly performing research and studies to meet or exceed the rule requirements.

Table 3-2. DOTs Measures of Effectiveness (MOEs) documentation practices

MOE	№ & %of DOTs
Exposure MOEs	
% of days or nights when work activity occurs	13 (45%)
% work activity hours with (1,2,3, etc.) lanes closed	9 (31%)
Average lane closure length	8 (28%)
Lane-mile-hours of closures	4 (14%)
Mobility MOEs	
Maximum queue length	8 (28%)
Average queue length	7 (24%)
Average queue duration	6 (21%)
Average vehicle delay / travel time	6 (21%)
% Time when work zone queue length exceeds a certain length	4 (14%)
Amount (or % of ADT) that encounters a queue	4 (14%)
Number or % of work activity periods when queuing occurred	1 (3%)

Overall the survey of practice showed that most DOTs implement static early merge (57%) strategies based solely on their earlier experiences and confirmed the lack of formal guidelines for implementing alternative merge control strategies. The findings showed the need for an in depth analysis of the impacts of various merge control options on work zone operations and scheduling.

MICROSCOPIC SIMULATION RESULTS

Link-based MOEs provide an understanding of the localized impacts of simulated merge control strategies at and in the vicinity of the work zone. In this study, the link-based MOEs selected were density per lane (vehicle/mile/lane), delay travel per vehicle (seconds/vehicle), and Emissions Total CO (grams/mile). These MOEs are key measures for illustrating mobility, user satisfaction, and environmental impacts of considered work zone configurations and merge control strategies (*39*). These MOEs were collected and averaged over five runs for each scenario while preserving the random seeds, and results were compared against preconstruction (i.e., baseline) conditions. The following subsections illustrate how each MOE was processed and prepared for further statistical analysis, along with a discussion of underlying observations that would offer an understanding of how implementing the studied work zone merge control strategies would impact construction planning and scheduling decisions.

Density per Lane (vehicles/mile/lane)

Density is the key measure for *Level of Service* (LOS) on freeway segments. CORSIM calculates link-based density as the average content divided by the link length divided by the average number of lanes on the link. Average content is the total number of vehicle seconds accumulated on the link since the beginning of the simulation divided by the number of seconds since the beginning of the simulation. To streamline the data processing and analysis, the CORSIM *Output Processor* was programed to report mean cumulative densities and corresponding standard deviations from all 84 scenarios across the 420 simulation runs. To evaluate the impact of a specific work zone configuration on density, a density index (I_D) was calculated as shown by the following Eq. (1):

$$I_{D(P,S)} = \frac{D_{P,S} - D_{P,PC}}{D_{P,PC}} \times 100 \qquad \text{Eq. (1)}$$

Where, $D_{P,PC}$ is the weighted average density preconstruction (i.e., baseline) of the segment for a given work scheduling period "P," and $D_{P,S}$ is the weighted average density for all segments within the defined work zone for a given work scheduling "P" and a given merge control strategy "S." Weighted average density was used following the guidelines of the *Highway Capacity Manual* (HCM) (*40*). Negative values for the index I_D indicate improvement of density compared to that of baseline conditions, and positive values would indicate more dense traffic, as in worsening traffic conditions.

Table 3-3 shows the values of I_D for each microscopic simulation study scenario, and Figure 3-3 illustrates a plot of the density index (I_D) against the four scheduling periods considered in this study, for each work zone length and merge control strategy considered. It is observed that for every merge control strategy and scheduling period pair, the values of I_D corresponding to each work zone length are clustered around the average value. Accordingly, the lines connecting these averages were plotted along the boundaries that define the six LOSs used within the HCM (*40*).

This observation indicates that work zone length appears to be insignificant to density changes due to the presence of work zones. It is also observed that density is heavily impacted by the implemented merge control strategy for each scheduling period. In addition, results indicate that during off-peak periods all merge control strategies yielded a LOS A. Moreover, results indicate that implementing early merge control would deteriorate the LOS beyond the LOS F limit. Finally, the results indicate that mainline merge metering was the most promising strategy during the three tested peak periods.

Table 3-3. Microscopic simulation results

Run	I_D	I_E	I_T	Run	I_D	I_E	I_T
1	-27.53%	-6.25%	88.56%	41	-63.40%	71.84%	151.94%
2	-18.92%	4.99%	170.32%	42	-59.15%	95.45%	263.86%
3	-20.02%	3.11%	158.36%	43	-59.43%	89.63%	240.92%
4	1.20%	1.92%	49.24%	44	16.74%	74.73%	614.12%
5	-26.77%	-5.73%	92.21%	45	-62.75%	77.04%	158.74%
6	-18.40%	4.85%	175.82%	46	-57.13%	95.50%	254.71%
7	-19.18%	2.79%	164.13%	47	-58.37%	88.24%	244.71%
8	-0.75%	1.50%	54.40%	48	22.37%	70.38%	597.59%
9	-25.63%	-6.57%	101.66%	49	-61.46%	76.33%	152.55%
10	-17.35%	4.79%	186.47%	50	-56.97%	97.02%	259.46%
11	-18.64%	1.62%	173.69%	51	-56.68%	90.48%	242.70%
12	0.00%	0.59%	85.85%	52	27.41%	70.82%	625.24%
13	-24.36%	-8.70%	115.73%	53	-58.84%	76.12%	148.08%
14	-16.82%	3.15%	197.31%	54	-53.74%	97.83%	253.53%
15	-17.52%	0.41%	186.74%	55	-55.11%	94.02%	244.20%
16	0.37%	1.18%	82.25%	56	33.97%	71.62%	618.75%
17	-23.43%	-9.60%	124.88%	57	-57.54%	76.01%	155.52%
18	-15.81%	0.95%	207.00%	58	-52.19%	93.67%	264.79%
19	-16.70%	-1.09%	198.69%	59	-53.32%	92.23%	247.28%
20	1.15%	0.58%	71.53%	60	43.41%	72.42%	648.73%
21	-6.02%	-7.38%	231.66%	61	-44.97%	11.07%	-31.33%
22	4.84%	3.45%	375.69%	62	-2.99%	31.43%	218.77%
23	3.12%	0.57%	346.19%	63	-6.75%	28.10%	172.09%
24	10.04%	0.75%	52.70%	64	1.16%	4.55%	127.33%
25	-2.17%	-7.77%	241.35%	65	-40.73%	10.11%	-13.87%
26	8.80%	2.38%	378.89%	66	2.25%	28.95%	273.46%
27	7.60%	0.03%	361.64%	67	-1.90%	26.49%	221.55%
28	13.94%	-0.12%	43.24%	68	2.59%	4.03%	136.65%
29	2.58%	-9.07%	249.45%	69	-40.23%	6.52%	-11.40%
30	14.15%	1.66%	392.09%	70	4.14%	24.85%	288.48%
31	12.57%	-0.63%	370.79%	71	-0.22%	22.73%	230.44%
32	21.93%	-0.38%	60.31%	72	1.29%	2.53%	140.97%
33	8.60%	-9.46%	263.24%	73	-39.60%	4.60%	-9.90%
34	19.95%	0.07%	396.39%	74	5.40%	22.88%	300.31%
35	18.76%	-2.53%	380.85%	75	0.89%	20.87%	236.85%
36	27.89%	-2.94%	82.60%	76	1.43%	2.29%	138.00%
37	15.49%	-11.28%	273.87%	77	-39.54%	1.61%	-10.67%
38	28.99%	-1.72%	422.28%	78	4.57%	18.27%	290.32%
39	27.36%	-3.80%	408.90%	79	0.86%	17.36%	237.22%
40	35.98%	-1.64%	86.02%	80	2.85%	0.95%	157.68%

Note: I_D is density index; I_E is emissions total CO index; and I_T is delay index

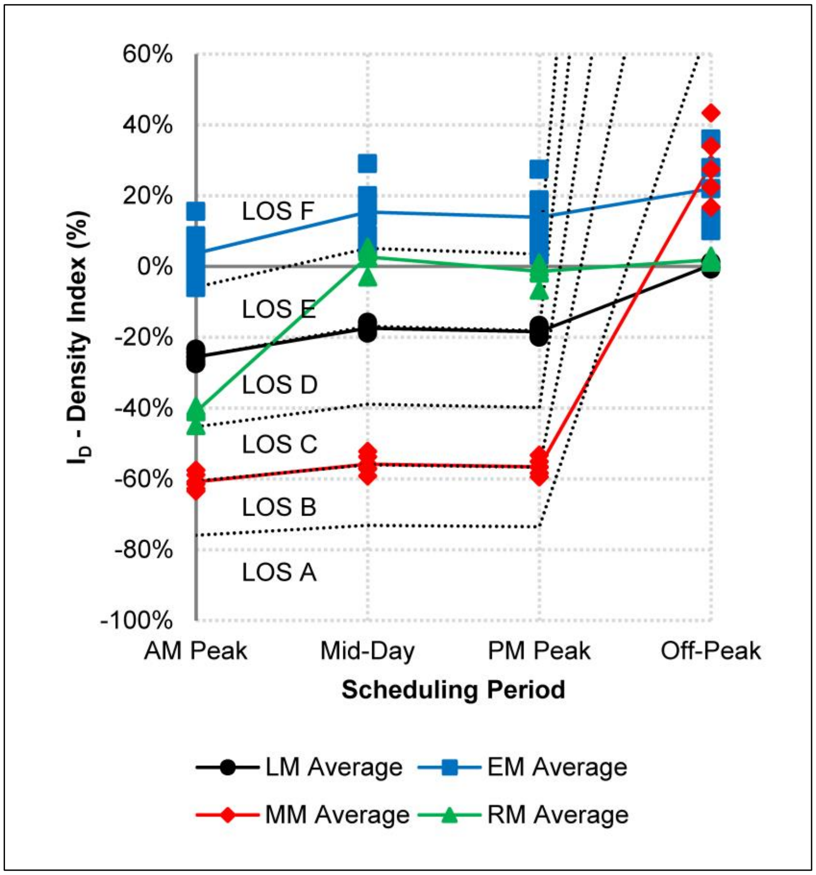

Figure 3-3. Average values for density index per simulated strategy

Additional Analysis for Density

The aforementioned analysis of Density index and the observation that work zone lengths is not significant motivated further in-depth analysis of the impacts on Density. Examination of Alabama Department of Transportation traffic data yielded that off-peak traffic represents 13.43% of the peak traffic. Accordingly, the spectrum between 13.43% and 100% represents the variations in traffic throughout any given day. Hence, 10 even intervals were considered to simulate the impact of the study merge control strategies, namely: 100%, 90.38%, 80.76%, 71.14%, 61.52%, 51.90%, 42.28%, 32.66%, 23.04%, and 13.43%. Accordingly, ten base models were developed to reflect the actual conditions along the test corridor during the traffic conditions under consideration. The base models were calibrated using field collected speeds and volumes, and all 10 base models yielded acceptable (within ± 10%) deviations from field data.

Similar to previous analysis, the CORSIM *Output Processor* was programed to report mean cumulative densities and corresponding standard deviations from 40 scenarios (4 merge control strategies by 10 traffic demand conditions) that were run five times each with a total of 200 simulation runs. To calibrate these scenarios, the study team used the test vehicle technique with average driving style through several work zones that were scheduled between February 2014 and February 2015. Calibration data were speeds, volumes, times to complete lane change maneuvers, and percentage of lane changes made on first attempt. The simulation models yielded accepted (within ± 20%) deviations from field data.

Figure 3-4 represents the plot of the I_D against simulated traffic volume as a percentage of peak hour traffic volume. The I_D plot for late merge control is represented by the continuous black curve, early merge control is represented by the continuous blue curve, mainline merge metering is represented by the continuous red curve, and temporary ramp metering is represented by the continuous green curve. The density limits for LOS *A* through *F* are represented by the dotted black curves, and the corresponding value of each density limit is presented right above each curve.

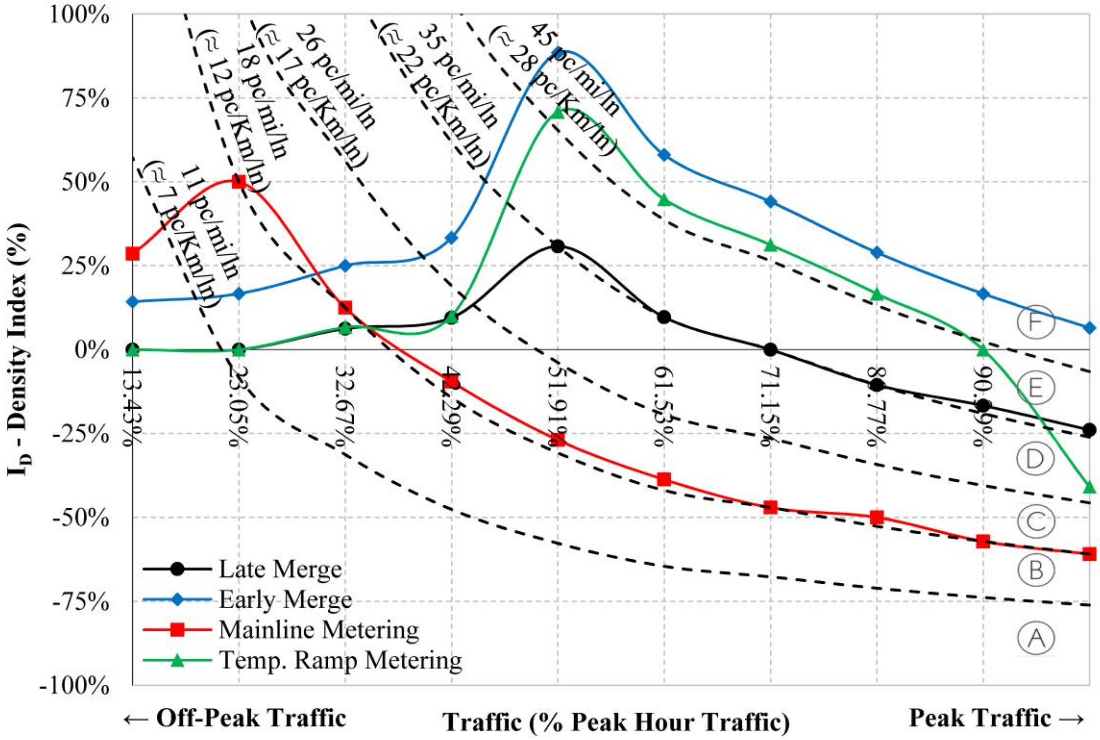

Figure 3-4. Raw microsimulation results for the impact of simulated strategies on density

A positive I_D value indicates that there is an increase in density compared to preconstruction density due to the presence of a work zone that is controlled by the corresponding merge control strategy. Hence, a positive I_D value implies that LOS has deteriorated and additional delays are expected due to the presence of the work zone.

It should be noted that the I_D values are calculated for the study segment only and there is no reported indication of density or LOS upstream or downstream from the study segment. In addition, the network level impacts were not considered in this study. Results, discussions, and any drawn conclusions are local to the work zone area, and represent the drivers' experience/perception of work zone presence and implemented merge control strategy for the work zone section.

Testing for outliers was performed by *Box Plots* and the data points for early merge control and temporary ramp metering corresponding to simulated traffic of 51.90% of peak hour traffic, were detected as outliers. Figure 3-5 represents the revised data plot after eliminating outliers.

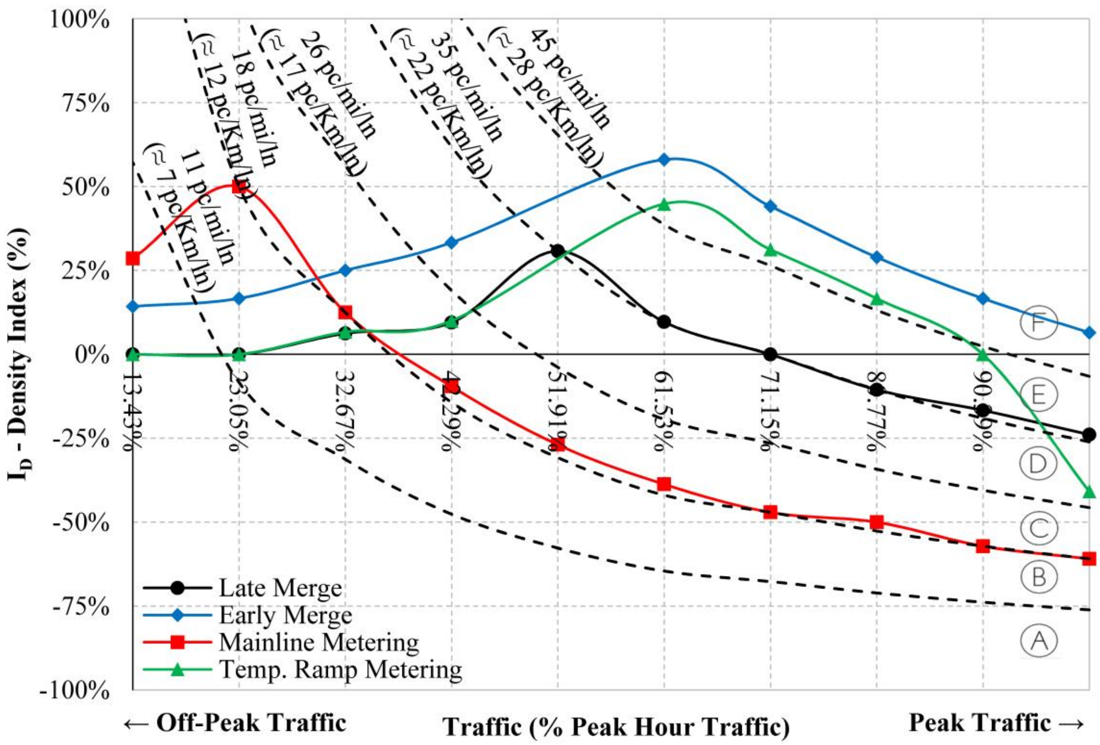

Figure 3-5. Microsimulation results (I_D vs. Traffic) after eliminating outliers

The study results summarized in Figure 3-5 indicate that mainline merge metering guarantees work zone LOS of *C* or better, late merge control results in LOS *E* or better while early merge control fails (LOS of F) for traffic exceeding ~55% of peak traffic. These results validate the practice of using late merge control for high traffic volumes, and early merge control for lower traffic volumes. In addition, these results prove the potential benefits of adopting mainline merge metering, which can be achieved by complementing existing late merge control practices by incorporating temporary merge meters (similar to ramp meters) at lane closures or merge tapers. While results indicate that some strategies would improve density (negative I_D) within the work zone section, the decision maker or analyst should carefully examine the corridor for any developed queues or on-ramp spill-backs upstream from the work zone, as the lowered density would be attributed to a traffic jam upstream of the work zone. In this study, a segment equivalent to the work zone length, upstream of the work zone, was included to account for such phenomena.

Refined results were further studied in an attempt to develop a mathematical relation between the introduced I_D and traffic flow (as a % of Peak Hour Traffic). The statistical package SPSS was used to find the best curve estimate for this data set. SPSS results indicated that the best fit is a sixth degree polynomial with no intercept. Equations 2, 3, 4, and 5 represent the regression results, where $I_{D(LM,i)}$ represents the I_D for late merge control as a function of a given traffic T_i, $I_{D(EM,i)}$ represents the I_D for early merge control as a function of a given traffic T_i, $I_{D(MM,i)}$ represents the I_D for mainline merge metering as a function of a given traffic T_i, and $I_{D(RM,i)}$ represents the I_D for temporary ramp metering as a function of a given traffic T_i.

$$I_{D(LM,i)} = -100.96\,T_i^6 + 313.21\,T_i^5 - 358.90\,T_i^4 + 183.12\,T_i^3 - 39.57\,T_i^2 + 2.87\,T_i \qquad \text{Eq. (2)}$$

$$I_{D(EM,i)} = -48.82\,T_i^6 + 177.81\,T_i^5 - 238.78\,T_i^4 + 143.04\,T_i^3 - 37.29\,T_i^2 + 4.12\,T_i \qquad \text{Eq. (3)}$$

$$I_{D(MM,i)} = 114.79\,T_i^6 - 349.17\,T_i^5 + 386.77\,T_i^4 - 180.56\,T_i^3 + 26.15\,T_i^2 + 1.42\,T_i \qquad \text{Eq. (4)}$$

$$I_{D(RM,i)} = 52.37\,T_i^6 + 177.82\,T_i^5 - 229.43\,T_i^4 + 133.24\,T_i^3 - 32.25\,T_i^2 + 2.59\,T_i \qquad \text{Eq. (5)}$$

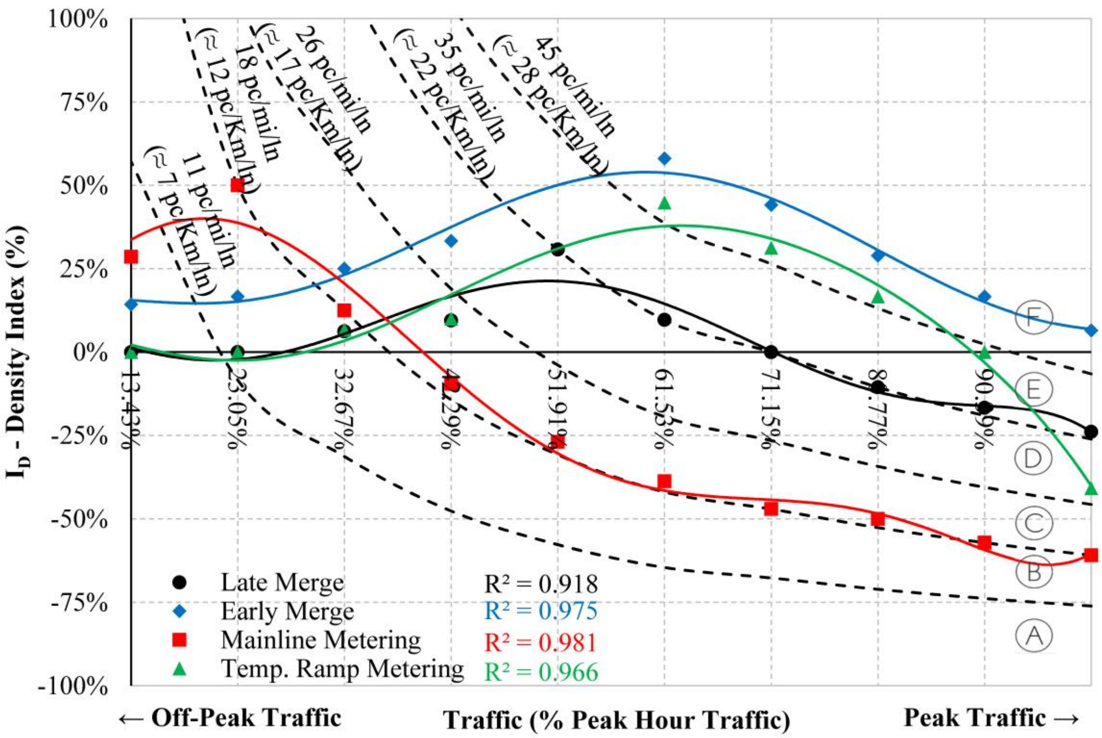

Figure 3-6. Line fit plots for *I_D* regression functions

To assess the goodness of fit of these equations, the R^2 statistic was considered. R^2 values were found to be 0.918, 0.975, 0.981, and 0.966 for late merge, early merge, mainline merge metering, and temporary ramp metering respectively. Furthermore, the goodness of fit was confirmed by line fit plots as illustrated by Figure 3-6. Overall, the goodness of fit tests yielded very satisfactory results, thus providing confidence in using the findings as a lasting reference. For a given project, transportation officials/practitioners can use these models to estimate the impact of considered merge control strategy on density and LOS by calculating the proposed I_D as a comprehensive mobility indicator.

Delay Travel per Vehicle (Seconds/Vehicle)

The HCM (*40*) defines delay as “the additional travel time experienced by a driver” estimated as the difference between an “ideal” travel time and the actual travel time. CORSIM produces the link-based MOE “delay travel per vehicle” as a measure for “delay.” It is calculated as the “total time per vehicle,” which represents the actual travel time, minus the “move time per vehicle,” also known as the ideal travel time. CORSIM calculates the “total time per vehicle” as the link length divide by the average speed of all vehicles on the link since the beginning of the simulation, and the “move time per vehicle” as the total theoretical time for discharged vehicles to travel the length of the link if moving unimpeded at the free-flow speed.

It is undisputed that the presence of work zones impacts travel time by adding to it some delay travel, which would impact travelers decisions regarding their trips. Accordingly, this study considered a delay travel index (I_T) that was calculated to show how much earlier a travel must start the trip (as a percentage of the delay they usually incur when starting their trip at a certain time) to arrive on time and not be delayed by a work zone. It is computed using Eq. (6):

$$I_{T(P,S)} = \frac{T_{P,S} - T_{P,PC}}{T_{P,PC}} \times 100 \qquad \text{Eq. (6)}$$

Where, $T_{P,PC}$ is the total preconstruction (i.e., baseline) delay travel per vehicle on a segment for a given work scheduling period “P,” and $T_{P,S}$ is the total delay travel per vehicle for the same segment within the defined work zone for a given work scheduling “P” and a given merge control strategy “S.” A positive delay index indicates that the considered work zone configuration adversely impacts travel, while a negative index indicates an improvement of travel times.

Table 3-3 shows the values of I_T for each microscopic simulation scenario, and Figure 3-7 illustrates a plot of the delay index (I_T) against the four considered scheduling periods, for each work zone length and merge control strategy. Again, it is observed that for every merge control strategy and scheduling period pair, the values of I_T corresponding to each work zone length are clustered around the average value. This emphasizes the suggestion that work zone length should be tested for significance as to delay impacts. The least impacts on delay are observed when a work zone is scheduled during morning peak period while implementing the late merge control strategy, except when scheduling a work zone at an entrance ramp in which case the temporary ramp metering yields better results than the late merge strategy. Conclusions from these results does not align with those of the density index (I_D), hence focusing on only one type of impacts would yield to less than optimal decisions.

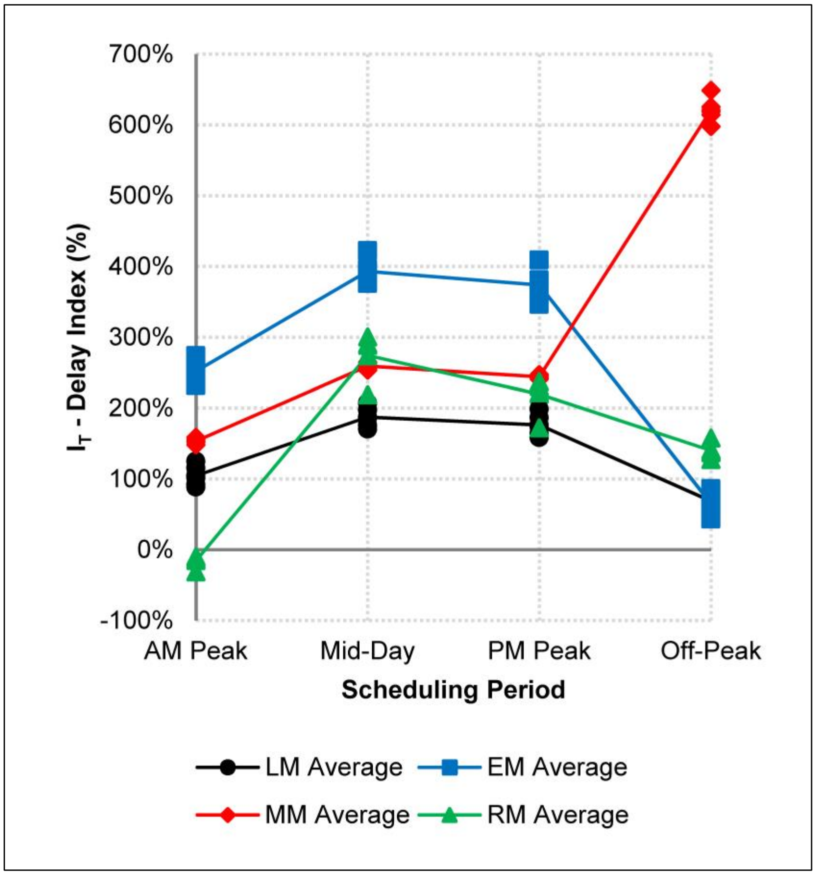

Figure 3-7. Average delay index per simulated strategy

Emissions Total CO (Grams/mile)

The link-based MOE emissions total *Carbon Monoxide* (CO) represents the total CO emissions per mile produced by all vehicles on the link. This MOE is the key environmental impacts indicator, and was collected for the links occupied by the work zone, in addition to links comprising a stretch of the interstate upstream and downstream of the work zone with the same length. An emissions total CO Index (I_E) was developed using Eq. (7) to illustrate the percentage change of emissions total CO from preconstruction (i.e., baseline) conditions by work zone length for each of the considered scheduling periods.

$$I_{E(P,S)} = \frac{E_{P,S} - E_{P,PC}}{E_{P,PC}} \times 100 \qquad \text{Eq. (7)}$$

Where, $E_{P,PC}$ is the cumulative preconstruction emissions total CO on the segment for a given work scheduling period "P," and $E_{P,S}$ is the cumulative emissions total CO for the same segment within the defined work zone for a given work scheduling "P" and a given merge control strategy "S" combination. Table 3-3 shows the values of I_E for each microscopic simulation scenario, and Figure 3-8 illustrates a plot of the emissions total CO index (I_E) against the four considered scheduling periods, for each work zone length and merge control strategy.

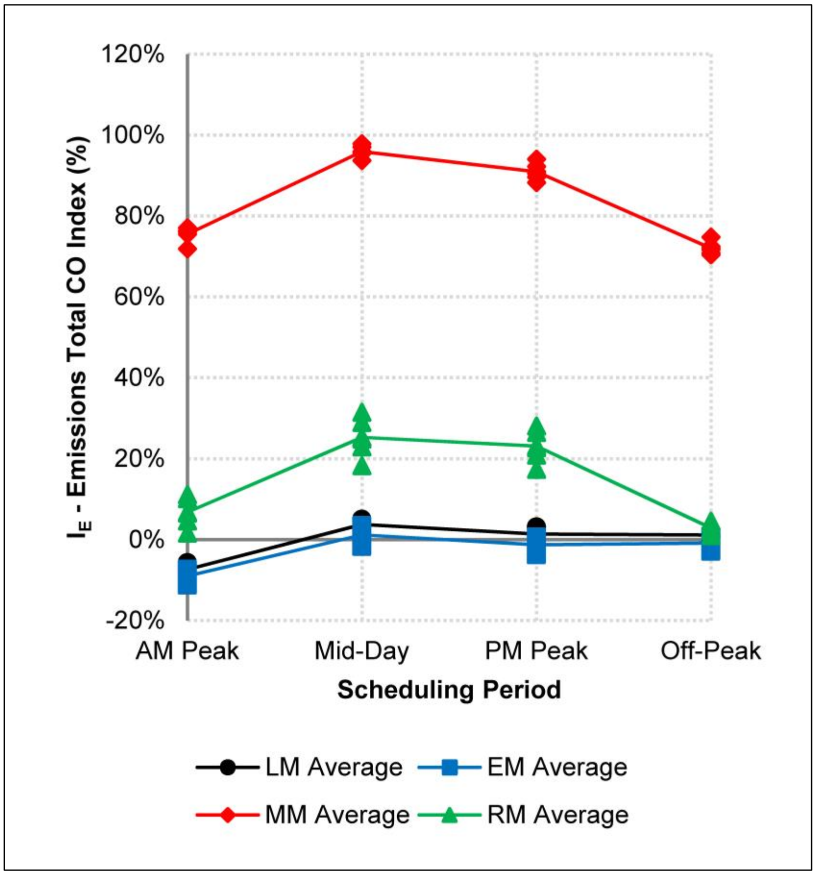

Figure 3-8. Average emissions total CO index per simulated strategy

It is observed that for every merge control strategy and scheduling period pair, the values of I_E corresponding to each work zone length are clustered around the average value. This emphasizes the previously suggested observation that work zone length should be tested for significance as to emissions impacts. Furthermore, it is observed that environmental impacts of early and late merge control strategies are minimal and consistent in comparison to those of mainline merge metering and temporary ramp metering strategies. For all strategies except mainline metering, tested merge control strategies resulted in a change of ± 20% of preconstruction values. However, mainline metering resulted in an increase of 70 – 100% compared to preconstruction conditions.

STATISTICAL ANALYSIS OF SIMULATED MOES INDICES

The categorical variables merge control strategy (S) and construction scheduling period (P), each was coded into four dichotomous mutually exclusive dummy variables. For merge control strategy (S) the dummy variables were early merge control (S_{EM}), late merge control (S_{LM}), mainline merge metering (S_{MM}), and temporary ramp metering (S_{RM}). As for the construction scheduling period (P) variable, the dummy variables were morning peak period (P_{AM}), mid-day peak period (P_{MD}), afternoon peak period (P_{PM}), and off-peak period (P_{NT}). A value of one (1) for any of the merge control strategy dummy variables indicates that this strategy is being implemented, and the same is valid for the scheduling period dummy variables.

Using SPSS, a Pearson's correlation was run first to determine the relationship between traffic density index (I_D) and work zone length (L), scheduling period (P), and implemented merge control strategy (S). Results indicated a significant negative correlation between density index and scheduling period ($r = -0.528, N = 80, p = 0.000$), a significant negative correlation between density index and implemented merge control strategy ($r = -0.355, N = 80, p = 0.001$), and an insignificant positive correlation between density index and work zone length ($r = 0.134, N = 80, p = 0.237$). A second run of Pearson's correlation was conducted for emissions total CO index (I_E), and results indicated a significant positive correlation with implemented work zone merge control strategy ($r = 0.419, N = 80, p = 0.000$), and insignificant negative correlations with scheduling period and work zone length ($r = -0.31, N = 80, p = 0.786$ and $r = -0.38, N = 80, p = 0.740$, respectively). A third run of Pearson's correlation was run for delay travel by vehicle index (I_T), and results indicated a significant negative correlation with scheduling period ($r = -0.245, N = 80, p = 0.029$), an insignificant positive correlation work zone length ($r = 0.081, N = 80, p = 0.477$), and an insignificant negative correlation with merge control strategy ($r = -0.123, N = 80, p = 0.277$). These correlations were confirmed by the scatter plots illustrated in Figure 3-9.

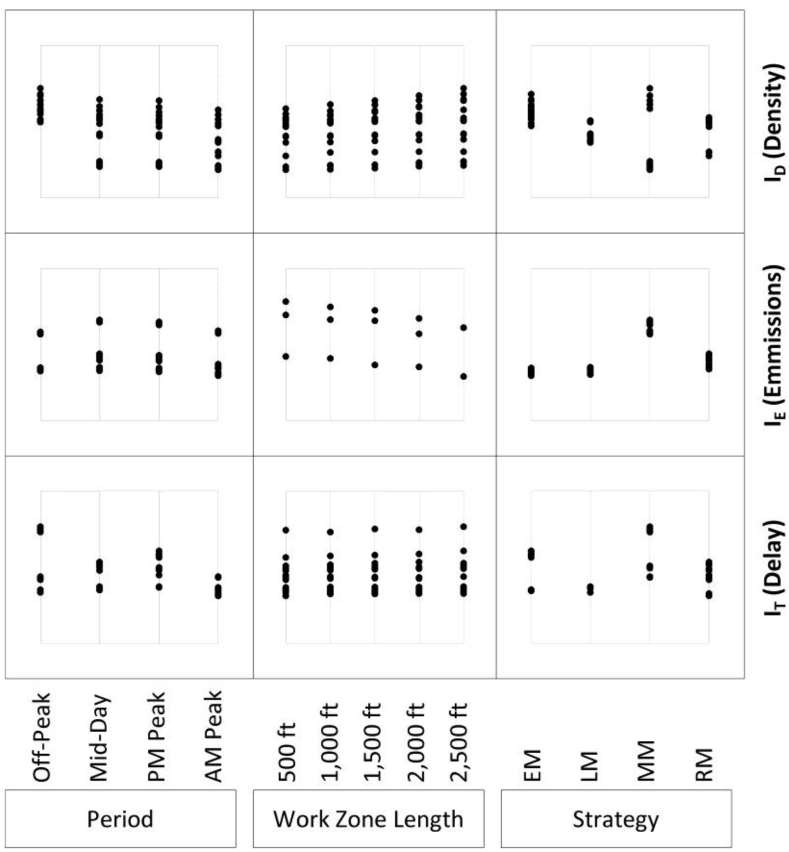

Figure 3-9. Scatter plot for key MOEs indices against period, work zone length, and strategy

Following the conclusions from Pearson's correlation tests and the scatter plots illustrated by Figure 3-9, further analysis was conducted after excluding work zone length. The previously coded dummy variables merge control strategy (S) and construction scheduling period (P) were used in this round of analysis. A value of one for the dummy variable S_y indicates that merge control strategy (y) is being used, and likewise for a dummy variable of P_x. Similarly, the dummy variables for strategies or periods not being used would be set to zero. In this analysis, the available setup combinations would be for a mutually exclusive setups of strategy and a scheduling period pairs. Accordingly, the impact of work zone setup can be represented by a matrix where columns represent available merge control strategies, rows represent available scheduling periods, and elements are indices for performance metrics. To calculate these generalized indices, linear regression was performed as shown in Eq. (8) that represents the studied index (I_i) as a function of merge control strategy (S_y) and scheduling period (P_x), where A_x, B_y, and C_{xy} are constant coefficients representing the impact of scheduling period, merge control strategy, and the interaction between them, respectively.

$$I_i = A_x\, P_x + B_y\, S_y + C_{xy}\, P_x\, S_y \qquad \text{Eq. (8)}$$

Table 3-4 illustrates the regression results matrix for the generalized performance indices by scheduling periods and merge control strategies. Each element of the matrix is the summation of the three coefficients A_x, B_y, and C_{xy} representing the impact on the corresponding performance index as a result of setting up a work zone during the corresponding period and while implementing the corresponding strategy. The R^2 statistic was calculated to ensure the goodness of fit.

Table 3-4. Generalized performance indices

		Late Merge	Early Merge	Merge Metering	Temp. Ramp Metering
Generalized density indices (R^2 = 0.968)	**AM Peak**	-0.2554	0.0370	-0.6080	-0.4101
	Mid-Day Peak	-0.1746	0.1535	-0.5584	0.0267
	PM Peak	0.3159	0.6388	-0.0658	0.4858
	Off-Peak	0.0039	0.2196	0.2878	0.0186
Generalized emissions indices (R^2 = 0.996)	**AM Peak**	-0.0737	-0.0899	0.7547	0.0678
	Mid-Day Peak	0.0375	0.0117	0.9589	0.2528
	PM Peak	0.5137	0.4873	1.4092	0.7311
	Off-Peak	0.0115	-0.0087	0.7199	0.0287
Generalized delay indices (R^2 = 0.989)	**AM Peak**	1.0461	2.5191	1.5337	-0.1543
	Mid-Day Peak	1.8738	3.9307	2.5927	2.7427
	PM Peak	2.2632	4.2367	2.9396	2.6963
	Off-Peak	0.6865	0.6497	6.2089	1.4013

Furthermore, agencies can assign relative weights ($0 \leq \omega_i \leq 1$ and $\sum_{i=0}^{n} \omega_i = 1$) to prioritize indices based on their importance. Accordingly, an objective function can be used to find the least overall weighted impact (I_ω) that results from the finite set of work zone setups considered at the particular location. Eq. (9) represents the proposed objective function:

$$I_\omega = \omega_D \, I_D + \omega_E \, I_E + \omega_T \, I_T \qquad \text{Eq. (9)}$$

CHAPTER 4
CONCLUSIONS, RECOMMENDATIONS, AND SUGGESTED RESEARCH

CONCLUSIONS

Maintenance and rehabilitation projects are essential and necessary to keep the transportation system operational and functional. In most cases, full closure of an interstate segment is not required; rather it is required to close one or more lanes per direction of travel to provide space for work zone activities. Some type of traffic control is typically utilized to facilitate the merging process at lane drop locations upstream of work zones. Available literature sources identified bottleneck merge control options as conventional merge control, static or dynamic early merge control, static or dynamic late merge control, temporary ramp metering, and mainline merge metering. In addition, the issue of work efficiency and accelerated construction has been investigated. Review of literature showed a lack of consideration of impacts of the implemented bottleneck merge control strategy on construction activities, and the overall costs of projects. Furthermore, no formal guidelines were identified on how to assess the impacts of identified merge control strategies.

In addition to a comprehensive synthesis of the literature, this study also presented a review of current DOTs practices for selecting bottleneck merge control strategies, coordination with construction activities, and rationale behind such decisions. In addition, agencies' practice towards collection of mobility and exposure MOEs for work zones were reviewed. Results received from 27 State DOTs indicated that most DOTs implement the early merge control strategy based on earlier experience. The survey also revealed that DOTs set a range or a defined value for work zone length driven by the develop bottleneck merge control plan. Such range or value is also provided for the contractors to prepare their construction plans and schedules. Results also pointed to the lack of systematic methods and/or guidelines for bottleneck merge control at incidents or work zones, which forces most agencies to rely exclusively on past experiences.

Based on the literature review and survey of practice findings, this study identified several gaps in research and practice. There is a gap in research regarding the influence of bottleneck merge control strategies on construction activities. Another gap was identified in agency practices as most agencies rely on past experience rather than formal criteria for selecting an appropriate bottleneck merge control strategy. In addition, the review and survey findings show that agencies lack the consideration of cost effectiveness when selecting a bottleneck merge control strategy, which indicates a lack of documentation of direct and indirect costs of associated with non-recurrent congestion due to bottlenecks and the corresponding merge control strategies. Accordingly, a comprehensive study is needed to set the foundation for the development of formal guidelines that would guide agencies in their efforts to select bottleneck merge control strategies. In addition, it is recommended to closely investigate the potential impacts of bottleneck merge control strategies on highway construction activities.

To address some of these concerns, four merge control strategies for interstate work zones were identified and evaluated in this study. Eighty work zone configurations were tested in a CORSIM-based microscopic simulation test bed to determine the feasibility of scheduling work zones around the clock while maintain the same, or near, existing facility performance. Three performance indices were developed representing density, delay travel, and emissions total CO.

Results indicated that work zone length is insignificant which implies that work zones could be setup in one long stretch hence eliminating the need for repetitive setups. Study results also provided a comprehensive view of density and LOS under a full spectrum of traffic conditions ranging from peak traffic to off-peak traffic. Specifically, study findings indicated that mainline merge metering holds great promise toward controlling bottleneck merge maneuvers at work zones, even under heavy traffic demand conditions. Results were further refined and processed to develop models that would predict a density index which could be used as a comprehensive indicator of mobility at such locations. The produced charts and equations can enhance current methods incorporated in the HCM and be used by transportation officials/practitioners to decide on the most appropriate merge control strategy to implement given a particular traffic condition.

Also, the analysis showed that there are several feasible options for scheduling work zones during any period of day. The study established a set of generalized performance indices, and proposed a combinatorial optimization approach to find the work zone setup with minimal impacts on facility performance. The proposed practice is expected to improve efficiency and reduce costs without any significant impacts on operations at and around work zone locations.

RECOMMENDATIONS

Based on the findings from this study, it is recommended that FHWA revise the Part 6 of the MUTCD to include explicit provisions on planning and implementing alternative TTC strategies, namely early merge control, late merge control, mainline merge metering, and temporary ramp metering. In addition, it is recommended that agencies focused on project management (such as the Project Management Institute) and/or construction management (such as Construction Management Association of America) include special provisions for construction planning and scheduling of highway work zones. Such provisions should include facility performance as criteria for developing construction plans and schedules.

SUGGESTED FUTURE RESEARCH

To broaden the scope of this research, and overcome its limitations, it is suggested to expand this study to include other lane-closure configurations such as 4-to-3, 4-to-2, 4-to-1, 3-to-1, and 2-to-1, while focusing on collecting MOEs upstream of the work zone bottleneck and excluding the work zone itself as well as downstream segments from the analysis. Additionally, it is suggested to conduct field operational tests for implementing alternative TTC strategies in order to capture field data. Such data can be used for further calibration purposes as well as to validate the study findings. It is also suggested that this study be expanded to consider potential effects of heavy vehicles at different percentage on the efficiency of each TTC strategy. Finally, it is recommended to further investigate and expand this study to consider network wide impacts and possible queue formations or spillbacks upstream of the work zone location.

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Appendix

Technology Transfer

APPENDIX:
TECHNOLOGY TRANSFER

The significance of the results from this study and its importance to local, regional, and State agencies, motivated the study team to conduct a set of technology transfer efforts to disseminate the results of the study to transportation agency personnel and other professionals, and to familiarize them with the methods and techniques that were used to conduct the study.

A technology transfer activity was conducted at the UAB campus in Birmingham, AL on March 8, 2017, complimentary to the technical program of 2017 Spring meeting of the Alabama section of the Institute of Transportation Engineers. The presentation began by an introduction of the study topic, and its relevance to operations and processes of local, regional, and State agencies. Then the technical part of the presentation was introduced and used to showcase the methods used in this study, present and interpret the results obtained, and address issues related to transferability and implementation. An open discussion followed to address any comments, or questions the audience had. A total of 54 participants attended the event and showed great interest in the topic and study findings.

UAB faculty and students volunteers; ALSITE technology transfer event, Birmingham, AL

Additionally, the work was presented in a 45-minute session at the 2017 Annual Meeting of the Southern District of the Institute of Transportation Engineers (SDITE) in Columbia, SC on March 27, 2017. Nearly 80 practitioners, agency personnel, and academics attended the session. The presentation was well-received and commended by several participants. Also, there is an online version of this presentation available through the sponsor's (STRIDE) website. The slides used in these sessions are presented hereinafter. The research team recognized STRIDE's support in all dissemination efforts. Results from this study were disseminated to the public during the 2017 STRIDE Research Seminar, and also in the form of webinar that has been archived on the STRIDE website.

Overall, the technology transfer activities in this project benefit both the scientific community and authorities responsible for planning, implementing, managing, and operating work zones in Alabama, the Southeast United States, and beyond.


Audience attending ALSITE (left) and SDITE (right) technology transfer events

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Evaluation of Traffic Control Options in Work Zones

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Transportation Engineering and Development Laboratory
(**TREND Lab**)

Department of Civil, Construction, and Environmental Engineering

Outline

- Introduction
- Study focus
- Literature review & survey of practice
- Case study of I-65 in Central Alabama
- Approach for performance-based scheduling
- Conclusions

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Introduction

- Increased activity in maintenance and rehabilitation
- Lane closures are required to provide a work space
- Work zones are 2nd largest cause of nonrecurring delay
- There is growing interest in performance monitoring
- Performance-based work zone mobility & safety

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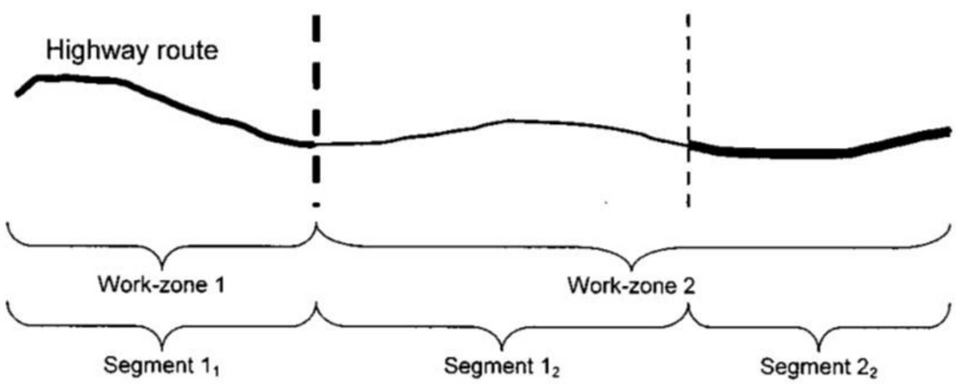
Introduction: WZ Construction Scheduling



Project division into work zones and segments
(Source: Hassanein and Moselhi 2004)

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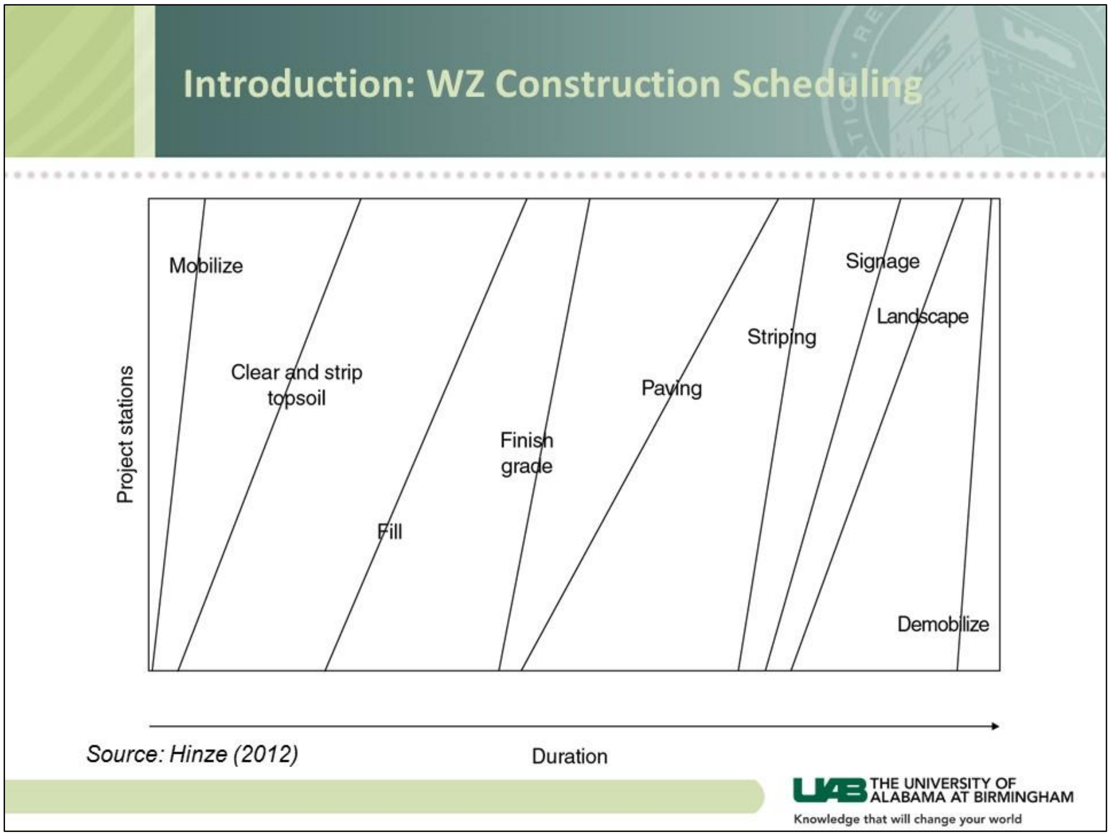
Introduction: WZ Construction Scheduling
Project stations
Mobilize
Clear and strip topsoil
Fill
Finish grade
Paving
Striping
Signage
Landscape
Demobilize
Source: Hinze (2012)
Duration
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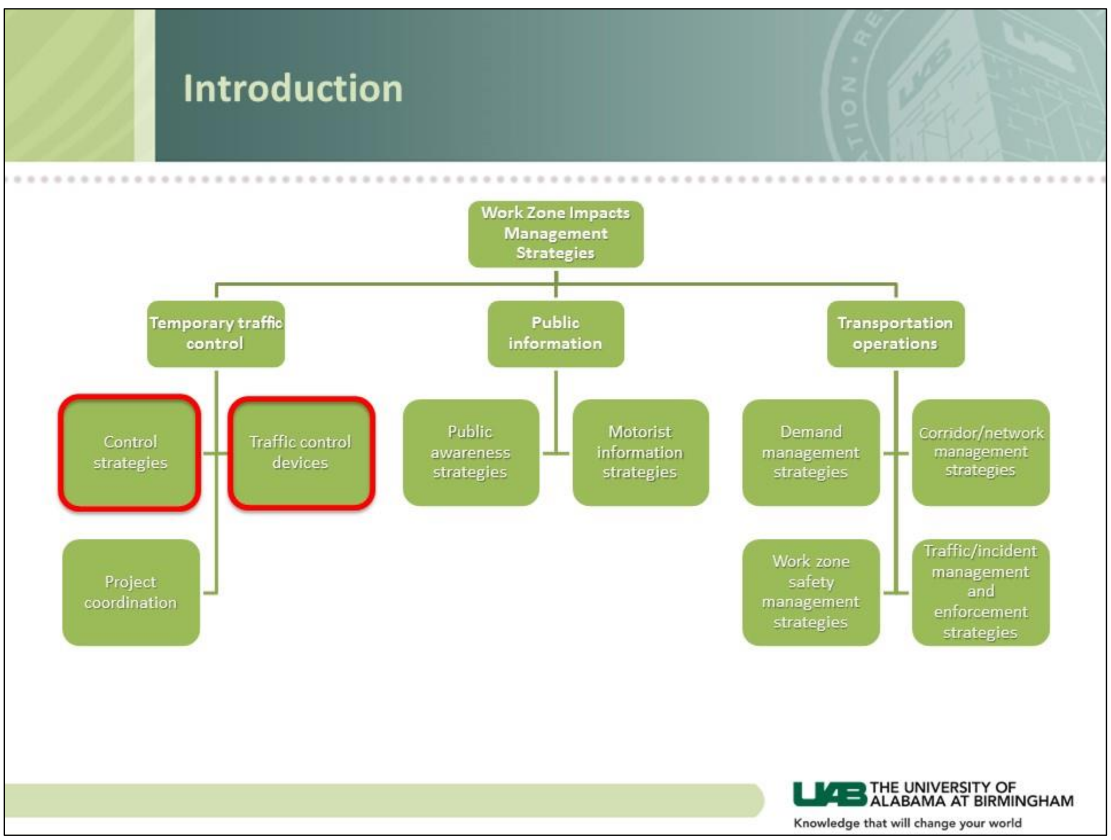
Introduction
Work Zone Impacts Management Strategies
Temporary traffic control
Public information
Transportation operations
Control strategies
Traffic control devices
Project coordination
Public awareness strategies
Motorist information strategies
Demand management strategies
Corridor/network management strategies
Work zone safety management strategies
Traffic/incident management and enforcement strategies
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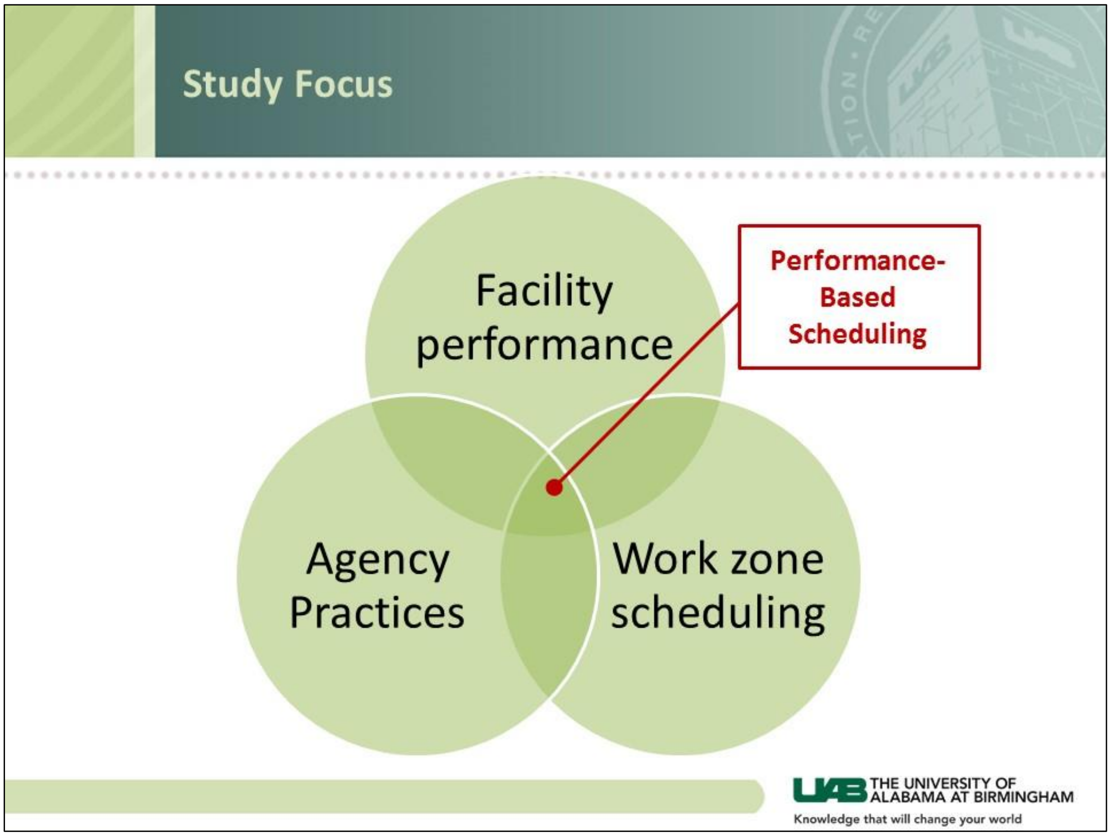
Study Focus
Facility performance
Agency Practices
Work zone scheduling
Performance-Based Scheduling
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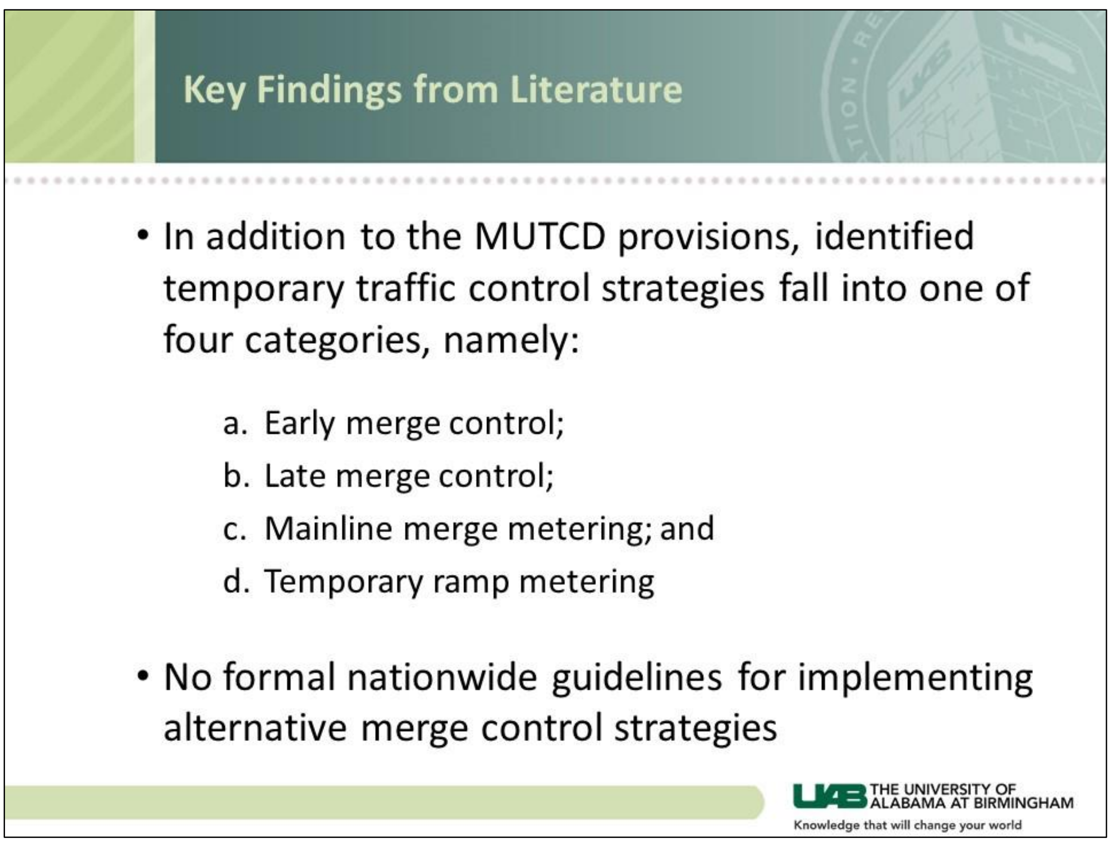
Key Findings from Literature
• In addition to the MUTCD provisions, identified temporary traffic control strategies fall into one of four categories, namely:
a. Early merge control;
b. Late merge control;
c. Mainline merge metering; and
d. Temporary ramp metering
• No formal nationwide guidelines for implementing alternative merge control strategies
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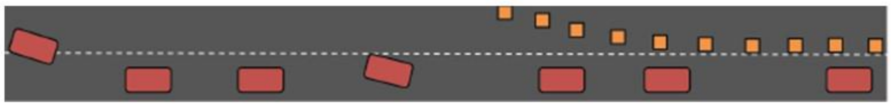
Early Merge Control



Early merge control (ATSSA, 2012)

Static

Notices to merge at fixed distances

Dynamic

signs at variable distances based on real-time traffic conditions

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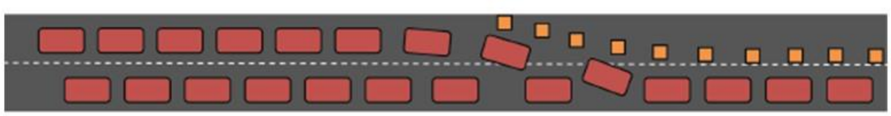
Late Merge Control



Late merge control (ATSSA, 2012)

Static

Notices provided via conventional signs

Dynamic

allows for switching between late merge control and conventional merge control according to traffic conditions

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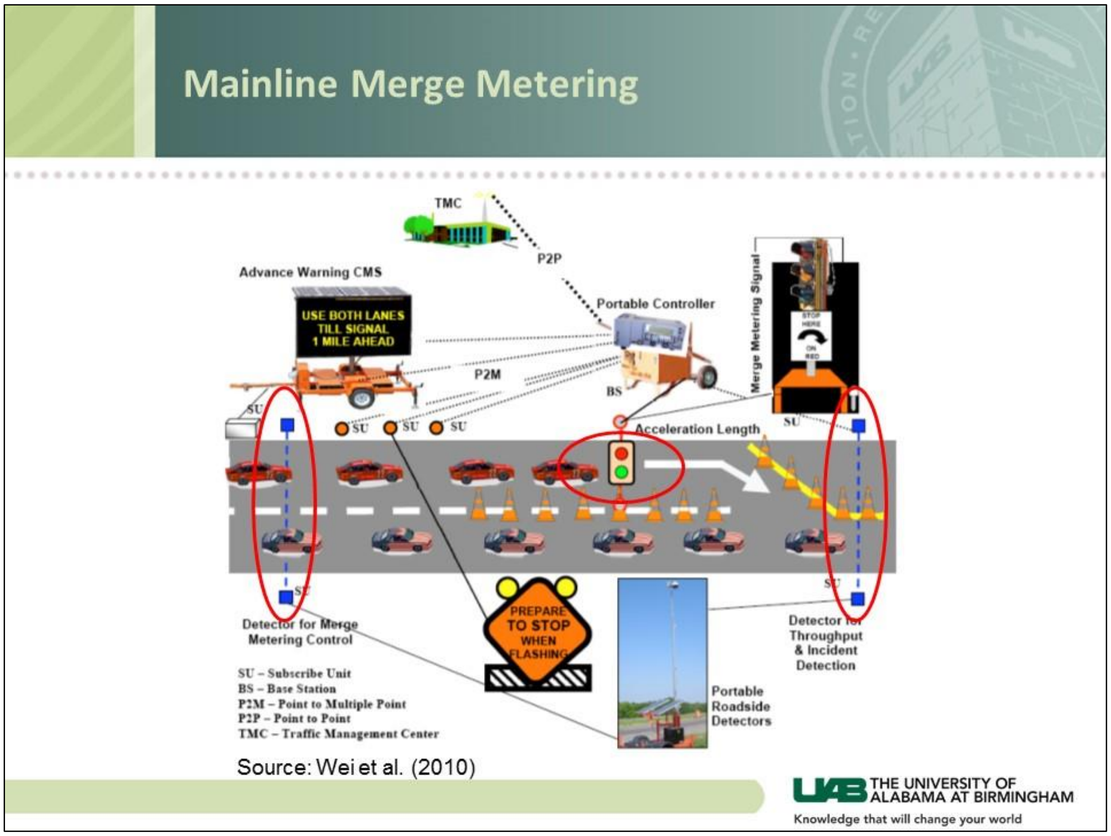
Mainline Merge Metering
TMC
P2P
Advance Warning CMS
USE BOTH LANES TILL SIGNAL 1 MILE AHEAD
Portable Controller
P2M
BS
Merge Metering Signal
SU
Acceleration Length
PREPARE TO STOP WHEN FLASHING
Detector for Merge Metering Control
Detector for Throughput & Incident Detection
Portable Roadside Detectors
SU – Subscribe Unit
BS – Base Station
P2M – Point to Multiple Point
P2P – Point to Point
TMC – Traffic Management Center
Source: Wei et al. (2010)
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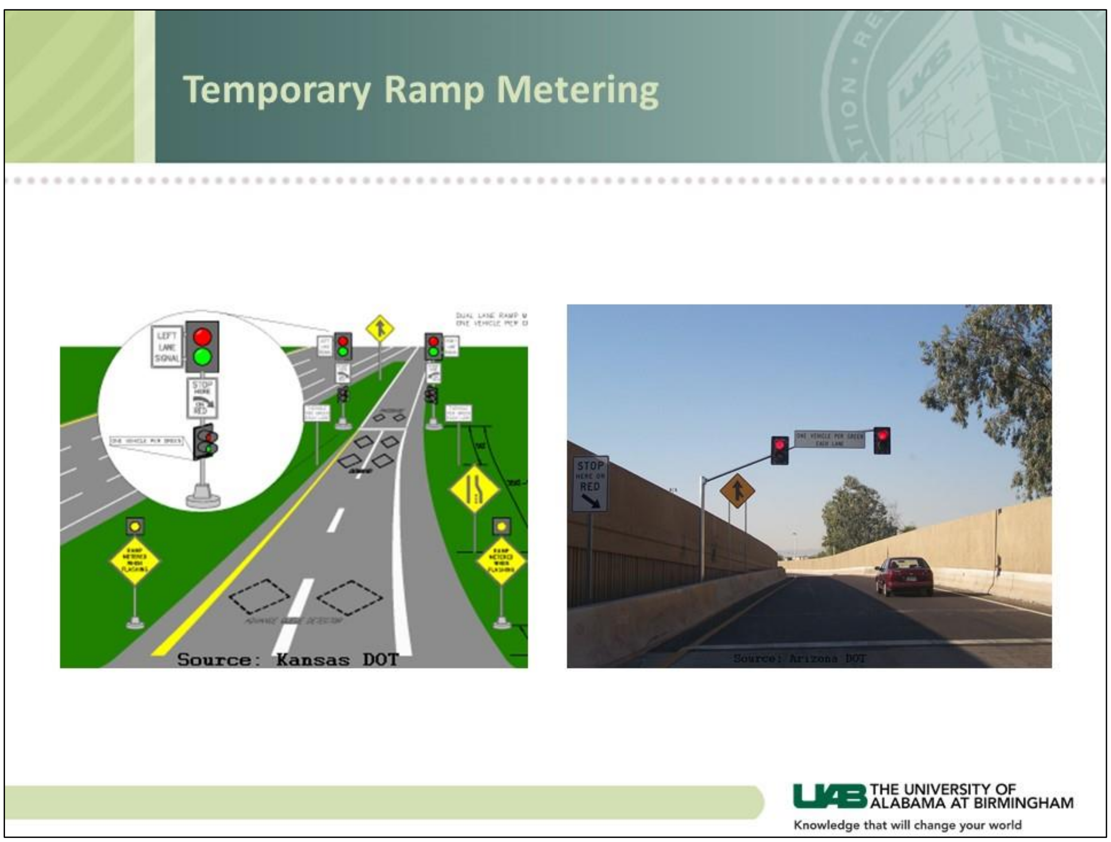
Temporary Ramp Metering
LEFT LANE SIGNAL
STOP HERE ON RED
Source: Kansas DOT
STOP HERE ON RED
Source: Arizona DOT
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Survey of Practice: Process

- Maintenance officials from all State DOTs were invited to participate
- Responses were received from 27 State DOT representatives over a 45-days period (54% response rate)
- Responses were received from Alabama, California, Colorado, Illinois, Iowa, Michigan, Minnesota, Mississippi, Missouri, North Carolina, South Carolina, South Dakota, Utah, Vermont, West Virginia, Wisconsin, and Wyoming, and 10 undisclosed States

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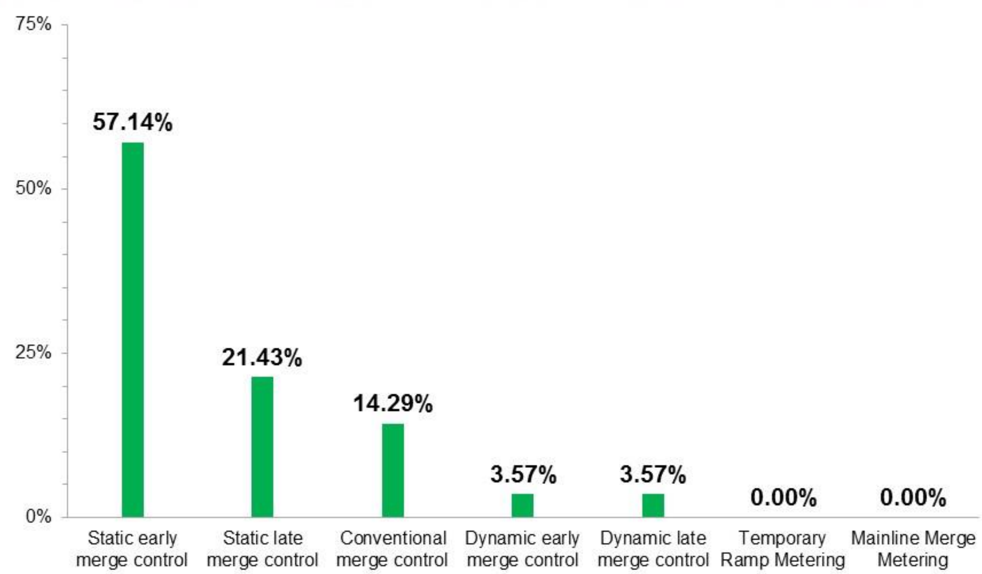
Survey of Practice: TTC Strategy at Work Zones



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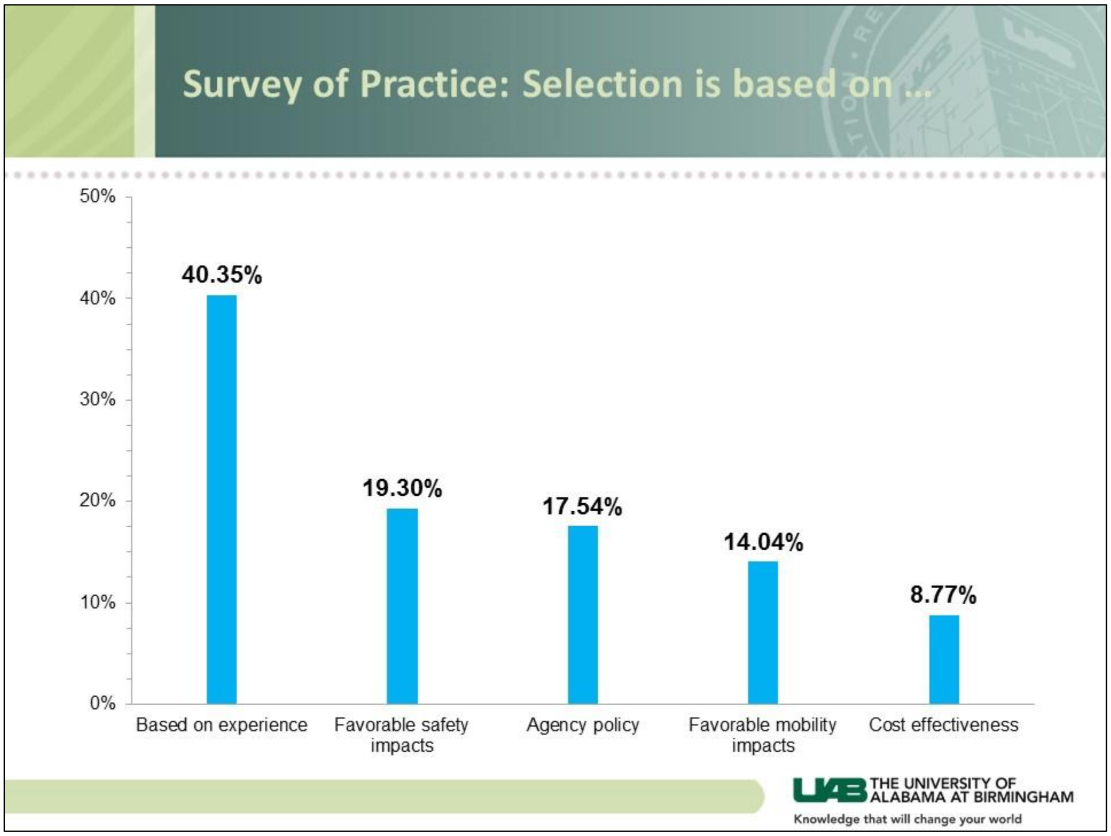
Survey of Practice: Selection is based on ...
50%
40%
30%
20%
10%
0%
40.35%
19.30%
17.54%
14.04%
8.77%
Based on experience
Favorable safety impacts
Agency policy
Favorable mobility impacts
Cost effectiveness
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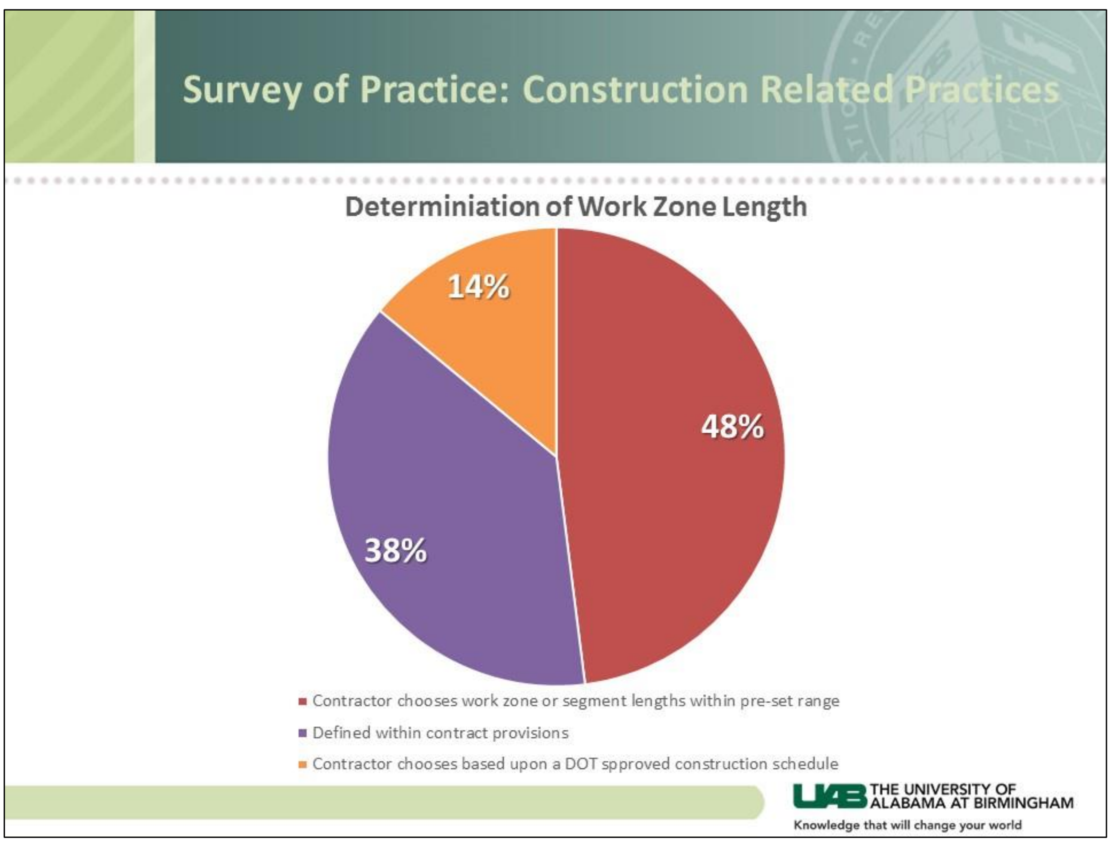
Survey of Practice: Construction Related Practices
Determiniation of Work Zone Length
14%
48%
38%
Contractor chooses work zone or segment lengths within pre-set range
Defined within contract provisions
Contractor chooses based upon a DOT spproved construction schedule
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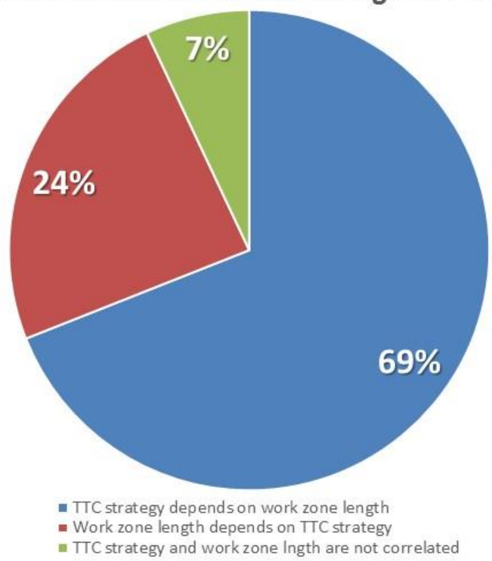
Survey of Practice: Construction Related Practices

Relation between work zone length & TTC strategy



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DOTs Performance Documentation Practices

Performance Measure (MOE)	№ & %of DOTs
Exposure MOEs	
% of days or nights when work activity occurs	13 (45%)
% work activity hours with (1,2,3, etc.) lanes closed	9 (31%)
Average lane closure length	8 (28%)
Lane-mile-hours of closures	4 (14%)
Mobility MOEs	
Maximum queue length	8 (28%)
Average queue length	7 (24%)
Average queue duration	6 (21%)
Average vehicle delay / travel time	6 (21%)
% Time when work zone queue length exceeds a certain length	4 (14%)
Amount (or % of ADT) that encounters a queue	4 (14%)
Number or % of work activity periods when queuing occurred	1 (3%)

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Conclusions from Literature & Survey of Practice

- Mostly, full closure of an interstate segment is not required; one or more lanes-closures per direction of travel to provide space for work zone activities
- Most DOTs implement static early merge (57%) strategies based on their earlier experiences
- No formal nationwide guidelines for implementing alternative merge control strategies exist
- All available studies were performed under off-peak conditions

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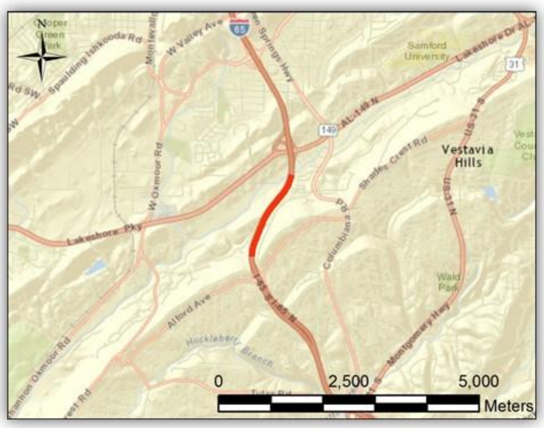
Birmingham Case Study



A work zone on I-65 N in Birmingham, Alabama was considered as a case study

The segment typically has three 12-ft lanes per mainline direction, with auxiliary lanes added at ramps locations

AADT: 122,510 veh/day

Peak: 7:00-9:00 AM

Posted Speed Limit: 60 mph

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Methods

- Three factors considered, namely work zone length, traffic period (time of day), and merge control strategy
- Three outcomes considered, namely density, delay travel per vehicle, and emissions total CO
- Four control (baseline) models were developed, and 80 scenarios representing a full factorial design
- A microscopic simulation testbed was used

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Approach

- *Corridor Simulation* (CORSIM) version 6.3 was used to develop a stochastic microscopic simulation model of a section of I-65 in Birmingham, Alabama

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CORSIM Calibration

- A calibrated base model was developed for each traffic period
- 80 scenarios (5 WZ length, 4 MCS, 4 Periods) that were run five times each with a total of 400 (+20) simulation runs
- Scenario specific models were calibrated to simulate driver/vehicle behavior at work zones specially:
  1. Speeds and volumes
  2. Time to complete lane-change maneuver
  3. Percent drivers yielding to merging vehicles

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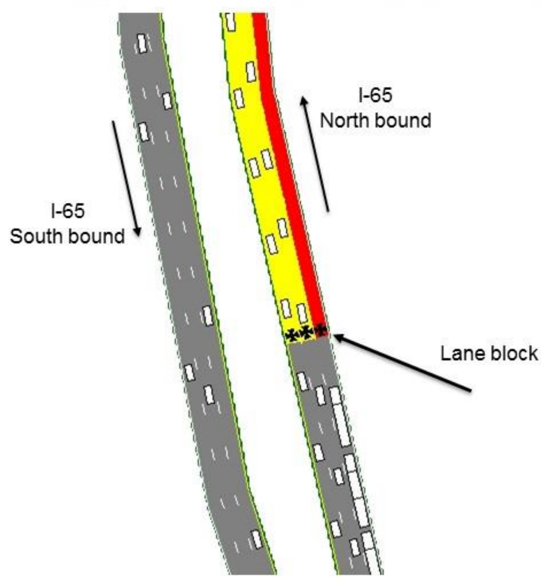
Simulation of Late Merge Control



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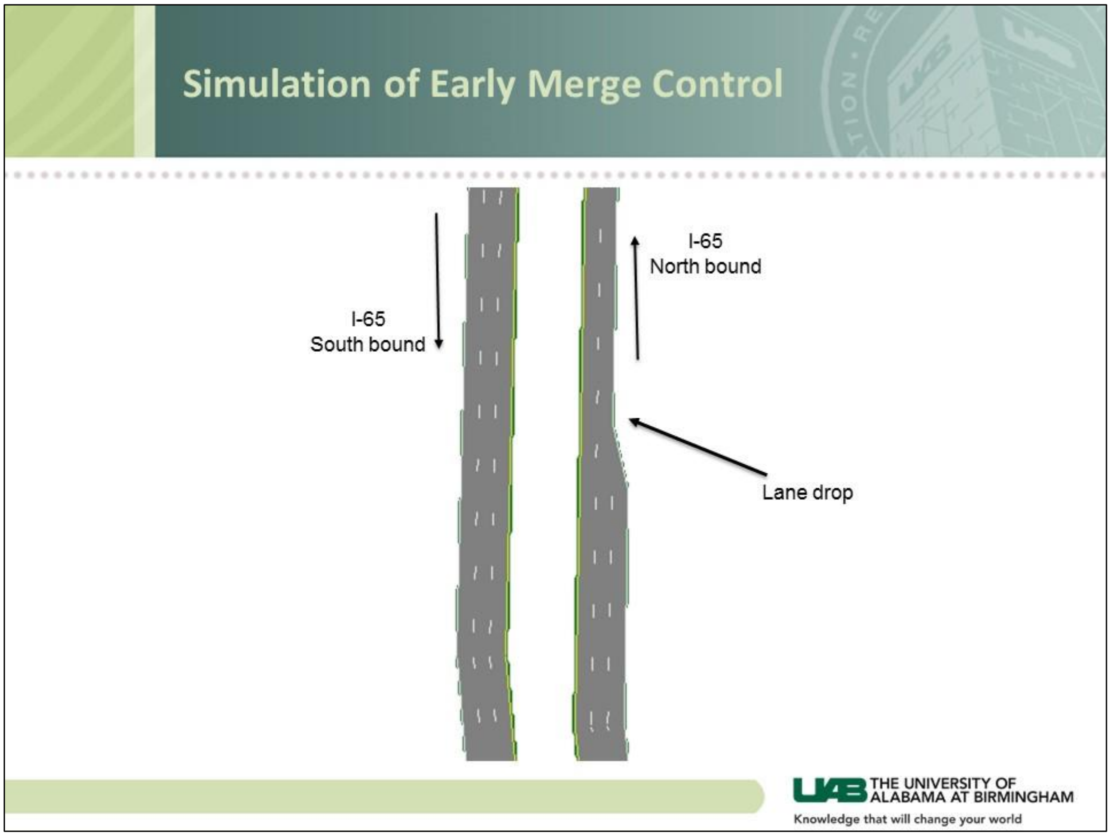
Simulation of Early Merge Control
I-65
North bound
I-65
South bound
Lane drop
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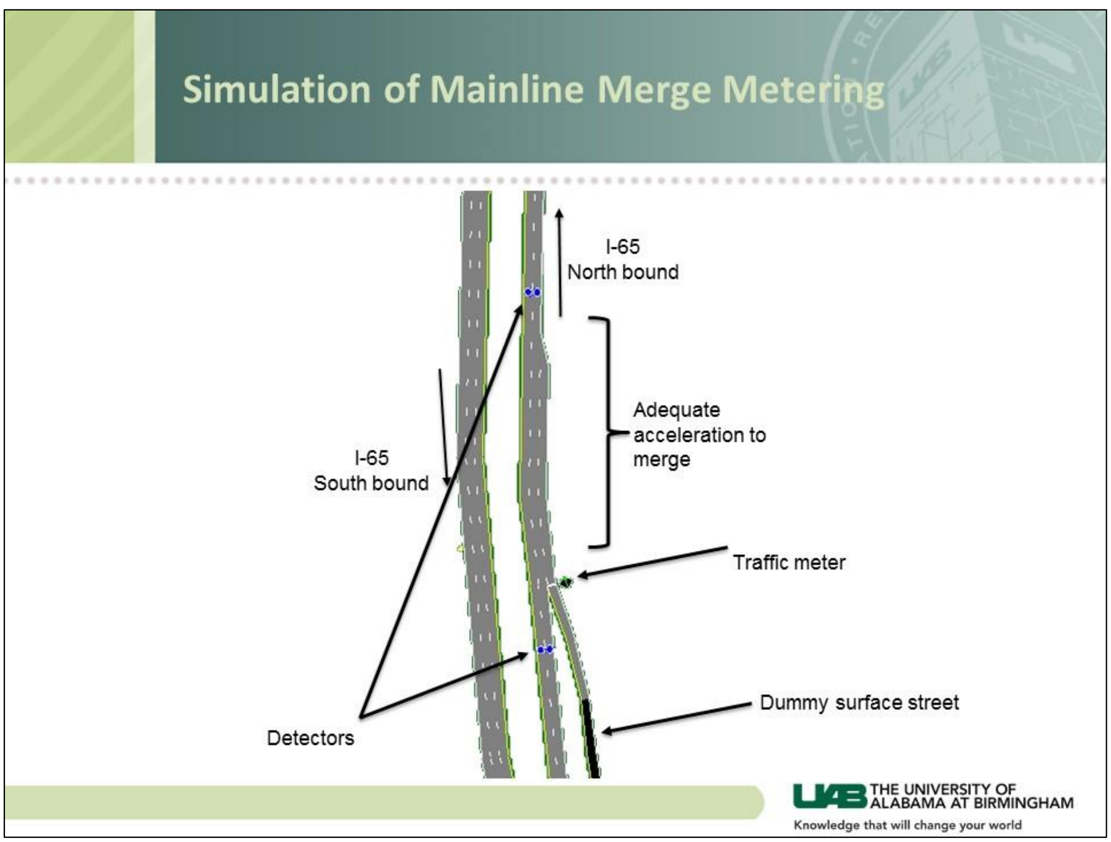
Simulation of Mainline Merge Metering
I-65
North bound
Adequate acceleration to merge
I-65
South bound
Traffic meter
Dummy surface street
Detectors
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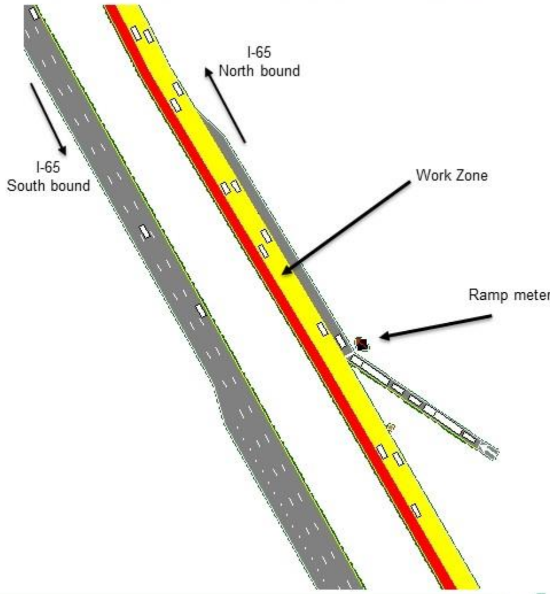
Simulation of Temporary Ramp Metering



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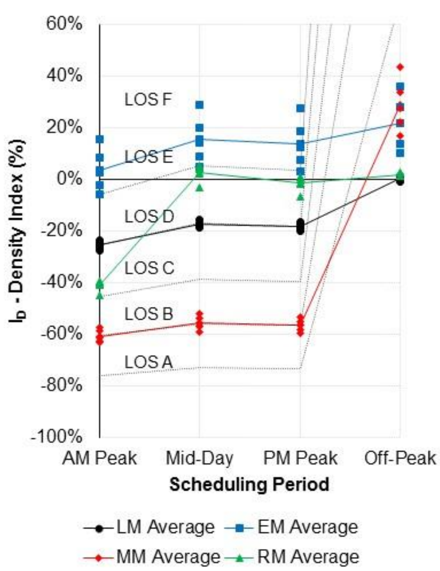
Results: Density Index



A **density index (I_D)** was calculated

- $I_{D(P,S)} = \frac{D_{P,S} - D_{P,PC}}{D_{P,PC}} \times 100$

Where: $D_{P,PC}$ is the weighted average density preconstruction (i.e., baseline) of the segment for a given work scheduling period “P”,

$D_{P,S}$ is the weighted average density for all segments within the defined work zone for a given work scheduling “P” and a given merge control strategy “S”

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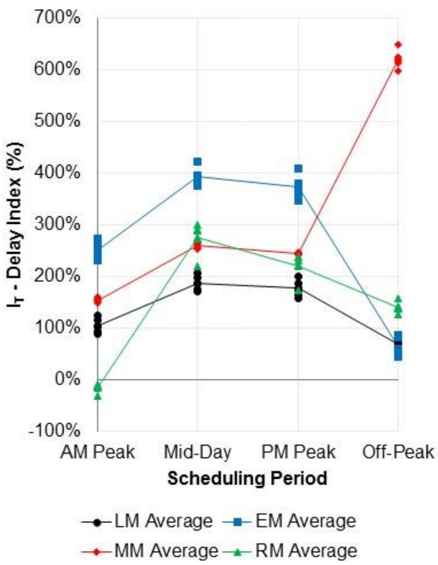
Results: Delay Index



A **delay travel index (I_T)** was calculated

- $I_{T(P,S)} = \frac{T_{P,S} - T_{P,PC}}{T_{P,PC}} \times 100$

Where: $T_{P,PC}$ is the total preconstruction (i.e., baseline) delay travel per vehicle on a segment for a given work scheduling period "P", and

$T_{P,S}$ is the total delay travel per vehicle for the same segment within the defined work zone for a given work scheduling "P" and a given merge control strategy "S"

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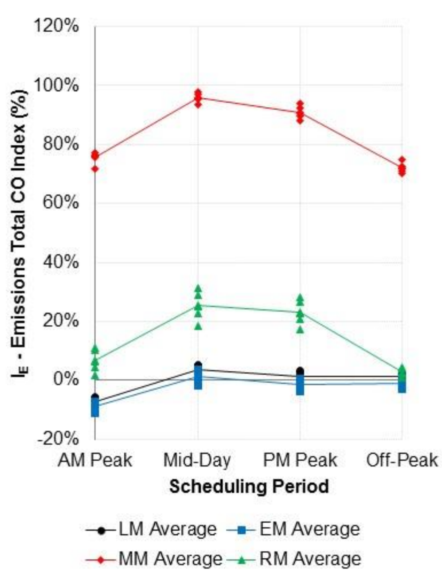
Results: Emissions Total CO Index



An emissions total CO Index (I_E) was calculated

- $I_{E(P,S)} = \frac{E_{P,S} - E_{P,PC}}{E_{P,PC}} \times 100$
- Where: $E_{P,PC}$ is the cumulative preconstruction emissions total CO on the segment for a given work scheduling period "P", and
- $E_{P,S}$ is the cumulative emissions total CO for the same segment within the defined work zone for a given work scheduling "P" and a given merge control strategy "S"

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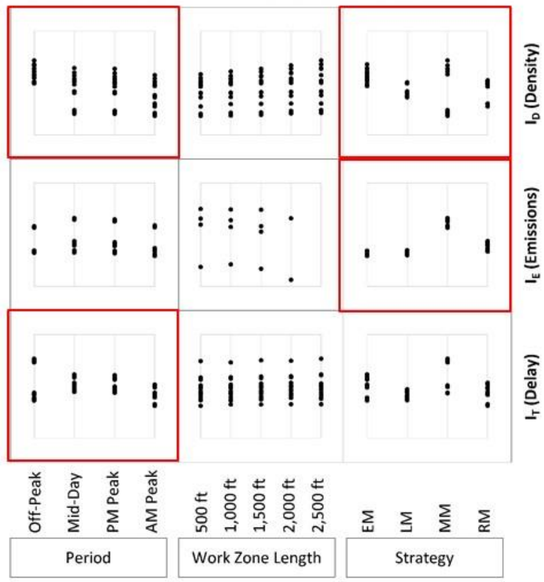
Scatter Plots for Factors and Outcomes



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Regression Analysis for Indices

$$I_i = A_x\, P_x + B_y\, S_y + C_{xy}\, P_x\, S_y$$

Where:

- I_i Studied performance index (i)
- S_y Merge control strategy (y)
- P_x Scheduling period (x)
- A_x Impact of scheduling period (x)
- B_y Impact of merge control strategy (y)
- C_{xy} Impact resulting from the combination (x,y)

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Regression Results

		Late Merge	Early Merge	Merge Metering	Ramp Metering
Generalized density indices ($R^2 = 0.968$)	AM Peak	-0.2554	0.0370	-0.6080	-0.4101
	Mid-Day Peak	-0.1746	0.1535	-0.5584	0.0267
	PM Peak	0.3159	0.6388	-0.0658	0.4858
	Off-Peak	0.0039	0.2196	0.2878	0.0186
Generalized emissions indices ($R^2 = 0.996$)	AM Peak	-0.0737	-0.0899	0.7547	0.0678
	Mid-Day Peak	0.0375	0.0117	0.9589	0.2528
	PM Peak	0.5137	0.4873	1.4092	0.7311
	Off-Peak	0.0115	-0.0087	0.7199	0.0287
Generalized delay indices ($R^2 = 0.989$)	AM Peak	1.0461	2.5191	1.5337	-0.1543
	Mid-Day Peak	1.8738	3.9307	2.5927	2.7427
	PM Peak	2.2632	4.2367	2.9396	2.6963
	Off-Peak	0.6865	0.6497	6.2089	1.4013

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Generalized Index

$$I_\omega = \omega_D \, I_D + \omega_E \, I_E + \omega_T \, I_T$$

I_ω Overall weighted performance index

ω_i Relative importance/preference for (i)

I_i Performance index (i)

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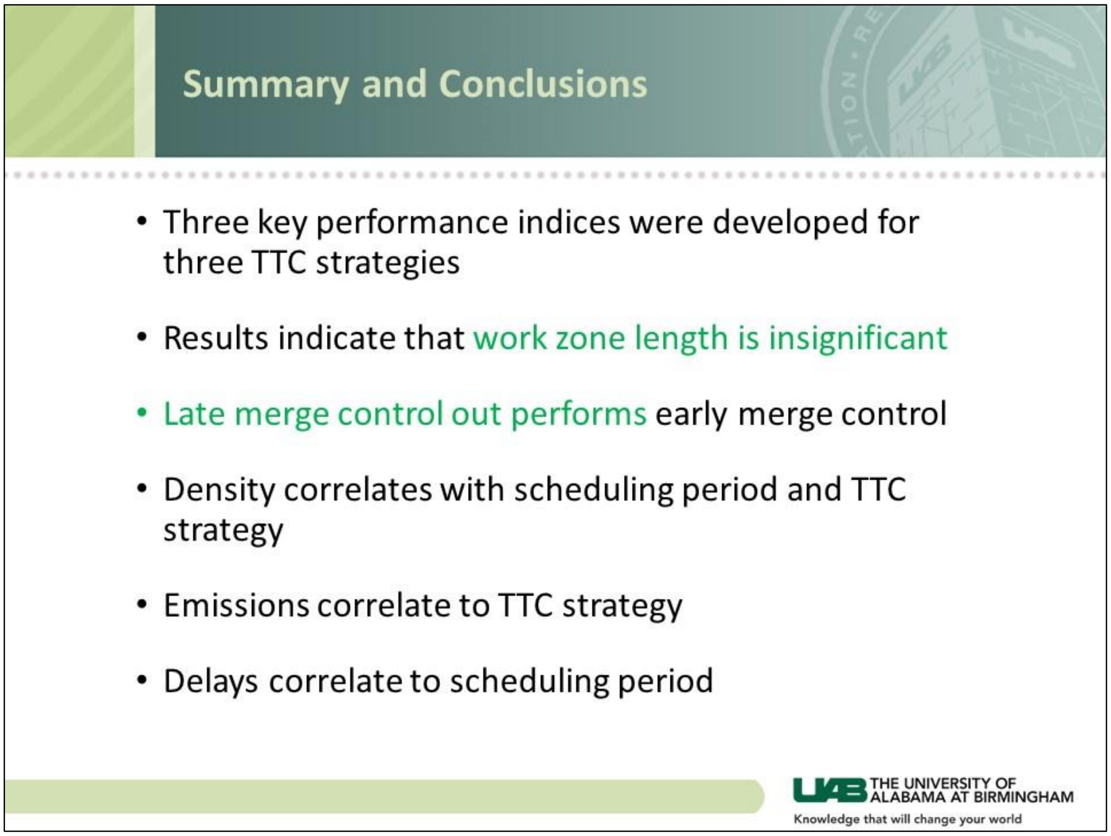
Summary and Conclusions
• Three key performance indices were developed for three TTC strategies
• Results indicate that work zone length is insignificant
• Late merge control out performs early merge control
• Density correlates with scheduling period and TTC strategy
• Emissions correlate to TTC strategy
• Delays correlate to scheduling period
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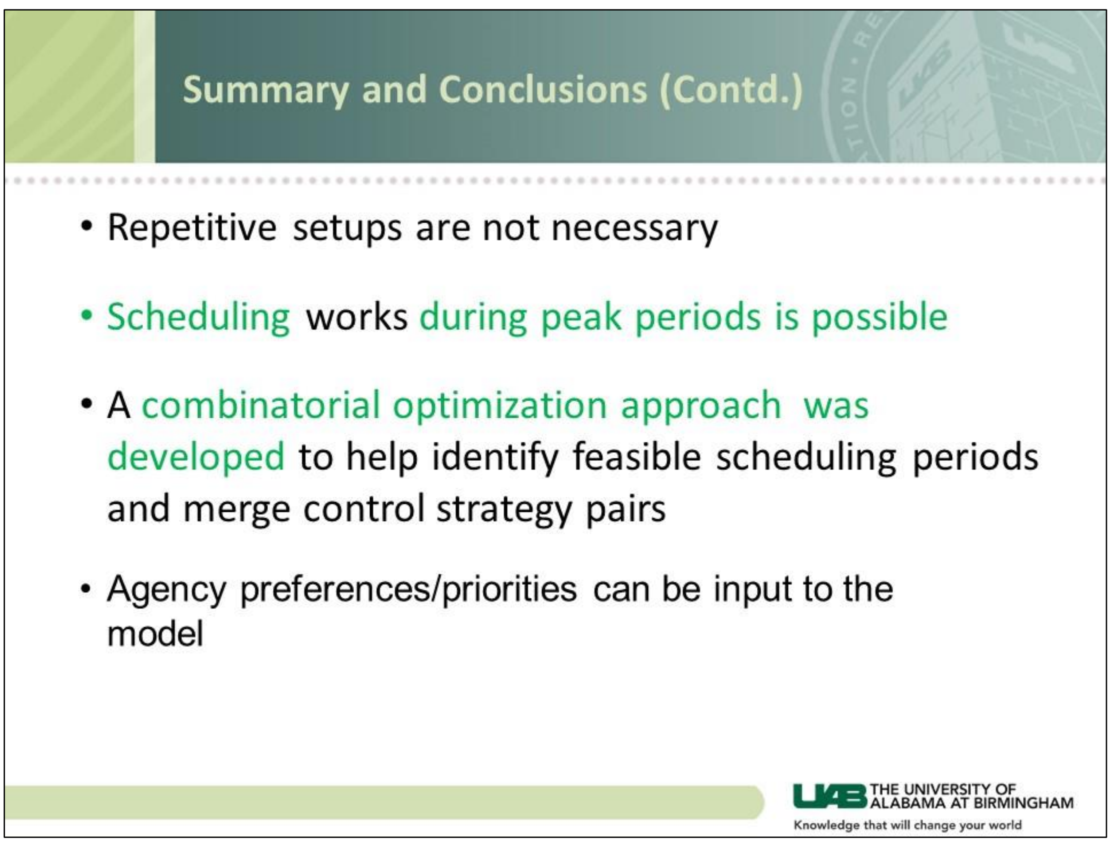
Summary and Conclusions (Contd.)
• Repetitive setups are not necessary
• Scheduling works during peak periods is possible
• A combinatorial optimization approach was developed to help identify feasible scheduling periods and merge control strategy pairs
• Agency preferences/priorities can be input to the model
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Summary and Conclusions (Contd.)

- Findings provide guidance for transportation researchers and professionals on TTC strategies capable of optimizing construction schedules
- Scheduling work zones around the clock without compromising operational performance adds flexibility.

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Future Work

Expand the research scope to include:

- Microscopic simulation analysis of the 3-to-1 lane configuration for early and late merge control
- Collection and analysis of field data from active work zones in Alabama thus incorporating field collected information that is usable by practitioners.
- Development of guidelines for transportation agencies regarding spatial and temporal placement of freeway work zones with lane closures

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Acknowledgments

- This work was sponsored by a grant from STRIDE (STRIDE project 2016-001S). The STRIDE center is funded through the U.S. DOT's University Transportation Centers Program.
- We would like to express our appreciation to STRIDE and U.S. DOT for the funding provided in support of this project.

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Additional Information

For questions, comments, or to request additional information please contact:

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- Dr. Ossama Ramadan oramadan@uab.edu

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