

Exploring the Effectiveness of Variable Speed Limit Controls on Highway Work-Zone Operations

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10 *Despite the well recognized fact that a proper control of traffic speed can contribute to both reduction in accidents and efficiency of highway operations, most existing strategies for work-zone speed control in either Europe or the U.S. tend to primarily focus on improving traffic safety. This article presents two online algorithms for variable speed limit (VSL) controls at highway work zones that can take full advantage of all dynamic functions and concurrently achieve the objectives of queue reduction or throughput maximization. To evaluate the effectiveness of these proposed algorithms, this study has conducted extensive experiments based on simulated highway systems that have been calibrated with field data. The results of these simulation analyses have confirmed that VSL algorithms can yield a substantial increase in both work-zone throughputs and reduction in total vehicle delays.*

15 *Moreover, traffic flows implementing VSL controls tend to exhibit lower speed variances than other non-controlled traffic scenarios. The speed variance reduction may indirectly contribute to improving the overall traffic safety in work zones.*

01 **Keywords**

INTRODUCTION

20 Contending with congestion and incidents in highway work zones has long been recognized as one of the major priorities of most highway agencies. A common practice over the past several decades for work-zone operations is to recommend or enforce a reduced speed limit using variable message signs (VMS), which may not respond to fluctuation in approaching traffic demand. In order to improve traffic safety and increase the compliance rate of drivers, traffic professionals in recent years have experimented using variable speed limit (VSL) controls in place of the conventional posted speed limit (PSL) operations in highway work zones (Committee for Guidance on Setting and En-

forcing Speed Limits, 1998). Most such field studies have indicated that by properly regulating traffic flow speeds with VSL, the potential risk of rear-end collisions in work zones can be reduced (Committee for Guidance on Setting and Enforcing Speed Limits, 1998; Coleman et al., 1996). 35

Despite the potential effectiveness of using VSL for improving highway operations, most existing studies or practices have focused on the impacts of safety related issues. For example, Coleman et al. (1996) reported the use of automated speed management in Australia, which is a fog warning and speed advisory system installed south of Sydney. In the same study, they also introduced a control system in Germany, which used a VSL sign to display the current speed limit under the following types of scenarios: construction, fog, crash ahead, ice, and high winds. Pili-Sihvola and Taskula (1996) introduced a VSL control to warn drivers of black ice and other hazards in Finland. Smulders (1992) and van den Hoogen and Smulders (1996) stated that the goal of the Dutch speed limit system installed on frequently congested interchanges was not to reduce average speeds but mainly to 45 50

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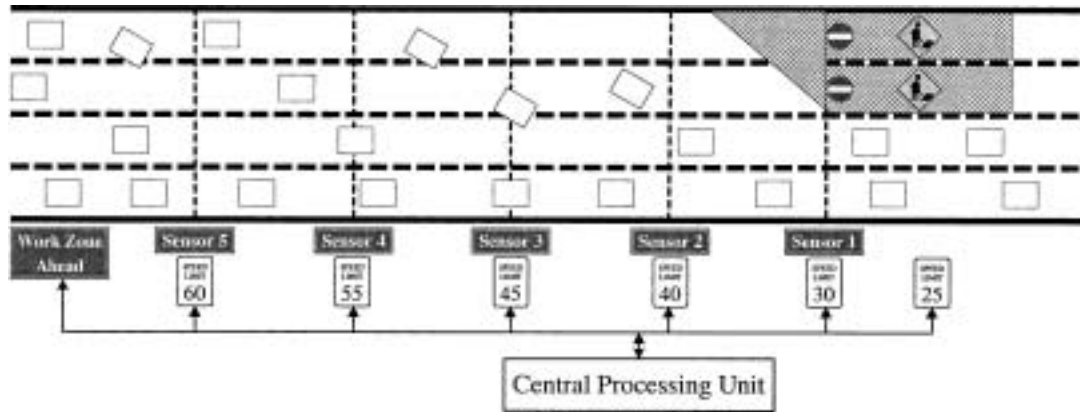


Figure 1 Configuration of a VSL system.

narrow the speed dispersion. Likewise, a system in the United Kingdom described by Wilkie (1997) was designed to minimize the stop-and-go conditions during heavy traffic. Sumner and Andrews (1990) have also reported a variable speed limit system (VSL) in the state of New Mexico, which was intended to be flexible in responding to various environmental conditions.

In brief, most existing VSL related systems have been to improve traffic safety, yet little attention has been focused on improving the operational efficiency such as to maximize the throughput from a work zone or to minimize the average vehicle delay through the entire highway segment plagued by the work-zone incurred traffic queue. This study intends to use two proposed algorithms to explore the potential benefits of using a dynamic VSL control for highway work-zone operations. The objective of the first algorithm (VSL-1) is to minimize the queue in advance of the work zone by dynamically reducing the speed limit. The second algorithm (VSL-2) is designed to maximize the throughput over the entire work-zone area, based on the time-dependent traffic demand, spatial distribution of vehicle speeds, and driver compliance to VSL messages.

The remaining sections of the paper are organized as follows. The key features of the proposed VSL control system are briefly described in the next section. The core concepts and the formulations of VSL-1 and VSL-2 control algorithms are presented below. The design of simulation experiments along with extensive analytical results for the performance evaluation of both proposed VSL control algorithms are also reported. Conclusions and on-going research work are summarized in the last section.

VSL SYSTEM DESCRIPTION

A VSL control system typically consists of sensors, variable speed limit signs, variable message signs and

a central processing unit to execute control actions. As shown in Figure 1, VMS are used to inform drivers of the traffic condition ahead and to display the enforced speed limit based on the implemented VSL control strategy.

Depending on the approaching volume, driver compliance rate, and the resulting congestion, the central processing unit that integrates all system sensors and signs will dynamically compute the time-varying optimal speed limit for each VMS and display it in a timely fashion.

Our proposed VSL control algorithms for work-zone operations include the following variables and parameters:

- Control time and subsegment indices
 - T : Unit time interval for control operations (e.g., 1 min., 5 min., 10 min., etc.),
 - k : Time interval index,
 - i : Subsegment index ($i = 1 \dots N$);
- Network geometric and physical data
 - l_i : Length of subsegment i ,
 - n_i : Number of lanes in subsegment i ;
- Traffic volumes
 - $q_i(k)$: Transition flow rate entering subsegment $(i - 1)$ from i during interval k ,
 - $Q_i(k)$: Average flow rate in subsegment i during interval k ;
- Model parameters
 - α_i : Space transition flow weight factor for subsegment i ,
 - β_i : Time transition flow weight factor for subsegment i ,

- ρ_i : Speed-density equation adjustment factor for subsegment i ,
- γ_i : Shockwave weight factor for subsegment i ;
- Control variables
- 120 • $v_i(k)$: Variable speed limit in subsegment i during interval k ,
- $q^c(k)$: Control flow rate entering the work zone from subsegment 1 during interval k ;
- State variables
- 125 • $d_i(k)$: Mean traffic density in subsegment i during interval k ,
- $u_i(k)$: Mean speed in subsegment i during interval k ,
- $u_i^f(k)$: Free flow (boundary) speed in subsegment i during interval k ,
- 130 • $\lambda_i(k)$: Speed compliance ratio for subsegment i during interval k .

THE VSL-1 CONTROL ALGORITHM

Figure 2 illustrates an example of a highway work zone where the capacity has been reduced due to a two-lane closure operation. Obviously, the peak-hour traffic demand of 4 lanes is likely to cause substantial queue spill-back to its maximum length. One of the most effective ways to minimize the standing queue at such a work zone is to reduce the incoming flow rate, which can be accomplished with properly reducing traffic flow speeds. This core concept of the VSL-1 control algorithm aims to minimize the difference between q_{in} and q_{out} (as shown in Figure 2) with a proper dynamic control of speed over the entire area impacted by the work zone. More specifically, the VSL-1 control algorithm is designed to perform the following tasks:

- Reducing approaching traffic speed so as to increase the average headway for vehicles to merge onto adjacent lanes, and
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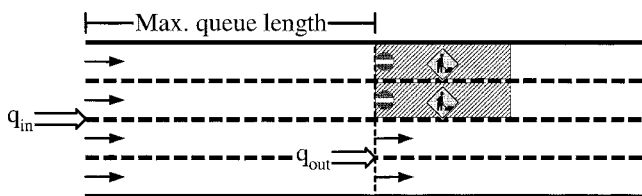


Figure 2 The maximum queue and the traffic flow.

- Take into account the responses of drivers in setting the appropriate control speed.

The VSL-1 control algorithm consists of two modules. As shown in Figure 3, the first module (Module 1) functions to compute the initial speed of each VSL sign, and the second module (Module 2) is responsible for updating the displayed speed for each VMS, based on the estimated difference between the detected flow speed and the target control speed.

Module 1

In order to minimize the potential queue formation ahead of the lane-closure location at a typical freeway work zone as shown in Figure 4, the upstream segment of the potential maximum queue length should be divided into a number of subsegments with each being monitored by a set of sensors, VMS, and VSL signs. The control target for Module 1 is that the traffic flow rate over the first segment should approximately be equal to the flow rate entering the lane-closure segment. Such a control target can only be accomplished if all upstream approaching traffic flow rates can be properly reduced accordingly to lower approaching speeds.

To do so, a set of traffic models is needed to capture the complex interaction of traffic states between neighboring highway subsegments. Those traffic state evolution equations should be mathematically formulated to represent the actual operational constraints. As recognized in many studies (Chang et al., 1995; Wu and Chang, 1999; Cremer and Schoof, 1989), traffic density and speed have been used as state variables, of which the former is a key factor affecting a driver's choice of speed and the VSL system's selection of appropriate speed limits. A step-by-step description of the VSL-1 control algorithm is presented below.

Step 1: Compute the Time Weighted Flow Rate for Each Control Interval

The actual traffic flow rate for interval k is approximated with a weighted average between two consecutive time intervals. Equations (1) and (2) represents the transition flow for the work-zone segment and the last control segment N , respectively:

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

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

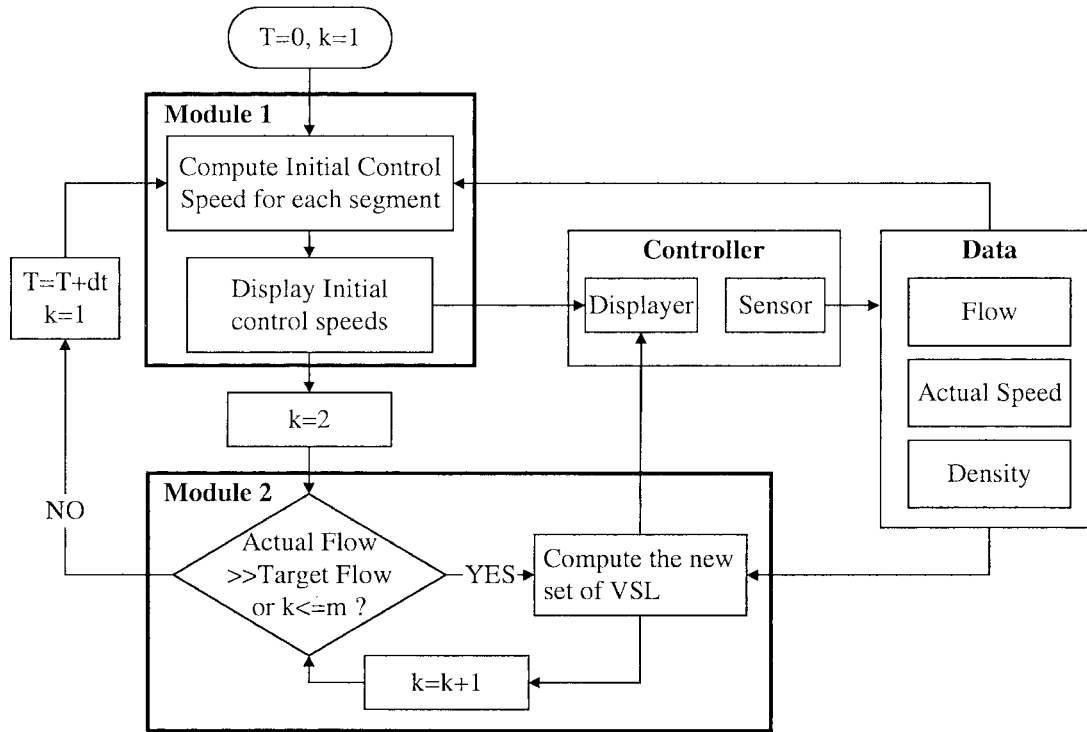


Figure 3 A flow chart of the VSL-1 control algorithm.

where β_i is a model parameter (i.e., time weighting factor), which can be calibrated with field measurements. Wu and Chang (1999) stated that it should lie within the interval [0.5, 1.0], and Cremer and Schoof (1989) calibrated it to be 0.95 using field data.

from the flow rate at the work-zone segment and the last segment N as shown in Equation (3):

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

where α_i is the model parameter (i.e., space weight factor).

Step 2: Compute the Space Weighted Transition Flow as the Control Target

Due to the point-measurement nature of detector data, the traffic flow rate over each subsegment is measured as a weighted average of two neighboring subsegment flows. The actual target control flow rate $q^c(k)$ shall be computed

Step 3: Compute the Target Density for Segment 1

With the above variables and parameters, the conservation law is used to approximate the evolution of traffic density (Chang et al., 1995). The temporal variation of mean density, $d_1(k)$, during each control time interval

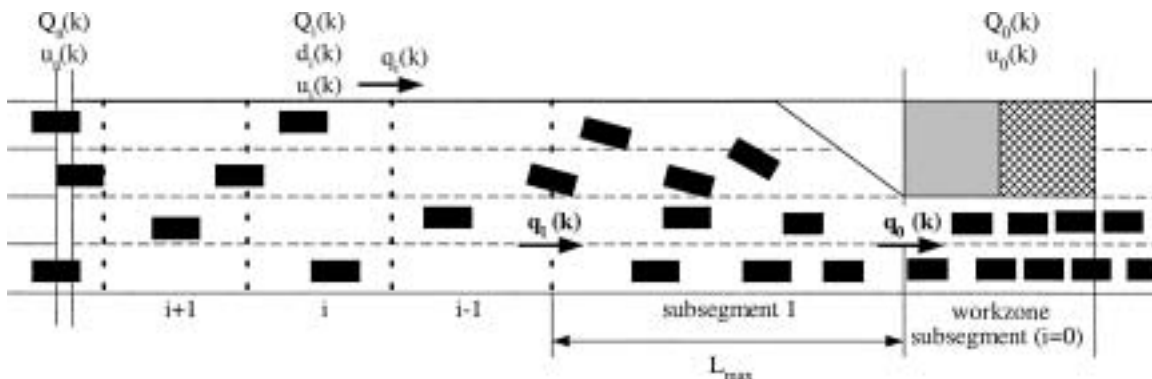


Figure 4 Typical freeway work zone for VSL-1 control algorithm.

(Δt) can be determined from the difference between the input and output flows, $q_1(k)$ and $q_0(k)$, at the boundaries of Segment 1, and be presented as follows:

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

215 *Step 4: Compute the Target Control Speed for Segment 1*

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

$$220 \quad v_1(k) = q^c(k)/d_1(k) \quad (5)$$

Step 5: Compute the Target Control Speed for Each Upstream Segment

As shown in Figure 5, the $v_1(k)$ to $u_n(k)$ line represents the speed reduction process under ideal conditions.

225 To maintain the constant control speed limit within each subsegment, a step relation to compute displayed control speeds is used. The ideal target flow speed can be approximated as follows:

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

230 *Module 2*

Since drivers typically do not follow the displayed control speeds, Module 2 is designed to compute the differences between the detected flow speeds and the target control speeds, and to update the displayed speeds accordingly. The computing procedures are shown below.

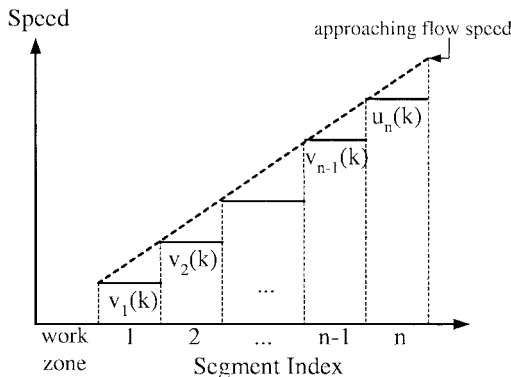


Figure 5 The ideal graphic relationship between the control speed and the displayed speed.

Step 1: Compute a Compliance Ratio Based on Detected Speed and the Control Speed

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

240

$$\gamma_i(k) = v_i(k)/u_i(k), \quad i = 1, \dots, n - 1. \quad (7)$$

Step 2: Update Control Speed for the Next Time Interval

By assuming the linear relationship between the compliance ratio and the control speed, the displayed control speed for the next time interval can be computed as follows:

245

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

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

250

THE VSL-2 CONTROL ALGORITHM

The objective of the VSL-2 control algorithm (Kang et al., 2003) is to maximize the total throughput from the work zone; however, it is subject to some predefined safety constraints. As shown in Figure 6, the proposed VSL-2 algorithm uses the same variables and parameters mentioned previously.

255

As stated previously, the flow conservation law is used to express the evolution of mean density, $d_i(k)$, determined by the difference between transition flows, $q_{i+1}(k)$ and $q_i(k)$ at the subsection boundaries. That is,

260

$$d_i(k) = d_i(k - 1) + \frac{T}{l_i \cdot n_i} [q_{i+1}(k) - q_i(k)] \quad (9)$$

In addition, the transition flow between adjacent subsections is taken as a weighted average of two neighboring subsection flows using the space-weighting factor, α_i .

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$$q_i(k) = \alpha_i \cdot Q_i(k) + [1 - \alpha_i] \cdot Q_{i-1}(k) \quad (10)$$

For the average speed, $u_i(k)$, one can establish its evolution relationship using the following properly selected speed-density relation and shockwave formation equations:

270

$$u_i(k) = u_i(k - 1) + \rho_i \cdot \{S[d_i(k - 1), v_i(k - 1)] - u_i(k - 1)\} + \gamma_i \cdot w_i(k - 1) \quad (11)$$

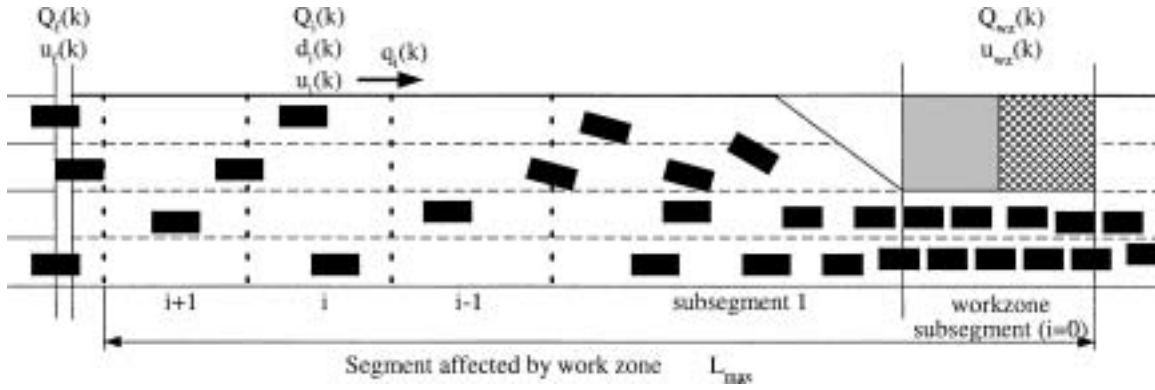


Figure 6 Typical freeway work zone for VSL-2 control algorithm.

where, the second component describes an adaptation of the average speed to the speed-density characteristics, $S[d_i(k-1), v_i(k-1)]$ as

$$S[d_i(k), v_i(k)] = [u_{i+1}^f(k) \cdot v_i(k)] \cdot \left[1 - \frac{d_i(k)}{d_i^J(k)} \right]^\theta. \quad (12)$$

275 This equation is originally formulated with the Green-shield model (i.e., $\theta = 1.0$) and can be modified to account for the linear interaction between $d_i(k)$ and $v_i(k)$. The third component takes into account the shock wave between downstream ($i-1$) and upstream (i), as follows:

$$280 \quad w_i(k) = \frac{[Q_{i-1}(k) - Q_i(k)]}{[d_{i-1}(k) - d_i(k)]}. \quad (13)$$

Model parameters, ρ_i and γ_i are speed-density equation adjustment factor and shockwave weight factor, respectively. The actual average speed measured from detectors does not typically match the proposed linear speed-density equation. Thus, based on the differences between the calculated and measured speeds during the previous time interval $(k-1)T$, the average speed needs to be adjusted with ρ_i during the time interval kT . In addition, γ_i is needed to include the impact of the shockwave on the subsequent upstream subsections.

290 Using the above formulations, the control model for highway work-zone operations can be constructed to optimize the variable speed limit based on a predetermined objective function, maximization of work-zone throughput:

$$295 \quad \text{Max.} \quad \sum_k \left(\sum_i^N [q_{wz}(k) + Q_i(k)] \cdot T \right) \quad (14)$$

where $q_{wz}(k) = Q_0(k)$ describing the work-zone downstream boundary flow, and $Q_i(k) = u_i(k) \cdot d_i(k)$. The set of constraints for the above control objective is shown below: 300

- Dynamic constraints
 - Equations (9)–(13)
- Boundary constraints
 - $0 \leq d_i(k) \leq d_i^J$ (15)
 - $u_{i-1}^f \leq u_{i+1}^f(k) \cdot v_i(k) \leq u_{i+1}^f$ (16) 305
 - $0 \leq v_i(k) \leq 1$ (17)

The researchers fully recognize the likely non-linear nature of speed-density relations in traffic flow. However, due partly to the lack of such a model for work-zone traffic in the literature and partly to the need for efficient online operations, the proposed model approximates the speed-density relation with a linear function, but constantly updated it with the differences between field measured speeds (i.e., from detectors) and the model output, and adjusted the results with embedded parameters. By using such an algorithm, one can circumvent the need to solve a non-linear formulation, which may or may not have a solution, and is certainly not sufficiently fast for real-time operations. 310

Figure 7 presents the principal steps of the proposed control algorithm for VLS operations, including the interactions between sensors, VLS, and the feedback relations. The entire process is designed to ensure that the VSL can always reflect the optimal speed limit and take into account some embedded safety constraints. Primary activities to be performed in each step are summarized below. 325

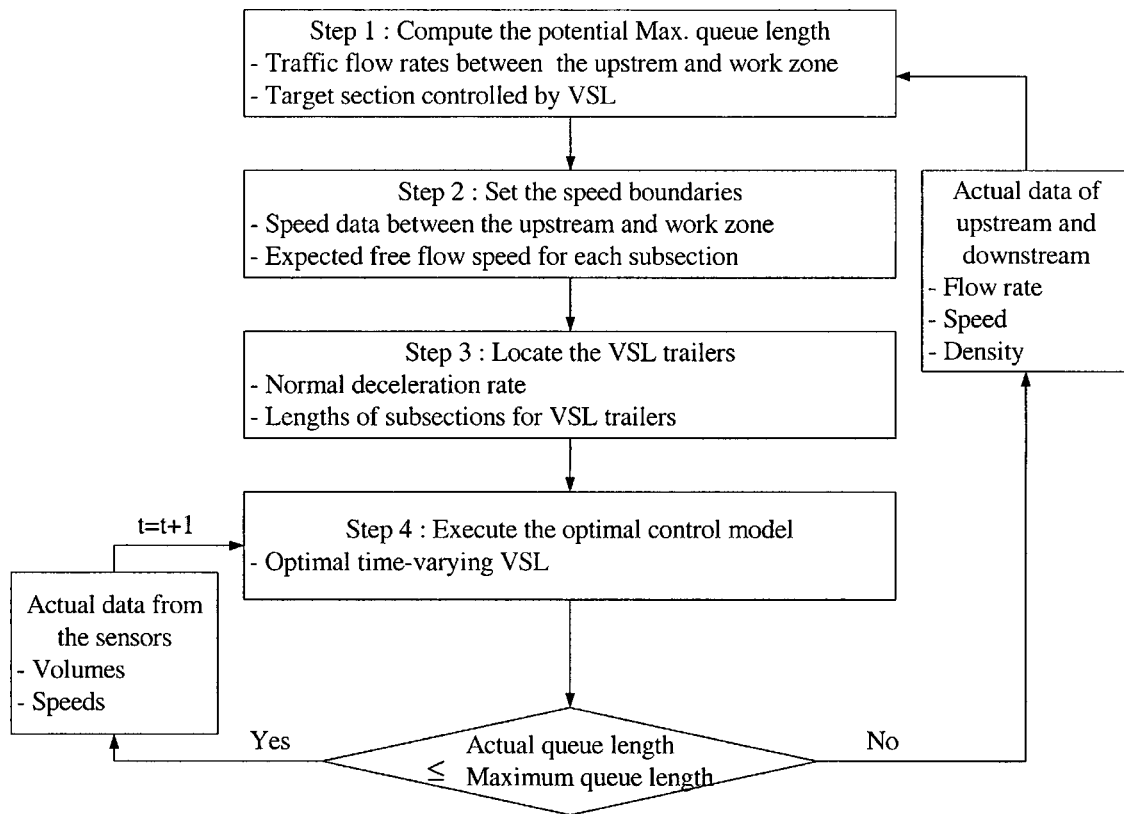


Figure 7 The flow chart of the VSL-2 control algorithm.

Step 1: Compute the Potential Maximum Queue Length Due to Work-Zone Operations

330 The purpose of this step is to approximate the maximum queue length based on the difference in the maximum flow rates (Q_{wz} , Q_f) between the upstream segment and the work zone. This is done because the computed queue length will be used as the target segment (L_{max}) controlled by VSL as shown in Figure 7. If the actual traffic queue 335 caused by the work-zone operations exceeds the L_{max} , then the target segment should be extended to cover the entire roadway segment, which could potentially be impacted by the work-zone traffic queue.

340 **Step 2: Set the Speed Boundaries for VSL Control**

This step is designed to set a speed boundary (u_i^f) that reflects the free flow speed for each subsegment i . This boundary is designed to prevent the optimal speed limit of subsegment i from exceeding the speed boundary of its upstream subsegment ($i + 1$). Thus, a set of optimal VSL based on these speed boundaries will enable drivers to smoothly adjust their speed when approaching the work zone. Such speed boundaries will be revised dynamically based on the detected speed data (i.e., u_f and u_{WZ}).

Step 3: Locate the VSL Trailers

The locations of the VSL trailer set should be determined based on the average decelerating rate of drivers when they perceive each displayed VSL sign. By using a normal deceleration rate (e.g., $a = 3.3$ mph/sec; Transportation and Traffic Engineering Handbook), the target 350 segment can be divided into N subsegments (i.e., x_i) as follows. 355

$$x_i = u_{i+1}^f \cdot t + \frac{1}{2} a \cdot t^2, \quad \text{and} \quad x_i = \frac{(u_{i+1}^f)^2 - (u_i^f)^2}{2a} \quad (9) \quad Q3$$

This is to ensure that when perceiving the VSL signs, drivers will not experience uncomfortable and unsafe deceleration rates within each control subsegment. 360

Step 4: Execute the Optimal Control Model

Step 4 is used to optimize a set of VSL over all subsegments during each control time interval based on the embedded LP optimizing model. As mentioned in Step 1, if the actual queue length is longer than the computed 365 maximum queue length, then go to Step 1. Otherwise, the system shall repeat Step 4 with actual data updated from the sensors.

MODEL EVALUATION WITH SIMULATION

370 EXPERIMENTS

Design of Experiments

The first step for simulation experiments is to design a simulated work-zone system that can replicate real-world work-zone traffic conditions. This study has evaluated
375 both VSL algorithms on the following highway work zones:

- Type 2–1: one-lane closure on a two-lane highway, observed throughput between 1500~1600 vphpl (Dixon et al., 1996; Krammes and Lopez, 1992; Dudek and Richards, 1981; Kermod and Myyra, 1970; Jiang, 1999).
380
- Type 3–1: one-lane closure on a three-lane highway, observed throughput between 1400~1500 vphpl (Dudek and Richards, 1981).
385
- Type 3–2: two-lane closure on a three-lane highway, observed throughput between 1300~1500 vphpl (Krammes and Lopez, 1992; Dudek and Richards, 1981).

The simulation evaluation of VSL controls can be preceded only after the simulated work-zone system has yielded the same throughputs and speeds as those observed from field studies (Dixon et al., 1996; Krammes and Lopez, 1992; Dudek and Richards, 1981; Kermod and Myyra, 1970; Jiang, 1990; Kim et al., 2001).
390

To ensure the reliability and the quality of the simulated results, this study has calibrated the simulation program, CORSIM, with the field data collected on non-control days. The entire calibration task includes the following activities:
395

- Calibration of key simulation parameters to reflect the behavior of driving populations:
400
 - Rubbernecking factor,
 - Car-following sensitivity factor, and
 - Desired free-flow speed;
- Replicate target traffic conditions:
405
 - Upstream volume,
 - Work-zone throughput, and
 - Average speed at the merging point.

Table 1 summarizes the example calibration results for the 2–1 work-zone operations.

410 To simulate the interactive online relationship between VSL control actions and the response of traffic systems, this study employs the CORSIM-RTE (CORridor SIMulation—Run Time Extension) program, which is

Table 1 Calibration results for the CORSIM simulation network

Traffic conditions	Actual volume	Simulation results	
		Before calibration	After calibration
Upstream volume	2887 vph	2880 ph	2890 vph
Heavy truck percentage	15%	15%	15%
Average speed at merging point	17.0 mph	30.6 mph	17.7 mph
Work-zone throughput	1536 vph	1845 vph	1531 vph

designed to capture the online interaction between execution of the control algorithm and the impacts on traffic conditions. This program offers three effective functions (i.e., initialization, VSL control, and termination) to develop optimal VSL modules that can communicate with simulated traffic systems during each time interval.
415

To investigate the performance of the proposed VSL control algorithms under different traffic conditions, the simulation evaluation has experimented using a wide range of traffic volumes under the previously mentioned work-zone types as shown in Table 2.
420

Notably, the upper bounds in Table 2 were selected based on the maximum feasible range of traffic flows in work zones, which is about 2200 vphpl for both the 2–1 (i.e., one lane closure out of two lanes) and 3–1 lane-blockage scenarios. For the 3–2 work-zone operations, the simulation analysis did not go beyond 5,000 vph as the total approaching flows have already far exceeded their capacity (i.e., only one open lane). The low bound for each scenario was identified from the approximate capacity of the total amount of open lanes in the work zone (i.e., one open lane for 2,500 vph). This is due to the fact that VSL controls can effectively manage traffic flow only if the levels of approaching volume begin to be interfered by the work-zone operations.
425
430
435

Figure 8 illustrates an example work-zone system for simulation experiments, where one lane was closed on a 2-lane highway due to work-zone activities. The maximum link speed limit and the length of the work zone are set to be 65 mph and 4,000 ft, respectively. This simulated work-zone segment was simulated for one hour with
440

Table 2 Upstream entry volumes used in experimental scenarios

Work-zone types	Upstream entry volumes (vph)		
	Lower bound	Upper bound	Increment
2–1	2500	4500	500
3–1	4000	6500	500
3–2	2500	5000	500

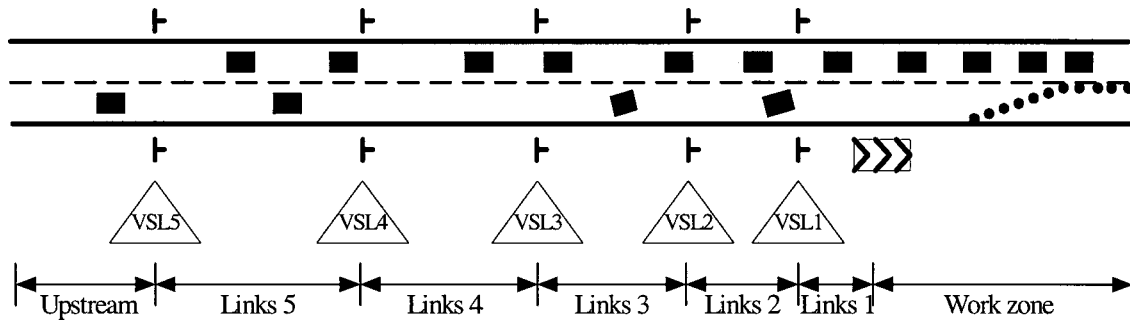


Figure 8 An example of typical work-zone configuration (2 lanes—1 closed type).

445 a microscopic traffic simulation model, CORSIM that was produced by Federal Highway Administration (ITT Industries, 2003).

Evaluation of the VSL Model Performance

450 To facilitate the comparison, this study employs the work-zone maximum throughput, average delay and speed as the primary MOEs (measures of effectiveness). In addition, the variance of speeds over the entire upstream segment of the work zone is used to measure the potential improvement on the driving environment as it is often

highly correlated with traffic safety. The total throughput 455 is measured at the middle point of a work zone while the average delay and speed is obtained over the pre-specified subsegments (i.e., link 1 to link 5), which are located upstream of the work zone as shown in Figure 8.

460 Figures 9 and 10 show the examples of VSL displayed speeds from the 2-1 type simulation results based on the VSL-1 and VSL-2 control algorithms, respectively. These results show that the VSL displayed speeds are within the reasonable range and with small speed variations. It is notable that as the upstream volumes increase to a critical level, 465 the VSL speeds seem to converge to stable values.

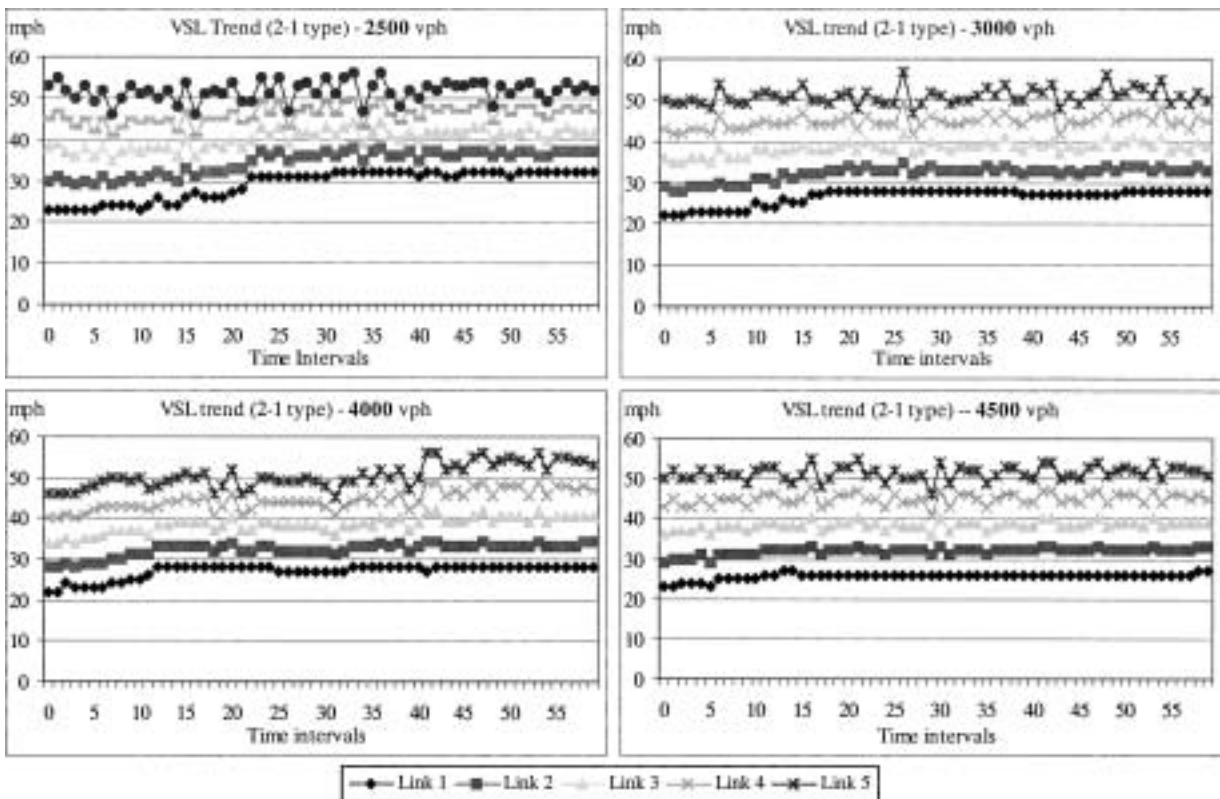


Figure 9 VSL displayed speeds for the VSL-1 control algorithm.

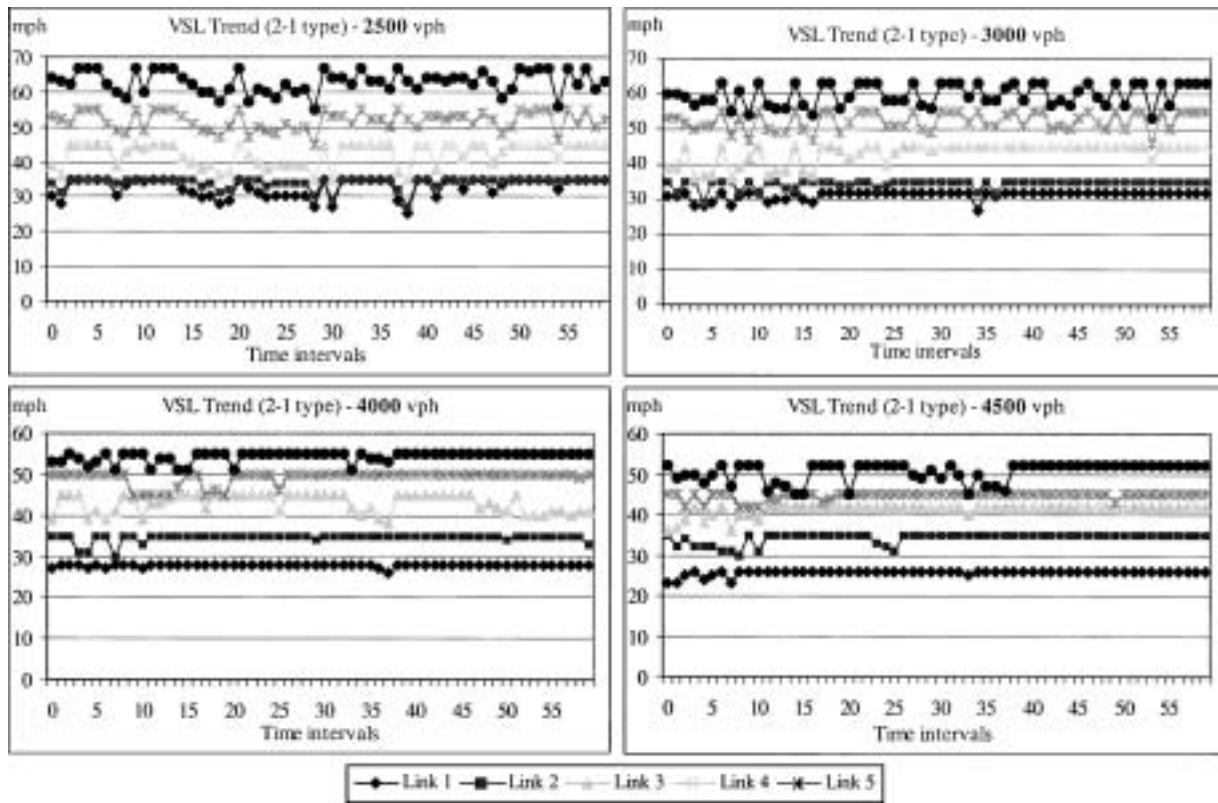


Figure 10 VSL displayed speeds for the VSL-2 control algorithm.

Figure 11 shows an example of the detected speed distribution from the 2-1 type simulation results at the volume level between 2,500 vph and 4,500 vph under Non-VSL, VSL-1, and VSL-2 controls. The detected speeds under the Non-VSL control drop dramatically over time, especially for those segments near the work-zone area. In contrast, the detected speeds under both VSL-1 and VSL-2 controls drop at a smoother rate, compared to those under the Non-VSL control.

For convenience of illustration, Figures 12-15 present the differences of MOEs (i.e., work-zone throughput, average delay, average speed, and speed variance) under the Non-VSL control and two VSL control algorithms.

As evidenced in the previous simulation results, both presented VSL control algorithms can increase the throughput and reduce an average delay per vehicle for those traversing through the work-zone area. Overall, the VSL-2 control algorithm seems to outperform the VSL-1 control algorithm. However, the VSL-1 control algorithm features can be easily implemented as it does not involve any optimization algorithm.

As mentioned previously, the speed differences between Non-VSL and VSL controls are not significant (see Figure 14). This indicates that the VSL control algorithms

do not result in a lower average speed despite the speed limitation.

Although operational efficiency can be evaluated using the three MOEs, it is actually difficult to evaluate safety improvements because accident data cannot be realistically captured in simulated scenarios. Instead, as mentioned previously, this study has used the speed variances over each subsegment as an indicator for the traffic safety related environment. The comparison results in Figure 15 show the speed variances over three links in advance of the work zone, where the average speed data was obtained over each time interval from the detectors. It is notable that the speed variances under the VSL control are lower than those under the Non-VSL control. The low speed variance along with an increased throughput clearly indicates that the proposed VSL algorithms can help drivers safely and efficiently pass through work zones. Furthermore, the result of the average speed and the speed variance for the VSL-1 control algorithm are lower than those without any control and with the VSL-2 control algorithm as shown in Figures 14 and 15. This seems to reflect the fact that the VSL-1 control algorithm, designed for its convenience in implementation, can indeed achieve its mission of effectively reducing traffic queue, delay, and speed variance.

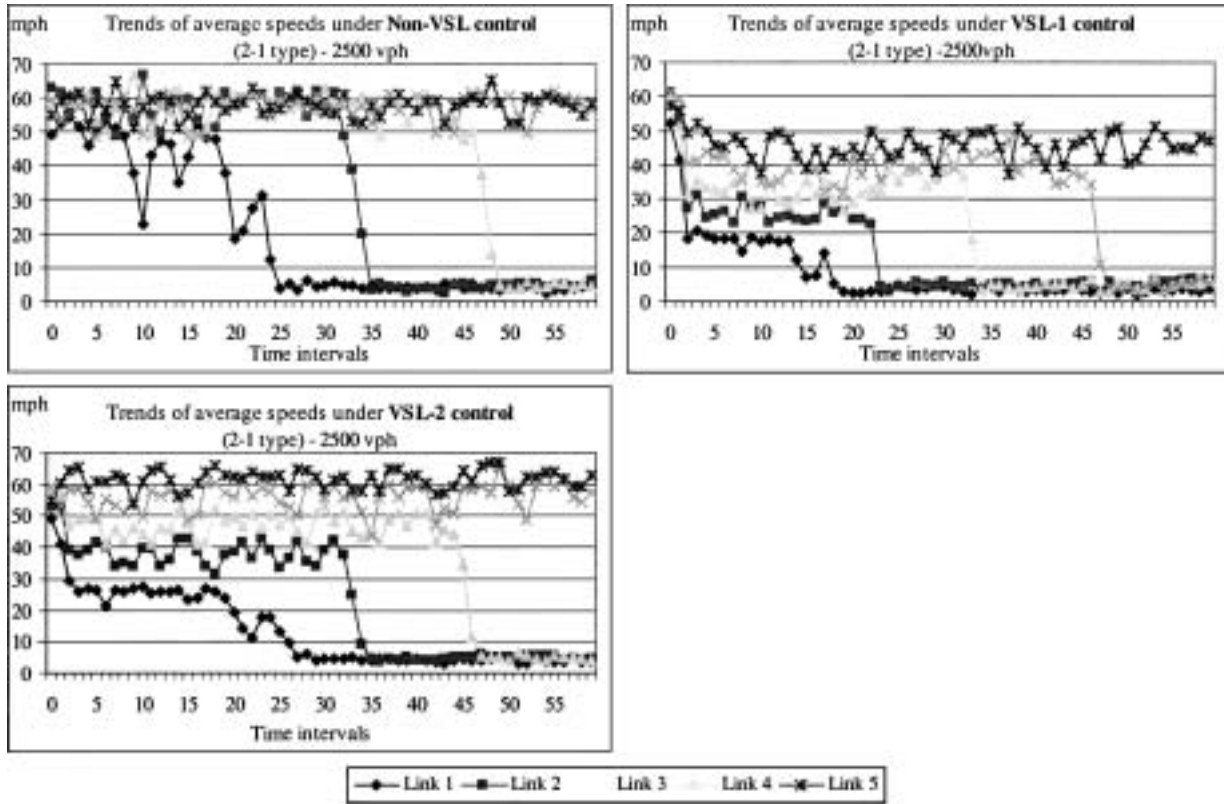


Figure 11 The detected speed distributions under Non-VSL, VSL-1, and VSL-2 controls.

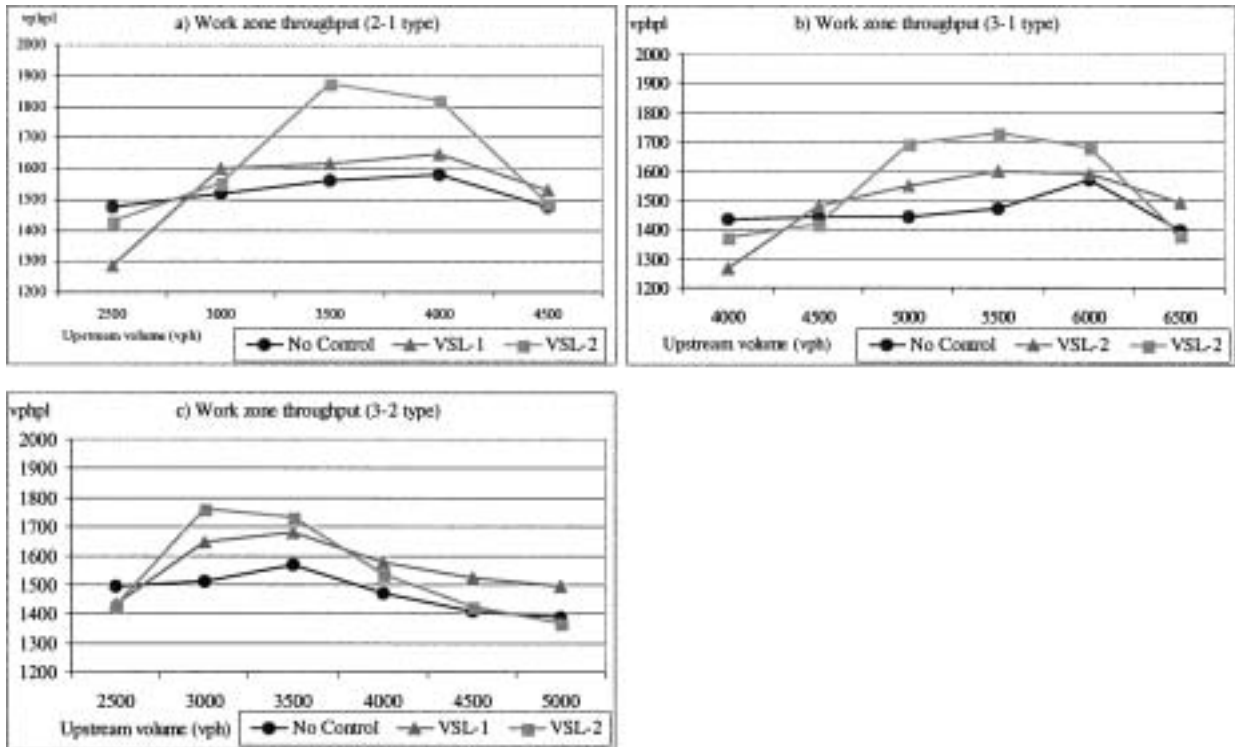


Figure 12 The MOEs—work-zone throughput.

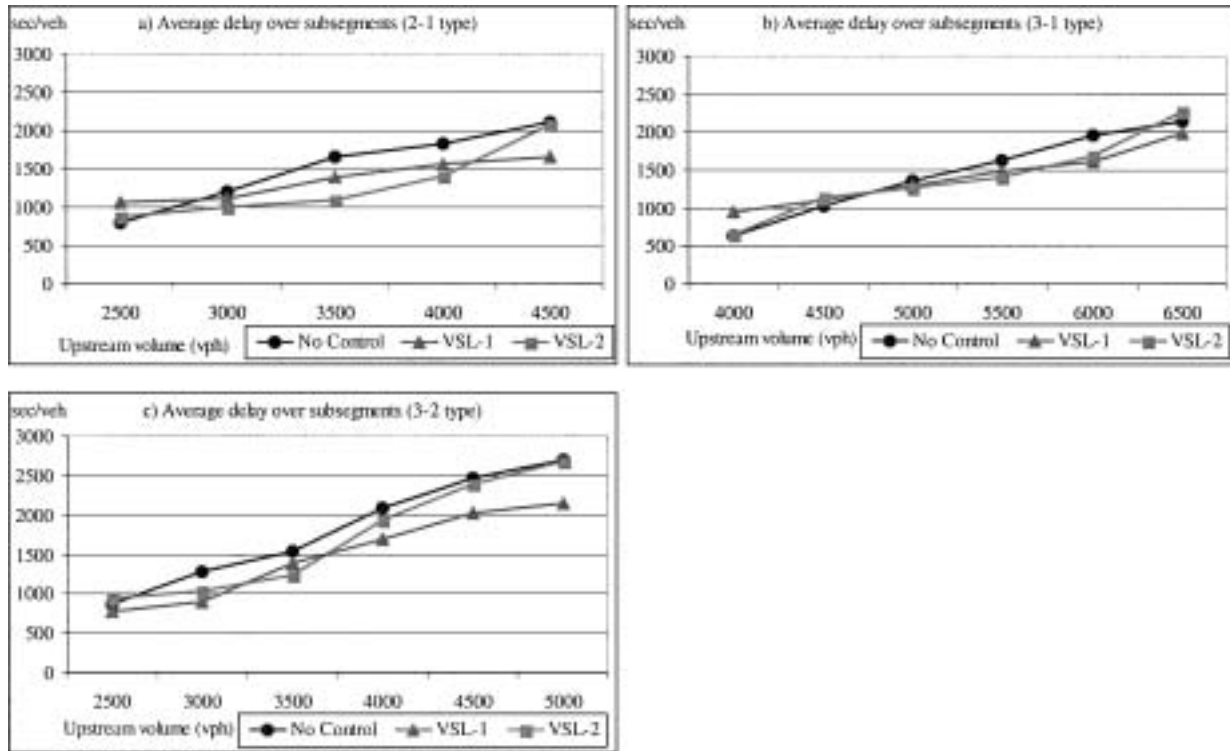


Figure 13 The MOEs—average delay over subsegments.

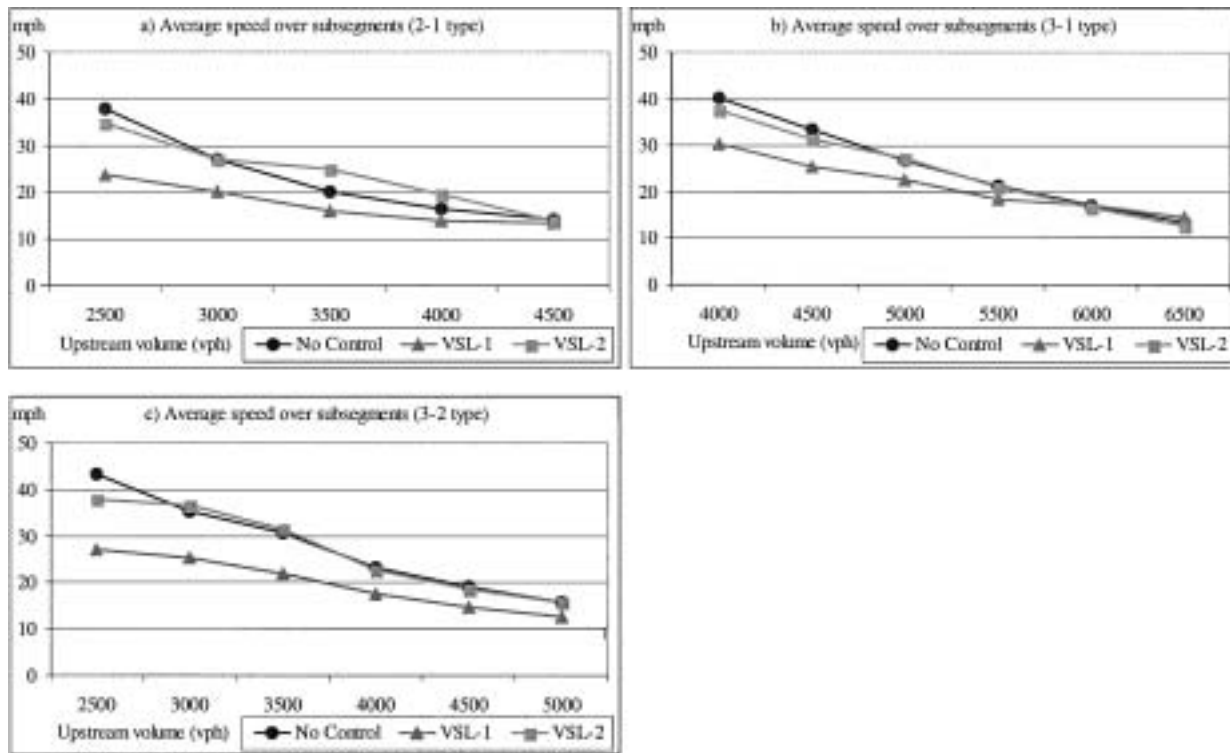


Figure 14 The MOEs—average speed over subsegments.

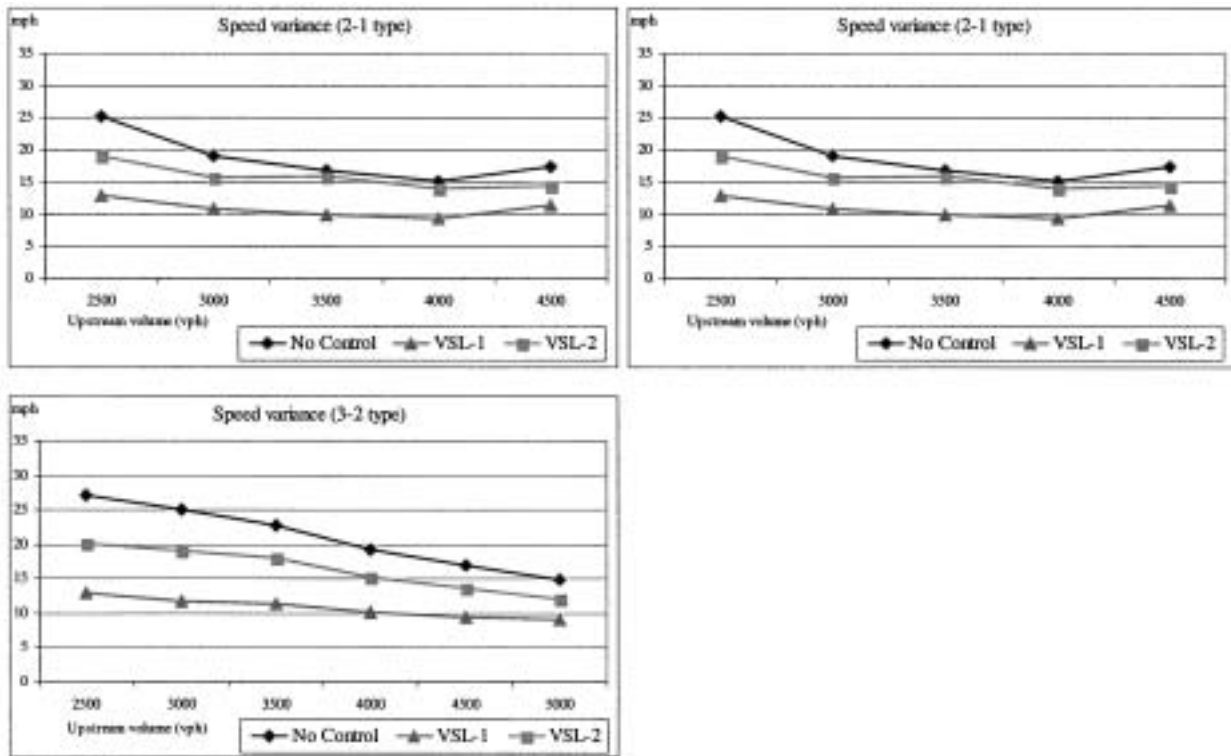


Figure 15 The MOEs—speed variance under different controls.

CONCLUSIONS AND RECOMMENDATIONS

This article presented two online algorithms for variable speed limit controls on highway work zones. The objective of the VSL-1 control algorithm is to reduce the traffic queue in advance of the work-zone area, while the VSL-2 control algorithm aims to maximize the total throughput over the entire work zone. The proposed models, using a well-calibrated set of parameters, have demonstrated that under normal traffic conditions, the throughput in a work zone can be increased and the average delay over upstream segments of the lane-closure location can be reduced. The simulation results have also indicated that although the average speeds under the VSL controls do not vary significantly versus those under Non-VSL controls, the resulting speed variance among those vehicles traveling through the work zone is substantially lower than those under non-control scenarios.

In brief, the proposed VSL control algorithms seem to offer promising alternatives for contending with congestion and safety related issues in highway work zones. Further studies along this line will focus on developing the optimal control algorithm for each type of work-zone operations, and collecting extensive field data for further model testing and enhancements.

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