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Bottleneck Merge Control Strategies for Work Zones: Available Options and Current Practices

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Abstract

Maintenance and rehabilitation projects of interstate facilities typically mandate lane closures. Lane closures require merging maneuvers that often result in reduced speeds and traffic bottlenecks. Conventionally, bottleneck merge control plans are developed to address bottlenecks impacts. However, there is a need to better understand the various merge control options and their potential impacts on traffic operations and safety. This study reviewed available options and current practices of bottleneck merge control strategies at work zones, and summarized transportation agencies' considerations to mitigate adverse impacts. An extensive literature review was performed and a questionnaire survey was developed and used to gather relevant information. Input was solicited from all US State Departments of Transportation. Responses from 27 States revealed that transportation agencies currently rely on experience when selecting a bottleneck merge control strategy and often do not consider influence on construction activities. Thus, a gap was identified between bottleneck merge control and construction plans. Another gap was identified regarding the lack of formal criteria or guidelines for selecting a bottleneck merge control strategy. These gaps need to be addressed through investigating the influence of bottleneck merge control strategies on construction activities, and the development of formal criteria for effective selection of such strategies.

Keywords

Bottlenecks, Traffic Control, Traffic Congestion, State of the Practice, Surveys

1. Introduction

Work zones and incidents mandate lane closures to provide space for maintenance or incident management

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crews [1]. As a result, normal traffic operations are disrupted and bottlenecks are formed often leading to traffic congestion. The bottleneck-induced congestion negatively impacts traffic operations as well as increases the risk of rear-end collisions, specifically when congestion extends further upstream of the lane closure or warning signs [2]. Earlier research suggests that work zones and incidents together represent the largest cause of nonrecurring delay on principle arterials with nearly 50% of all nonrecurring delay [3]. Transportation agencies rely on conventional traffic control plans to minimize the traffic impacts from work zone or incident presence, usually following the conventional temporary traffic control strategies set by Part 6 of the *Manual on Uniform Traffic Control Devices* (MUTCD) [4]; however, some agencies opt to implement alternative strategies that would promise more effectiveness than conventional merge control.

Most available literature references report on the study of a single bottleneck merge control strategy, or comparison of two strategies for a specific site. Apparently, there is a lack of a comprehensive reference source that identifies all available bottleneck merge control strategies and discusses the current state-of-the-practice in the United States.

Having identified a potential gap in current research, the objective of this study was set to identify available bottleneck merge control strategies and current transportation agencies' practices to implement such strategies, in an effort to clearly identify existing gap(s) between research and practice.

2. Study Method

This study has been performed using a two-step approach. The first step involved an extensive literature review to identify available bottleneck merge control strategies, and efforts used to investigate or assess their costs, benefits, and barriers to implementation. **Table 1** lists the 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. The study team excluded any articles that are 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 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.

The second step was to conduct a 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

Table 1. Sources of literature.

Database	Publisher
Academic One File	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	United States Department of Transportation, Office of the Assistant Secretary for Research and Technology
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

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 bottleneck merge 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. Efforts were made to assure that the respondents had an adequate level of expertise with the topic, as well as documented hands-on experience enough to give confidence to their responses.

3. 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 2** 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: 1) Early and late merge control; 2) Temporary ramp metering; and 3) Mainline merge metering. The findings of this literature review are summarized in the following subsections.

3.1. 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 [2] 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 [6]. 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 [2] 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.* [10] 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:

Table 2. Key articles for bottleneck merge control.

Article	Scope	Approach
Federal Highway Administration [6]	Policies and agency-level practices	Descriptive
Kurker *et al.* [7]	Early merge, late merge, signal merge	Microscopic traffic simulation
Lentzakis *et al.* [8]	Mainline metering/control	Microscopic traffic simulation
McCoy and Pesti [2]	Early merge, late merge, and dynamic late merge	Field test
Oner [9]	Temporary ramp metering	Process simulation
Pesti *et al.* [10]	Dynamic merge	Microscopic traffic simulation
Sun *et al.* [11]	Temporary ramp metering	Microscopic traffic simulation
Tympakianaki *et al.* [12]	Mainline metering/control	Microscopic traffic simulation
Wei *et al.* [1]	Dynamic late merge and Merge metering	Microscopic traffic simulation

- 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.* [7] 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.

3.2. 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 [13]. 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 [9] 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.* [11] 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.

3.3. 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.* [8] 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.* [12] 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 was 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 (acronym for Verkehr In Städten-SIMulations modell, which is German for "Traffic in cities-simulation model"). 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.

3.4. 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 selecting a bottleneck merge control strategy. Review of literature indicated that planning and construction are among key processes within current project delivery systems [14]. In addition, available literature discusses 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 [15] 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.* [16] 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 [17] 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.

3.5. Discussion of Literature Review Findings

A comprehensive review of available literature performed in this study indicates that there is no national reference that documents *Department of Transportation* (DOT) 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 bottleneck merge control strategies at work zones. The study documents current bottleneck merge control practices for highway work zones, and considerations related to impacts on mobility and construction activities.

4. Results of the Survey of Practice

Responses were received from 27 State DOT representatives 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.

4.1. 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 1**. Responses also indicated that temporary ramp metering and main line merge metering are not used at all.

Figure 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%; following agency policy ranked third by 17.54%; favorable mobility impacts ranked fourth by 14.04%; and cost effectiveness ranked in the last place by 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.

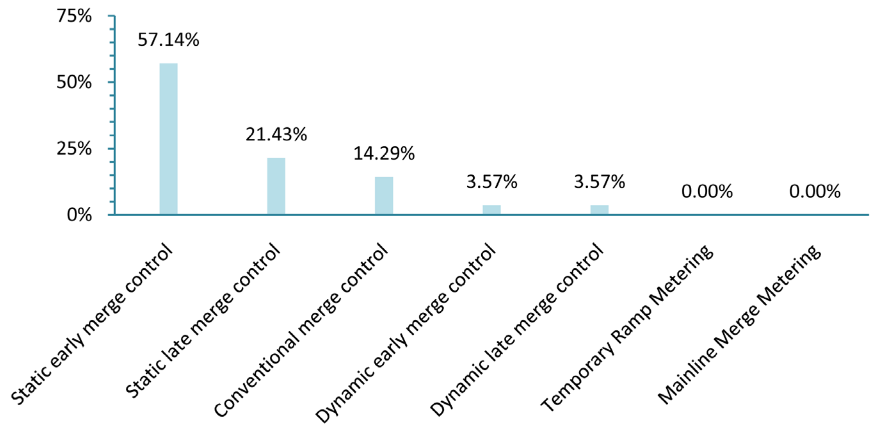

Figure 1. Selected bottleneck merge control strategy.

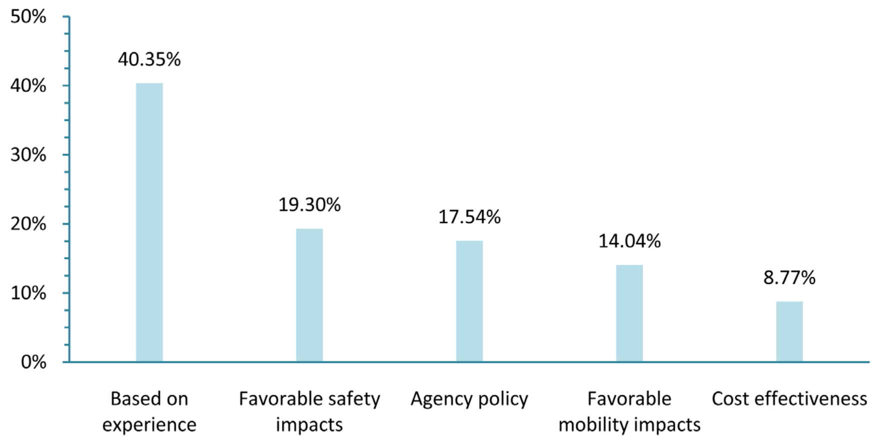

Figure 2. Rationale behind selection of bottleneck merge control strategies.

4.2. 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, 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.

4.3. Construction Planning and Scheduling Practices

The survey also addressed 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.

4.4. 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** documents DOTs efforts towards collecting and documenting MOEs for work zones. **Table 3** 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%).

Table 3. 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	
Number or % of work activity periods when queuing occurred	1 (3%)
Average queue duration	6 (21%)
Average queue length	7 (24%)
Maximum queue length	8 (28%)
% Time when work zone queue length exceeds a certain length	4 (14%)
Amount (or % of ADT) that encounters a queue	4 (14%)
Average vehicle delay/travel time	6 (21%)

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.

5. Conclusions and Recommendations for Further Research

Maintenance and rehabilitation projects are essential and necessary to keep the Nation's Interstate freeway 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.

Available literature 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. Available literature and current practices do not consider any 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 indicate 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 developed bottleneck merge control plan. Such range or value is also provided for the contractors to prepare their construction plans and schedules. Results also point to the lack of systematic methods and/or guidelines for bottleneck merge control at incidents or work zones, which force 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 results 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, it is recommended to conduct a comprehensive study that would set 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.

Disclosure Statement

No potential conflict of interest was reported by the authors.

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