Optimal Dynamic Speed-Limit Control for Highway Work Zone Operations

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Despite the well-recognized fact that proper control of traffic speed can contribute to both a reduction in accidents and improved efficiency of highway operations, most existing speed-control strategies implemented in Europe and the United States tend to aim only at improving traffic safety. An on-line algorithm for variable speed-limit control at highway work zones is presented that can take full advantage of its dynamic functions and concurrently achieve the objectives of throughput maximization and accident minimization.

Contending with congestion and incidents in highway work zones has long been recognized as one of the priority tasks 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 via variable message signs (VMS), which may or may not respond to fluctuations in approaching traffic demand. To properly respond to traffic conditions and to increase the compliance rate of drivers, traffic professionals in recent years have experimented with variable speed limit (VSL) control in place of the conventional posted speed limit operations in highway work zones (*1*). Most such field studies have indicated that properly regulating traffic-flow speeds with VSL can indeed reduce the potential risk of rear-end collisions in work zones.

Despite the potential effectiveness of using VSL for highway operations, most existing studies or practices have focused mainly on its impacts on safety-related issues. For example, Coleman et al. (*2*) reported the use in Australia of a type of automated speed management, which is a fog warning and speed advisory system installed south of Sydney. In the same study, they also introduced a control system that uses a variable speed limit sign to display the current speed limit, "Under Construction," "Fog," "Crash Ahead," "Ice," and "High Winds" in Germany. Pili-Sihvola and Taskula (*3*) introduced a VSL control to warn drivers of black ice and other hazards in Finland. Smulders (*4*) and van den Hoogen and Smulders (*5*) stated that the goal of a Dutch speed limit system installed at frequently congested interchanges was not so much to reduce average speeds but to narrow the speed dispersion, and a system in the United Kingdom described by Wilkie (*6*) was designed to minimize stop-and-go conditions during heavy traffic. Sumner and Andrews (*7*) have also reported a VSL system in the state of New Mexico, which was intended to be flexible in response to various environmental conditions.

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In brief, most existing VSL-related systems have been designed in response to traffic safety concerns but not for improving operational efficiency, such as to maximize the throughput from a work zone segment or to minimize the average delay for vehicles traveling through the entire highway segment plagued by the work zone-imposed traffic queue. Our study intends to address this critical issue with a dynamic VSL control algorithm for highway work zone operations. Our proposed VSL system has the following distinct features: (*a*) adopts the maximization of work zone throughput as its control objective, which is subjected to some embedded safety-related constraints; (*b*) computes a sequence of optimal transition speeds for approaching vehicles based on dynamic interactions between the work zone traffic flows and those in upstream highway segments; and (*c*) dynamically adjusts the set of displayed optimal speed limits based on the detected speed distributions and flow rates, so as to effectively respond to potential demand variation and noncompliance behavior of some drivers.

The paper is organized as follows. The key features of our proposed VSL system are briefly described in the next section. A set of equations for the evolution of a dynamic traffic state is presented along with the VSL optimization model in the third section. The operation algorithm for the VSL control is illustrated in the fourth section. Design of simulation experiments for evaluating the performance of our proposed algorithm under the real-time control environment is reported in the fifth section. Conclusions and future research work are summarized in the last section.

VSL SYSTEM DESCRIPTION

The proposed VSL system 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 VSL control strategies.

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

METHODOLOGY FOR VSL OPERATIONS

Figure 2 illustrates an example of a highway work zone whose capacity has been reduced due to lane-closure operations. To minimize the potential queue formation ahead of the lane-closure location, the upstream segment of the maximum queue length is divided into a number of segments, with each being monitored by a set of sensors, VMS, and VSL signs. The objective of variable speed limit

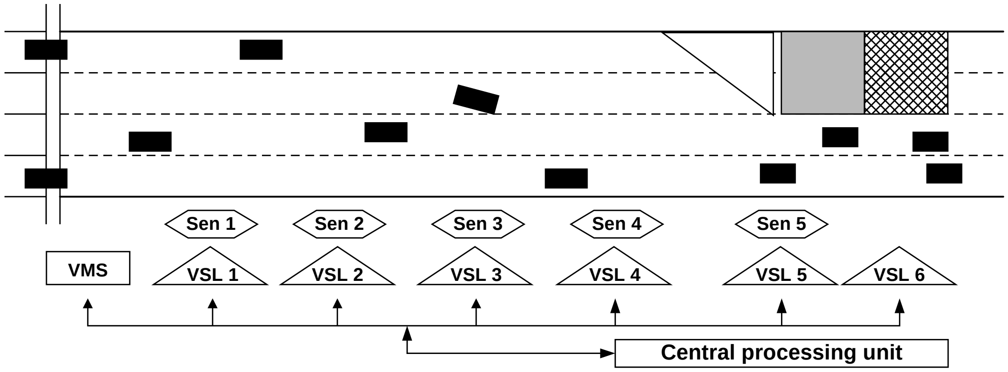

FIGURE 1 Configuration of a VSL system.

control is thus to maximize the total throughput from the work zone, but subject to some predefined safety constraints.

To perform an optimal dynamic VSL control, a set of traffic models must capture the complex interactions between traffic-state evolution and all control parameters. In particular, those traffic-state evolution equations should be mathematically formulated to represent the actual operational constraints. As recognized in many studies (*8–10*), traffic density and speed have been taken as state variables, of which the former is a key factor affecting drivers' choice of speed and the VSL system's selection of appropriate speed limits.

Our proposed optimal control VSL algorithm for work zone operations includes the following variables and parameters:

- Control time and subsection index
  – T: Unit time interval for control operations (e.g., 1 min, 5 min, 10 min, etc.),
  – k: Time interval index, and
  – i: Subsection index ($i = 1, 2, \ldots, N$).
- Network geometric and physical data
  – l_i: Length of subsection i and
  – n_i: Number of lanes in subsection i.
- Traffic volumes
  – $q_i(k)$: Transition flow rate entering subsection $(i-1)$ from subsection i during interval k and
  – $Q_i(k)$: Average flow rate in subsection i during interval k.
- Model parameters
  – α_i: Transition flow weight factor,
  – β_i: Speed–density-equation adjustment factor, and
  – γ_i: Shock-wave weight factor.
- Control variables
  – $v_i(t)$: Variable speed limit ratio in subsection i during interval k.
- State variables
  – $d_i(k)$: Mean traffic density in subsection i during interval k,
  – $d_i^j(k)$: Jam (maximum) traffic density in subsection i during interval k,
  – $u_i(k)$: Mean speed in subsection i during interval k, and
  – $u_i^f(k)$: Free flow (boundary) speed in subsection i during interval k.

With the above variables and parameters, first it is necessary to use the conservation law to approximate the evolution of dynamic density (*8*). The temporal variation of mean density, $d_i(k)$, during each control time interval (T) is determined by the difference between the input and output flows, $q_{i+1}(k)$ and $q_i(k)$, at the subsection boundaries and can be presented as follows:

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

In addition, the transition flow between adjacent subsections is taken as a weighted average of two neighboring subsections flows. That is,

$$q_i(k) = \alpha_i \cdot Q_i(k) + (1-\alpha_i) \cdot Q_{i-1}(k) \tag{2}$$

where α_i is the model parameter (i.e., transition flow weight factor) that can be calibrated with field measurements. Wu and Chang (*9*) stated that it should lie within the interval [0.5, 1.0]. Cremer and Schoof (*10*), for example, calibrated it to be 0.95 with field data.

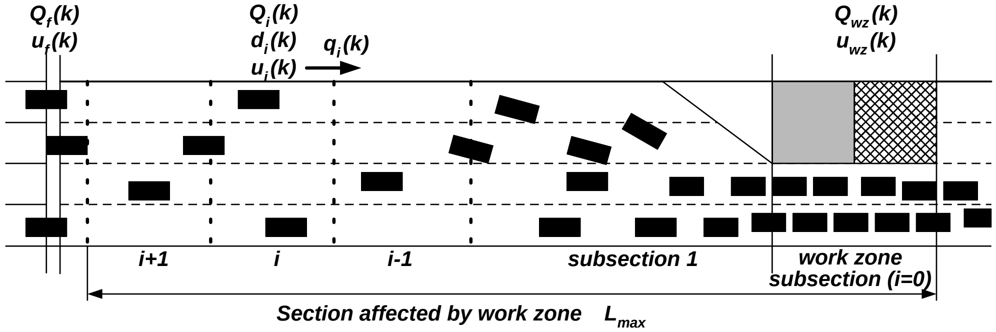

FIGURE 2 Typical freeway work zone.

For the average speed, $u_i(k)$, one can also establish its evolution relation with the following properly selected speed–density relation and shock-wave formation equations:

$$u_i(k) = u_i(k-1) + \beta_i \cdot \{S[d_i(k-1), v_i(k-1)] - u_i(k-1)\} + \gamma_i \cdot w_i(k-1) \tag{3}$$

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

$$S[d_i(k), v_i(k)] = [u_{i+1}^f(k) \cdot v_i(k)] \cdot \left[1 - \frac{d_i(k)}{d_i^J(k)}\right] \tag{4}$$

This equation is originally formulated with the Greenshields model and can be modified to account for the linear interaction between $d_i(k)$ and $v_i(k)$; and the third component takes into account the shock wave between downstream $(i-1)$ and upstream (i), that is,

$$w_i(k) = \frac{Q_{i-1}(k) - Q_i(k)}{d_{i-1}(k) - d_i(k)} \tag{5}$$

Model parameters β_i and γ_i are speed–density equation adjustment factor and shock wave weight factor, respectively. Note that the actual average speed measured from detectors doesn't usually fit with the proposed linear speed–density equation. Thus, based on the difference between the calculated and measured speeds during the previous time interval $(k-1)T$, the average speed needs to be adjusted with β_i during the time interval kT. In addition, γ_i is required to include the impact of the shock wave on the subsequent upstream subsections.

With the above formulations, we can construct the control model for highway work zone operations to optimize the variable speed limit. Although there are several performance measures for highway control, we have employed the maximization of the total throughput as the main measure of effectiveness (MOE) for the proposed highway work zone operation system. Thus, one can express the objective function as follows:

$$\max \sum_k \left(\sum_i^N [q_{wz}(k) + Q_i(k)] \cdot T \right)$$

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 objective is shown below:

- Dynamic constraints: Equations 1 through 5 and
- Boundary constraints:

$$0 \le d_i(k) \le d_i^J \tag{6}$$

$$u_{i-1}^f \le u_{i+1}^f(k) \cdot v_i(k) \le u_{i+1}^f \tag{7}$$

$$0 \le v_i(k) \le 1 \tag{8}$$

Note that we fully recognize the likely nonlinear 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 of efficient on-line operations, our proposed model has approximated speed–density with a linear function but constantly updated it with the differences between field measured speeds (i.e., from detectors) and the model output and also adjusted the results with the embedded parameters. With such an algorithm, the need is circumvented to solve a nonlinear formulation that may or may not have a solution and is certainly not sufficiently fast for real-time operations.

VSL CONTROL ALGORITHM

Figure 3 presents the principal steps for executing the proposed control algorithm for VSL operations, including the interactions among

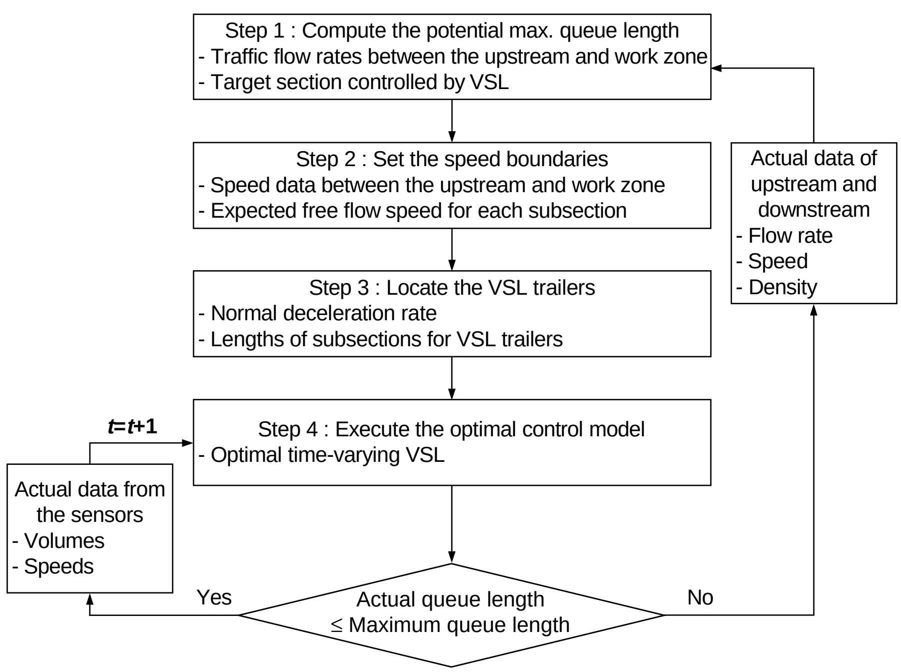

FIGURE 3 Step-by-step description of dynamic algorithm for the VSL control.

sensors, VSL, and the feedback process. 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.

Step 1: Compute the Potential Maximum Queue Length

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

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 subsection *i*. This boundary is designed to prevent the optimal speed limit of subsection *i* from exceeding the boundary of its upstream subsection ($i + 1$). 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 on the basis of the average deceleration rate of drivers when they perceive each displayed VSL sign. By using a normal deceleration rate, for example, $a = 3.3$ mph/s (*11*, pp. 168–169), the target section can be divided into *n* subsections (i.e., x_i) as follows:

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

This is to ensure that when perceiving the VSL signs, drivers need not experience uncomfortable and unsafe deceleration rate because the normal deceleration rate is calculated with the assumption of taking smooth speed reduction.

Step 4: Execute the Optimal Control Model

Finally, Step 4 is to optimize a set of VSL over all subsections during each control time interval based on the linear programming (LP) formulations shown in the third section. As mentioned in Step 1, if the actual queue length is longer than the computed 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 EXPERIMENTS

Design of Simulated System

The system design for simulation experiments is based on the actual highway work zone traffic conditions. All system parameters (e.g., rubbernecking factor, car-following sensitivity factor, and desired free-flow speed) need to be calibrated with the real work zone data. The work zone throughput, based on a total of 93 sites reported in the literatures (*12–17*), is summarized in Table 1.

Although the ranges of some work zone types are widely scattered because of differences in surveys, one can approximate their distributions of maximum throughput as follows:

- Type 2-1: 1,500 to 1,600 vehicles per hour per lane (vphpl),
- Type 3-1: 1,400 to 1,500 vphpl,
- Type 3-2: 1,300 to 1,500 vphpl,

TABLE 1 Work Zone Throughput Data Measured in Previous Studies

Type*	Work Zone Throughput (vphpl)									Sources
	1000	1100	1200	1300	1400	1500	1600	1700	1800	
2-1		2	5	6	5	7	8	1		Dixon et al. (*12*) Krammes and Lopez (*13*) Dudek and Richards (*14*) Kermode and Myyra (*15*) Jiang (*16*)
3-1					3	5				Dudek and Richards (*14*)
3-2	3	1		4	4	3	1			Krammes and Lopez (*13*) Dudek and Richards (*14*)
4-1		1	1	3	2	5	6	2		Krammes and Lopez (*13*) Dudek and Richards (*14*) Kermode and Myyra (*15*) Lovell et al. (*17*)
4-2			4		9	1			1	Krammes and Lopez (*13*) Dudek and Richards (*14*) Lovell et al. (*17*)
Sum	93									

* 2-1 (the number of total lanes – the number of closed lanes)

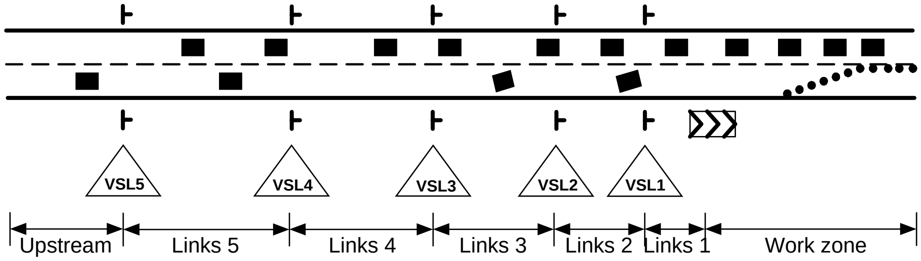

FIGURE 4 Example of typical work zone configuration (2 lanes, 1-closed type).

- Type 4-1: 1,500 to 1,600 vphpl, and
- Type 4-2: 1,200 to 1,400 vphpl.

Figure 4 illustrates an example work zone system for simulation experiments, in which one lane was closed on a two-lane highway due to work zone activities. The maximum link speed limit and the length of work zone area are set to be 65 mph and 4,000 ft, respectively. This system has been simulated for 1 h with a microscopic traffic-simulation model, CORSIM, produced by FHWA (*18*).

The maximum throughput through the simulated system was then compared with the empirically observed throughput (i.e., 1,500 to 1,600 vphpl) for calibration of simulation-model parameters that reflect driver behavior, such as rubbernecking factors and car-following factors. A simulated work zone system will be used in the VSL evaluation only after the completion of its parameter calibration.

Simulation of On-Line Control Process

To simulate the on-line work zone control with our VSL algorithm, we employ a CORSIM–RTE (CORridor SIMulation–Run-Time Extension), a program designed to capture the on-line interaction between execution of the control algorithm and the time-varying traffic conditions due to the control operations. This mechanism has been programmed to provide three main functions (i.e., initialization, VSL control, and termination), which enable our developed optimal VSL module to communicate with CORSIM during every time interval *k*. Figure 5 illustrates the interaction process among CORSIM, linear-optimization program, and the VSL algorithm.

More specifically, with the interactive process shown in Figure 5, this system continues to simulate the work zone condition at each unit time interval *k* (e.g., 60 s), and feeds back to RTE to generate a set of optimal speed limits for each subsection *i* during subsequent control intervals. Such interactive procedures will be repeated for the entire simulation time period (e.g., 1 h). Note that Lindo–API is a linear-optimization program used to solve the optimal set of speed limits for all controlled subsections during each control interval.

Evaluation of the Performance of the VSL Model

To evaluate the proposed VSL model, the study employed the work zone maximum throughput, average delay, and speed as the critical MOEs. 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 that is often correlated significantly with traffic safety. The total throughput is detected at the middle point of the work zone while the average delay and speed are obtained over the prespecified subsections (i.e., Link 1 to Link 5) in advance of the work zone (see Figure 4).

To investigate the performance of this proposed VSL under different traffic conditions, the simulation experiments have included five types of work zones and various traffic-volume levels as shown in Table 2.

Tables 3 to 5 show the comparisons of work zone throughput, average delay, and average speed, respectively, from the simulation

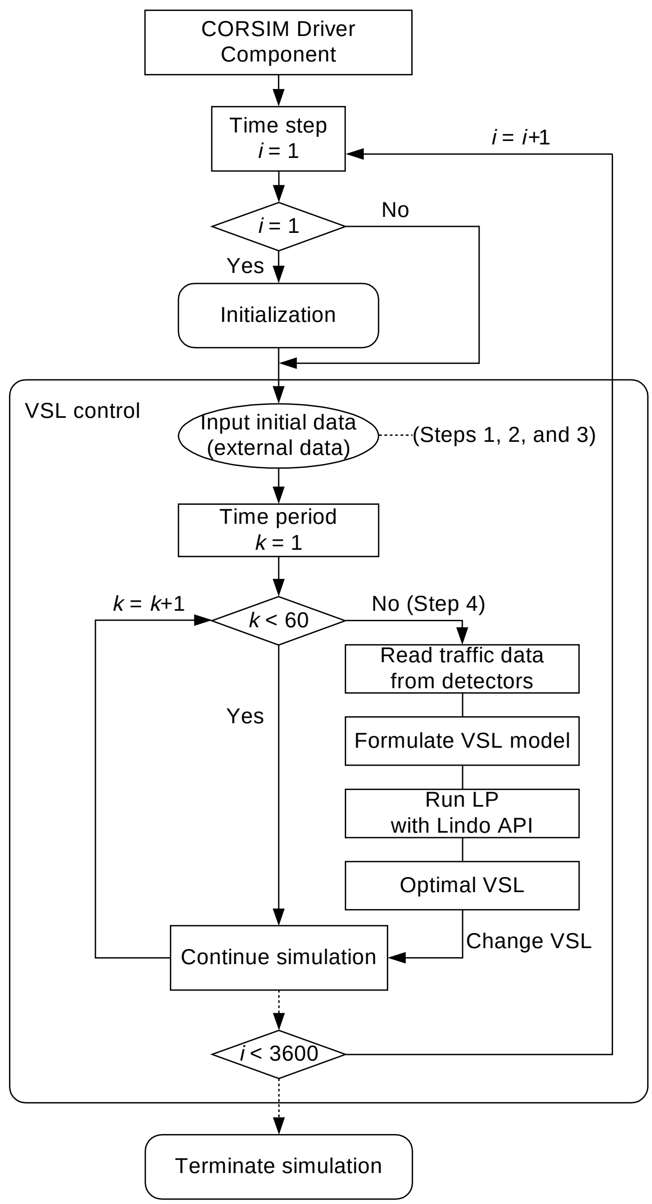

FIGURE 5 Interfacing mechanism for executing the VSL algorithm.

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
4-1	5500	8000	500
4-2	4000	6500	500

results. These results seem to clearly demonstrate the effectiveness of the proposed VSL optimization model.

For example, as shown in Table 3, under the normal level of upstream volume, the proposed control model can increase approximately 310 vphpl of work zone throughput in Type 2-1, 260 vphpl in Type 3-1, 250 vphpl in Type 3-2, 270 vphpl in Type 4-1, and by 200 vphpl in Type 4-2. Likewise, Table 4 indicates that, under the normal level of upstream volume, the VSL model can reduce about 560 s of the average delay per vehicle for traffic through the work zone in Type 2-1, 230 s in Type 3-1, 300 s in Type 3-2, 270 s in Type 4-1, and 290 s in Type 4-2. With respect to the average speed, the results in Table 5 indicate that the implementation of VSL does not result in a substantial reduction in the average speed under various approaching traffic volumes.

However, it should be noted that as the upstream traffic volume increases, the improvement in each MOE with VSL (e.g., work zone throughput and average delay) first increases and then decreases. This means that the proposed VSL algorithm should again be reset based on Steps 1 to 3 because the actual queue length has exceeded the initially estimated maximum queue length (Figure 3). It should also be noted that the benefits of implementing VSL control seem to diminish from moderately congested to heavy-traffic conditions. Thus, it is expected that under oversaturated traffic jam conditions, the benefits of implementing VSL may not justify its operating costs.

For convenience of illustration, Figures 6 to 8 present the differences in MOEs (e.g., work zone throughput, average delay, and average speed, respectively) under the VSL control in the Type 2-1 work zone.

As reflected in those graphical results, under the normal level of the upstream volume (e.g., 3,500 vph), the presented VSL optimization model can increase the throughput by 310 vphpl and reduce an average delay per vehicle by 560 s for traversing over the work zone area (Figures 6 and 7). As mentioned previously, Figure 8 proves that the speed differences between no-VSL and VSL controls are not significant. This indicates that our VSL control strategy does not slow down the average flow speed despite the speed limitation.

TABLE 3 Work Zone Throughput (vphpl)

Volume Levels	Work Zone Types									
	2-1		3-1		3-2		4-1		4-2	
	No-VSL	VSL	No-VSL	VSL	No-VSL	VSL	No-VSL	VSL	No-VSL	VSL
2500	1477	1430			1497	1430				
3000	1520	1553			1512	1761				
3500	1561	1875			1570	1732				
4000	1582	1820	1436	1371	1469	1538			1297	1250
4500	1476	1489	1443	1419	1410	1424			1304	1318
5000			1444	1694	1388	1368			1387	1461
5500			1579	1729			1547	1528	1323	1526
6000			1571	1682			1608	1593	1444	1521
6500			1395	1383			1558	1824	1392	1449
7000							1596	1840		
7500							1522	1687		
8000							1503	1592		

TABLE 4 Average Delay (s/vehicle)

Volume Levels	Work Zone Types									
	2-1		3-1		3-2		4-1		4-2	
	No-VSL	VSL	No-VSL	VSL	No-VSL	VSL	No-VSL	VSL	No-VSL	VSL
2500	801.8	875.0			871.2	938.8				
3000	1205.4	1005.0			1282.8	1039.4				
3500	1661.2	1097.0			1535.8	1237.5				
4000	1825.4	1412.2	624.7	648.1	2080.6	1926.5			656.0	810.0
4500	2107.8	2084.1	1025.6	1141.1	2460.6	2383.8			1170.0	1159.2
5000			1362.2	1255.8	2702.5	2686.1			1518.9	1326.0
5500			1631.5	1400.0			489.5	501.6	1639.0	1348.1
6000			1962.0	1683.5			689.2	694.7	1801.2	1550.0
6500			2150.5	2272.0			1040.8	812.3	2090.4	1941.8
7000							1256.9	987.4		
7500							1529.4	1203.8		
8000							1766.3	1641.1		

TABLE 5 Average Speed (mph)

Volume Levels	Work Zone Types									
	2-1		3-1		3-2		4-1		4-2	
	No-VSL	VSL	No-VSL	VSL	No-VSL	VSL	No-VSL	VSL	No-VSL	VSL
2500	37.8	34.7			43.3	37.8				
3000	27.0	27.1			35.4	36.7				
3500	20.0	25.1			30.7	31.4				
4000	16.5	19.7	40.1	37.6	23.2	22.8			39.6	35.2
4500	14.2	13.9	33.4	31.3	19.0	18.6			31.4	32.0
5000			26.7	27.2	15.8	15.6			25.4	24.1
5500			21.2	20.9			46.3	43.8	20.9	20.0
6000			17.0	16.5			41.4	40.2	18.1	17.9
6500			13.4	12.7			35.4	34.6	15.7	14.9
7000							29.7	29.0		
7500							25.6	24.9		
8000							20.1	19.8		

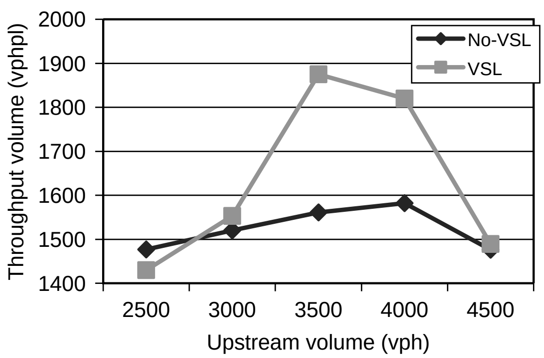

FIGURE 6 Work zone throughput volume for Type 2-1.

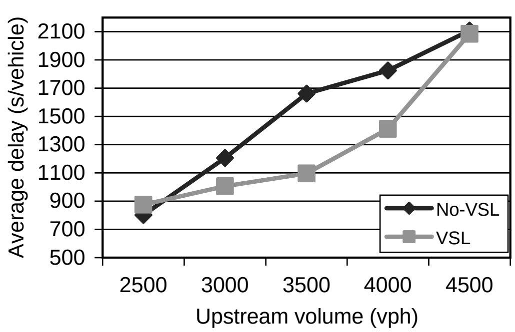

FIGURE 7 Average delay over subsections for Type 2-1.

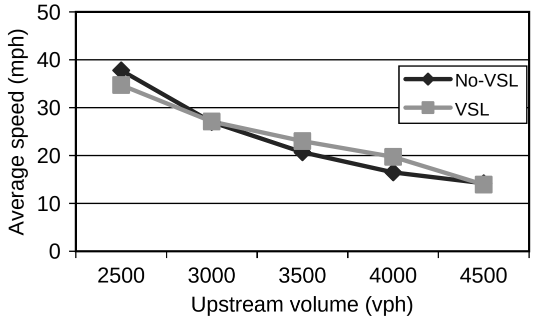

FIGURE 8 Average speed over subsections for Type 2-1.

Although the operational efficiency can be evaluated on the basis of those three MOEs, it is actually difficult to evaluate the improvement in safety because accident data cannot be realistically captured with simulation. Instead, as mentioned previously, this study has used the speed variance over each subsection as an indicator for reflecting the traffic-safety-related environment.

Table 6 reports the comparison results of speed variances over three links (i.e., Links 1 to 3) in advance of the work zone, where the average-speed data were obtained over each time interval from the detectors. It is notable that most speed variances under the VSL control are lower than those under the no-VSL situation at four levels of traffic volume. The low speed variance along with an increased throughput seems to indicate that the proposed VSL algorithm can help drivers pass the work zone safely and efficiently.

CONCLUSIONS

This paper has presented an optimal variable speed-limit control model and algorithm for highway work zone operations, based on the evolution of dynamic traffic states and macroscopic traffic characteristics. For on-line applications, some nonlinear traffic-flow relations have been approximated with linear functions but updated continuously from on-line detector data. To reflect the need of improving traffic safety, a set of speed boundaries has been given as model constraints. Moreover, the normal deceleration rate has been used in determining the length of each subsection, which is to ensure that drivers can reduce their speeds at an acceptable braking rate in response to those displayed VSL signs.

The proposed model with a proper set of parameters has demonstrated that under normal traffic conditions, it can increase the throughput over the work zone and reduce the average delay over upstream segments of the lane-closure location. The simulation results have also indicated that although the average speeds under the VSL control do not vary significantly for those under no-VSL control, the resulting speed variance among those vehicles traveling over the work zone is substantially lower than that under no-control scenarios.

In brief, the proposed VSL control seems to offer a promising alternative for contending with congestion and safety-related issues. Further studies along this line will be focused on developing the optimal control algorithm for each type of work zone operation and collecting extensive field data for further model testings as well as enhancements.

TABLE 6 Comparisons of Speed Variances (Standard Deviations)

Volume Levels	Work Zone Types									
	2-1		3-1		3-2		4-1		4-2	
	No-VSL	VSL	No-VSL	VSL	No-VSL	VSL	No-VSL	VSL	No-VSL	VSL
2500	25.2	19.0			27.1	20.2				
3000	19.1	15.7			25.0	19.1				
3500	16.9	16.0			22.7	18.0				
4000	15.1	14.0	29.6	23.8	19.3	15.3			32.0	27.4
4500	17.4	14.4	26.5	22.8	17.0	13.6			29.3	25.9
5000			23.7	19.0	14.8	12.1			22.5	19.8
5500			20.7	17.6			34.9	29.7	18.8	15.5
6000			18.8	14.2			32.0	27.4	16.3	13.6
6500			15.7	13.2			29.9	26.0	11.6	8.8
7000							25.4	22.7		
7500							20.9	17.7		
8000							12.0	9.0		

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