MD-10-SP608B4J

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STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

APPLYING ITS TECHNOLOGIES TO CONTEND WITH HIGHWAY CONGESTION

Part-I: Variable Speed Limit Control for Recurrent Congestion

Part-II: Lane-based Signal Merge Control for Work Zone Operations

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SP608B4J

FINAL REPORT

DECEMBER 2010

Technical Report Documentation Page

Report No. MD-10-SP608B4J	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Applying ITS Technologies to Contend with Highway Congestion: Part-I: Variable Speed limit Control for Recurrent Congestion Part-II: A Lane-based Signal Merge Control System for Work Zone Operations		5. Report Date December 2010 6. Performing Organization Code
7. Author/s Sun Yoon Park and Gang-Len Chang		8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Civil and Environmental Engineering, University of Maryland, College Park, MD 20742		10. Work Unit No. (TRAIS) 11. Contract or Grant No. SP608B4J
12. Sponsoring Organization Name and Address Maryland State Highway Administration Office of Policy & Research 707 North Calvert Street Baltimore, MD 21202		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code (7120) STMD - MDOT/SHA
15. Supplementary Notes		

16. Abstract

This report presents the research results of two ITS applications: The first is an innovative field implementation of variable speed limit (VSL) control for a recurrently congested highway segment, and the second is a laboratory experiment of a lane-based signal merge (LBSM) control for highway work zone.
VSL control is an advanced traffic management strategy (ATMS) that has received increasing interest from the transportation community since the advent of intelligent transportation systems (ITS) in the 1980s. A complete VSL system typically comprises a set of traffic sensors to collect flow and speed data, several properly located variable message signs (VMSs) to display messages, a reliable control algorithm to compute the optimal speed limit for all control locations, a real-time database, and a communications system to convey information between all principal modules. The field experimental results over a 10-week period clearly indicate that VSL control supplemented with the display of estimated travel times can significantly increase both the average speed and throughput for highway segments plagued by recurrent congestion.
LBSM is a new merge control strategy that employs a signal at the proper merging point to assign the right-of-way for traffic in each lane if the approaching volume exceeds 800 vehicles per hour per lane. The results of extensive simulation evaluation clearly indicate that the design, even preliminary in nature, can significantly increase the throughput and reduce the average vehicle delay, average vehicle stop delay, and the number of vehicle stops for highway work zones under congested traffic conditions.

17. Key Words variable speed control, recurrent congestion, license plate recognition, lane-based merge, work zone	18. Distribution Statement: No restrictions This document is available from the Research Division upon request.		
19. Security Classification (of this report) None	20. Security Classification (of this page) None	21. No. Of Pages 87	22. Price

Form DOT F 1700.7 (8-72) Reproduction of form and completed page is authorized.

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PART I

Variable Speed Limit Control for Recurrent Congestion

CHAPTER 1: INTRODUCTION

1.1 Research Background

Variable speed limit (VSL) control is an advanced traffic management strategy (ATMS) that has received increasing interest from the transportation community since the advent of intelligent transportation systems (ITS) in the 1980s. A complete VSL system typically comprises a set of traffic sensors to collect flow and speed data, several properly located variable message signs (VMS) to display messages, a reliable control algorithm to compute the optimal set of speed limits at all control locations, a real-time database, and a communication system to convey information between all principal modules.

The core VSL logic is to dynamically adjust a set of speed limits on VMSs properly located along a target roadway segment so as to smooth the speed transition between the upstream free-flow and downstream congested traffic states, thereby preventing the formation of excessive queue due to the shockwave impacts. It is widely believed that properly implemented VSL, coupled with reliable traffic information messages, can facilitate traffic flows to fully utilize the available roadway capacity of the bottleneck segment, thus increasing the average traffic speed and volume throughput during the most congested period. With its dynamic adjustment capability, VSL control can also improve traffic safety on some hazardous highway segments that often experience poor weather conditions, justifying the reduction in speed limit to prevent any potential accidents.

Depending on the cause of congestion along the target roadway segment, VSL can be an effective strategy to control traffic flows in a highway work zone that suffers from a short-term capacity reduction or to guide drivers over a commuting roadway plagued by recurrent congestion due to downstream traffic volume surges. The former application of VSL has the primary purpose of improving traffic safety over the capacity-reduced segment by gradually reducing the speed limit. As a byproduct of such a speed control, if implemented properly, the capacity-reduced segment, such as a work zone, may yield a shorter queue length or an increase in the average speed and volume throughput. Most existing VSL studies conducted in the United States belong to this category, and their findings on the resulting effectiveness are all quite consistent.

In contrast, the research on applying VSL to minimize the volume-induced recurrent congestion remains at its infancy in the United States, even though there are many successful deployments in the Europe. In view of the deteriorating commuting traffic conditions in most major metropolitan areas and the diminishing resources for infrastructure renovation or expansion, exploring the potential of such non-construction strategies as VSL control to mitigate recurrent highway congestion has emerged as a priority task for the traffic management community.

1.2 Project Objective

To address the deteriorating traffic conditions on major commuting corridors, this project has the primary objective of evaluating the potential of deploying VSL controls to alleviate recurrent congestion, and especially to minimize the duration of stop-and-go traffic and increase the volume throughput at bottleneck segments. Through a rigorous field test and comprehensive data collection, this study intends to identify all critical factors associated with the effectiveness of VSL deployments and to produce insightful information for the development of VSL field implementation guidelines. More specifically, this study attempts to accomplish the following objectives:

- Identifying criteria for selecting congested roadway segments suitable for VSL implementation;
- Constructing an experimental VSL system for mitigating recurrent congestion on commuting corridors;
- Evaluating the effectiveness of the proposed VSL system with comprehensive field experiments, based on the resulting average speed, the total throughput over the bottleneck location, and the speed transition from free-flow to congested traffic conditions.

1.3 Report Organization

The six chapters of this report illustrate the proposed VSL system, explain its implementation plan, and describe our field evaluation results. The report also includes a brief review of related VSL applications over the past decade. A detailed description of information contained in each chapter is presented below.

Chapter 2 starts by summarizing VSL-related studies for work-zone operations and for improving the operational efficiency of highway segments plagued by recurrent congestion. Presenting the findings from both simulation and empirical studies pertaining to safety improvements and speed increases constitute the core of this chapter. Critical issues reported in the literature on VSL deployments and driver responses to the advisory messages serve as the basis for selection of the candidate recurrent-congestion segments and design of field operation plans.

Chapter 3 illustrates two VSL control algorithms proposed for use in computing the set of optimal speed limits for transition between free-flow and congested segments. The illustration includes the traffic information to be collected in real time, the variables to be measured from the field data, and the selection of time-varying speed control limits based on the spatial distribution of traffic flow speed and driver responses to displayed control messages. This chapter also covers the calibration of the proposed algorithms and their integration with communications systems for field operations.

Chapter 4 provides a detailed description of the field demonstration plan, including the geometric features of the selected roadway segment and the distribution of sensors, VMSs, and all supplemental hardware within the control boundaries for VSL deployment. This chapter also describes the structure of the proposed VSL system and the interrelations between its principal components: the information collection module, the communications module, the real-time database, the roadside VMSs, and the algorithm module. This chapter also discusses the operational procedures for collecting traffic performance information under four experimental scenarios: no-control, travel time display only, VSL control, and the integration of VSL control and travel time display.

Chapter 5 summarizes the control results of the above four experimental control scenarios, including the transition state between the free-flowing and congested conditions, the average traffic flow speed and volume throughput over the most congested segment, and travel time distribution over the entire roadway segment during peak hours. Comparisons of traffic operating efficiency under the incremental level of control such as VSL only or VSL and travel time display are also the primary part of this chapter.

Chapter 6 reports key research findings from the eight-week field study. It also discusses critical operations-related issues that could affect the VSL control’s effectiveness. To take advantage of lessons and findings from our extensive field experiments, this chapter also highlights some imperative tasks to tackle prior to a full-scale deployment of VSL control.

CHAPTER 2: FIELD VSL DEMONSTRATION PLAN

2.1 Design of Field Demonstration Plan

Due to the operational complexity and cost associated with the field experimental work, the research team has carefully reviewed all critical tasks to be conducted in the VMS demonstration and developed the following research plan:

- review all VMS literature and identify critical issues that may affect the performance of the field demonstration work;
- select candidate locations for field experimental work based on the literature review results, research objectives, and available resources for this study;
- review the selection criteria and identify the most appropriate location for a field demonstration;
- select VSL control algorithms based on the traffic characteristics of the selected roadway segment and the available hardware, as well as the communications equipment; and
- design the implementation plan and performance evaluation procedures.

This chapter presents the first three tasks, focusing on the literature review and on the selection and identification of the field experiment location. The selection of VSL algorithms and the design of the implementation plan will be discussed in the ensuing chapters.

2.2 Related VSL Studies

Variable speed limit control has long been explored over the past several decades, but it has received increasing attention by traffic professionals since the advent of ITS. Thus, compared with most existing strategies for traffic management, VSL control remains relatively new to the traffic community, and much needs to be done on its theoretical development and field evaluation. This section focuses on summarizing some major VSL-related studies conducted over the last five years which offer some insights into how to design and deploy VSL controls for roadway segments suffering recurrent congestion.

Based on the purpose of control, one can divide most recent studies on VSL operations into two categories: improving work-zone safety or augmenting the efficiency on recurrent congestion roadways. In the first category, the Michigan Department of Transportation (MDOT), in response to the solicitation of the FHWA, conducted a field test of variable speed limits in some highway work zones in 2003. The purpose of these VSL experiments was to test the hypothesis that drivers are more likely to comply with a “reasonable” speed limit in work zones, thereby resulting in low speed variance in the traffic flow and safer roadway conditions. It was a joint public-private venture led by the MDOT and reported to achieve promising empirical results with respect to the VSL effectiveness. Inspired by the promising field studies, Lin, Kang, and Chang (2004) researched the theoretical aspects of VSL control and produced two algorithms to maximize the effectiveness of work-zone operations under VSL control with respect to various selected measures of effectiveness (MOEs). The results of their simulation experiments also confirmed the effectiveness of VSL control in work zones if detectors are placed at proper locations and the control algorithms are sufficiently responsive to accommodate the behavioral patterns of target drivers.

Kwon, Brannan, and Daniel (2007) also conducted an extensive field evaluation of a variable advisory speed limit system for work zones on I-494 in the Twin Cities, Minnesota, for a three-week period. They reported that the VSL control resulted in a 25 to 35 percent reduction of the maximum speed variance during the morning peak hours. The reduction in speed variance also contributed to an approximate 7 percent increase of total throughput measured at the downstream work-zone boundary. Their field observations of difference between the displayed and actual traffic flow speeds also confirmed that drivers will more likely comply with speed limits set properly to reflect the traffic conditions.

Along the same line of research, Kang and Chang (2007) presented a set of VSL algorithms to integrate with dynamic late merge (DLM) control strategies. Their proposed integrated control process used the optimal VSL model as a supplementary strategy of the entire DLM and coordinated the sequence of VMSs. Both the simulation and field demonstration results indicated that the integration of VSL and DLM controls performed quite well in the time-varying traffic conditions and yielded higher throughput than typical merge controls. Their study also reported an increase in the average speed and a reduction in the speed variation.

The two most recent field demonstrations of VSL control in work zones were conducted in Utah (2009) and on the I-495 Capital Beltway (2008). The Utah Department of Transportation installed a work-zone VSL control on a six-mile segment of I-80 north of Wanship, focusing on the response of drivers to the dynamically posted speed limits. Using five speed detectors and two VSL signs for system demonstration, the data collected over three months revealed a significant reduction in traffic speed variance, especially at the first speed detector location downstream of the first VSL sign. The latter demonstration project, on the I-495 Capital Beltway, was a VSL system installed in a major work zone. Its main focus was to collect sufficient field data on traffic conditions resulting from the collective response of drivers to the variable speed limit information. Using the well-calibrated simulation tool, this study indicated that VSL can indeed delay the onset of congestion and help produce more rapid recovery from congestion, provided that actual traffic volumes do not exceed the remaining roadway capacity. The simulation results also showed that the location of VSL sign is critical to its effectiveness; signs must be positioned properly so that drivers will accelerate back to the normal speed after passing the work-zone bottleneck.

Another category of VSL applications is on highway segments experiencing recurrent congestion or inclement weather conditions. The focus of such applications, mostly deployed in Europe, was to either improve roadway safety or increase its operational efficiency. One recent VSL study along this line was the work by Hegyi and Bart (2004), who developed a predictive control model to optimally coordinate variable speed limits for highway traffic. With the objective of minimizing the total vehicle travel time in the network and the embedded constraints to prevent drivers from experiencing a sudden speed drop, they reported that their model can effectively reduce the traffic flow shock waves and result in less congestion and a higher throughput.

To analyze some critical factors affecting driving behavior under recurrent congestion in response to VSL control, Bertini and Bogenberger (2005) presented the results of a field study that focused on analyzing traffic data from multiple sources, including roadway detectors, probe vehicles, dynamic navigation systems, and VMS in a congested highway corridor in Munich, Germany. Based on the empirical results, they developed a set of algorithms for travel time estimation, travel information system, and dynamic VSL control to improve the operational efficiency on recurrently congested highways.

Mainly to address safety concerns, Washington State (Ulferasson and Shankar, 2005) installed several VMSs to display variable speed limits on I-90 in the vicinity of Snoqualmie Pass. Classified by the on/off status of VMSs, the empirical results indicated a significant decrease in the mean traffic flow speed and an increase in the speed variance. The study also revealed that the VSL/VMS effectively reduced traffic flow speeds only within the control boundaries and those drivers may engage in compensatory behavior outside the target zone. The compensatory behavior and increased speed variation caused by implementing VSL/VMS on uncongested but potentially hazardous highway segments can potentially temper safety improvement. To improve both operation efficiency and safety performance, Steel, McGregor, and Robyn (2005) reported an application of VSL along the Trans-Canada Highway in Banff National Park, a highway segment of approximately 35 kilometers tied in to the existing twinned section of the Trans-Canada Highway at Castle Mountain Interchange. Their study summarized some critical issues associated with the effectiveness of VSL applications in non-work zones.

Also focusing on safety issues, but intending to address the effectiveness of VSL strategies on reducing rear-end and lane-changing crash risks, Abdel-Aty and Mohamed (2008) analyzed data from using VSL on I-4 in Orlando, Florida. Their study also investigated the optimal distance over which VSL should be implemented from a station of interest. Based on the results of extensive analyses, they concluded that VSL could effectively prevent crashes when freeways are operating in the transition state between free-flow and congested traffic conditions.

One potential VSL application is to inform drivers of inclement weather conditions and post the new speed limit to control traffic flow. The two most recent studies for this type of application were reported by Jonkers and Klunder (2009) from the Netherlands and by Buddemeyer and Young (2010) from Wyoming. The former study focused on the following three critical issues: (1) when to change the speed limit; (2) how to convey speed limit information to drivers; and (3) what algorithm to use to set the appropriate speed limit. The latter study, conducted on I-80 in the southeastern part of Wyoming, primarily focused on improving traffic safety during severe weather conditions. Preliminary results from the first several months indicated that drivers reduced their speeds between 0.4 and 0.9 mile per hour (mph) for every one mph in posted speed reduction.

Some recent studies about contending with recurrent highway congestion begun to investigate whether integrated VSL and travel information can effectively improve safety and operational efficiency. For instance, Bertini and Boice (2006) reported their empirical findings from deploying a dynamic VSL system surrounding bottlenecks on the German Autobahn. This study primarily focused on analyzing the compound impact of VSL control and travel time information on the compliance of drivers and the formation of recurrent congestion bottlenecks. The study found that drivers more willingly complied with the VSL control if they were informed of approaching congestion conditions. Anund and Ahlstrom (2009), in another recent empirical study, investigated the acceptance and effect of VSL control with two different message display systems: one combined the speed limit sign with a message to slow down, and the other integrated the VSL with flashing lights. Both VMSs were activated if the passing vehicle was driving too fast as it approached the speed limit sign. The study, conducted in two Swedish villages, found that VSL significantly reduced the average speed of traffic flow, but adding the warning of flashing lights did not further increase the compliance rate.

Also attempting to mitigate recurrent congestion, some researchers started to explore the potential of integrating VSL with freeway ramp metering control. For instance, Ghods and Kian (2009) proposed the integration of adaptive freeway ramp metering with a VSL control. Their preliminary findings indicated that incorporating VSL with various advanced traffic management strategies could be a promising direction for maximizing the operational efficiency on recurrently congested highway segments.

2.3 Selection of Candidate Locations

Based on the results of the literature review and previous research (Kang and Chang, 2007), this study employed the following criteria to select a candidate roadway segment for the field demonstration of VSL control for recurrent congestion:

- The roadway segment shall contain some significant variation in geometric features (e.g., weaving or lane drop) that may cause the traffic flow to change its speed or incur some safety concerns.
- The roadway segment shall experience significant fluctuations in traffic flow speed during peak hours, such as evolving from free-flow conditions to a stop-and-go congestion pattern.
- Some subsegments of the target roadway segment shall experience traffic volume surges during the peak period, causing the upstream entry flows to dramatically reduce in speed.
- The spatial distribution of traffic volume along the candidate roadway segment shall vary significantly from its upstream to downstream subsegments due to merging flows from intersections or ramps.
- The target roadway segment shall experience a significant number of incidents per year.

Considering the available resources and operational convenience, the research team, in consultation with SHA, applied the above criteria and selected the following three candidate segments (see Figure 2-1) from the roadway of MD 100 between I-95 and Arundel Mills Blvd. for field demonstration:

Site 1: MD 100 West from MD 713 to Coca Cola Drive: This segment contains a bridge and has a short sight distance. It typically receives a high level of volume from Coca Cola Drive via its right-side ramp and weaving area during the evening peak hours. There are both vertical and horizontal curves on this roadway segment.

Site 2: MD 100 West to I-95: This segment contains a weaving area to receive two ramp volumes from I-95 and an on-ramp volume from southbound US1. During the peak commuting hours, the congestion on I-95 frequently causes its queue to spill back to MD 100.

Site 3: MD 100 West at Arundel Mill Blvd.: This segment contains a weaving area to receive traffic from northbound MD 295 and to accommodate exiting flows to Arundel Mills Blvd. via an off-ramp. During the evening peak period, this segment often experiences a high-level of exiting volume to Arundel Mill Blvd, causing traffic to slow down.

Several preliminary surveys of traffic conditions during peak hours indicated that all three field sites offer similar characteristics for potential VSL control. The research team finally selected Site 1, the segment of *MD 100 West from MD 713 to Coca Cola Drive,* as the target site to experiment with various VSL-related controls, because this segment, in 2008 alone, experienced a total of 39 accidents, significantly higher than the other two sites. Figure 2-2 provides a more detailed view of this segment.

MD 100 is a highway that has two lanes (in each direction) and a speed limit of 55 mph. During average weekdays, its evening peak hours usually start at 5 PM, and its speed usually drops quickly from 60 mph to 20 mph (i.e., in five minutes) at the onset of congestion. Over Coca Cola Drive, its speed typically climbs and can reach up to 30 to 40 mph. The free-flow travel time on MD 100 between MD 170 and US 1 is about four to five minutes, but it may take up to 15 minutes during the congestion period, due to the merging flow starting at Coca Cola Drive. Figure 2-3 illustrates the target MD 100 segment selected for VSL control and its spatial distribution of traffic flow speeds during peak hours. As evident in the speed profile data, traffic flows generally started at the speed of 60 mph from the location intersecting with MD 170 and then gradually reduce to about 50 mph when reached MD 713 during peak hours. Its speed exhibited a sharp drop, to 20 to 25 mph, after encountering the ramp flows from MD 295 and continued at the same stop-and-go speeds until the highway passed Coca Cola Drive. The dramatic speed drop over a distance of around two miles offered ideal traffic conditions for a VSL control. It also seemed desirable to post the estimated travel time from MD 170 to US 1 to ease drivers' concerns about downstream traffic conditions.

To further identify the factors contributing to the downstream congestion, this study conducted a preliminary survey on MD 100 between MD 295S and Coca Cola Drive during both peak and off-peak periods. Table 2-1 summarizes the results of the preliminary volume and speed survey over the segment with recurrent congestion, where locations A, B, and C are on the MD 100 mainline and locations C and D are on the on-ramp and off-ramp, respectively. As the survey results show, the average traffic flow speeds were all above 55 mph during the off-peak period except at location E (43 mph). In contrast, the traffic flow speeds during peak hours, from the upstream segment C to locations B and A, were all below 25 mph due to the large volumes of merging traffic from the ramps of MD 295 and Coca Cola Drive. The merging flows also increased the total volume from about 1,600 vehicles per lane per hour to about 1,950 per lane per hour.

In brief, based on the selection criteria and field survey results, this study selected the MD 100 segment between MD 170 and Coca Cola Drive, where the speed reduces from 60 mph to 25 mph, to experiment with the potential of VSL control. During the VSL control period, the system also concurrently displayed the estimated travel time from MD 170 to US 1, the segment between the beginning of substantial speed reduction and its recovery to the free-flow condition.

Figure 2-1: Graphic view of the three candidate field sites

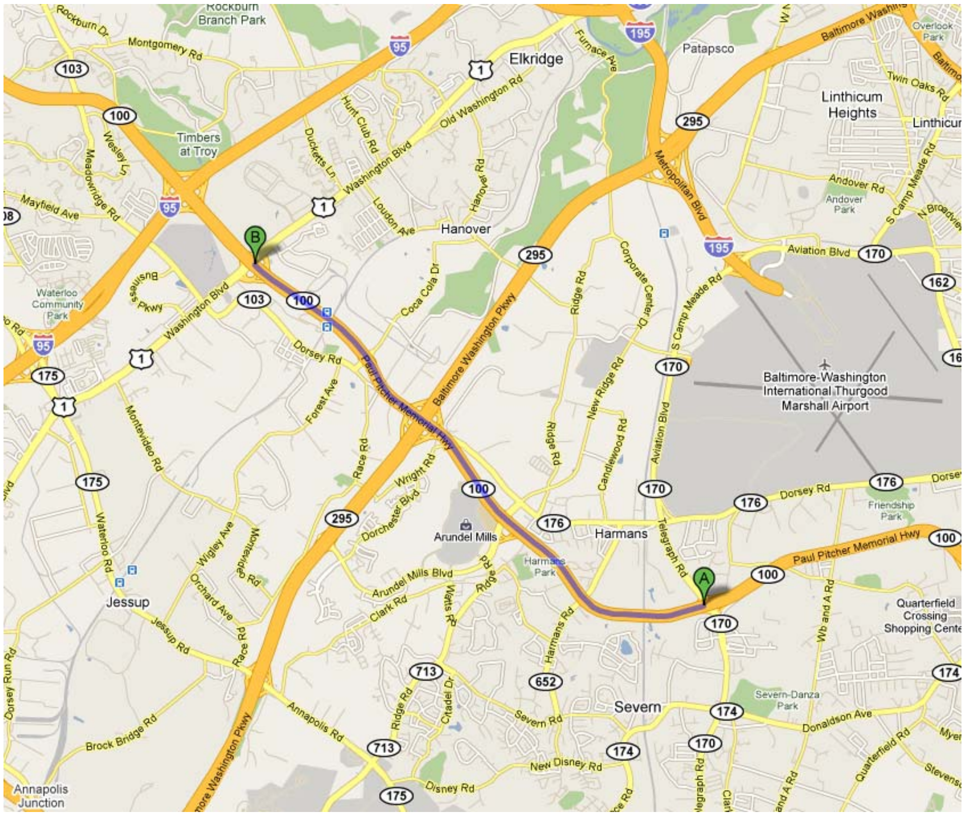


Figure 2-2: A graphical view of the road segment from MD 713 to Coca Cola Drive.

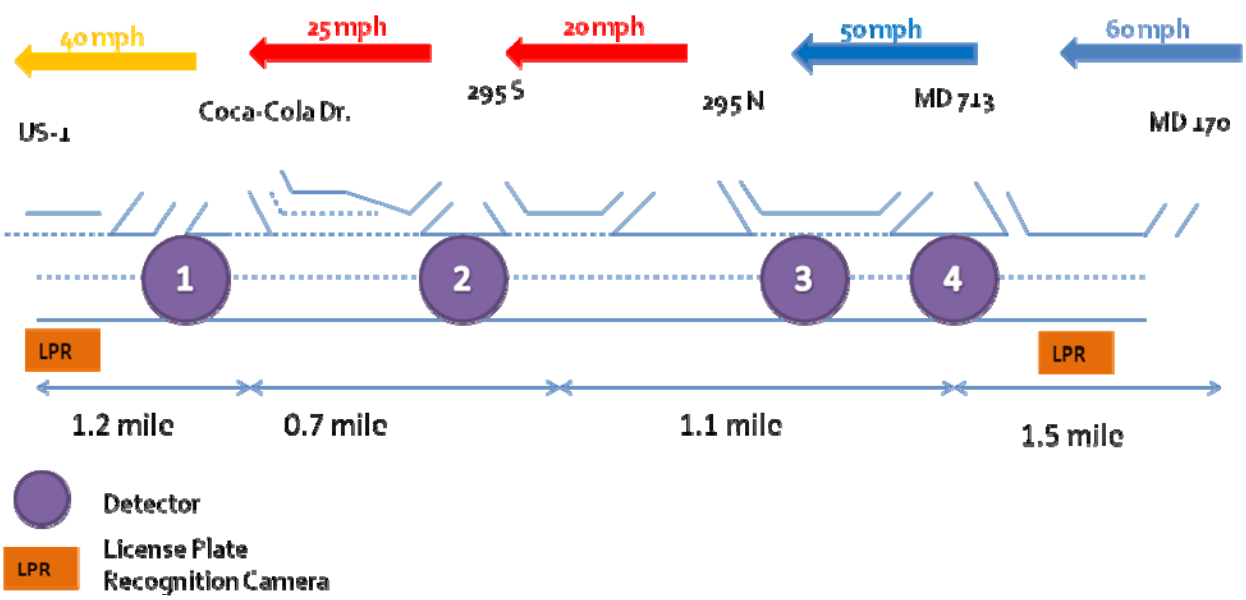


Figure 2-3: Spatial distribution of traffic flow speeds over the VSL control segment

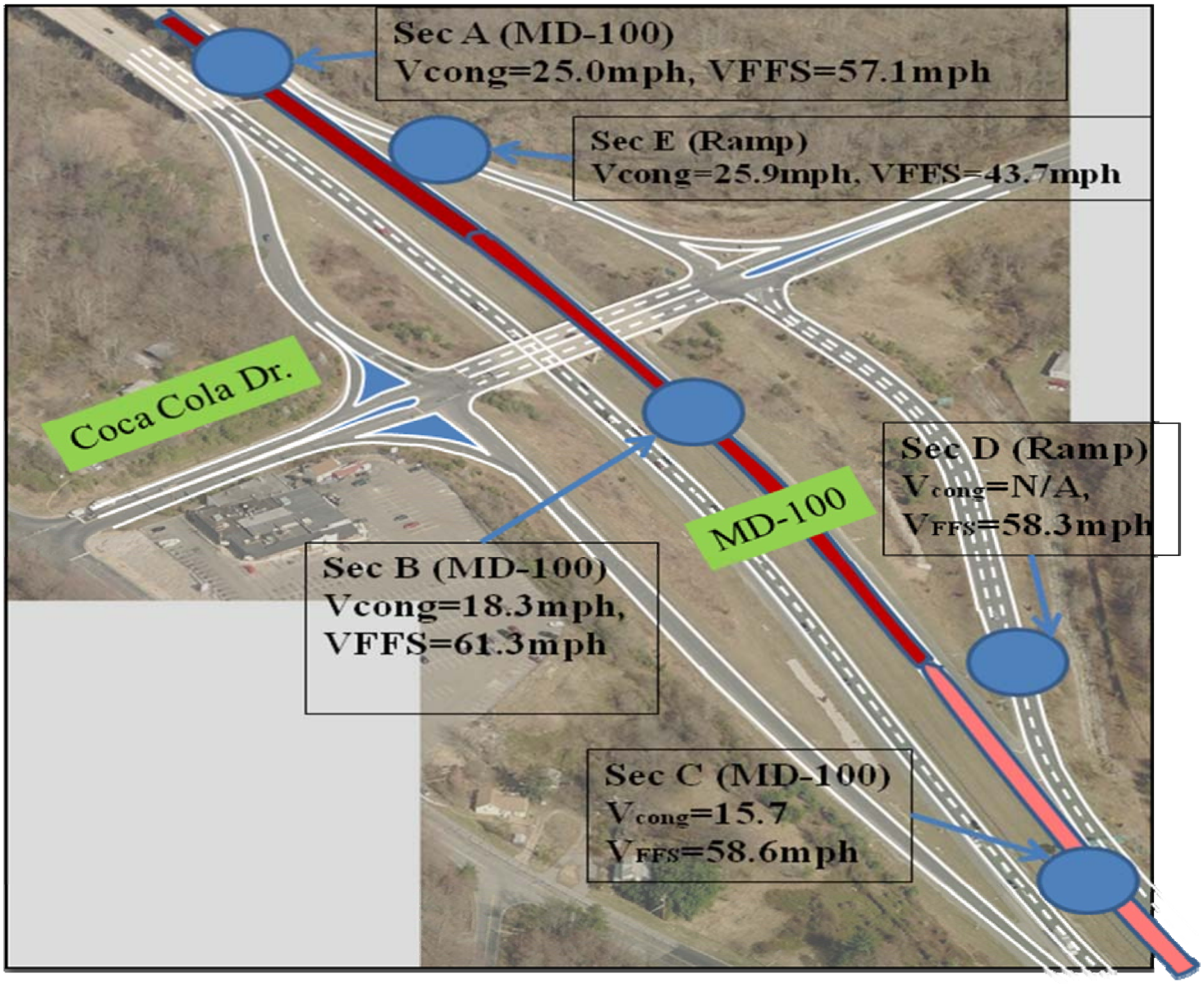


Figure 2-4: Spatial speed distribution on MD 100 between MD 295S and Coca Cola Drive

Table 2-1: Spatial distribution of volumes and speeds on MD 100 between MD 295S and Coca Cola Drive

Location	Free-Flow Speed				Congestion speed			
	Volume (vplph)	Speed		Time	Volume (vplph)	Speed		Time
		Mean (mph)	Standard Deviation			Mean (mph)	Standard Deviation	
Section A	1972	57.1	5.9	17:02~17:07	998	25.0	11.4	17:07~17:12
Section B	1644	61.3	5.7	16:16~16:21	1240	18.3	5.3	17:15~17:22
Section C	1638	58.6	5.3	17:50~17:55	1147	15.7	7.3	17:15~17:22
Section D	66 (ramp)	58.3	4.3	17:50~17:55	N/A	N/A	N/A	N/A
Section E	540 (ramp)	43.7	3.7	17:02~17:07	412	25.9	6.2	17:07~17:12

CHAPTER 3: VSL CONTROL ALGORITHMS

3.1 Introduction

This chapter presents the control algorithms embedded in the VSL system for smoothing the transition between the upstream free-flow and downstream congested traffic speeds. The proposed VSL system comprises sensors, variable speed limit signs, variable message signs, and central processing units to execute the real-time control actions. Depending on the approaching volume, driver compliance rate, and congestion level, the central processing unit that integrates all system sensors and signs can employ its VSL algorithm to compute the time-varying optimal speed limit for each VMS and display it in a timely fashion. The remaining sections of this chapter will discuss the core logic of the employed VSL algorithm.

3.2 VSL Control Algorithm

Figure 3.1 illustrates the operational flowchart for generating the optimal variable speed limit for each VMS under a real-time control environment. Its first module computes the initial speed of each VSL location, and the second module is responsible for updating the speed displayed on each VMS, based on the estimated difference between the detected flow speed and the target control speed. The VSL control module employs the algorithms developed by Lin and Chang (2004) to compute the optimal set of speed limits for control operations, and takes into account the response of drivers in setting the appropriate speeds displayed on VMS.

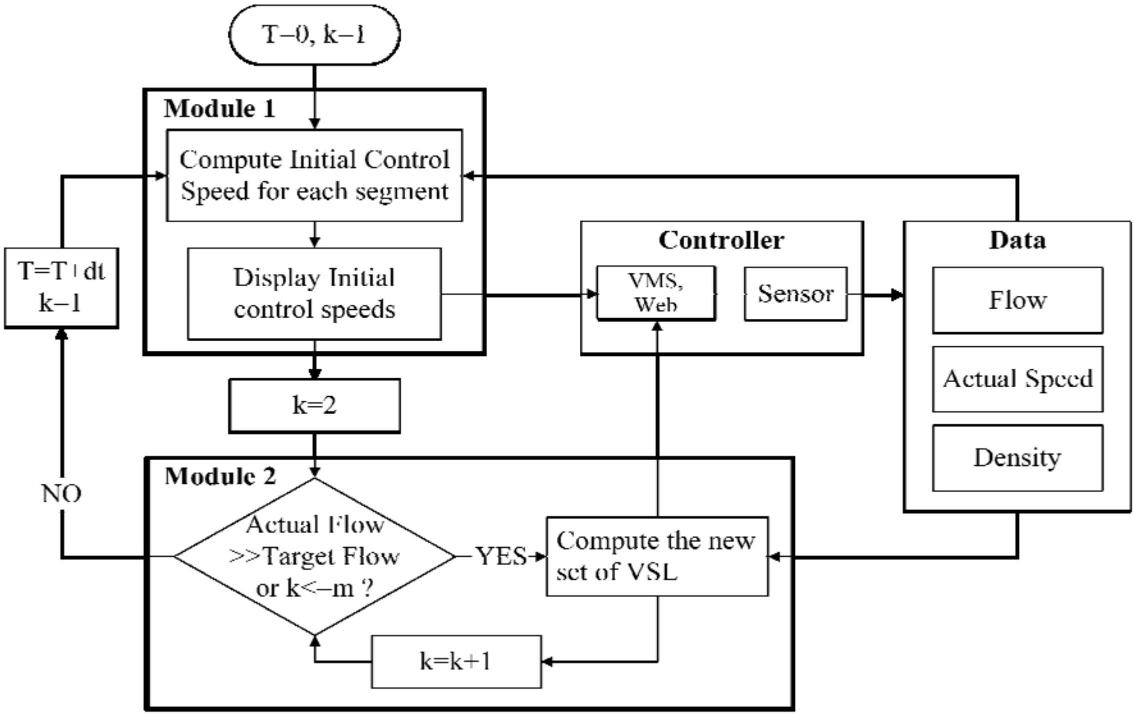


Figure 3-1: The flowchart for computing the optimal set of VSLs

To apply the VSL algorithm by Lin and Chang (2004), one needs to first divide the upstream segment of the potential maximum queue length into a number of sub segments with each being monitored by a set of sensors, VMS, and VSL signs (see Figure 3-2). Its control target is to ensure that the traffic flow rate moving into the congested area from upstream segments should approximately be equal to the flow rate moving out of the bottleneck area so that excess queue or stop-and-go traffic condition will not incur. Execution of the VSL control algorithm in a real-time environment shall include the following steps:

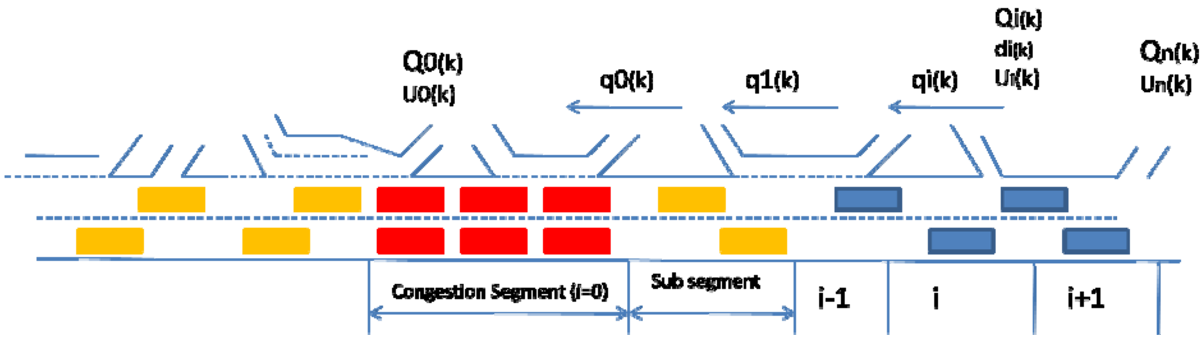


Figure 3-2: Control Area for applying the VSL Control Algorithm

Step 1: Compute the weighted flow rate for each control segment over each control interval

The actual traffic flow rate for interval k shall be approximated with a weighted average between two consecutive time intervals. Equations (1) and (2) represent the transition flow for the congested segment and the first control segment (*i* =1), respectively.

$$q_0(k) = \beta_0 \cdot Q_0(k-1) + (1-\beta_0) \cdot Q_0(k) \tag{1}$$

$$q_1(k) = \beta_1 \cdot Q_1(k-1) + (1-\beta_1) \cdot Q_1(k) \tag{2}$$

Where β_i is a model parameter (i.e., time weighting factor), which can be calibrated with field measurements. Chang (1995) stated that it should lie within the interval [0.5, 1.0], and Cremer et al. (1989) calibrated it to be 0.95 from the field data. The notation *k* denotes the time interval; $Q_i(k)$ represents the detected flow rate for segment *i* at interval *k*.

Step 2: Compute the space weighted transition flow for each segment

Due to the point-measurement nature of detector data, the traffic flow rate over each sub segment is measured as a weighted average of two neighboring sub segment flows. Hence, one shall apply Equation 3 to compute the actual target control flow rate, $q^c(k)$, from the flow rates on the congestion segment and the first segment *(i = 1).*

$$q^{c}(k) = \alpha_0 \cdot q_0(k) + (1-\alpha_0) \cdot q_1(k) \tag{3}$$

where α_i is a model parameter (i.e., space weight factor) to be calibrated; and $q_0(k)$ and $q_1(k)$ are the weighted flow rate at the target congested segment and its neighboring upstream segment (*i* =1).

Step 3: Compute the target density for segment *1*

With the above variables and parameters, one can apply the conservation law to approximate the evolution of traffic density for the first segment upstream of the target congested area. Equation 4 illustrates the relation for updating the temporal variation of the mean density for the first segment, $d_1(k)$, during each control time interval, based on the difference between the input and output flows, $q_1(k)$ and $q_0(k)$, at the boundaries of segment *1*.

$$d_1(k) = d_1(k-1) + \frac{q_0(k) - q_1(k)}{L_1} \cdot \Delta t \tag{4}$$

Step 4: Compute the target control speed for segment *1*

Based on the assumption that traffic density remains approximately constantly within a short distance and a short time period, one can approximate the target control speed for the 1st segment at interval k as follows:

$$v_1(k) = q^{c}(k) / d_1(k) \tag{5}$$

Step 5: Compute the target control speed for each upstream segment

Given the target speed to reach the congested area, Figure 3-3 illustrates the speed reduction process under the ideal condition, where the slope of the speed reduction line is based on the approaching traffic flow speed on the last segment within the control boundaries and the target speed to move into the bottleneck area. To maintain the constant control speed limit within each sub-segment, one shall adopt the following step relation to compute the speed limit for each VMS.

$$v_i(k) = v_1(k) + \frac{u_n(k) - v_1(k)}{n-1} \cdot (i-1) \tag{6}$$

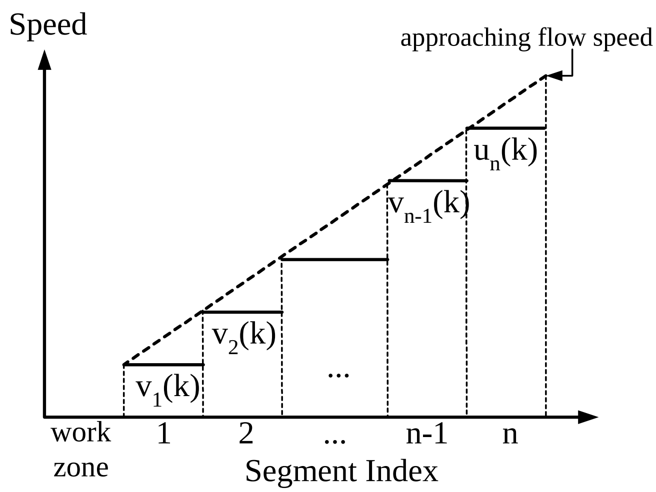


Figure 3-3: Graphic Relationship between the Control Speed and the Displayed Speed

Since drivers typically do not follow the displayed control speeds, Module 2 in the VSL control unit functions to compute the differences between the detected flow speeds and the target control speeds over each control segment, and then to update the displayed speeds accordingly. The computing procedures are shown below.

Step 1: Compute a compliance rate based on the detected speed and the control speed.

The compliance rate, defined as the ratio between the displayed control speed and the detected flow speed, can be computed as follows:

$$\gamma_i(k) = v_i(k) / u_i(k) \quad \text{i=1, n-1.} \tag{7}$$

Step 2: Update the control speed for the next time interval

By assuming the linear relationship between the compliance rate and the control speed, one can compute the displayed control speed for the next time interval as follow:

$$v_i(k+1) = \gamma_i(k) \cdot v_i(k), \quad i=1..,n-1 \qquad (8)$$

This is to accommodate the fact that most drivers tend to drive, for example, 5-10 mph over the recommended speed limit.

CHAPTER 4: DESIGN OF THE VSL SYSTEM DEMONSTRATION

4.1 System Framework

The entire VSL operating system for the field demonstration includes hardware deployment, communications setup, software, and an online database for real-time monitoring and management. Figure 4-1 illustrates all principal system components and their interrelationships. The key functions associated with each component are summarized below:

- *Traffic sensors*: four HD sensors from Wavetronix were used to measured speed, occupancy, and flow rate by lane at 30-second intervals.
- *LPR (license plate recognition) system*: a pair of LPR systems was deployed, one at either end of the target roadway segment, to measure the travel time of vehicles under various control strategies.
- *VMSs*: two VMSs were used for the system demonstration — one to display the estimated travel time and the other to inform drivers of the advisory speed under various control environments and traffic conditions.
- *Real-time data conversion/transmission module*: a specially designed program was used to collect all available real-time information — such as a timestamp of each observed license plate, site ID, traffic volume, and the average speed of time interval — for transfer to the central database via the wireless network.
- *Real-time database module:* a customized database was designed to receive data from traffic sensors and LPR units, and then to forward the required information to the travel time and VSL modules.

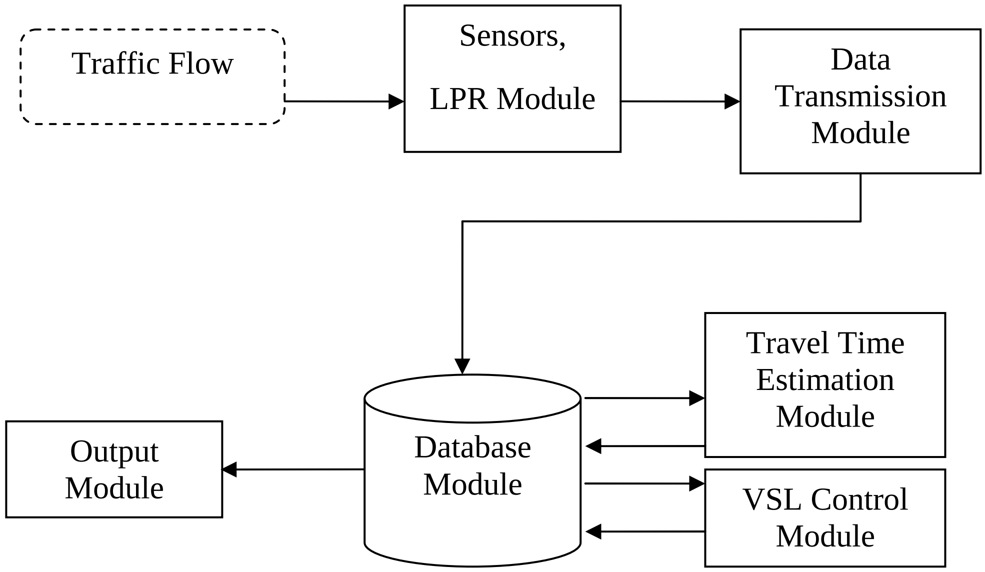


Figure 4-1: Principal modules and their interrelationships

Figure 4-2 illustrates the operational flows between the control system, the roadside units, and the web display module. The traffic flow data detected by the roadside sensors and the LPR system will trigger the VSL algorithm module to calculate the estimated travel times and advisory speed limits. That information, updated at one-minute intervals, will then be displayed in real time on the roadside VMS and on a customized website.

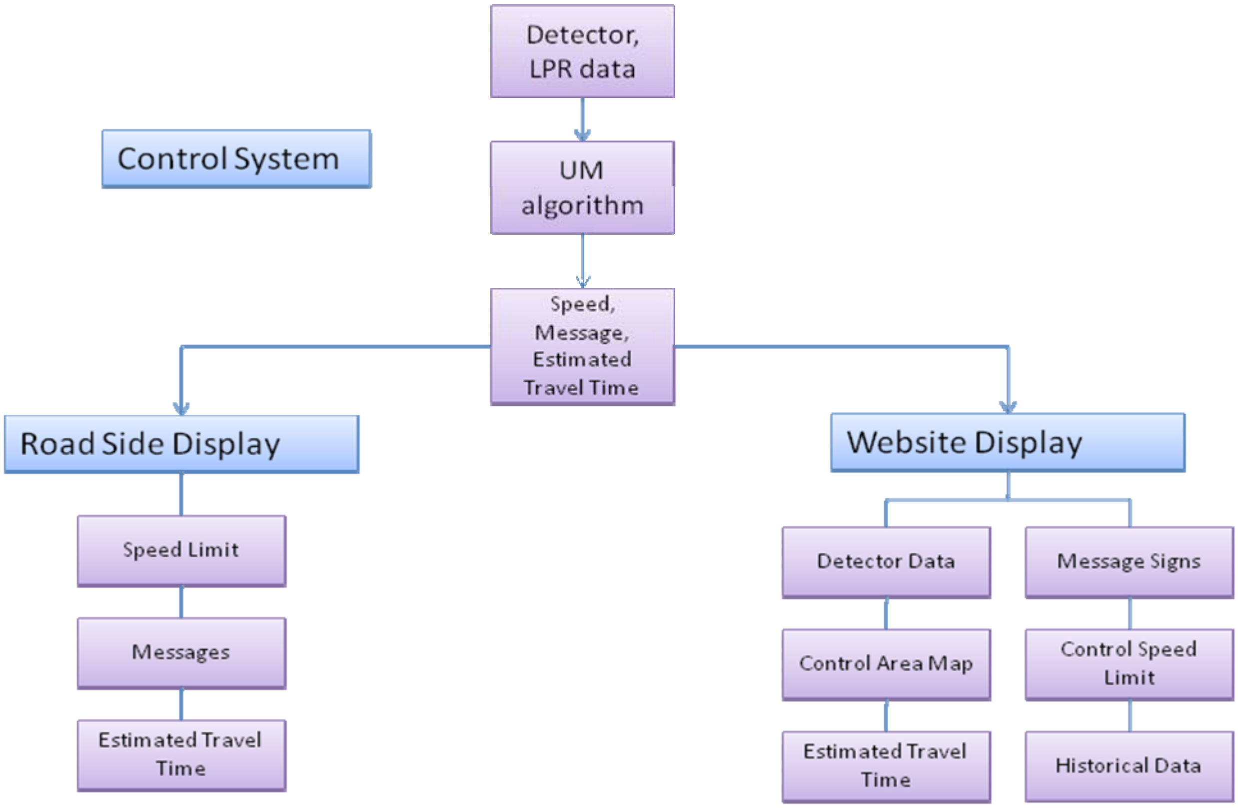


Figure 4-2: Operational flowchart between key components

Note that since the demonstration system contains only four sensors, VSL, and VMS data, the research team found that the MySQL version 5.0 (http://www.mysql.org) database server was sufficiently efficient to handle the data processing tasks. Hence, a database was set to retrieve sensor data every 30 seconds and to record the VSL and VMS results every minute. Estimated travel times, warning messages, and the advisory speed limit at different roadway segments were the primary outputs of this database module.

The research team used the Microsoft Internet Information Service (web server software) and PHP (a web server scripting language that enables server-side programming for web services) to provide real-time, web-based travel time information, sensor data, displayed messages, and historical queries. PHP's support for MySQL server made it relatively convenient to implement the connection between the web server and the database server.

4.2 Roadside System Configuration

As Figure 4-3 shows, the entire roadside system consists of four detectors, two VMSs, two VSLs, and two LPR trailers; these were deployed over the target roadway segment during the three demonstration periods. Based on the spatial distribution of traffic flow speeds from MD 170 to Coca Cola Drive (shown at top of the figure), this study selected the segment of MD 100 from MD 713 to Coca Cola Drive as the target control segment, because the traffic flow speed within this segment drops substantially, from an average of 50 mph to 25 mph, due to the traffic volumes coming from on-ramps.

To capture the traffic flow and speed evolution, the research team placed detector 4 on MD 713 to detect the upstream traffic condition, and detector 3 at 0.3 miles downstream to measure the incoming traffic volumes from its ramp — since, during peak hours, many vehicles entered MD 100 from this ramp. Detector 2, located between two ramps from MD 295 to MD 100, functioned to detect the starting point of speed drop in traffic flow, where traffic volumes from Coca Cola Drive and MD 295S often start queues and cause stop-and-go traffic conditions during daily peak hours. This detector also served to monitor the speed transition between detectors 1 and 3.

Note that the roadside component contained two speed advisory signs: the first one was deployed next to detector 4, where traffic began to change from free-flow to constrained traffic conditions, and the second was placed around detector-2 to respond to the observed stop-and-go recurrent congestion. To alert drivers about the speed advisory control plan, the roadside component also includes two VMSs, placed about one mile apart preceding the speed advisory sign, to inform travelers of the downstream traffic conditions and the travel time to US 1.

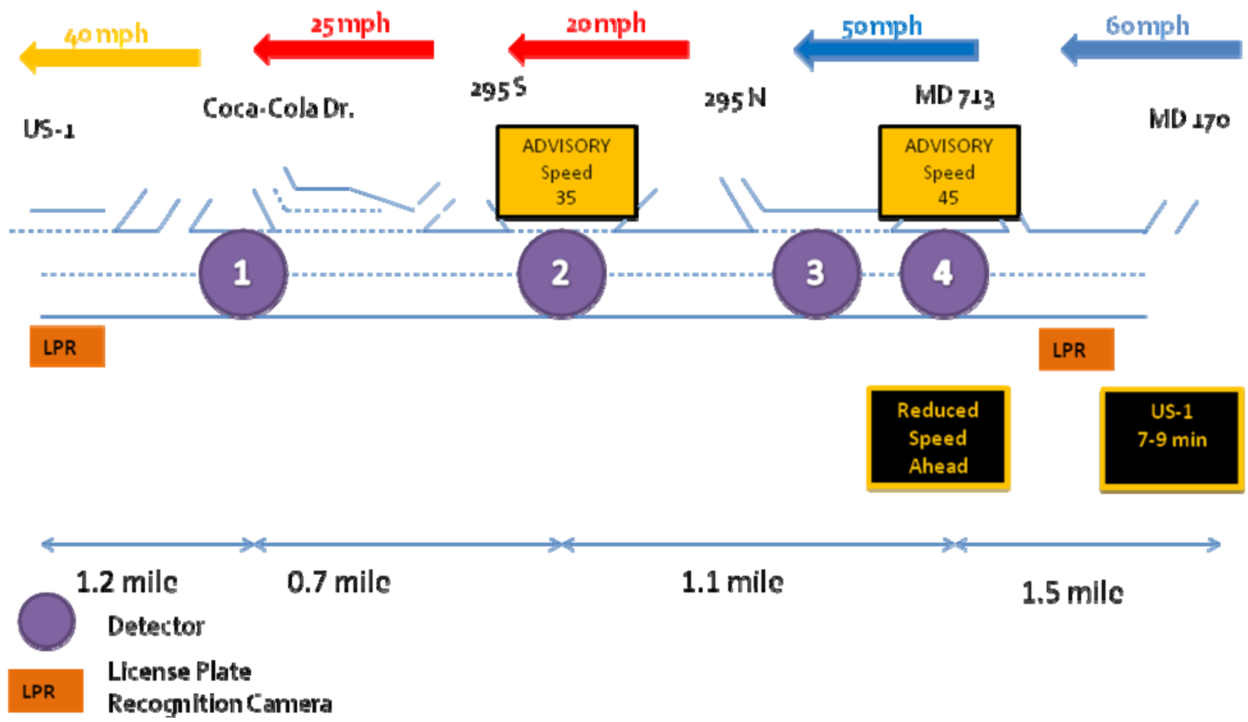


Figure 4-3: The roadside System Configuration

4.3 Experimental plans

The entire experimental plan consisted of four control periods: no-control, display of estimated travel time, VSL control only, both the VSL control and display of estimated travel time. Each control period lasted at least two weeks. Through these four operational plans, the research team was able to observe the response of drivers to the incremental level of control or information availability, and their collective impacts on the traffic condition with respect to speed, throughput, and travel times. All key research activities conducted during each experimental period are summarized below:

Demonstration Period 1: No-Control Scenario

This demonstration period started from November 11 to November 30, 2009, and covered the following major activities:

- Deployed two LPR trailers, four sensor trailers, two VMS, two VSL at pre-selected locations;
- Calibrated LPR system, sensor data, VMS and VSL;
- Collected background traffic such as traffic volumes, speeds, and travel times;
- Tested the main functions of each system component; and
- Experimented the interactions between principal components and the operations of the entire system.

During this per-control period, neither the VMS nor the website displayed any traffic information.

Demonstration Period 2: Display Estimated Travel Time

The focus of this experiment was to evaluate the potential impact of travel time display on the spatial evolution of traffic flow speeds, because it is likely that the reduction of traffic uncertainty ahead may ease the stress of drivers and consequently smooth the transition of traffic flow between free-flow and congested states. The following activities took place during this experimental period, from December 1 to December 13 2009:

- Started the roadside display of estimated travel time from MD 170 or MD 713 to US 1;
- Tested the VSL algorithm with the field data, but without the roadside display;
- Continued system operations of travel time estimation and sensor data update.

Note that the estimated travel times were calculated from the deployed LPR system and displayed on VMSs for the roadway segments from MD 170 or MD 713 to US 1. Figure 4-4 shows the system design for this experimental period. While VMSs displayed the estimated travel times, VSL trailers were folded and located on the roadside.

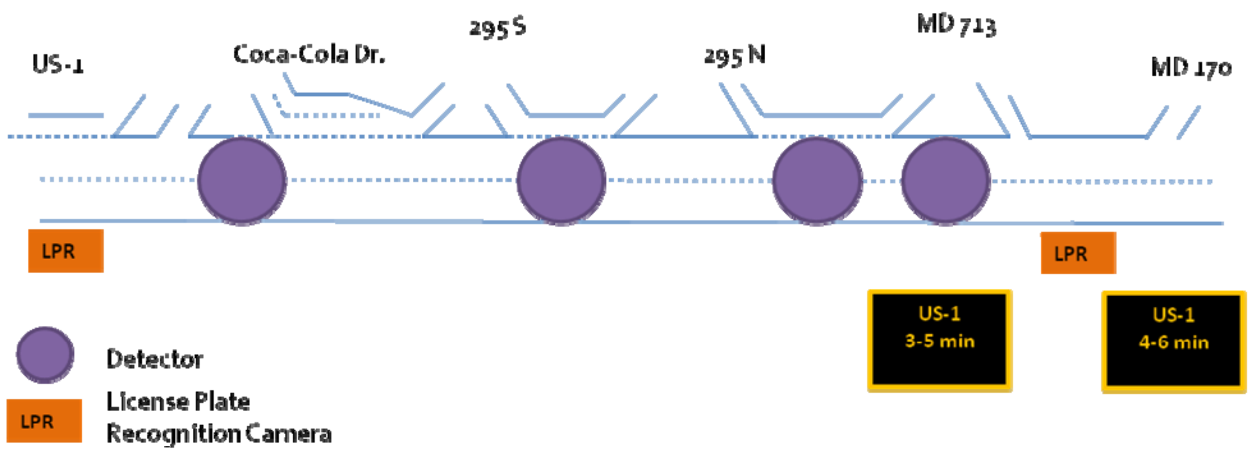


Figure 4-4: System layout for travel time display only

Demonstration Period 3: VSL control only

Based on the traffic data collected over the previous two periods, this demonstration task evolved to implementation of actual control on the traffic flows along the target control segment. The central control module was responsible for constantly computing the optimal speed at each control point and displaying the advisory speed limit on the roadside VSL trailers. To respond to rapid changes in traffic conditions, the VSL module produced the updated speed limits at one-minute intervals. This experimental period, from December 14 to December 27, 2009, focused on the following activities:

- estimated the travel times from the LPRs and displayed the information on two VSL trailers;

- filtered the data from traffic sensors and executed the VSL algorithm to produce and display the advisory speed limits;
- displayed the "Reduced Speed Ahead" message on two VMSs when the VSL module was activated;
- operated the system continuously, which included computing the VSLs, estimating travel times, and updating sensor data.

Note that travelers during this experimental period received only advisory speed limits, which were displayed on two roadside VSL trailers. Figure 4-5 illustrates the system layout during this VSL control period. The system activated the VSL control only during the daily peak periods, when traffic was getting slowed due to recurrent congestion. Also note that the other VMSs would show the "Reduced Speed Ahead" message when the VSL system was on the action mode. Otherwise, it would be turned off.

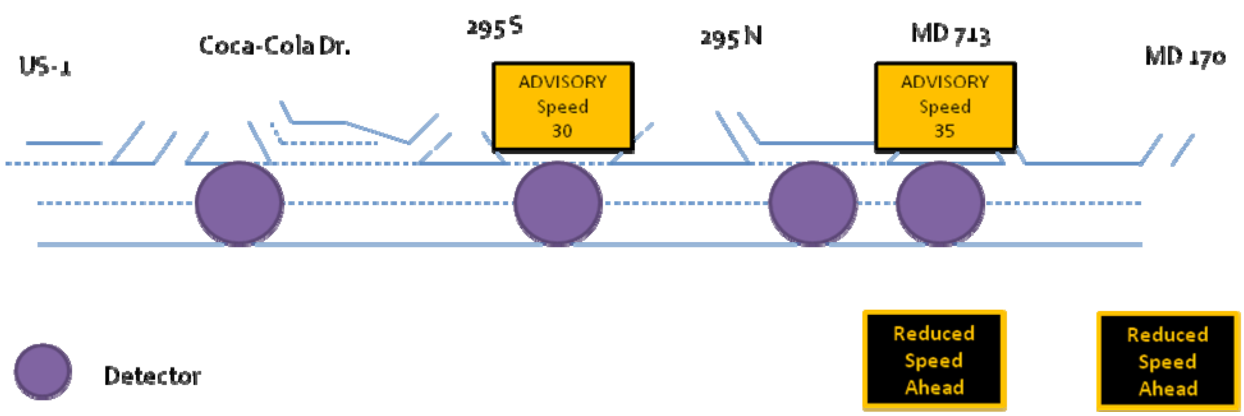


Figure 4-5: System layout for VSL control only

Demonstration period 4: VSL control combined with display of estimated travel time

During this experimental period (from December 28, 2009, to January 25, 2010) drivers over the target roadway segment received information about both estimated travel time and advisory speed limits. This period tested the hypothesis that drivers would more likely follow the advisory speed limits if they were aware of the downstream traffic conditions reflected in the estimated travel time. The following operational activities occurred during this period:

- displayed the advisory control speed limits on the two roadside VSL trailers and the estimated travel time on one of the two VMSs; the other VMS was used to display the "Reduced Speed Ahead" message; and
- updated the VSL module and the travel time estimation module with the online sensor data received at 30-second intervals.

Note that drivers received not only travel time information but also advisory speed limits during this control period. Figure 4-6 illustrates the system layout for the combined VSL control and display of estimated travel time. The VMSs for the travel time display continuously showed the time-varying trip time from MD 713 to US 1 during the entire experimental period, regardless of the operational state of the VSL system. The warning message "Reduced Speed Ahead" was always activated whenever traffic conditions evolved to a congested state, triggering activation of the VSL control module.

In brief, since this experimental study intended to explore the impact of various levels of information on driving behavior and the resulting congestion, this study kept the traffic monitoring module (sensors and LPR) operational 24 hours a day over the entire eight-week demonstration period. The data collected over three experimental periods on traffic characteristics offers a very rich base for identifying the congestion patterns best suited for implementing VSL control and other complementary strategies.

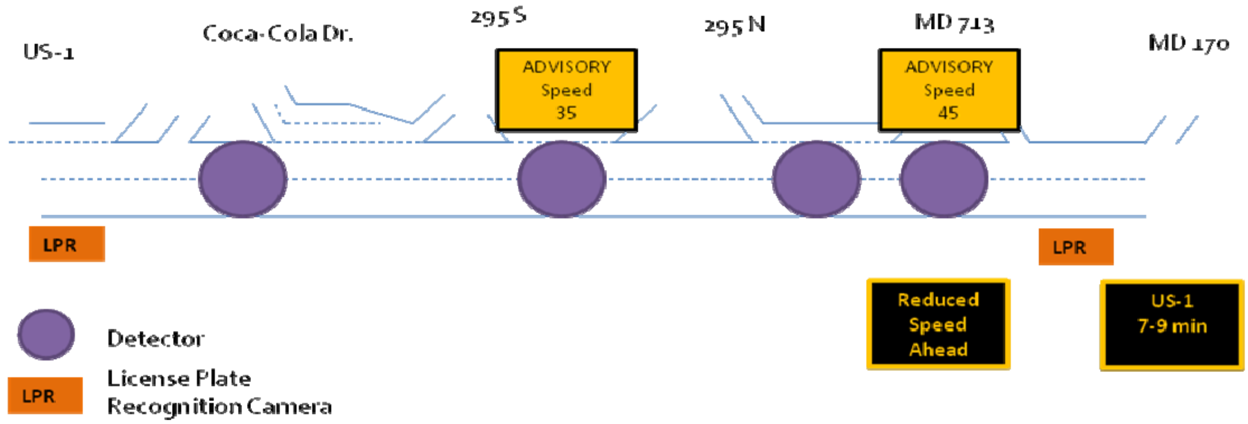


Figure 4-6: System layout for the VSL control and estimated travel time display

CHAPTER 5 ANALYSIS OF EXPERIMENTAL RESULTS

5.1 Procedures for Performance Comparison

This chapter presents the experimental results of the three control strategies presented in previous chapters and compares their performance with respect to the selected measures of effectiveness (MOEs). In view of the potential day-to-day traffic fluctuation during the eight-week experimental period, this study adopted the following analysis procedure to ensure the reliability of the concluding findings:

Step 1: Evaluating the stability of traffic conditions before and during the field experimental periods, including the speed and volume of traffic entering the target roadway segment experiencing recurrent congestion by time of day.

Step 2: Identifying the spatial and temporal impacts of different control strategies on the average travel time and speed on the target congested segment by time of day.

Step 3: Comparing the average MOEs for different control strategies on the target roadway segment over their respective deployment periods, including the average throughput and travel time over different control periods and on different days.

Based on the results of this analysis, the last section of this chapter summarizes some definitive findings and critical issues associated with a full-scale deployment of VSL/LPR to contend with nonrecurrent congestion.

5.2 Stability Evaluation

The primary purpose of the stability analysis is to test if the traffic patterns, including volume and speed entering the target control roadway segment, are statistically stable from day to day. This will ensure that one can attribute any significant changes in traffic conditions during the experimental period to the implemented control strategy, rather than to natural day-to-day variations. Figure 5-1 illustrates the spatial distribution of sensor locations and the average traffic speed over the target roadway segment. Since this study placed sensor 4 at the entry point of the entire segment, one can use the speeds and volumes detected there prior to the control deployment for stability analysis.

Figure 5-2 shows the time-varying traffic volume collected at five-minute intervals from sensor 4 over the four days prior to system deployment. Figure 5-3 displays the speed evolution over time from sensor 1 (the end point of the target roadway segment) during the same four days. Since MD 100 is a primary commuting corridor, the traffic patterns exhibited in both figures are quite stable from day to day. The statistical tests with either parametric or nonparametric methods also confirm the stability of both speed and volume patterns over those four days.

Figure 5-4 presents the comparison of traffic volumes per 5-minute interval over time during the eight-week experimental period. The overall traffic pattern exhibited the same level of stability regardless of the implemented control strategy. Figure 5-5 displays the speed evolution patterns under the three different control strategies, confirming that the overall traffic demand and traffic conditions were quite stable before and during the experimental period. Thus, one can perform a detailed performance analysis and attribute any MOE variations to the deployed control measures.

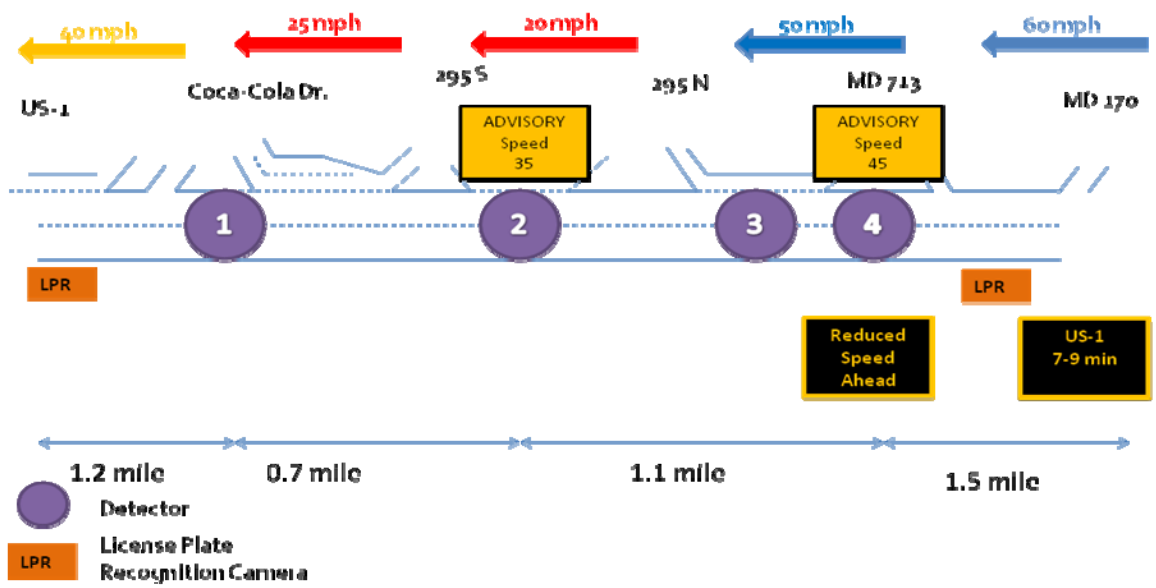


Figure 5-1: Spatial distribution of traffic sensors and traffic flow speeds (peak hours)

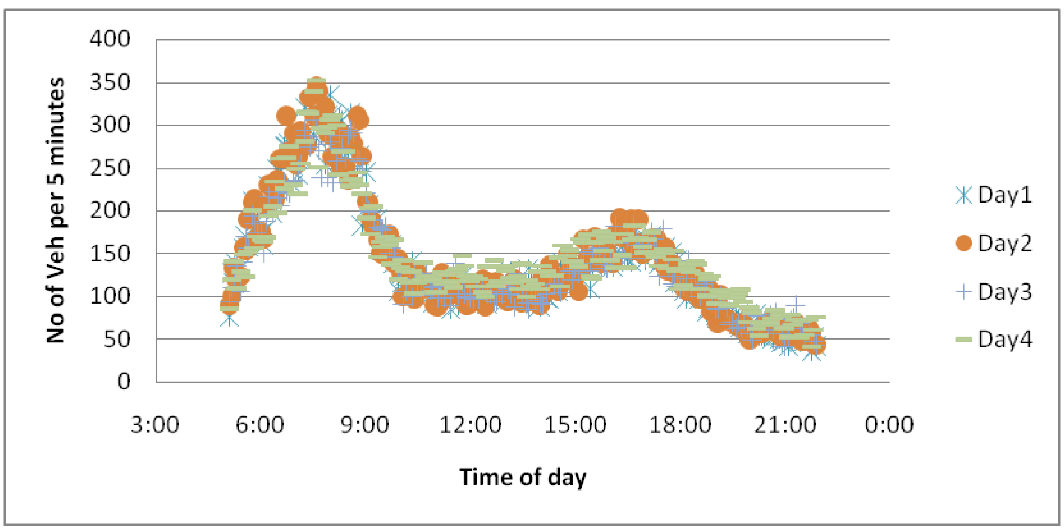


Figure 5-2: Distribution of average traffic volumes over time before the experimental period — from sensor 4, the entry point of the target roadway segment

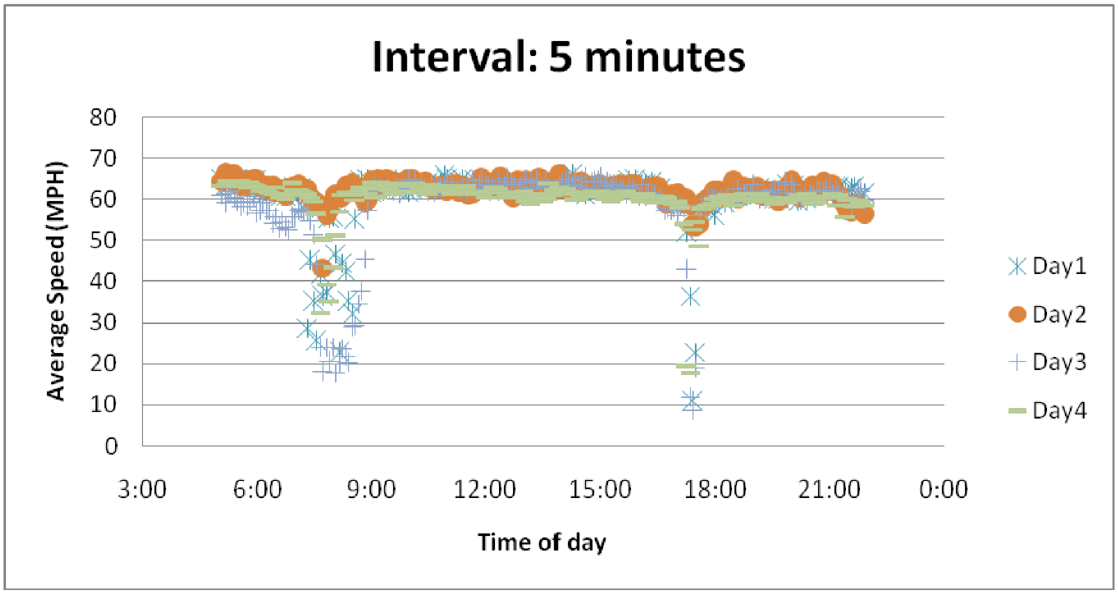


Figure 5-3: Distribution of average traffic speeds over time before the experimental period — from sensor 1, the end point of the target roadway segment

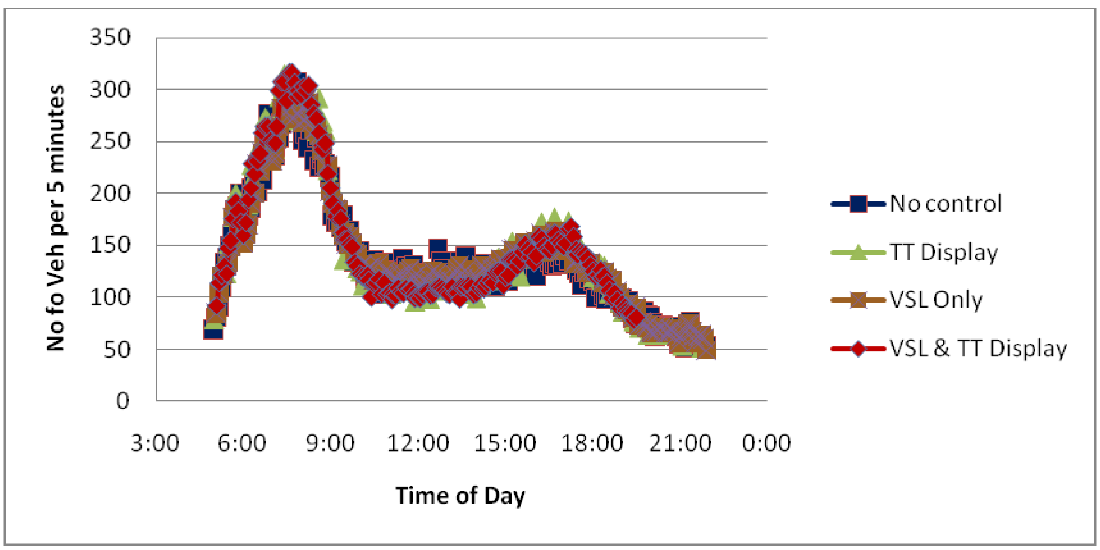


Figure 5-4: Distribution of average traffic volumes during different experimental periods — from sensor 4, the entry point of the target roadway segment

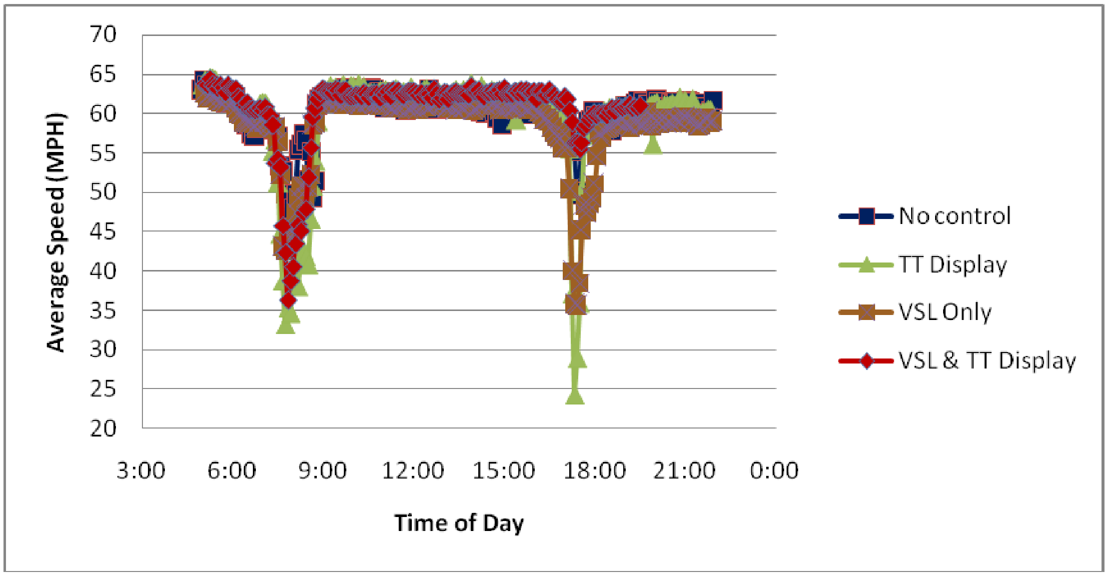


Figure 5-5: Distribution of average traffic speeds over time during the experimental period — from sensor 1, the end point of the target roadway segment

5.3 Spatial and Temporal Impacts

As stated in previous chapters, the main purpose of implementing VSL is to smooth the traffic from its free-flow condition to a much lower speed state that truly reflects the actual capacity of the congested location so as to avoid a drastic speed drop and the subsequent forming of a stop-and-go bottleneck. This study employed additional VMS to display the estimated travel time to encourage drivers' compliance with the suggested speed change, intending to convince them that their cooperation would improve the overall traffic conditions on the congested segment without incurring excessive delay. Hence, prior to the performance analysis, one needs to first evaluate the impacts of each deployed control on the spatial evolution of traffic patterns along the entire target roadway segment.

Figure 5-6 displays the traffic flow speed along MD 100, starting from its interchange with MD 170 and ending at its interchange with Coca Cola Drive. As evidenced by the graphical shape, drivers under the no-control or travel time display scenarios experienced a speed drop from 60 mph to around 20 mph when moving up to the location receiving the MD 295 traffic flow. Such a sharp speed reduction over the short distance of less than two miles inevitably forms a stop-and-go bottleneck and often causes some crashes. In contrast, under the control strategies of VSL and VSL combined with travel time displays, traffic flow maintained an average speed of between 35 and 40 mph over the most congested segment. Although all three implemented control strategies were advisory rather than mandatory in nature, they were impressively effective at reducing speed variance. A further investigation of the time-varying travel time over the entire segment during the evening peak-period also confirmed the effectiveness of the experimental control strategies.

For instance, the average travel time under the control of VSL combined with travel time display, as shown in Figure 5-7, was significantly shorter than under the no-control condition during the most congested interval from 5 to 5: 30 p.m. The travel time differences between no-control and the three control scenarios, as expected, diminished when the traffic conditions on the target roadway were less congested, such as between 6 and 6:30 p.m. Overall, the general trend from the graphic patterns in Figure 5-7 also supports the hypothesis that smoothly reducing the speed to a proper level over a highway segment experiencing recurrent congestion will not cause drivers to experience longer travel times. In fact, due to the smooth speed transition under proper control, drivers need not suffer stop-and-go traffic conditions and are likely to have shorter travel times.

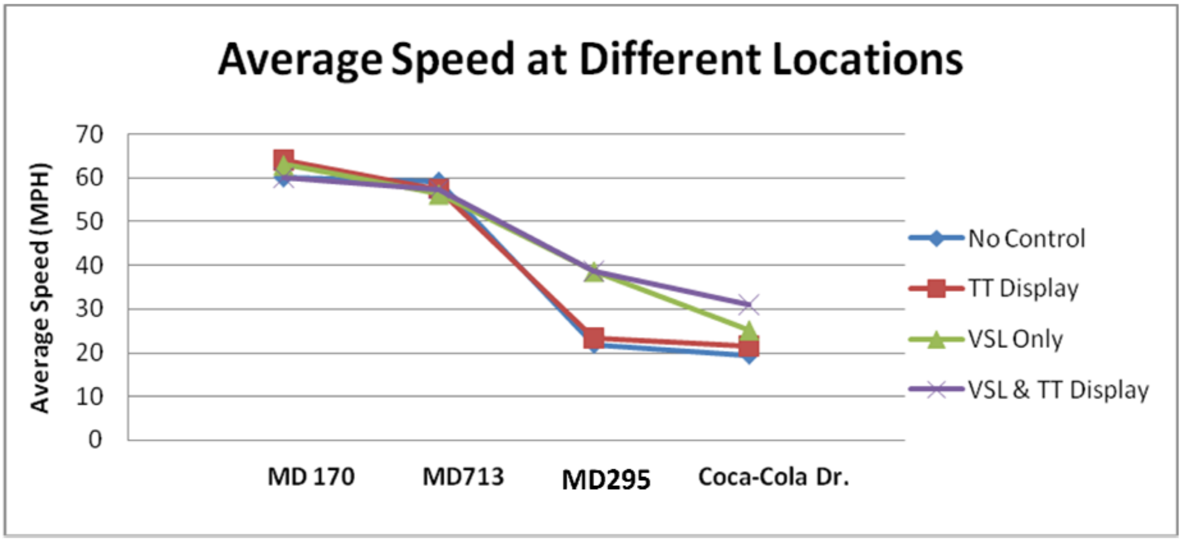


Figure 5-6: Spatial distribution of average traffic flow speed under different controls

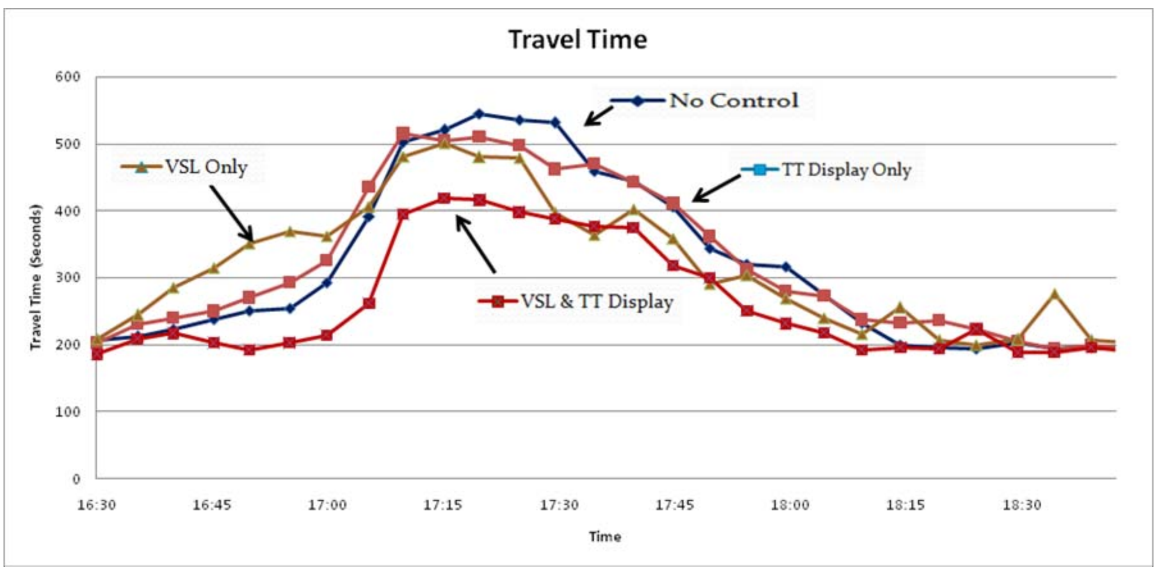
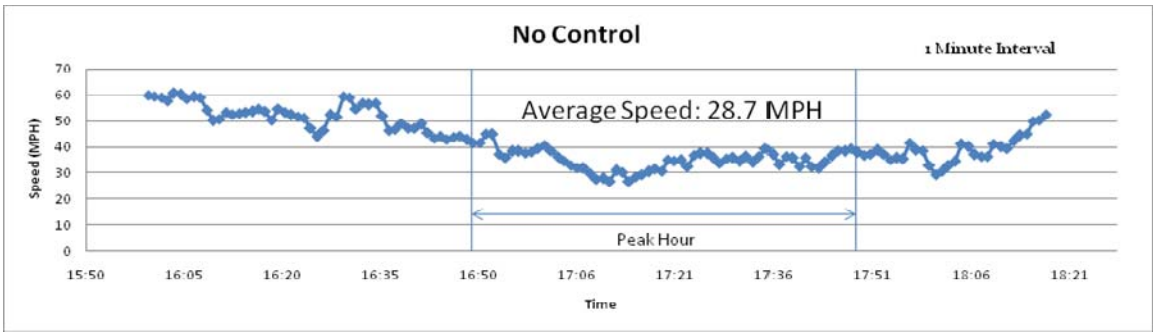
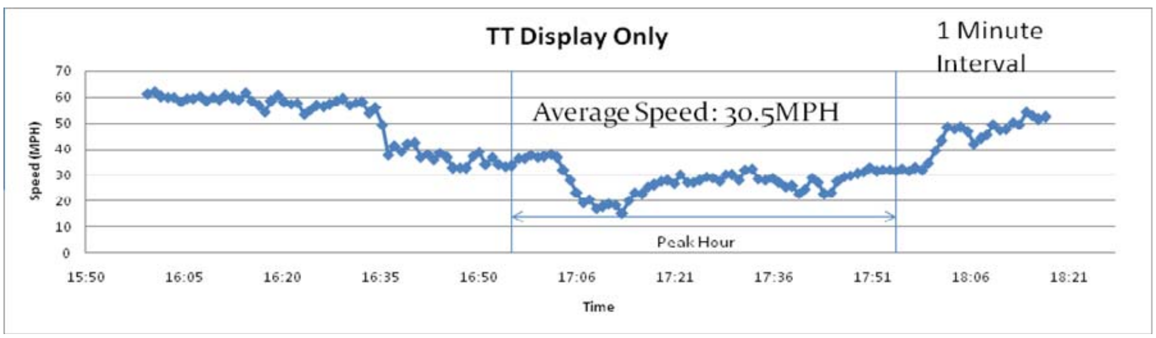


Figure 5-7: Distribution of average travel times (measured by the LPR system) under different control strategies

Figure 5-8 presents the average speed collected by sensor 4 over the most congested location from 4 to 6 p.m. under different control strategies. As shown in the evolution patterns, the most congested interval varied among the four experimental scenarios: the lowest average speed experienced by drivers was 28.7 mph under the no-control scenario, but increased to 33.1 mph under the control of VSL with travel time display. The lowest average speed was around 30 mph when VSL or travel time display was implemented independently. These empirical results seem to further support the hypothesis that using VSL control can indeed prevent sudden speed drops at a recurrent congestion location, thereby reducing stop-and-go delays. The smooth transition between free-flow and congested traffic conditions can also minimize potential rear-end collisions caused by a large speed variance between vehicles.





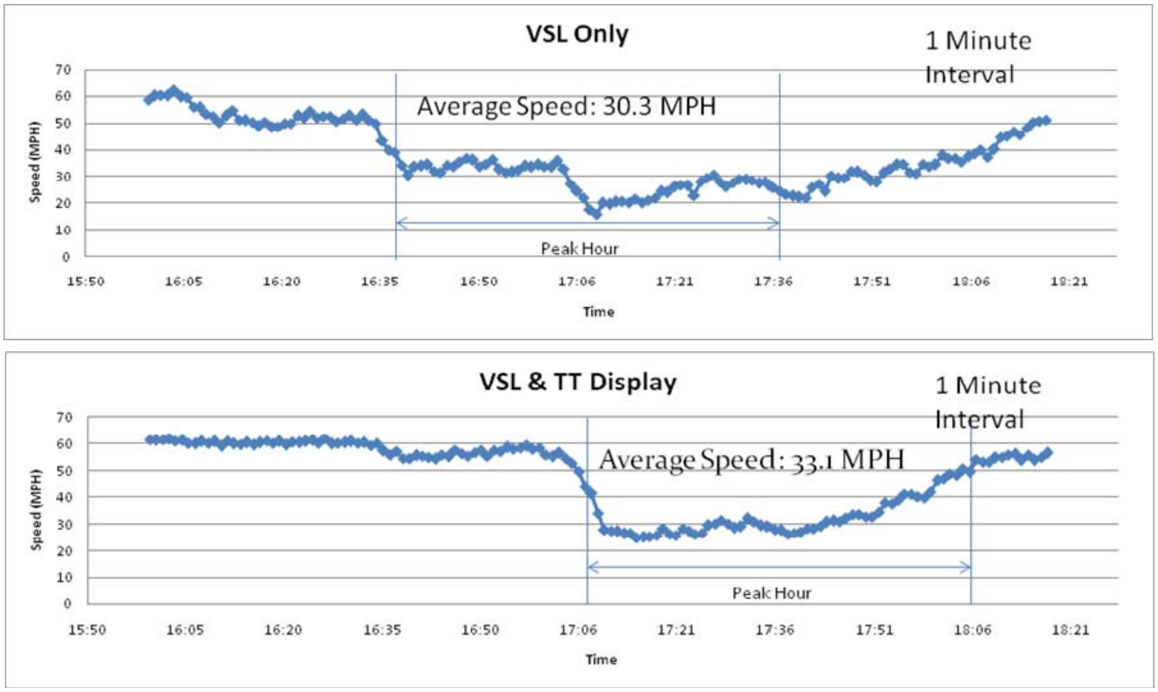


Figure 5-8: Identification of the most congested hour under different control strategies

5.4 Comparison of MOEs

In addition to the average speed measured with radar detectors, this study also selected the total throughput and average travel time over a target interval as MOEs. In theory, a mandatory VSL and travel time display control, if properly implemented, should increase the average flow speed and throughput over the target roadway segment. Since all control strategies deployed on the demonstration site were advisory only, it is critical to carefully analyze their impacts on the traffic conditions.

Figure 5-9 compares average travel times under different control scenarios over selected peak-hour intervals. Note that the travel times were measured directly with the deployed LPR system rather than estimated from detector data. As the comparison charts show, the average travel time during the most congested half hour under the no-control scenario was about 539 seconds — significantly longer than the average of 400 seconds under the VSL and travel time display environment. The average travel times over the same period, using either travel time display or VSL control alone, were 503 seconds and 484 seconds, respectively. A similar trend also exists in the average travel time comparison over the most congested hour and 1.5 hours. For example, drivers under the no-control scenario experienced average travel times of 469 seconds during the peak one-hour period, but only took 345 seconds during the same period if VSL and travel time display control. Considering that the two-mile distance of the target roadway segment typically took commuters less than 180 seconds during off-peak periods, reducing travel time by about 25 percent during the peak hour was quite impressive.

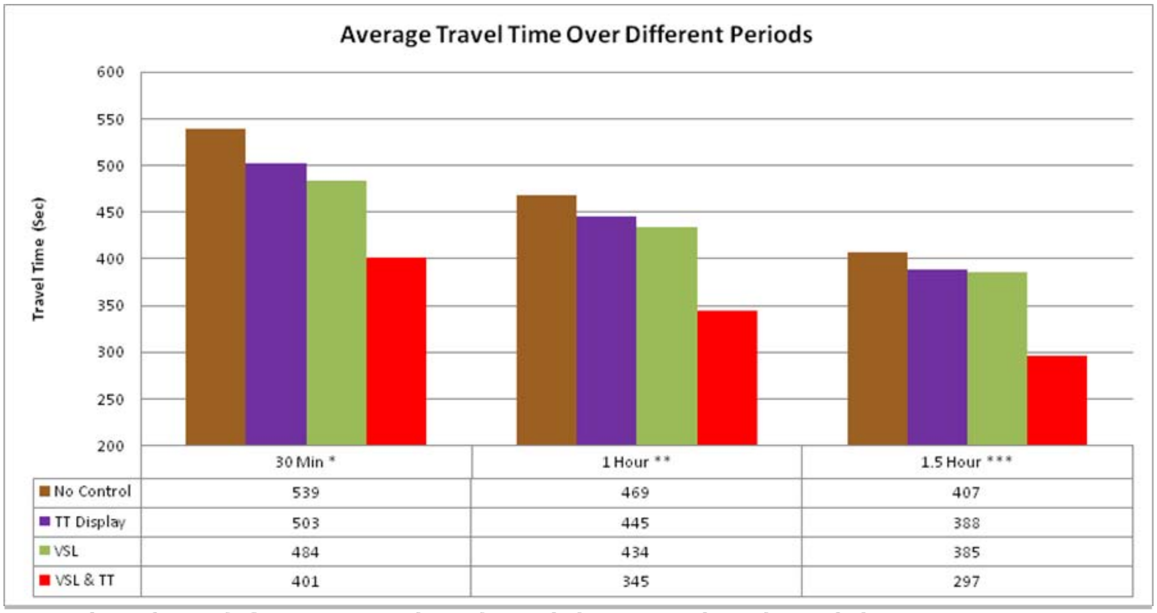
Figure 5-10 illustrates the total throughput under different control scenarios over the peak 30-minute and one-hour periods. The comparison results clearly indicate that all three control strategies, if properly implemented, can significantly increase the total throughput over the recurrently congested target segment. For instance, the total throughput during the most congested half hour increased from 1,883 vehicles to 1,974 vehicles under the travel time display scenario, and to around 2,040 vehicles in a VSL or combined VSL and travel time display control environment. A further comparison of the total throughput over the peak one-hour period reveals that a target roadway segment that suffers recurrent congestion can accommodate 230 (3,713 vs. 3,980 or 3,841) more vehicles under either the VSL or the VSL and travel time display environment, indicating the unquestionable effectiveness of those control strategies.

Note that Figure 5-10 shows that the combined use of VSL and travel time display yielded a slightly lower total throughput than using the VSL alone; this occurred because the travel time display over the target segment further smoothed the traffic during the peak period, reducing the congestion level. Hence, during the most congested period, vehicles could travel at slightly higher speed and in less condensed platoon conditions. This is evidenced in the pattern shown in Figure 5-6 and in the speed evolution data in Table 5-1.

Figure 5-11 compares the total throughput on different weekdays. As evidenced in the revealed patterns, VSL alone and VSL combined with travel time display have a quite consistent effectiveness on the total throughput among different days of a week.

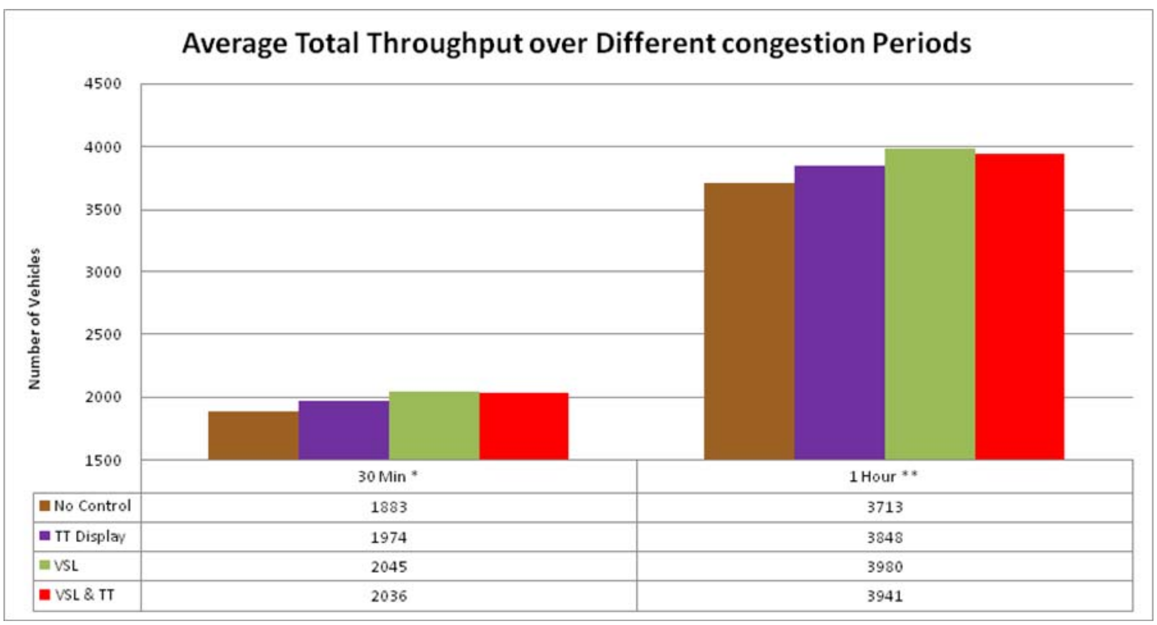
The third MOE selected for performance evaluation is the average speed evolution during the peak hour under the four different traffic control environments. As shown in Table 5-1, the average speed during the first 15 minutes of the most congested hour does not seem to benefit from the implemented control strategies. However, drivers appeared to be able to progressively respond to the control strategies and significantly improve their travel speeds after about 30 minutes. For example, the average speed during the peak hour increased from the no-control scenario of 22.4 mph to 37.4 mph when VSL was combined with travel time display control — a better than 50 percent increase in traffic flow speed. However, interestingly, implementing VSL or travel time display alone did not seem to significantly affect the average traffic flow speed. A plausible explanation for this fact is that drivers will more willingly comply with the advisory speed produced by the VSL system if they are informed of the resulting travel time over the downstream roadway segment. The higher the compliance rate is, the more effective the VSL control would be.

In brief, the experimental results clearly indicate that implementing VSL combined with travel time display control can indeed offer highway segments experiencing recurrent congestion with significant benefits, including travel time reduction and an increase in travel speed, as well as greater overall throughput during peak periods.



* The Peak-Period of 30 Minutes ** The Peak-Period of 1 Hour *** The Peak-Period of 1.5 Hour

Figure 5-9: Comparison of average travel times over selected peak periods under different control strategies



* The Peak-Period of 30 Minutes ** The Peak-Period of 1 Hour

Figure 5-10: Comparison of total throughput over selected peak periods under different control strategies

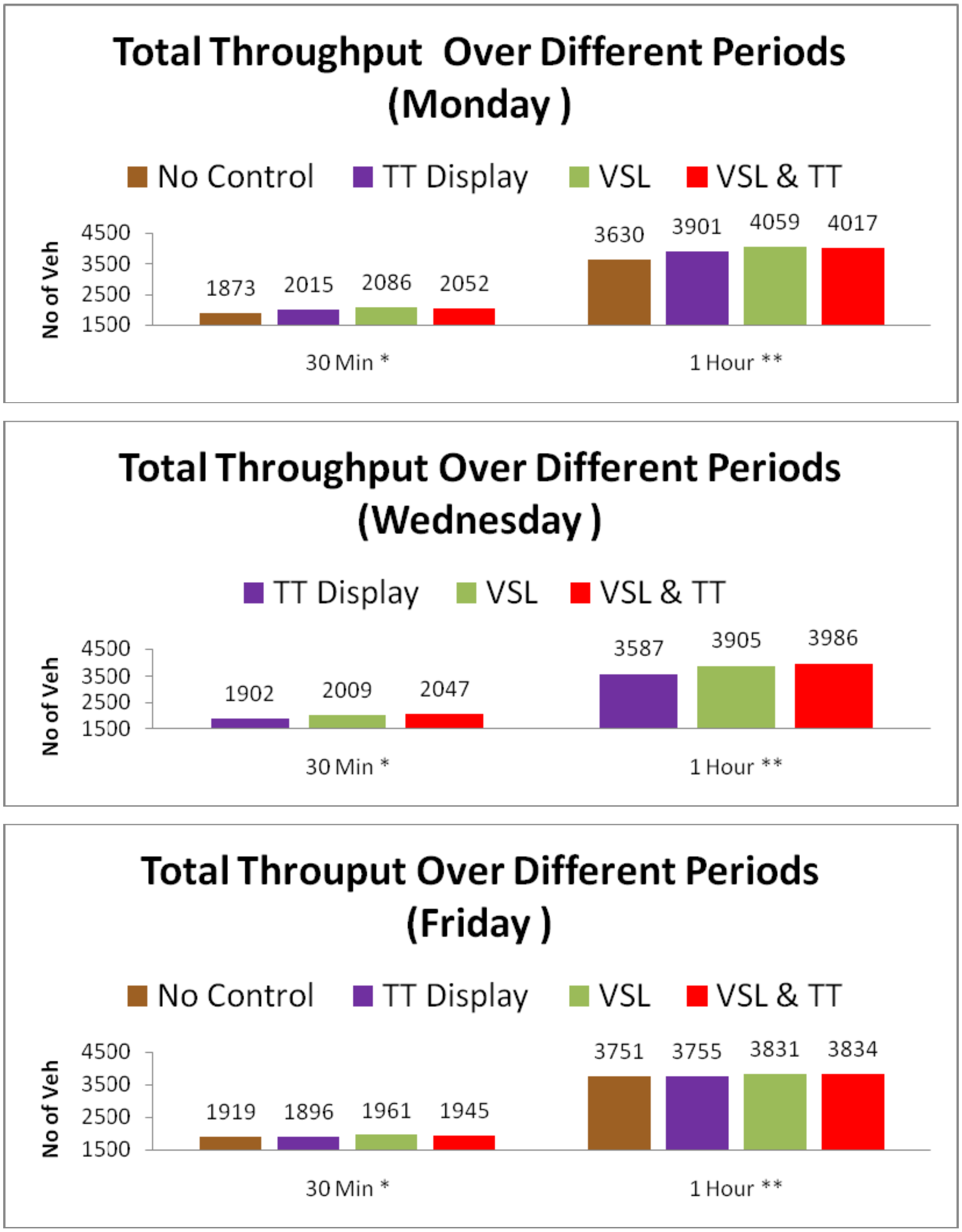


Figure 5-11: Comparison of total throughput over selected weekdays under different control strategies

Table 5-1: Evolution of the average speed during the peak hour under different controls

Control / Selected interval	No control (MPH)	TT Display (MPH)	VSL (MPH)	VSL & TT (MPH)
First 5 Min	27.8	25.2	24.2	26.6
15 Min	19.7	19.6	22.2	20.0
30 Min	18.1	19.3	20.8	24.8
1 Hour	22.4	22.3	23.6	37.4

CHAPTER 6: CONCLUSION

6.1 Summary of Research Findings

This study conducted an extensive evaluation of the VSL effectiveness on improving the operational efficiency of recurrently congested highway segments. Over an experimental period of more than nine weeks, the research team installed traffic sensors, VMSs, and LPR systems along the target segment of MD 100 between MD 170 and Coca Cola Drive to observe the temporal and spatial evolution of traffic flow characteristics under four operational environments: no-control, travel time display only, VSL control only, and implementing both VSL and travel time display.

Among these four experimental scenarios, the second control strategy that provides only the estimated travel time over the target segment allowed us to investigate the collective response of drivers to traffic conditions when they were informed of the approaching downstream congestion. In contrast, the implementation of VSL control focused on the compliance of drivers to the posted advisory speed limits and their resulting impact of mitigating traffic congestion. Since the effectiveness of the VSL control is likely to depend on driver compliance, this study further assessed an integrated control environment where drivers were aware of the approaching traffic conditions via the displayed travel time and the suggested travel speeds that could prevent them from encountering a sudden speed drop downstream. This experimental scenario tested the hypothesis that drivers are more likely to follow suggested speed limits when fully informed of the resulting travel times.

Based on the MOEs of travel time, average speed, and total volume throughput during the peak hours, the research team analyzed the extensive field data, yielding the following insights for VSL applications:

- Providing travel time information alone over a recurrently congested roadway segment is unlikely to improve traffic efficiency but may ease the stress of drivers when they encounter a substantial speed reduction.
- VSL can be an effective control strategy if the spatial distribution of the traffic speed on the highway segment exhibits a dramatic reduction from free-flow speed to a congested or stop-and-go condition due to a surge in traffic volume over a short distance.
- Implementation of VSL controls at proper locations over a recurrently congested segment, even if only advisory in nature, can effectively smooth the transition between free-flow and stop-and-go congested conditions.
- Although a VSL control seeks to advise the entire traffic flow to gradually reduce speed in response to approaching downstream congestion, it can actually result in a higher average speed at the downstream bottleneck and over the entire roadway segment by reducing the shockwave impact.
- The effectiveness of VSL on improving the average traffic flow speed increases with the speed difference between the upstream free-flow and downstream forced-flow traffic conditions.
- Implementing VSL with even a simple algorithm can reduce the overall travel time on a segment of recurrently congested roadway that is experiencing a drastic spatial change in traffic flow speed due to a surge in volume at its downstream end.

- By properly reducing the approaching speed from its upstream traffic flows, VSL can effectively increase the average speed at the congested downstream segment and yield a higher volume throughput than if staying at the stop-and-go state.
- Integrating travel time information with the VSL control can increase the system effectiveness, as measured by total travel time, average flow speed, and volume throughput during congested periods.
- Displaying a warning message about VSL control and estimated travel time can minimize drivers' concerns about the approaching traffic condition, increase their compliance with the displayed advisory speeds, and reduce the potential impact of rubbernecking on traffic flow.
- Properly integrating travel time displays with the VSL control can increase the traffic flow speed during the peak hours for a recurrently congested roadway segment.
- The effectiveness of the VSL control might be more pronounced if its primary contributing factor for a substantial speed reduction along the target roadway segment is due to a surge in volume over a short distance.
- VSL controls should be active only when the spatial distribution of traffic flows begins to cause spillback and a shock wave from the downstream traffic volume surge affects upstream traffic speeds; however, the display of estimated travel times can remain active throughout the day.

Note that the above findings are based on the empirical data collected over a period of eight weeks on one sample roadway segment. Although the overall findings — that VSL can be effective in increasing traffic speed and throughput over a highway segment plagued by recurrent congestion — are quite convincing, how to maximize the effectiveness of VSL under various traffic congestion patterns and resource constraints remains a challenging issue. More experimental studies to improve our understanding of the interrelations between driver responses and VSL control strategies are essential for the development of reliable implementation guidelines.

6.2 Recommendations for Future Research and Experimental Work

As one of the pioneering studies for exploring the VSL control for recurrent highway congestion, the research results have revealed some imperative issues that need to be addressed prior to the development of an operational manual for VSL applications and the comprehensive deployment of such a control strategy. Each of those issues is briefly presented below:

- What criteria and/or guidelines should be used to select target roadway segments suited to the deployment of VSL controls to mitigate their recurrent congestion? Such guidelines should discuss highway geometric features, the spatial and temporal distribution of traffic flow speeds, time-varying volume patterns between upstream and downstream segments during the peak hours, the length of the bottleneck segment versus the entire target segment for speed transition, the transition distance between free-flow and congested flow speeds, and the theoretically available capacity at the most congested location.
- How many speed advisory points should be selected for speed transition between free-flow and congested speeds? The guidelines for this issue should consider all associated factors, such as the actual speed at the bottleneck location and the theoretical speed based on its volume and capacity ratio, the speed of the

upstream traffic approaching the target segment, the appropriate speed reduction rate for optimal safety, and the duration of the peak period.

- What are the optimal locations for sensor deployment and display of VSL information? Ideally, sensors should be deployed at all locations where traffic flow speeds or volumes exhibit significant changes. However, budget constraints may limit the number of sensors available for field operations. Hence, how to determine the minimal number of detectors and their optimal distribution along the target roadway segment becomes another essential issue.
- How should one develop an effective VSL control algorithm that uses a minimal set of parameters and thus requires minimal field calibration? Such algorithms should account for several critical factors, including drivers' responses to advisory speeds, available sensor data, the required update frequency, the speed variance among drivers and among all subsegments within the control area, the number of VMSs for message display, and the allowable difference between two successively displayed advisory speeds.
- When should the VSL control be activated and deactivated for a target roadway segment plagued by recurrent congestion? These guidelines should consider both the operational costs and the potential resulting benefits, such as increased traffic flow speed and throughput, travel time reduction, and less speed variance among vehicles and over the entire roadway segment.
- How should the various VMS messages be coordinated within the VMS control boundaries so that they can complement each other, providing the best advisory picture to the target drivers rather than confusing them? Examples of such

messages include the upstream message warning drivers that they are approaching the control area, the display of estimated travel time for a selected origin-destination pair, the sequence of advisory speeds, and some static traffic regulatory signs.

In addition to the above vital issues, highway agencies intending to deploy VSL controls should also carefully conduct surveys to understand local drivers' preferences and responses to various messages displayed via VMS to increase the likelihood that the design will be well received by drivers, which will increase their compliance with advisory actions.

PART II

Part-II: Lane-based Signal Merge Control for Highway Work Zones

CHAPTER 7: INTRODUCTION

7.1 Research Background

Performing work zone activities in freeway segments is one of the principal contributors to nonrecurrent congestion, and it may have a significant impact on traffic mobility as well as safety since the capacity reduction due to lane closures often causes drivers to perform mandatory lane-changing and merging maneuvers. To best manage the traffic approaching and traveling through the work zone, transportation professionals have proposed a variety of merge control strategies over the past 2 decades including conventional merge (CM), early merge (EM), and late merge (LM). However, how to maximize the operational efficiency and safety of a work zone under high traffic volume remains a challenging issue.

7.2 Related Merging Control Studies

The CM specified in the Manual of Uniform Traffic Control Devices (MUTCD) (FHWA 2003) is the most commonly used strategy for work zone operations. The EM (McCoy et al. 1999; Tarko and Venugopal 2001) seeks to reduce the frequency of forced merge so as to produce smoother traffic flows, while the LM (McCoy et al. 1999; Pesti et al. 1999; Walters and Cooner 2001; Beacher et al. 2004; Kang and Chang 2006) is designed to provide a larger queue storage area and to reduce the frustration level of drivers. Both EM and LM can be operated in either a static or dynamic form, where the former is to provide advanced notice at a fixed distance ahead of the lane closure, and the latter is to display the message at a location varying with traffic conditions at the work zone (McCoy and Pesti 2001).

The benefits and limitations of the CM, EM, and LM have been extensively discussed in the literature. In general, the EM seems to perform well in terms of enhancing traffic safety under light and moderate traffic conditions, while the LM can improve the operational efficiency mainly under congested traffic conditions (McCoy and Pesti 2001; Beacher et al. 2004; Kang et al. 2006).However, neither EM nor LM can yield the expected effectiveness with respect to traffic safety and mobility under the heavy congestion level. This is due to the fact that the inevitable traffic conflicts resulting from complex merging and lane-changing maneuvers could increase the potential of traffic accidents and induce stop-and-go movements to degrade the operational efficiency (Kang et al. 2006). Moreover, the difficulty for drivers to recognize who has the right-of-way at the merge point may aggravate those traffic conflicts under the heavily congested conditions. Although the advanced speed control such as the variable speed limit (Lin et al. 2004) can mitigate those impacts by regulating their average speeds dynamically, it cannot directly control the lane-by-lane merging and lane-changing maneuvers.

This part of the report explores a new merge control strategy that employs the signal at the proper merging point to assign the right-of-way for traffic in each lane. The problem nature and requirements for applying the proposed lane-based signal merge control strategy (LBSM) are presented in Chapter 8, followed by a brief description of the proposed system configuration and core control concept. Simulation experiments for evaluating the effectiveness of the proposed system along with some tentative research findings are summarized in Chapter 9. Conclusions and Future Studies are reported in Chapter 10.

CHAPTER 8: LANE-BASED SIGNAL MERGE CONTROL SYSTEM

8.1 Introduction

Right-of-way confusion at the merging point near the work zone taper is widely recognized as one of the main causes to traffic queues and accidents, especially during congested conditions. The message signs “MERGE HERE” and “TAKE YOUR TURN” are not sufficient for drivers to ensure their right-of-way during the merging processes, especially at the presence of some aggressive drivers. Hence, the merging behavior guided by the variable message signs (VMSs) or portable changeable message signs (PCMSs) may turn out to be an unsafe and inefficient process, which may in turn result in a substantial capacity reduction. To prevent such undesirable and unsafe merging maneuvers, this study proposed a new concept of the LBSM control system for work zone operations.

8.2 Concept of LBSM Control System

The basic concept of the LBSM is to use lane-based signals or variable signs to give drivers in different lanes the right of way to proceed through the open lane(s) in a work zone area. As illustrated in Figure 8-1, the LBSM that employs either a pretimed or actuated signal system is to function like an intersection signal control. The proposed LBSM is expected to achieve the following operational benefits: (1) increase traffic mobility by fully utilizing the open lane capacity; and (2) improve traffic safety by using traffic signal to prevent traffic conflicts often incurred to vehicles between the open and closed lanes.

It should be noted that the proposed LBSM system should only be considered in the presence of congestion on the freeway where traffic demand has exceeded the work zone capacity and queues have already formed. Otherwise, the traffic interruptions induced by activating mainline signals on low density-high speed freeways may raise the risk of rear-end collisions and other safety concerns. In addition, additional stops and delays caused by red signals are the price to pay during uncongested traffic conditions.

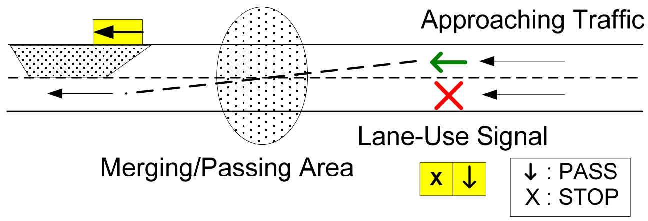


Figure 8-1: Concept of the LBSM at Freeway Work Zones

8.3 System Configuration

To produce the aforementioned benefits, the proposed LBSM system should be consistent with the guidelines described in MUTCD. The upstream VMS or PCMS should not be conflicted with the existing static signs, which may otherwise confuse drivers. This study investigated only the pretimed LBSM control system for 2-to-1 highway work zone operations. The configuration and experimental results will serve as the basis for extending its operations to multiple-lane work zones.

System Components

Figure 8-2 illustrates the principal components of the LBSM control system that includes:

1. A base controller to integrate all system signs/signals and sensors and execute the control commands;
2. A set of sensors (SEN-1) for detecting volumes and speeds in each lane, and to activate/deactivate the LBSM system, based on the measured traffic conditions;
3. Dynamic message signs (DMS-1and 2) for alerting the approaching drivers (e.g., DMS-1) and directing them to follow the instruction of the lane-use signal;
4. A set of portable changeable message signs (PCMS-1, 2, and 3) to inform the approaching vehicles of the upcoming merging type and the lane-use instructions;

5. Overhead lane-use signals (SIGNAL) to assign the right-of-way to the open and closed lanes alternatively;
6. Red-light camera to increase the driver compliance rate;
7. Double solid white lines to prohibit lane-changing maneuvers between the open and closed lanes within the specified distance (e.g., standby zone);
8. Transition zone (TZ) for vehicles on the open and closed lanes to pass and/or merge to the work zone area; and
9. Stand-by zone (SZ) for vehicles on the open and closed lanes to wait for their right of ways without changing the lane.

Among the above elements, the lane-use signal, transition, and standby zones are the most critical components and the subsequent sections will provide the description of their key features.

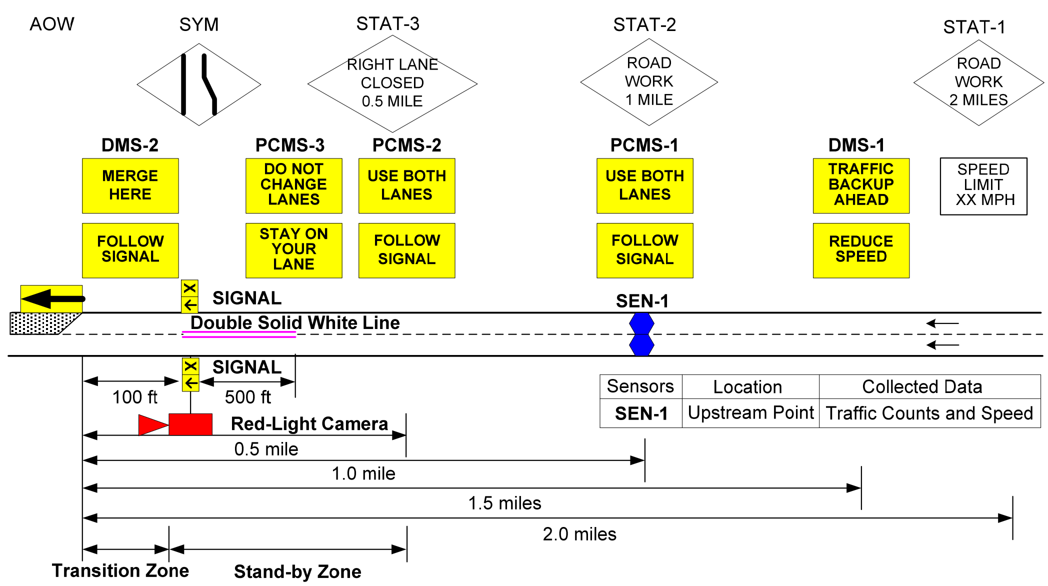


Figure 8-2: System Configuration of the LBSM Control System

Lane-Use Signal

Based on the instruction of the lane-use signals, the approaching vehicles shall either proceed through the open lane or stop at the waiting area. To operate such a system effectively, it is essential to inform the upstream traffic flows of the upcoming control type at the work zone. For example, the system should not display any messages of lane closure, but inform drivers of the signal merge control ahead (such as “FOLLOW THE LANE USE SIGNAL AHEAD,” “PREPARE TO STOP BEFORE SIGNALS AHEAD,” and “STAY ON YOUR LANE”/“DO NOT CHANGE LANES”).

For 2-to-1 work zones, a three-phase display (green, amber, and red) is sufficient to guide the merging priority of drivers (Figure 8-2). However, for multiple-lane work zones, it may be necessary to design better devices and pavement markings so that drivers on different lanes can clearly know who have the right-of-way and along what path to safely proceed through the merging/passing area.

Transition and Stand-By Zones

The transition zone is the distance between the first merge taper and the lane-use signals. Its main purpose is to provide enough space for vehicles merging from the closed lanes to the open lanes (Figure 8-3). Note that an excessively long TZ may incur the second lane-changing and merging maneuvers. The TZ length can be determined from the average speed of approaching vehicles and the work zone geographical characteristics. It was set as 100 ft in the experimental study.

The standby zone is the no-lane-changing area specified with the white lines (Figure 8-4). Note that a SZ of insufficient length may cause multiple merge points and thus diminish the benefits of the LBSM. On the contrary, if the SZ length is excessively long, it may prevent vehicles from balancing the queue lengths between lanes. The most effective distance for a SZ can be determined from the maximum queue length analysis. In this study, the research team set 500 ft as the baseline.

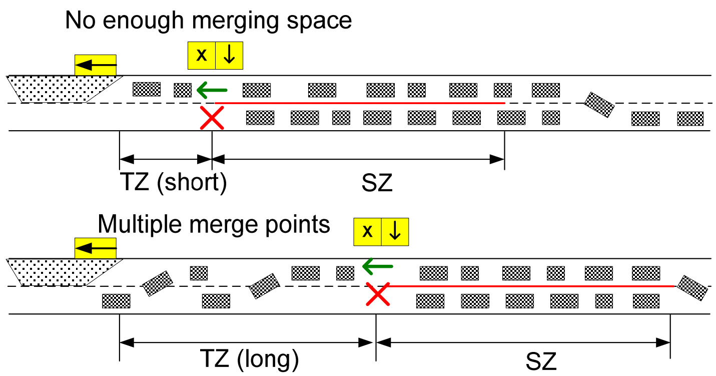


Figure 8-3: Transition Zone (TZ) between the Merge Taper and the Lane Use Signal

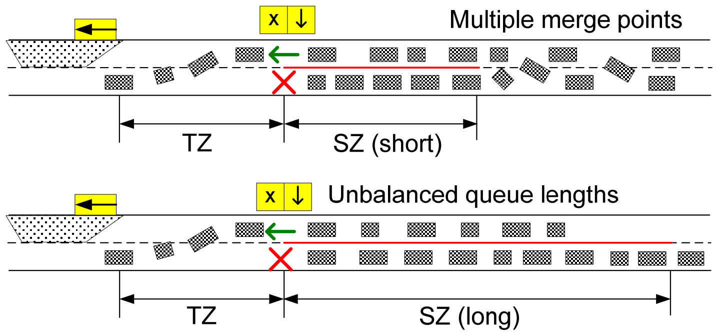


Figure 8-4: Stand-by Zone (SZ) in the Upstream Segment of the Work Zone

CHAPTER 9: PERFORMANCE EVALUATION BASED ON SIMULATION

9.1 Simulation Base

To ensure that the proposed LBSM can function effectively, this study also developed a simulation system based on the field data collected from an actual work zone by the research team in a previous related study (Kang et al. 2006). The well-calibrated simulation system serves as the test bed for this study to investigate the sensitivity of the LBSM's performance with respect to associated critical factors. VISSIM 3.7, one of the most sophisticated microscopic simulation software developed by Planung Transport Verkehr (PTV), was used as a tool to model the work zone control system.

9.2 Description of Test Network

The simulation experiment was conducted based on a freeway segment in Maryland on I-83 Southbound with a right-lane closure work zone near the overpass bridge of Cold Bottom Road. It was modeled with VISSIM as a unidirectional two-lane freeway segment consisting of three links, representing the upstream, work zone, and downstream links. The number of lanes in the work zone link is dropped to one for replicating the one-lane closure area. The model calibration with respect to the upstream volumes, truck percentage, work zone throughput, and average speed at merge point was based on the data collected in 2003 by the research team.

9.3 Experimental Design

To evaluate the potential benefits of LBSM and to investigate its best-applicable traffic conditions, this simulation-based experiment focused on comparing the performances of CM, static EM, static LM and LBSM in the volume range from 500 vehicles per hour per lane (vphpl) to 1500 vphpl, at an increment of 50 vphpl. In all these tested scenarios, the percentage of heavy vehicles was set as 10%, and the LBSM signals were set to operate with a cycle length of 60 seconds (sec) including an all-red phase of 1 second, an amber phase of 2 seconds and a green phase of 27 seconds for each lane. The traffic control plans of the CM, EM and LM are based on those studies identified in the literature reviews (FHWA, 2003; McCoy et al., 1999; Pesti et al., 1999).

This study also included sensitivity analyses to test the impacts of the cycle length and the percentage of heavy vehicles on the effectiveness of the LBSM system. Based on the traffic inflow of 1000 vphpl and the heavy vehicle percentage of 10%, the tested cycle length was set to range from 60 sec to 240 sec at an increment of 30 sec. The study then proceeded to check if the results may change with the heavy vehicle percentages (e.g. 5%, 10%, 15% and 20%). Table 9-1 lists the combination of factors that were examined in the experiments.

The performance evaluation for all the scenarios was based on the following four measures of effectiveness (MOEs): (1) the hourly work zone throughput; (2) the average delay time per vehicle (sec/veh); (3) the average stop delay per vehicle (sec/veh); and (4) the average number of stops per vehicle (#/veh).

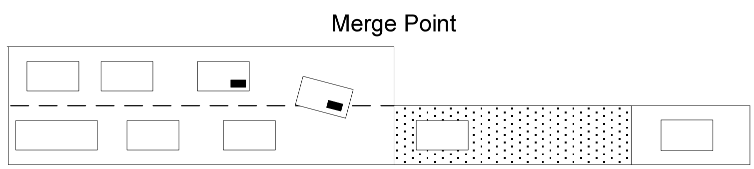
Each scenario was simulated for 4800 sec, including an initialization period of 1200 sec. Each MOE is the average of results from 10 independent simulation replications with different random number seeds for reducing the statistical variance existing in any stochastic simulation program such as VISSIM.

Table 9-1: Variables Tested in the Simulation Experiment

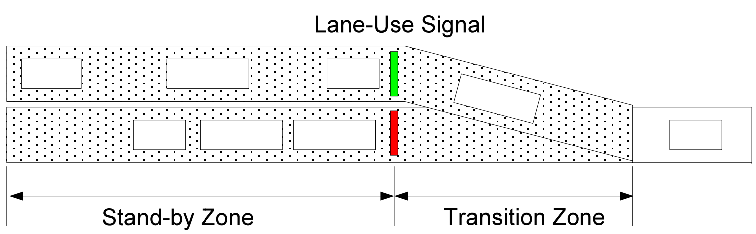
Test Factor	Number of Level	Value of the Test Factors			
		Min	Max	Increment	Baseline
Approaching Volume (vphpl)	21	500	1500	50	1000
Cycle Length (sec)	4	60	240	30	60
Truck Percentage (%)	4	5%	20%	5%	10%

9.4 Development and Calibration of Simulation Models

For modeling CM, EM and LM controls with VISSIM, this study created a connector to link a lane in the double-lane upstream link with the single lane in the work zone link and specified the lane-choice decision for all entry vehicles (Figure 9-1 (a)). The lane-changing parameter in the link connector is used to define the distance at which vehicles will begin to change lanes in response to a lane-closure warning sign. For the LM, merge-in-turn will be done automatically (PTV AG, 2006).



(a) VISSIM Model under CM, EM or LM (one connector)



(b) VISSIM Model under LBSM (two connectors)

Figure 9-1: VISSIM Simulation Models with CM, SEM, SLM and LBSM

For modeling the LBSM control with VISSIM, this study used two connectors to link each lane in the upstream segment with the lane in the work zone area (Figure 9-1 (b)). A traffic signal was set at each of the two connectors. Since vehicles running in one connector cannot change to another connector, the simulated system can replicate a non-lane-changing stand-by zone from the starting point of the connectors to the location of signals. As a result, driver compliance rate to the LBSM is close to 100% in the simulation models. Note that the focus of this study at this stage is to evaluate the system effectiveness with the assumption that all drivers are willing to follow the instructions under the surveillance of some monitoring devices.

Simulation parameters to be calibrated for the models are the upstream volumes, heavy vehicle percentage, and two driving behavior parameters (Wiedemann, 1999) in the upstream link, the minimum headway distance for the lane-changing behavior and the headway time that a driver wants to keep at a certain speed for the car-following behavior (VISSIM 3.7 User Manual, 2003). To identify the best set of parameters, the research team performed the search for these four parameters over a wide range of possible values until the simulated work zone throughputs and average speeds at merge points were consistent with the field data collected at the I-83 work zone site under the CM and LM controls.

Table 9-2 presents the calibration results for the simulated highway work zone, based on the field observed traffic information. The results indicate that the calibrated simulation system can realistically reflect the actual work zone traffic conditions around the merge point under the CM and LM controls.

Table 9-3 presents two sets of parameters calibrated for driver behaviors, one for those under CM and EM and the other for those under LM and LBSM, as the control strategies in each set share the similar operational characteristics.

Table 9-2: Comparison of Field Data with Simulation Results

Calibration Scenarios / Traffic conditions	CM (10/10/2003)		LM (10/22/2003)	
	Field Data	Simulation Results	Field Data	Simulation Results
Upstream Volume (vph)	1875	1875	1887	1887
Heavy Truck Percentage (%)	19%	19%	17%	17%
Work Zone Throughput (vph)	1340	1346	1469	1478
Average Speed at Merge Point (mph)	24	25	17	16.9

Table 9-3: Driver Behavior Parameters Calibrated in the Simulation Models

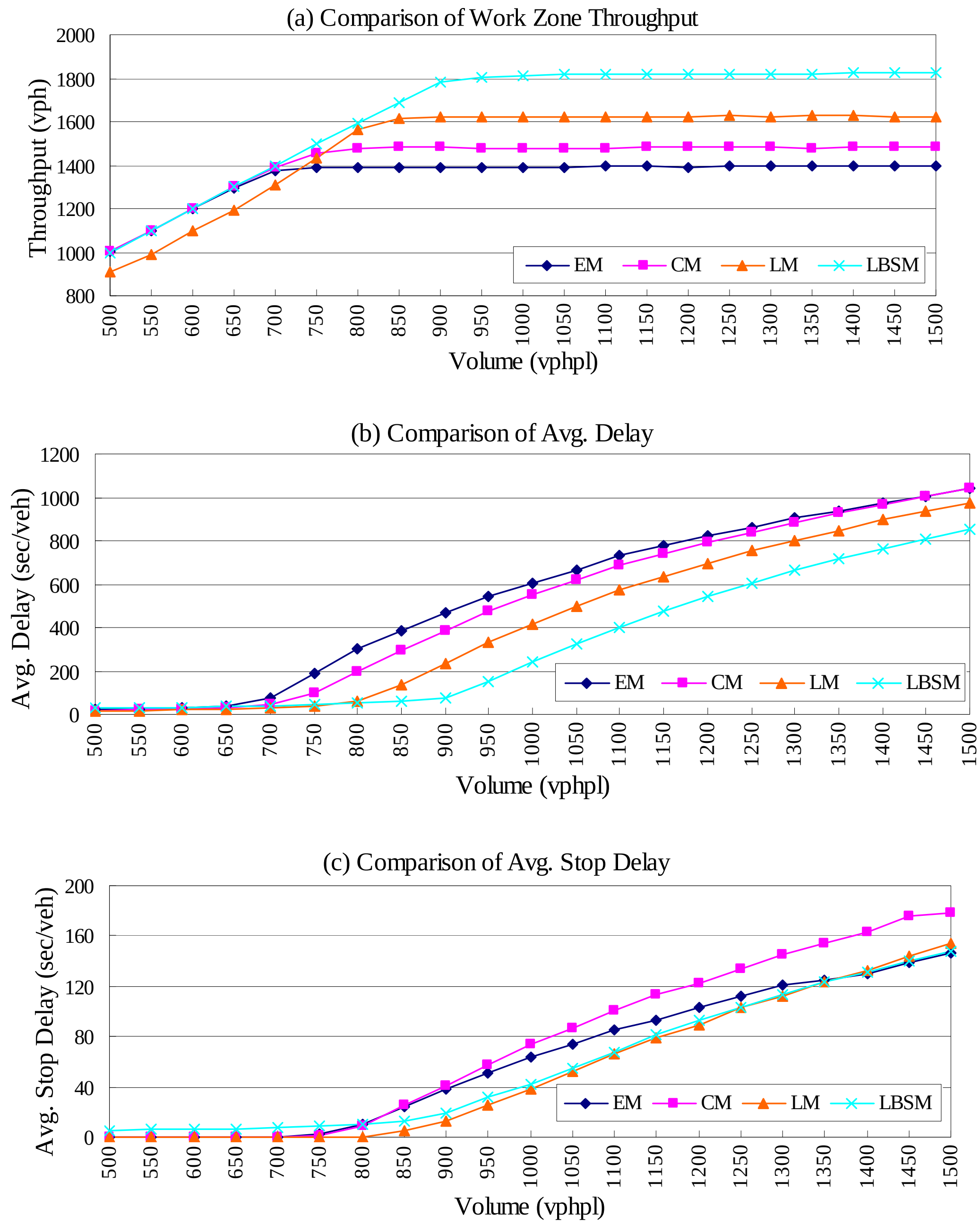
Calibrated Parameters in the work zone upstream link	CM and EM	LM and LBSM
Min Headway (ft)	17.21	11
Headway Time (s)	1.7	1.2

9.5 Analysis of Simulation Results

Performance Comparison between Different Control Strategies

The comparison between LBSM and three existing merge control strategies (CM, EM, and LM) based on the four selected MOEs under varying traffic volumes is shown in Figure 9-2. It is clear that the work zone capacity under the EM, CM, LM and LBSM control with the cycle length of 60 seconds is about 1,400, 1,500, 1,600, and 1,800 vehicles per hour per lane (vphpl), respectively, given the 10 percent heavy vehicles in the traffic flows.

As reflected in Figure 9-2 (a), the work zones with the LBSM always yield higher throughputs than those under the LM. This is expected since the LM can be viewed as a special case of LBSM with a very short cycle length under the forced flow conditions.



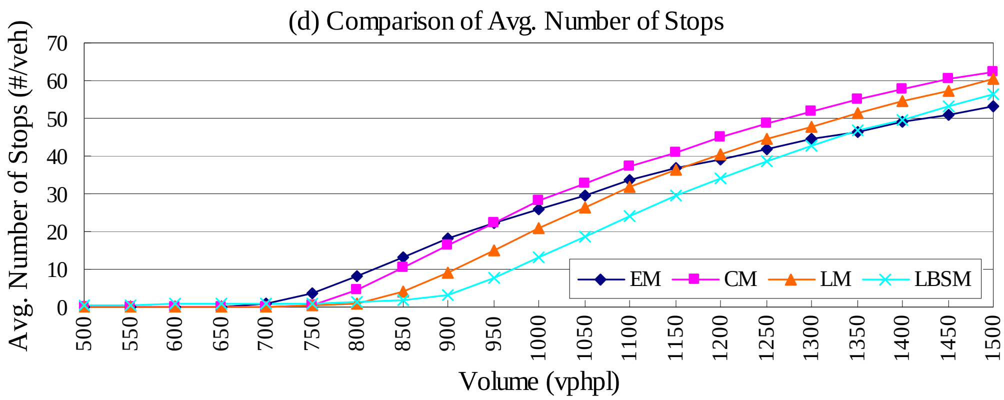


Figure 9-2: Performance Comparison of CM, EM, LM and LBSM (500~1500 vphpl)

The results in Figure 9-2 are also consistent with our expectation that the LBSM can achieve significant benefits, especially under heavily congested traffic conditions.

To explore the traffic condition most suitable for each control strategy, this study further conducted the following four sets of experiments:

Light volume level (500~700 vphpl)

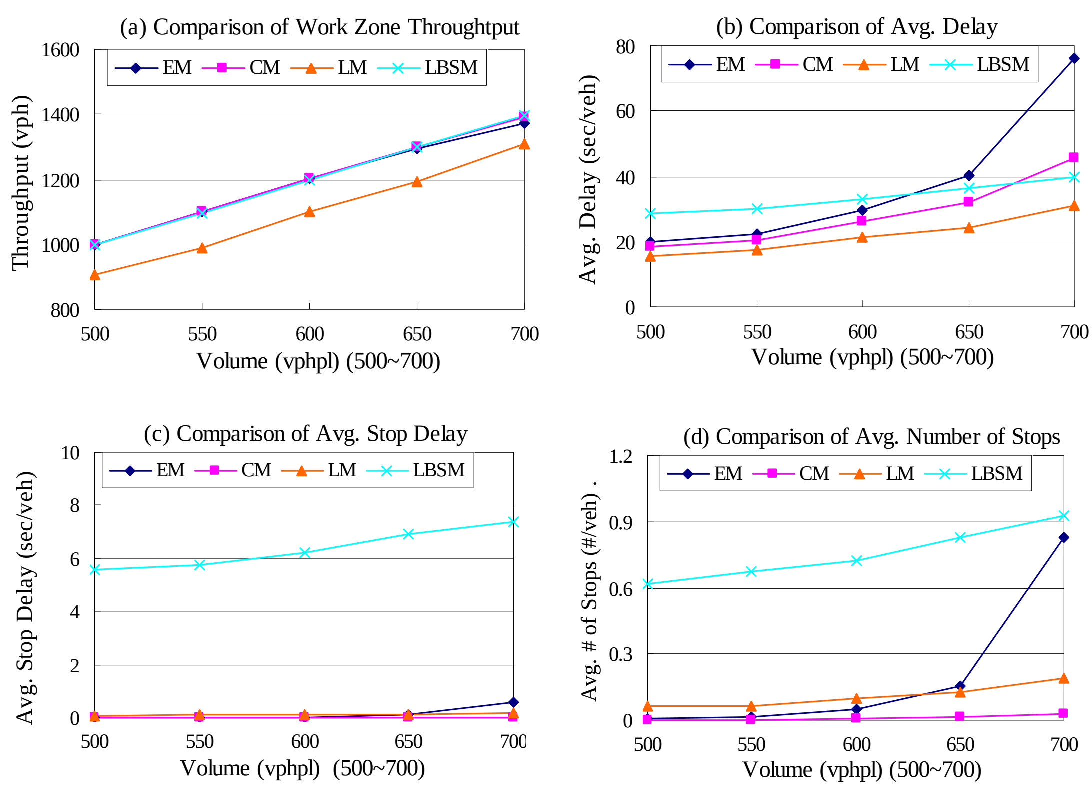


Figure 9-3: The Performance Comparison at the Light Volume Level (500~700 vphpl)

As shown in Figure 9-3, when the entry traffic volumes are less than the EM capacity (700×2=1400 vph), the CM and EM outperform LM with respect to the work zone throughput, and they also outperform LBSM with respect to the total delay and less number of stops. No significant difference exists between CM and EM, based on the simulation results. In general, considering the potential traffic safety issue, EM seems more desirable than others at this volume level.

Under the same range of light traffic volume, the LM control produces the lowest work zone throughput. This is likely due to the fact that under light traffic condition, most vehicles can easily find acceptable gaps to merge into the open lane without disturbing the traffic flows. Hence, the "merge-in-turn" instruction with the LM control under light volumes may excessively interrupt the traffic flow and decrease the merging efficiency.

The LBSM control exhibits no significant improvement over CM and EM and has only slight improvement over LM with respect to the work zone throughput. Furthermore, the LBSM results in the highest average vehicle delay, stop delay, and number of stops among the four control systems. This clearly indicates that placing a signal control at the work zone will cause excessive traffic queue and delay if the approaching volume is not sufficiently high to justify doing so.

Modest volume level (700~750 vphpl)

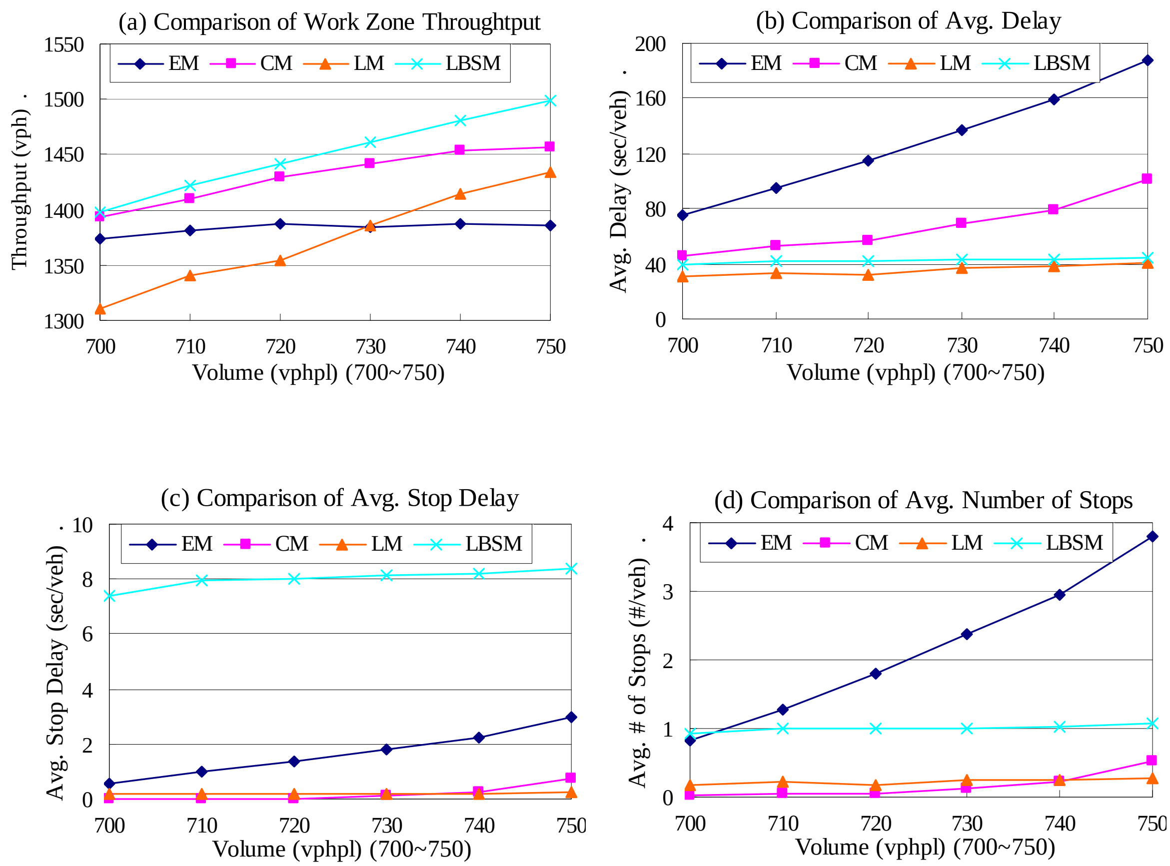


Figure 9-4: Performance Comparison the Modest Volume Level (700~750 vphpl)

When the entry traffic volume exceeds the EM capacity (700x2=1400 vph) but less than the CM capacity (750x2=1500 vph), the CM seems to achieve satisfactory performances in terms of the throughputs, delays and the number of stops (see Figure 9-4). Under this range of modest volumes, neither the LBSM nor the LM exhibits any substantial benefits over the CM.

As expected, the EM performs worse than the CM with respect to all MOEs, as at this volume level vehicles will begin to experience the difficulty in changing lanes and consequently cause traffic disturbances. Implementation of the EM under such traffic conditions could result in numerous merging points and yield negative impacts on the operation efficiency.

High volume level (750~800 vphpl)

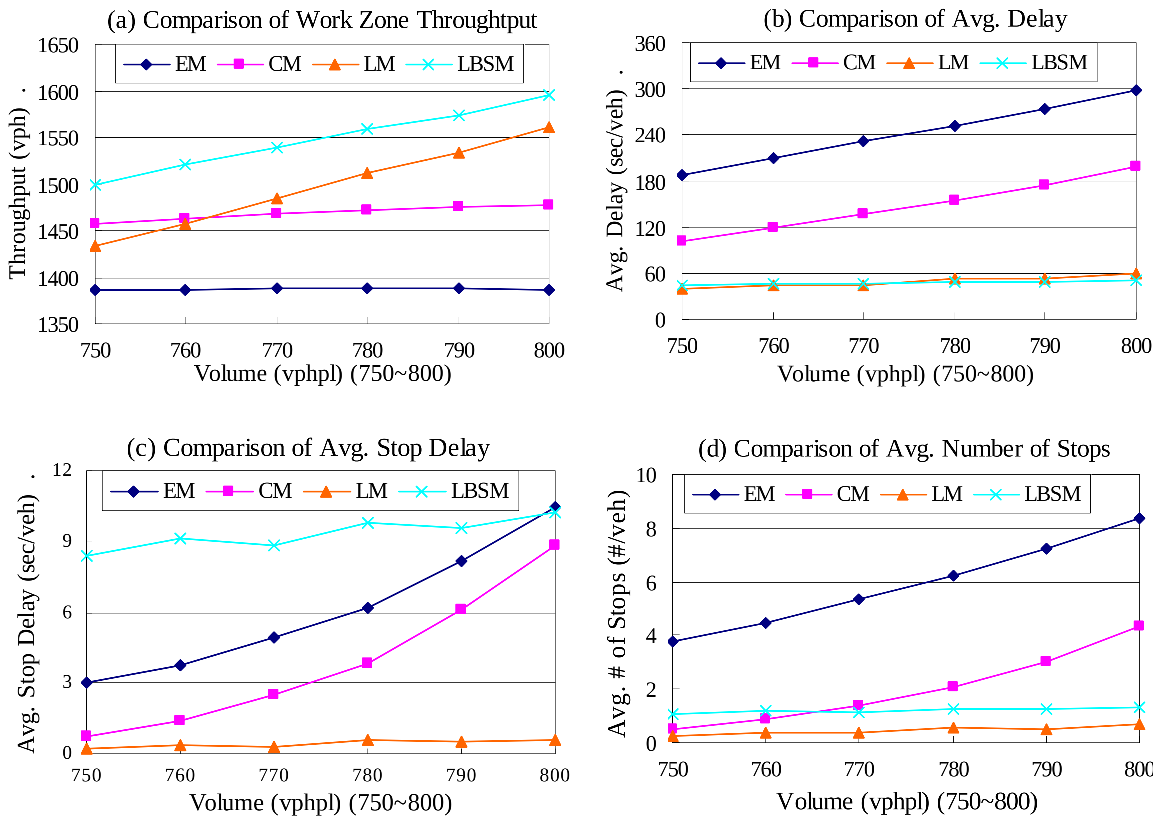


Figure 9-5: Performance Comparison at the High Volume Level (750~800 vphpl)

When the total entry traffic volumes exceed the CM capacity and approach the LM capacity, the LM outperforms EM and CM with respect to all four MOEs (see Figure 9-5).

Note that the work zone throughput under the LBSM in this range of volume is slightly higher than that under the LM. However, the improvement is not sufficiently significant as to compensate for the increase in the average delay, stop delay, and the number of stops.

Based on the resulting throughput and disturbance to the traffic flow, it is reasonable to view the LM as the most suitable control strategy under this range of traffic volumes.

Congested volume level (800~1500 vphpl)

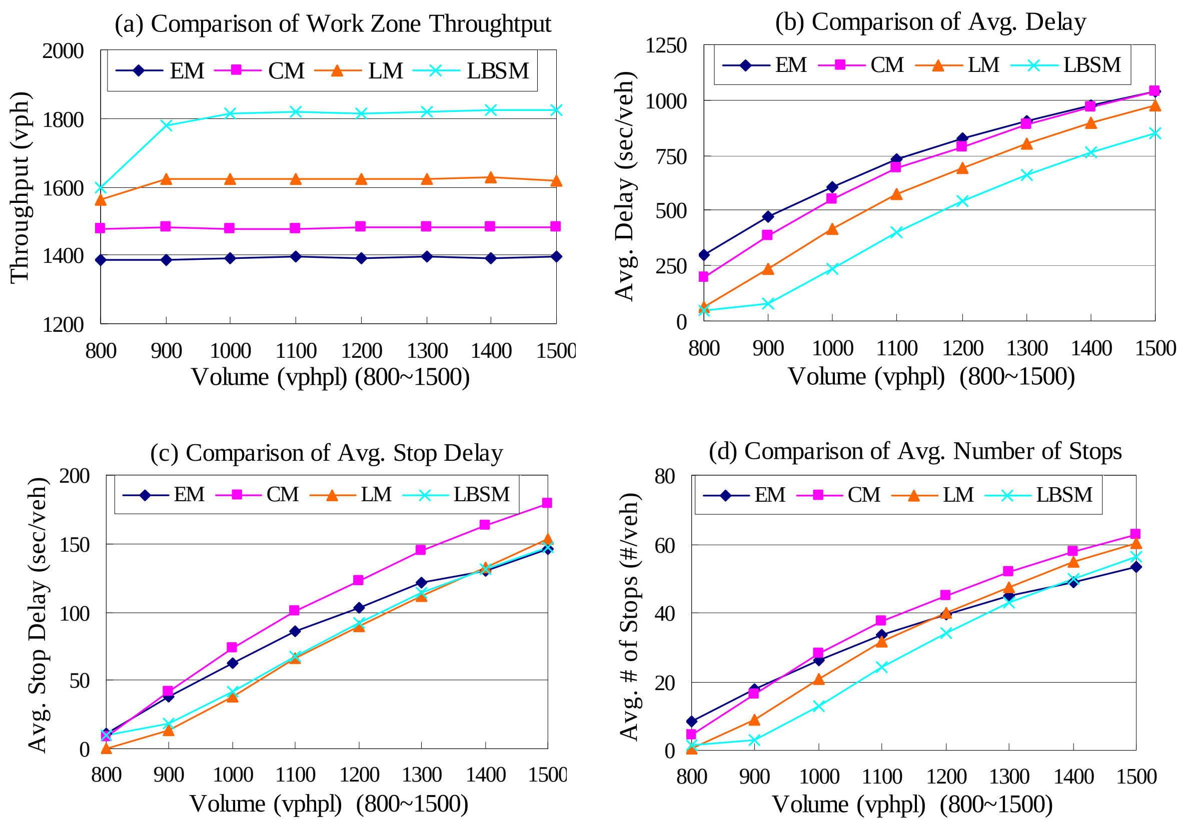


Figure 9-6: Performance Comparison at the Congested Volume Level (800~1500 vphpl)

As shown in Figure 9-6, when the traffic demands exceed the capacity of the LM, the LBSM control substantially outperforms the other three control strategies. On average, its resulting work zone throughput is about 30% higher than that under the EM, 22% more than the CM and 12% over the LM. The reduction in the average delay is 41% compared to the EM, 39% and 29% when compared with the CM and the LM, respectively. The decreases in the average stop delay and the number of stops are also remarkable.

At this volume level, traffic is heavily congested at the upstream point of the blockage link and a long queue may exist in both lanes. Since the LBSM control provides a rule to assign the right-of-way to vehicles in the queues, it can mitigate most merge conflicts and best use the available capacity of the open lane. Such a control strategy may also reduce the stop delay and number of stops as it prevents the likelihood of having multiple merge points.

Sensitivity Analysis with Different Cycle Lengths

In the example of two-lane highway with one lane closure, the LBSM system employs two phases to regulate the movement of vehicles in the two upstream lanes. Figure 9-7 displays the performance results of the LBSM under different cycle lengths with the upstream demand of 1,000 vphpl and the heavy vehicles of 10 percent.

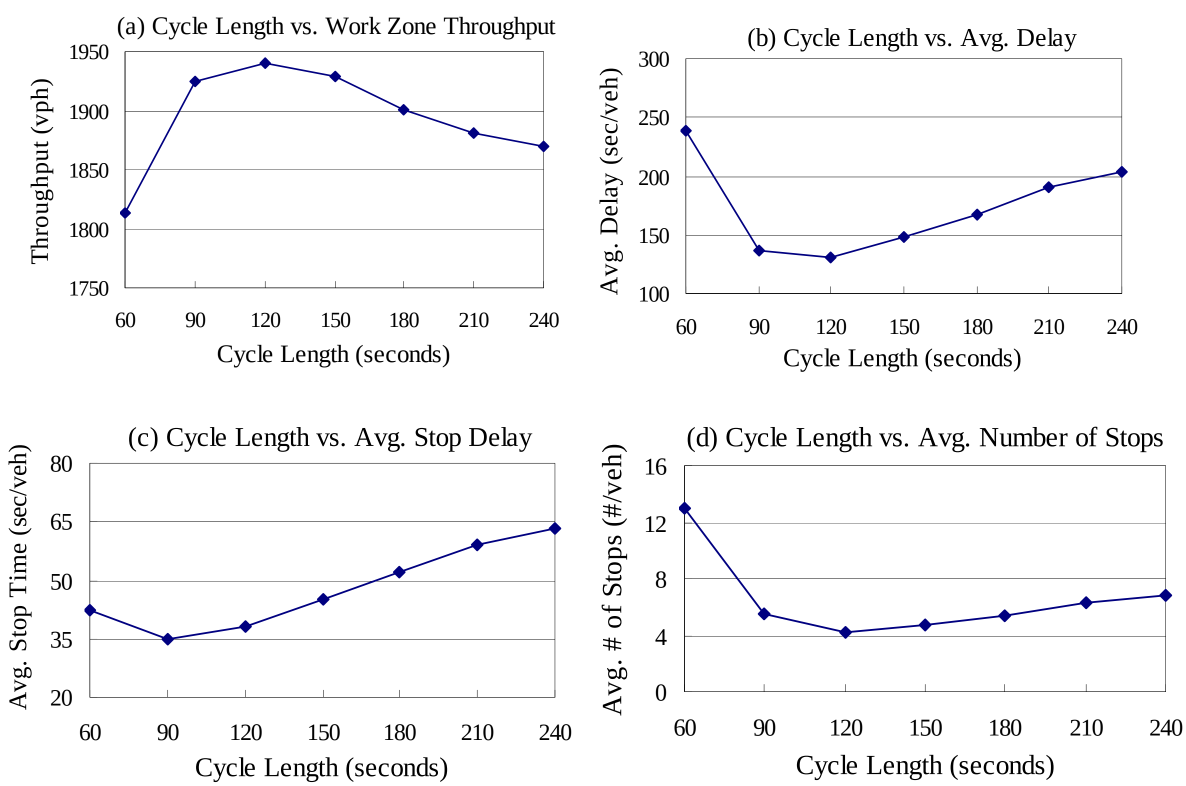


Figure 9-7: Performance of the LBSM with Various Cycle Lengths

The numerical results reflect that the cycle length of 120 seconds (2 min) yields the highest throughput, the lowest average vehicle delay, the least number of stops, and a low average stop delay. In general, a short cycle length may result in less efficient use of the green times, but excessively long cycle length may incur long queues. Usually, an optimal cycle length can be found in the same way under different traffic conditions.

Sensitivity Analysis with respect to Impacts of Heavy Vehicles

The performance results of the LBSM control system under various heavy vehicle percentages at the volume level of 1,000 vphpl are shown in Figure 9-8.

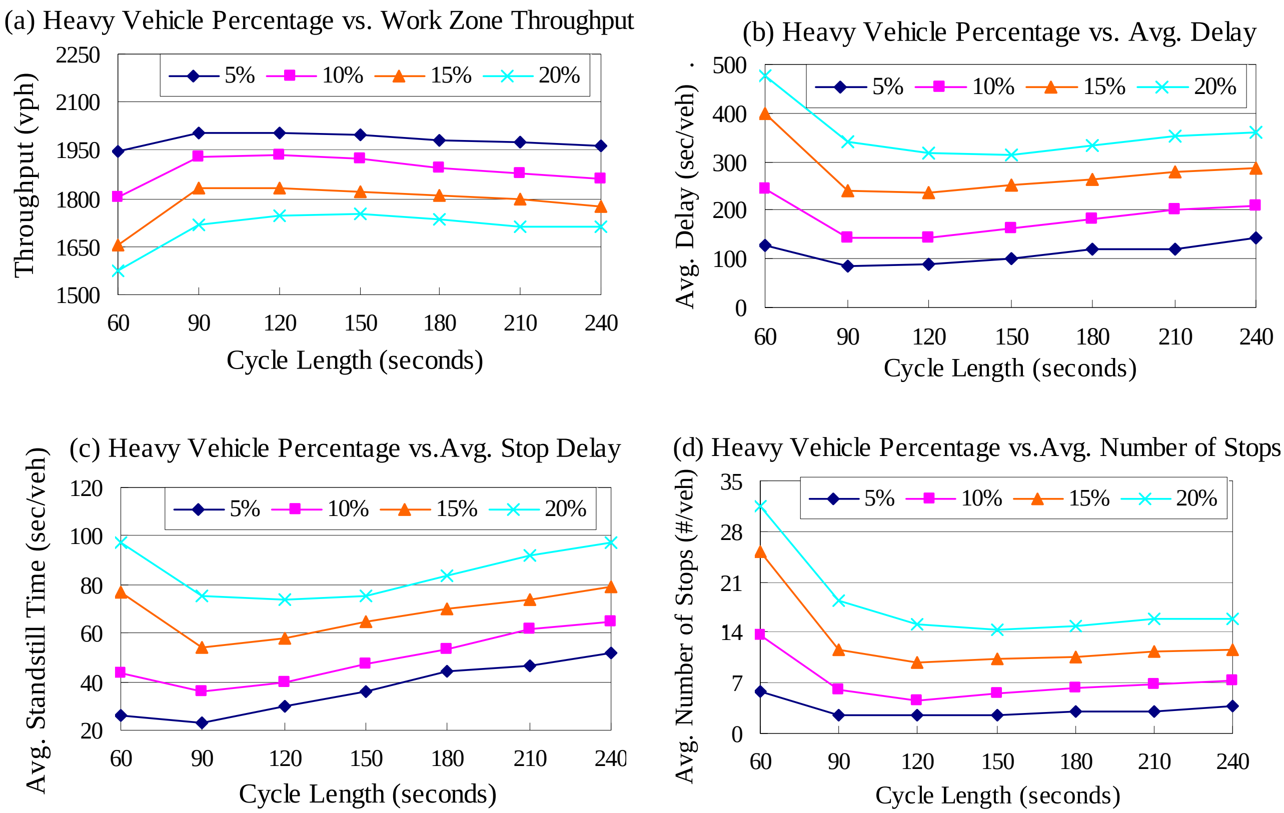


Figure 9-8: Performance of the LBSM with Various Heavy Vehicle Percentages

The graphical results clearly indicate that the presence of heavy vehicles will significantly degrade the operational efficiency of the work zone on all aspects under the LBSM. The optimal cycle length for such a control system seems to increase with the percentage of heavy vehicles. For example, the best cycle length increases from 90 to 150 seconds when the truck percentage increases from 5 to 20%. This is likely due to the fact that the average headway in the traffic flow often increases due to the presence of heavy vehicles, and thus a longer cycle length is needed to increase the throughput and improve other MOEs.

CHAPTER 10: CONCLUSION

This study employed a well-calibrated simulation system to explore the best control strategy designed for work zone operations under different volume levels. Through extensive experiments, this study also confirmed the general belief that the work zone control shall evolve along the sequence of early merge, conventional merge, to the late merge control when the incoming traffic volume increases over time. For example, for the test network, the early merge control is preferable under the range of volumes below 700 vphpl; the conventional merge control can perform satisfactorily when the volume ranges from 700 to 750 vphpl; the late merge control can best achieve its effectiveness under the volume range between 750 and 800 vphpl.

The results of this study clearly indicate that the above three merge controls can no longer be effective if the approaching volume exceeds 800 vphpl. Hence, this study has proposed an innovative design that employs a signal-based control to regulate the movement of vehicles waiting to proceed through the work zone under congested volume levels.

The extensive simulation evaluation with respect to the proposed LBSM also confirms that the new design, even preliminary in nature, can significantly increase the throughput and result in a reduction in the average vehicle delay, average vehicle stop delay, and the number of vehicle stops under congested traffic conditions. Because of its potentially higher capacity, which reduces the queue presence and the time when the backward shockwave is present on the approach to the freeway, the proposed system can also mitigate crash risk at the end of the queue (i.e., backward shockwave).

The experimental results also reveal that the optimal cycle length for the LBSM control seems to increase with the percentage of heavy vehicles in the traffic flows.

Despite the promising properties of the proposed LBSM control, it should be mentioned that much remains to be done to promote the implementation of such a new design. For instance, some well-designed field demonstrations will be needed to explore the impact of several critical factors on the system efficiency, including the optimal length for the transition zone and standby zone, the control limit of the upstream speed, and the enforcement design to increase the driver compliance rate. One shall also explore the potential of developing an advanced actuated LBSM system for regulating the merging operations at the work zone of multiple lanes and a dynamic merge control system which can automatically switch among EM, CM, LM, and LBSM according to real-time traffic conditions.

REFERENCES

1 Lyles, R.W., Taylor, W.C. and Grossklaus, J. (2003). Field Test of Variable Speed Limits in Work Zones (in Michigan). Michigan State University and Michigan Department of Transportation project.

2 Lin, P., Kang, P., Chang, G. L. (2004). “Exploring the Effectiveness of Variable Speed Limit Controls on Highway Work-Zone Operations,” Intelligent Transportation Systems, Vol. 8, pp. 155–168.

3 Kwon, E. and Brannan, D. (2007). “Development and Field Evaluation of Variable Advisory Speed Limit System for Work Zones,” Transportation Research Record, No. 2015, pp. 12-18.

4 Kang K. and Chang G. (2007). “Development of Integrated Control Algorithm for Dynamic Lane Merge and Variable Speed Limit Controls,” the 11th World Conference on Transport Research.

5 Virginia P. S., Andrew, S. and Germin, F. (2009). Implementing Active Traffic Management Strategies in the U.S., University of Alabama at Birmingham report.

6 Hegyi, A and Schutter, B. (2003). “Optimal Coordination of Variable Speed Limits to Suppress Shock Waves,” Transportation Research Record. No. 1852. pp. 167-174.

7 Bertini, R. and Bogenberger, K. (2005). “Impact of Driver Information System on Traffic Dynamics on a German Autobahn: Lessons for U.S. Applications,” the 12th World Congress on Intelligent Transport Systems.

8 Ulfrasson, G. and Shankar, V. (2005). “The effect of variable message and speed limit signs on mean speeds and speed deviations,” International Journal of Vehicle Information and Communication Systems, Vol. 1, pp. 69-87.

9 Steel, P. and McGregor, R. (2005). “Application of Variable Speed Limits along the Trans Canada Highway in Banff National Park,” Annual Conference of the Transportation Association of Canada, Calgary, Canada.

10 Abdel-Aty, Mohamed (2008). “Dynamic Variable Speed Limit Strategies for Real-Time Crash Risk Reduction on Freeways,” Transportation Research Record, No. 2078, pp. 108-116.

11 Jonkers, E. and Klunder, G. (2008). "Development of an Algorithm for Using Dynamic Speed Limits in Relation to the Weather Situation," the 15th World Congress on Intelligent Transport Systems and ITS America Annual Meeting, New York, U.S.

12 Buddemeyer, J and Young, R. (2010), "Rural Variable Speed Limit System for Southeast Wyoming," the 89th TRB Annual Meeting, Washington D.C.

13 Bertini, R., and Boice, S. (2006). "Dynamics of Variable Speed Limit System Surrounding Bottleneck on German Autobahn," Transportation Research Record, No.1978, pp. 149–159.

14 Anund, A. and Ahlström, C. (2009). Evaluation of local ITS solutions in urban areas. Swedish National Road and Transport Research Institute, No. 646.

15 Ghods, A, Kian A, and Tabibi, M. (2009). "Adaptive freeway ramp metering and variable speed limit control: a genetic-fuzzy approach," Intelligent Transportation Systems Magazine, IEEE. In Intelligent Transportation Systems Magazine, IEEE, Vol. 1, No. 1, pp. 27-36.

16 Chang, G. L., Wu, J. and Lieu, H. (1995). "Real-Time Incident-Responsive System for Corridor Control: Modeling Framework and Preliminary Results," Transportation Research Record 1452, pp.42-51.

17 Cremer, M. and Schoof, S. (1989). "On Control Strategies for Urban Traffic Corridors," International Federation of Automatic Control, pp. 213-219.

18 Beacher, A. G., Fontaine, M. D., and Garber, N. J. (2004). "Evaluation of the Late Merge Work Zone Traffic Control Strategy." Research Project No. VTRC 05-R6, Virginia Transportation Research Council, sponsored by the U.S. Department of Transportation.

19 Federal Highway Administration. (2003). Manual on Uniform Traffic Control Devices, U. S. Department of Transportation, Washington, D. C.

20 Kang, K. P. and Chang, G. L. (2006a). "Development of an Advanced Dynamic Late Merge Control Model and Algorithm," Transportation Research Board Annual Meeting (CD-ROM), Washington, D. C.

21 Kang, K. P., Chang, G. L., and Paracha, J. (2006b). "Dynamic Late Merge Control at Highway Work Zones: Evaluations, Observations, and Suggestions," Transportation Research Record, No. 1948, pp. 86-95.

22 Lin, P.W., Kang, K.P., and Chang, G.L. (2004). "Exploring the Effectiveness of Variable Speed Limit Controls on Highway Work-Zone Operations," Intelligent Transportation Systems, No. 8, pp. 1-14.

23 McCoy, P. T., Pesti, G., and Byrd, P. S. (1999). Alternative Driver Information to Alleviate Work Zone-Related Delays: Final Report. NDOR Research Project No. SPR-PL-1(35) P513, Department of Civil Engineering College of Engineering and Technology, sponsored by Nebraska Department of Roads.

24 McCoy, P.T. and Pesti, G. (2001) "Dynamic Late Merge Concept for Work Zones on Rural Interstate Highways," Transportation Research Record, No. 1745, pp. 20-26.

25 Pesti, G., Jessen, D. R., Byrd, P. S. and McCoy, P. T. (1999). "Traffic Flow Characteristics of the Late Merge Work Zone Control Strategy," Transportation Research Record, No. 1657, pp. 1-9.

26 PTV AG. (2006). "Models and algorithms", VISSIM FAQ, http://www.english.ptv.de/cgi-bin/traffic/traf_vissimfaq. 20Installation> (Oct.9, 2006)

27 Tarko, A. and Venugopal, S. (2001). Safety and Capacity Evaluation of the Indiana Lane Merge System. Research Project No. FHWA/IN/JTRP-2000/19, Joint Transportation Research Program, Purdue University, sponsored by Indiana Department of Transportation.

28 VISSIM 3.70 User Manual. (2003). PTV Planung Transport Verkehr AG, Karlsruhe, Germany.

29 Walters, C. H., and Cooner, S. A. (2001). Understanding Road Rage: Evaluation of Promising Mitigation Measures. Research Report 4945-2, Texas Transportation Institute, College Station, Texas.