A Robust Model for Optimal Time-of-Day Speed Control at Highway Work Zones

Kyeong-Pyo Kang and Gang-Len Chang

***Abstract*—This paper proposes a new speed control strategy, named time-of-day speed limit (TOD SL) control, for highway work-zone operations. The main purposes of the TOD SL control are to overcome the difficulty in setting the optimal real-time speed limit due to the lack of detectors and to maximize the use of available data such as the historical volume data on the target work zone. Its core logic is to divide the entire day of operations into a number of control periods and to accommodate the time-varying traffic conditions within each control period. The measure of effectiveness (MOE) selected in the TOD SL model takes into account both the operational efficiency and traffic safety. To encompass all possible traffic conditions during each control period, the control model employs traffic flow relations calibrated from historical data to estimate the speed and density data with available volume under possible traffic scenarios. The performance of the proposed TOD SL control has been evaluated with the simulation experiments and compared with the other speed control strategies based on the selected measures of effectiveness.**

***Index Terms*—Posted speed limit, robustness approach, time-of-day speed control, variable speed limit, work-zone operation.**

I. INTRODUCTION

IT HAS BEEN recognized by traffic professionals that speed control is one of the most effective strategies to improve both operational efficiency and safety in highway work zones under congested traffic conditions. However, most speed controls, in practice, are static in nature and are used mainly to post the regulatory speed limits, which are referred to as the posted speed limit (PSL) at upstream subsegments of a work zone during the operational period [1], [2]. Examples of procedures for such speed control at work zones can be found in the National Cooperative Highway Research Program (NCHRP [3]) and research articles in related literatures [2], [4]. The common focus of those existing studies [5], [6] for the PSL control is on safety improvement, rather than on maximizing the operational efficiency or on minimizing the delay.

In view of the increasing congestion in most urban networks and the significant delay incurred by frequent work-zone operations, some researchers and engineers have started the development of a variable speed limit (VSL) control system that aims to concurrently improve both traffic safety and operational efficiency (e.g., maximizing throughputs) with a dynamically adjusted optimal set of speed control that covers the entire upstream subsegments impacted by the work-zone operations. Such VSL control strategies [7]–[9] with properly coordinated messages have been proven to achieve promising performance and significantly outperform the PSL control with respect to both total throughputs and speed variance [9]. However, an effective operation of such a VSL control depends on an extensive deployment of traffic sensors and a sufficient number of portable changeable message sign (PCMS) to dynamically display coordinated messages. Both the hardware and communication costs for such operations could be quite high for a long period of work-zone projects.

To overcome substantial limitations of the PSL control and take advantage of the VSL functions, this paper presents an optimal time-of-day speed limit (TOD SL) control method. The proposed TOD SL control recognizes the time-varying nature of traffic volume to the work zone and divides the entire day of operations into a number of control periods. The TOD SL system will then employ precalibrated traffic flow models to estimate the speed and density data during each control period based on its volume. The estimated traffic characteristics are subsequently used in computing the optimal control speed for each time period. Through such a computing process, one can develop a set of optimal speed limits for the work zone over different time periods of a day, which shall be able to achieve a substantial increase in the overall throughputs and significant reduction in speed variances.

II. METHODOLOGY FOR THE TOD SL DEVELOPMENT

As indicated in Section I, the main motivation of the TOD SL control is to overcome the difficulty in setting the optimal time-varying speed limit due to the lack of detectors. It is proposed to maximize the use of limited available data (e.g., historical volume data) and to generate a set of optimal speed limits for time-of-day periods. Fig. 1 presents the flowchart for developing such a control strategy. Principal activities and computational work associated with each step are detailed below.

Fig. 2 illustrates a typical segment of the highway work zone, which is divided into several subsegments in the upstream of the lane-closed area.

A. *Step 1: Divide the Entire Day Into a Set of Control Periods*

Each control period can be defined as a set of time-of-day periods (p) under the TOD SL operation. Ideally, the traffic condition within each control period should be as uniform as

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The authors are with the Applied Technologies and Traffic Analysis Program, Department of Civil and Environmental Engineering, University of Maryland, College Park, MD 20742 USA (e-mail: kpkang@wam.umd.edu; gang@Glue.umd.edu).

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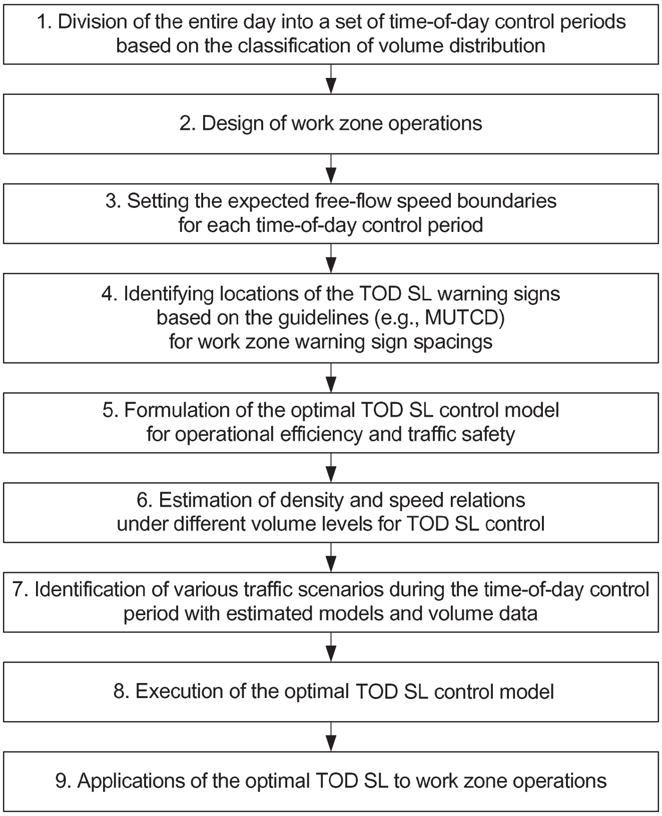

Fig. 1. Procedures for developing the TOD SL control.

possible. For example, the entire day can be divided into a set of time-of-day periods, and the target work zone in each time period shall have the minimal volume variation. An example for setting the control periods with historical volume data is presented in Section III.

B. Step 2: Design the Work-Zone Operations

It should be mentioned that if the actual queue is beyond the last sign (from the beginning of the lane closure), drivers may not know which lane is closed and what speed to follow. Some drivers may choose to overtake the preceding vehicles through the closed lane. Such maneuvers may decrease the performance of the speed limit control and increase the potential of having accidents such as rear-end collision. Thus, the purpose of this step is to approximate the maximum queue length during each time-of-day control period (p) and use such information to set the target segment by the TOD SL control.

C. Step 3: Set the Speed Boundaries for Each Time-of-Day Period

This step is designed to set a speed boundary (u_i^f; see Fig. 2 and Table I) that reflects the free flow speed of the upstream subsegment (i) during each time-of-day period (p). By setting $u_i^f > u_{i-1}^f$ (see Fig. 2), the specified set of optimal TOD SL under these constraints will enable drivers to smoothly adjust their speeds until reaching the lane closure location.

D. Step 4: Locate the TOD SL Warning Signs

As shown in Fig. 2, the locations of TOD SL signs can be determined based on the guidelines of the Manual on Uniform Traffic Control Devices, Part VI (MUTCD [2]) for work-zone operations. However, the distance between neighboring signs should be determined based on the maximum queue length computed in Step 2.

E. Step 5: Formulate the Optimal TOD SL Control Model

The purpose of this step is to select the measure of effectiveness (MOE) for the highway work-zone operations and to formulate the entire TOD SL control. The selected MOEs shall take into account both the operational efficiency and traffic safety in the TOD SL control. The notation and definitions of all model variables and parameters used hereafter are given in Table I.

Note that this study employs the maximization of total throughput over all upstream subsegments and the work-zone subsegment as the main MOE. This is to ensure that no bottleneck may exist in some upstream subsegments due to unregulated or aggressive lane-changing maneuvers. Also note that since the interval for real-time operations of the dynamic model is no longer applicable in TOD SL, the original VSL optimization model [9], [10], under a given traffic scenario (s) for the time-of-day period (p), can be modified as

$$w^s = f\left(X_i^s, D_i^s\right) = \max \sum_i^N \left[q_{\mathrm{WZ}}^s + Q_i^s\right] \cdot T \tag{1}$$

where X_i^s is the speed limit ratios for a given traffic scenario s in subsegment i, D_i^s is the set of possible traffic scenarios (i.e., $s = \mathbf{1}, \mathbf{2}, \ldots, M \in D_i^s$) in subsegment i, $q_{\mathrm{WZ}}^s (= Q_0^s)$ is the work-zone downstream boundary flow for a given traffic scenario s, $Q_i^s = (u_i^s \cdot d_i^s)$ is the average flow rate, the product by average speed (u_i^s), and density (d_i^s) for a given traffic scenario s in subsegment i, and $u_i^s (= u_i^{s,f} \cdot X_i^s)$ is the average speed defined as the product of the free-flow speed $(u_i^{s,f})$ and speed limit ratio (X_i^s) for a given traffic scenario s in subsegment i.

In order to generate the optimal speed limit over all possible traffic scenarios (D_i^s) in subsegment i for each time-of-day control period (p), the subsequent task is to determine the objective function of the TOD SL model with the selected MOE [i.e., (1)]. This study uses the minmax criterion of deviation between the deterministic function $f(X_i^s, D_i^s)$ for a given scenario (s) and the potential throughput maximization function $f(X_i^*, D_i^s)$ for all realizable traffic scenarios. This leads to generate one (X_i^*) that exhibits the best worst case of deviations from optimality among all feasible control variables over all realizable traffic scenarios during each time-of-day period (p), and this can be mathematically formulated as follows.

1) Objective Function: Based on the above minmax criterion, the objective function of the proposed TOD SL optimization model can be formulated as

$$w_D = \min y \tag{2}$$

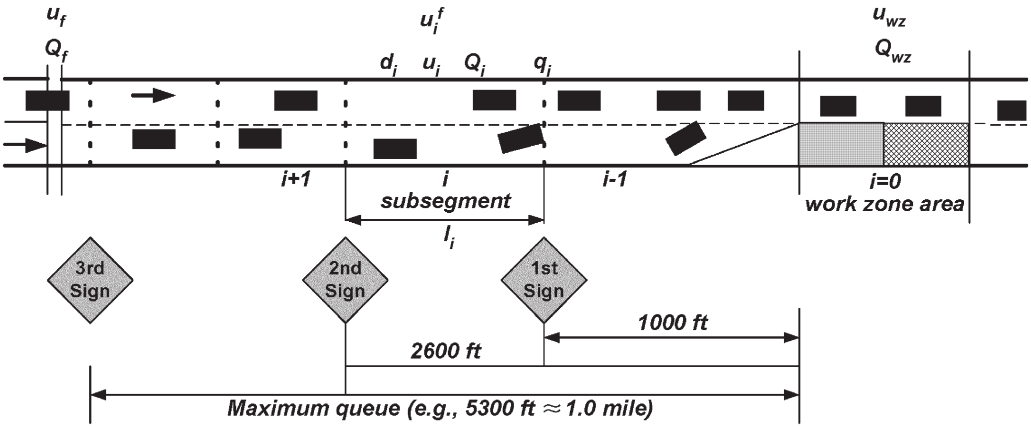

Fig. 2. Typical segment of highway work zone.

TABLE I
DEFINITION OF SYSTEM VARIABLES

- Control time, subsegment, time-of-day period, and traffic scenario index
  - T : Unit time interval for control operations (e.g., 1 hour)
  - i : Subsegment index ($i = \mathbf{1}, \mathbf{2}, \cdots, N$, where $i = WZ$ means work-zone subsegment.)
  - p : Time-of-day period index
  - s : A potential realizable traffic scenario ($s = \mathbf{1}, \mathbf{2}, \cdots, M$)
- Network geometric and physical data
  - l_i: Length of subsegment i
  - n_i: Number of lanes in subsegment i
- Traffic volumes
  - q_i^s: Transition flow rate entering subsegment (i+1) from subsegment i for a given traffic scenario s
  - Q_i^s: Average flow rate for a given traffic scenario s in subsegment i
- Model parameters
  - α_i: Transition flow weight factor in subsegment i
  - β_i: Speed-density equation adjustment factor in subsegment i
  - γ_i: Shockwave weight factor in subsegment i
- Decision variables
  - X_i^s: Speed limit ratio for a given traffic scenario s in subsegment i
- State variables
  - d_i^s: Mean traffic density for a given traffic scenario s in subsegment i
  - $d_i^{e,s}$: Estimated mean traffic density for a given traffic scenario s in subsegment i
  - $d_i^{j,s}$: Maximum (jam) traffic density for a given traffic scenario s in subsegment i
  - u_i^s: Mean speed for a given traffic scenario s in subsegment i
  - $u_i^{e,s}$: Estimated mean speed for a given traffic scenario s in subsegment i
  - $u_i^{f,s}$: Free flow (boundary) speed for a given traffic scenario s in subsegment i

such that

$$\sum_{i}^{N} [q_{\mathrm{WZ}}^s + Q_i^s] \cdot T \geq w^s - y, \qquad s = 1, 2, \ldots, M \in D_i^s \quad (3)$$

which means that $y = \max_{s \in D^s} [f(X_i^s, D_i^s) - f(X_i^*, D_i^s)]$ and X_i^* is a set of our optimal control variables (i.e., optimal speed limit ratios) over the subsegment i.

2) Traffic Flow Model Constraints: These constraints are a set of traffic flow models to represent the interrelations between density, flow rate, and speed at the work zone (see Table I and Fig. 2). That is, since neither entry nor exit ramp exists in the target highway segment, the mean density evolution in subsegment i can be expressed by the difference between transition flows [see (4)], based on the traffic flow conservation law, as

$$d_i^s = d_i^{e,s} + \frac{T}{l_i \cdot n_i} [q_{i+1}^s - q_i^s], \qquad s = 1, 2, \ldots, M \in D_i^s \quad (4)$$

where the transition flow between adjacent subsegments is taken as a weighted average of two neighboring subsegment flows [see (5)] as

$$q_i^s = \alpha_i \cdot Q_i^s + [\mathbf{1} - \alpha_i] \cdot Q_{i-1}^s, \qquad s = 1, 2, \ldots, M \in D_i^s. \tag{5}$$

The evolution relation of the average speed with density can be established by the carefully selected speed–density equation [see (6)] written as

$$u_i^s = u_i^{s,e} + \beta_i \cdot \{V[d_i^s, X_i] - u_i^s\} + \gamma_i \cdot \varpi_i^s \qquad s = \mathbf{1}, \mathbf{2}, \ldots, M \in D_i^s \tag{6}$$

where the second component [see (7)] describes an adaptation of the average speed to the speed–density characteristics with the linear approximation (e.g., Greenshields model) and the third component [see (8)] takes into account the average shock wave impacts between downstream $(i-1)$ and upstream (i) subsegments, which are written as

$$S[d_i^s, X_i] = \left[u_{i+\mathbf{1}}^{f,s} \cdot X_i\right] \cdot \left[\mathbf{1} - \frac{d_i^s}{d_i^{j,s}}\right], \qquad s = \mathbf{1}, \mathbf{2}, \ldots, M \in D_i^s \tag{7}$$

$$\varpi_i^s = \frac{\left[Q_{i-\mathbf{1}}^s - Q_i^s\right]}{\left[d_{i-\mathbf{1}}^s - d_i^s\right]}, \qquad s = \mathbf{1}, \mathbf{2}, \ldots, M \in D_i^s. \tag{8}$$

Model parameters β_i and γ_i are the speed–density equation adjustment factor and shock wave weight factor, respectively.

Note that the actual speed does not usually fit best with the linear equation (7). Thus, based on the differences between the estimated and actual speeds, the average speeds need to be adjusted with β_i. In addition, γ_i is required to include the impact of the shock wave on the subsequent upstream during the time-of-day period. A more detailed description of the model formulation procedure is available in the literature [9], [10].

3) Boundary Constraints: The constraints defined in (9)–(11) are needed to ensure that the subsegment densities and speed limit ratios are all within a reasonable range that can result in a smooth speed reduction

$$\mathbf{0} \le d_i \le d_i^j \tag{9}$$

$$u_{i-\mathbf{1}}^f \le u_i^f \cdot X_i \le u_{i+\mathbf{1}}^f \tag{10}$$

$$\mathbf{0} \le X_i \le \mathbf{1}. \tag{11}$$

F. Step 6: Collect Traffic Data Required for Optimizing the TOD SL Control

To reflect all possible traffic conditions during each time-of-day period (p), one needs traffic state data (e.g., speed and density) for use in the proposed TOD SL model. However, it should be noted that only the volume data of the target work-zone segment, in practice, is likely to be available for each time-of-day period (p). The best way to get those data is to develop or use estimated traffic flow models (e.g., speed–flow and density–flow relationships) applicable to the target work-zone traffic conditions. The example estimation of such models is discussed in the case study of Section III.

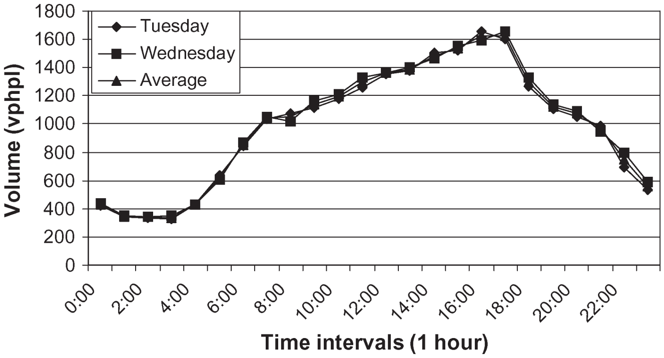

Fig. 3. Example volume distribution for normal days on the I-83 SB work zone.

G. Step 7: Design the Set of Possible Traffic Scenarios for Each Control Period

Using the developed or existing models, one can estimate the required traffic flow, speed, and density with the volume data during each time-of-day period, and then design the possible volume scenarios within each control period for optimizing the proposed TOD SL control. It should be mentioned that the range of each traffic data set should cover all possible traffic conditions during each time-of-day period (p). Examples for identifying possible traffic scenarios for the target freeway work zone are also available in Section III.

H. Step 8: Execute the TOD SL Control Model

With all possible traffic scenarios in each period, one can generate an optimal set of time-of-day speeds limits over all subsegments during each control period by solving the proposed TOD SL control model with a linear programming method.

I. Step 9: Apply the Optimal TOD SL Control to Highway Work-Zone Operations

As exploratory in nature, this study employs the simulation method to evaluate the performance of the proposed TOD SL based on critical MOEs for operational efficiency and traffic safety. The evaluation results in comparison with two other speed control strategies (i.e., PSL and VSL control strategies) are presented in Section IV.

III. CASE STUDY

This section discusses the procedures for developing the proposed TOD SL control in Section II, based on the work zone of one-lane closure on I-83 SB [11].

A. Identifying Time-of-Day Periods for Speed Control

Fig. 3 presents the available volume distribution on Tuesday and Wednesday [12] for this work zone. The first and second columns in Table II show a set of time-of-day periods and their corresponding volume ranges, respectively, for the TOD SL control.

TABLE II
TRAFFIC DATA FOR TIME-OF-DAY PERIODS

TOD No. (Time period)	Entry volume (vph)	Upstream point	Middle point	Merge point
1 (00:00 ~ 06:00)	600-1200	57-76 mph 4-8 vpmpl	53-74 mph 7-10 vpmpl	44-64 mph 12-19 vpmpl
2 (06:00 ~ 07:00, 21:00 ~ 24:00)	1201-2000	56-74 mph 7-13 vpmpl	53-65 mph 9-14 vpmpl	42-55 mph 17-31 vpmpl
3 (07:00 ~ 11:00)	2001-2500	57-70 mph 12-17 vpmpl	50-62 mph 12-18 vpmpl	40-36 mph 28-48 vpmpl
4 (11:00 ~ 14:00)	2501-3000	55-62 mph 15-22 vpmpl	45-51 mph 15-24 vpmpl	40-30 mph 41-66 vpmpl
5 (14:00 ~ 17:00)	3001-3600	44-54 mph 20-32 vpmpl	25-49 mph 22-55 vpmpl	22-30 mph 41-66 vpmpl
6 (17:00 ~ 21:00)	3601-4000	42-52 mph 30-41 vpmpl	30-34 mph 49-56 vpmpl	20-26 mph 56-66 vpmpl

B. Estimating the Relations Between Speed, Volume, and Density at Work Zones

This case study employs some empirical models to obtain traffic flow, speed, and density with the classified volume data (see Table II). Those models, developed through the following procedures, intend to capture traffic flow relations under the congested work-zone condition.

1) Estimation of Density Data Using the Extended Kalman Filtering (EKF) Method: To improve the estimation quality under congested traffic conditions, this study has performed the density estimation under the work-zone operations with the EKF algorithm [13], because most existing models address only the non-work-zone traffic flow relations and traffic density information cannot be measured directly from traffic sensors [13], [14].

2) Verification of the Estimated Density Data: The speed (u) and flow (q) models were developed using the observed field volume and speed data. Fig. 4 presents the speed–flow relations [15], [16] under the congested traffic condition (i.e., lower-limb), and such a relation can be represented with (12), written as

$$u = a_1 \cdot q + a_2 \cdot q^2. \tag{12}$$

3) Analysis of Traffic Flow Characteristics Under Work-Zone Conditions: With the statistical stability test, it has been found that the relations between density (d) and flow rate (q) vary with the evolution of traffic queues, the approaching flow rates, merging activities between lanes, and the capacity reduction due to the intensity of the lane-closure operations. Different equations will be needed to capture the flow–density relations under different conditions. Equations (13) and (14) were developed for such a purpose, based on the actual data. Figs. 5–7 present such relations at upstream [i.e, (13)], middle [i.e., (14)], and merge [i.e., (14)] points, respectively, ahead of the work zone. It should be noted that (14) has also been found to show significantly different model coefficients at locations of different distances (e.g., middle and merge points) to the lane-closure zone

$$q = b_{\mathbf{1}} d + b_{\mathbf{2}} d^{\mathbf{2}} \tag{13}$$

$$q = c_0 - \exp\left(c_1 + c_2 d^2 + c_3 d^3\right). \tag{14}$$

4) Observations of Work-Zone Traffic Conditions: As indicated in those empirical relations (see Figs. 4–7) between traffic flow parameters, there may exist a series of traffic jams and shock waves under the lane-closed work-zone operations. Those complex and unstable traffic flow patterns seem to be different from findings in previous studies [17], [18]. For example, the experimental data showed that the nearly stationary moving traffic jam can exist on the highway [17], and such a single jam and resulting shock wave can be eliminated or reduced with the dynamic speed control [18]. It should be noted that the stationary moving traffic jam may incur on a highway segment without any traffic interference (e.g., on- and off-ramp flows).

C. Design of Possible Traffic Scenarios Over Each Time-of-Day Period

With the models developed in the previous step, one can approximate the density and speed data with the available volume data for each time-of-day period. Table II summarizes the estimated traffic data for the proposed TOD SL control.

Finally, with those traffic data for each time-of-day period, all possible traffic scenarios can be identified for each time-of-day control period (p). Table III shows an example of traffic scenarios during the second control period (i.e., TOD 2).

To prove the robustness of the resulting solution, one needs to present the following definition: A solution $X^{s'^*}$ is said to dominate another solution $X^{s'}$ if and only if there exists a scenario $s' \in S$ such that $w_{D^{s'}}(X^{s'^*}) < w_{D^{s'}}(X^{s'})$ and $w_{D^{s'}}(X^{s'^*}) \leq w_{D^{s'}}(X^{s'})$. Table IV reports two objective function values, $w_{D^{s'}}(X^{s'^*})$ and $w_{D^{s'}}(X^{s'})$, under another scenario s' (e.g., average traffic flow data for each time-of-day period in Table II). Their comparison results indicate that the set of the speed

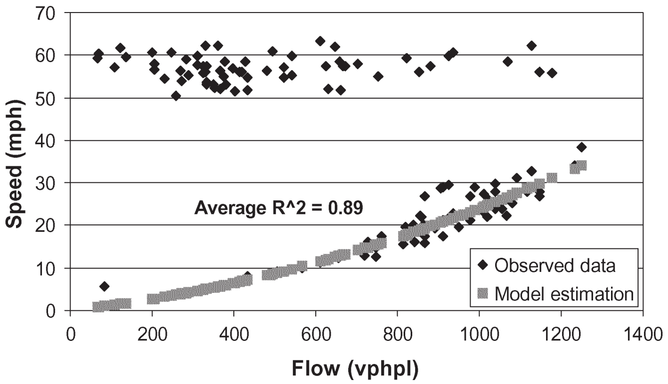

Fig. 4. Relation between speed and flow based on (12).

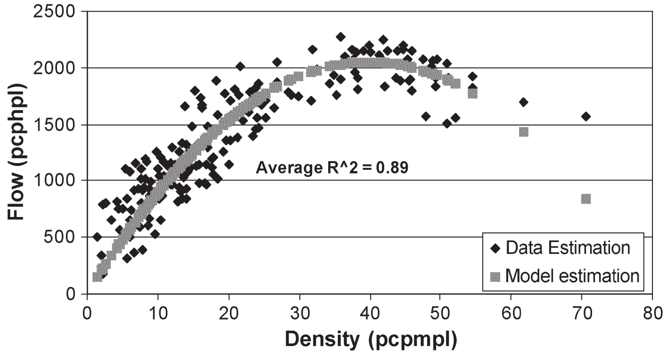

Fig. 5. Relation between density and flow at the upstream point based on (13).

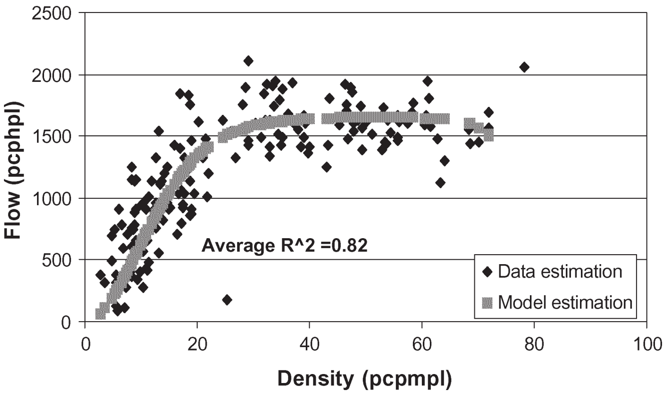

Fig. 6. Relation of density and flow at the middle point based on (14).

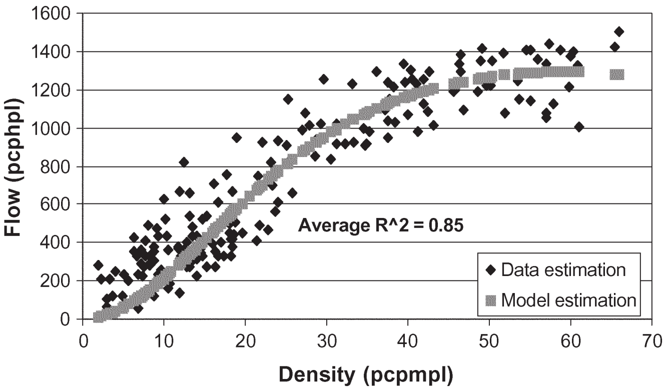

Fig. 7. Relation of density and flow at the merge point based on (14).

limits obtained from the proposed model is the robust optimal solutions.

D. Generating the Optimal Speed Limits for Time-of-Day Control Periods

After formulating the proposed TOD SL control model with those identified traffic scenarios, one can then execute the optimization problem for all time-of-day periods. Table IV shows a set of the optimal TOD SL for those three locations (merge, middle, and upstream) at the I-83 SB work zone (2–1 type, i.e., one-lane-closed work-zone operations of a two-lane highway).

IV. EVALUATION OF THE TOD SL CONTROL MODEL

To evaluate the effectiveness of the proposed TOD SL model, this study employs the simulation program CORSIM [19, version 5.10] to perform the comparison of the work-zone throughputs and other MOEs with and without the time-of-day control. Fig. 8 illustrates the target work-zone segment of I-83 SB, where the locations of the posted signs [e.g., portable changeable message sign (PCMS)] can be determined based on the previous studies [9], [10]. As a general rule, their distances should be sufficient for drivers to comfortably decelerate to the recommended speed and to make necessary speed transitions between neighboring subsegments.

As illustrated in Fig. 8, the proposed TDO SL system consists of three PCMSs, a variable message sign (VMS), and a central processing unit to execute control actions. PCMSs are used to display the enforced speed limit based on the TOD SL strategies, and the VMS is used to inform drivers of work-zone traffic information ahead. Depending on the time-of-day periods, the central processing unit that integrated all PCMSs and VMS will dynamically display the optimal TOD SL on each PCMS. Each set of the displayed speed limits is expected to reduce the impacts of some potential shock waves on the upstream subsegments during the corresponding time-of-day period, if some drivers are willing to follow the instruction when approaching the lane-closure area.

A. Design of Simulation Experiments for Model Evaluation

Prior to performing the comparison, the work zone modeled with CORSIM has been calibrated with the following information:

1) key simulation parameters:
    a) rubbernecking factor;
    b) car-following sensitivity factor;
    c) desired free-flow speed;
2) target traffic conditions to reflect the I-83 SB work-zone operations:
    a) work-zone throughput;
    b) average speed at the merging point.

Table V reports calibration results of the target work-zone highway segment.

TABLE III
EXAMPLE OF TRAFFIC SCENARIOS DURING THE SECOND CONTROL PERIOD

Possible scenarios #	Upstream			Middle			Merge		
	Vol. (vph)	Speed (mph)	Density (vpmpl)	Vol. (vph)	Speed (mph)	Density (vpmpl)	Vol. (vph)	Speed (mph)	Density (vpmpl)
1	1200	74	7	1200	65	9	1200	55	17
2	1300	72	8	1300	63	10	1300	53	19
3	1400	70	9	1400	61	11	1400	51	21
4	1500	68	10	1500	59	12	1500	49	23
5	1600	64	11	1600	57	12	1600	47	25
6	1700	60	12	1700	55	13	1700	45	27
7	1800	58	12	1800	55	13	1800	45	29
8	1900	56	13	1900	53	14	1900	44	31
9	2000	56	13	2000	53	14	2000	44	31

TABLE IV
OPTIMAL SPEED LIMITS FOR THE TIME-OF-DAY CONTROL PERIODS

TOD #	Speed limits (mph)			Objective function values (vphpl)	
	Merge	Middle	Upstream	$w_{D^{s'}}(X^{s'*})$	$w_{D^{s'}}(X^{s'})$
1	39.8	50.6	64.1	437.7	1110.7
2	38.9	47.1	60.5	161.4	1076.4
3	37.5	46.7	58.9	244.6	1001.8
4	27.4	38.3	55.0	292.1	959.9
5	28.0	36.8	42.8	256.2	781.2
6	16.1	29.0	40.0	375.5	496.9

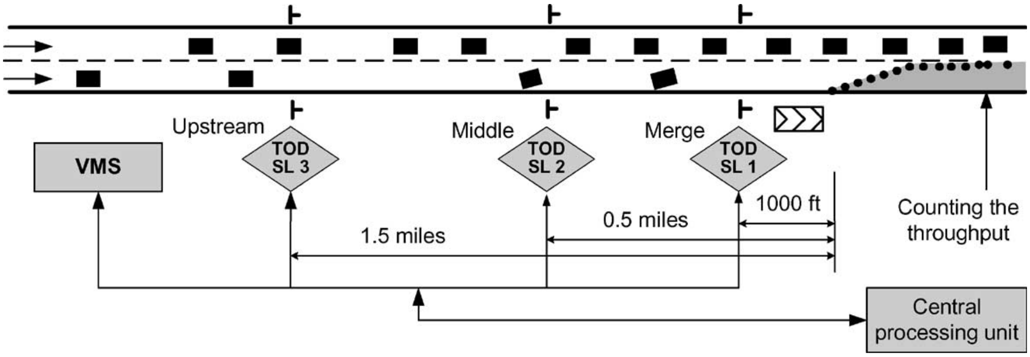

Fig. 8. Target work-zone configuration on I-83 SB (2–1 type).

B. Performance Comparison

In the simulation evaluation, we intend to explore the maximum effectiveness, if drivers are all willing to cooperate with the PSL, VSL, and TOD SL controls. Simulation experiments for performance comparison are designed as follows:

1) range of upstream volumes:
   a) TOD 1 to TOD 6 (see Table II);
2) output MOEs for comparison:
   a) operational efficiency: work-zone throughput, average speed, and average delay;
   b) traffic safety: speed variances;
3) control strategies for comparison:
   a) conventional PSL control (referred as no-control);
   b) VSL control [9], [10];
   c) TOD SL control.

The total throughput is detected at the middle point of the work-zone area (see Fig. 8), while the average delay and speed are obtained over those upstream subsegments in advance of the work-zone area. Figs. 9 and 10 summarize the comparison results with respect to both the throughput and average delay among those three types of control. The results have demonstrated that the proposed time-of-day control model clearly outperforms the no-control strategy and is close to the performance of the VSL control under those experimental scenarios.

With respect to the average speed, the results in Fig. 11 indicate that the implementation of TOD SL control does not lead to a substantial reduction in the average speed. Under the lower volume levels, the average speeds of no-control are higher than the other two controls, as both have imposed a set of constraints for reducing speed smoothly due to the safety concern. As the volume increases, however, the average speed

TABLE V
CALIBRATION RESULT FOR THE SIMULATED WORK-ZONE OPERATIONS: A VEHICLE (∗) WITH MORE THAN FOUR WHEELS TOUCHING THE PAVEMENT DURING NORMAL OPERATION (HIGHWAY CAPACITY MANUAL 2000)

Traffic conditions		Actual data	Simulation results	
			Before calibration	After calibration
Upstream volume		1475 vphpl	1490 vphpl	1493 vphpl
Heavy vehicle* percentage		24 %	24 %	24 %
Middle point	Average speed	31.0 mph	50.4 mph	34.3 mph
	Volume	1362 vphpl	1406 vphpl	1398 vphpl
Merge point	Average speed	24.0 mph	46.0 mph	22.6 mph
	Work-zone throughput	1310 vphpl	1380 vphpl	1288 vphpl

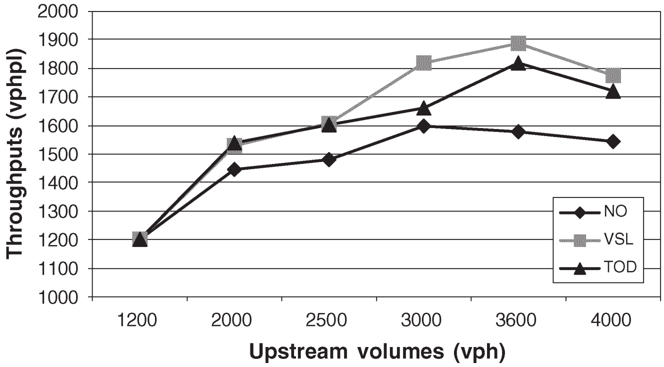

Fig. 9. Comparison of work-zone throughputs.

of the proposed TOD control reveals the same decreasing trend as with the VSL control.

Although one can evaluate the operational efficiency based on those three MOEs, it is difficult to evaluate the improvement on safety, because accidents data cannot be realistically captured with simulation. Instead, as mentioned previously, this study has used the speed variance as a substitute for assessing the resulting traffic safety.

Fig. 12 illustrates the comparison results of speed variation under those three types of control over subsegments in advance of the work-zone area. It is notable that as the volume increases, the speed variances under the TOD SL control decrease at a higher rate than the other two types of control results. The low speed variation along with an increased throughput clearly indicates that our proposed TOD SL model can help drivers pass the work zones safely as well as efficiently. The reason for having a lower speed variance than that under the VSL control is due to the fact that under the TOD SL control displays, the optimal speed limit varies only between control periods (e.g., 1 h), while the VSL control changes the optimal speed limit at every control interval (e.g., 1 min). This result is also supported by the previous study [20] that the use of an unjustified short time interval for dynamic speed control often results in frequent speed changes and may not contribute to the safety improvement.

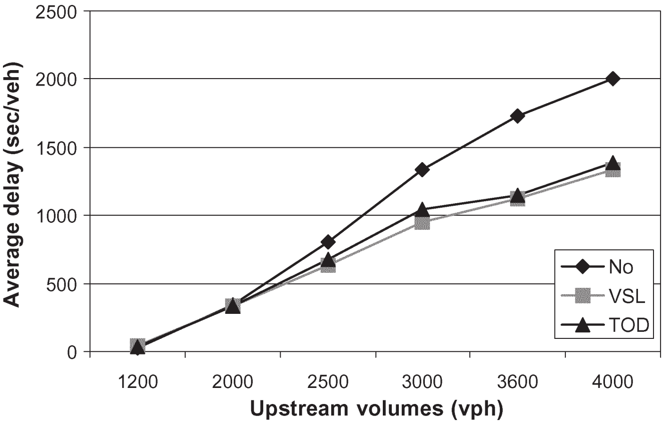

Fig. 10. Comparison of average delay over subsegments.

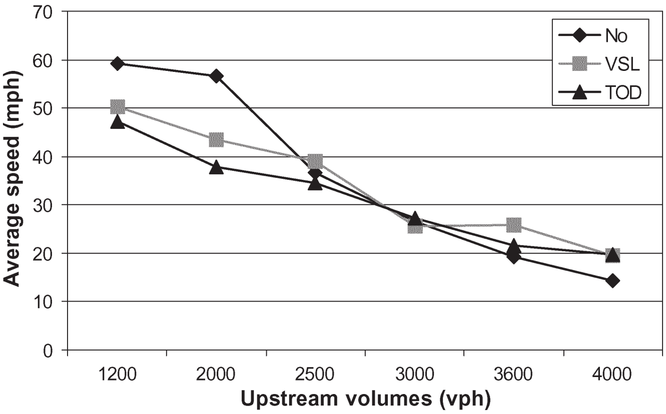

Fig. 11. Comparison of average speed over subsegments.

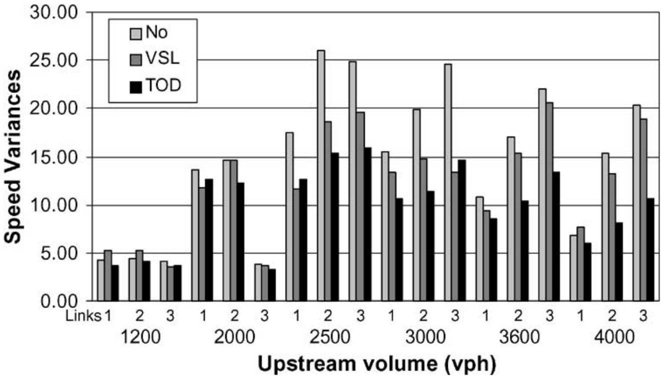

Fig. 12. Comparison of speed variances under three control strategies.

V. CONCLUSION

This paper has presented an optimal time-of-day speed control for highway work-zone operations. The proposed model can overcome substantial limitations embedded in the PSL control and take advantage of the functions provided by the VSL.

The core logic of the TOD SL control is to recognize the time-varying nature of traffic volume at the work zone and to divide the entire day of operations into a number of control periods. The TOD SL system will then employ precalibrated traffic flow models to estimate the speed and density during each control period based on its volume. The estimated traffic characteristics are subsequently used in computing the optimal control speed for each time period. Through such a computing process, one can develop a set of optimal speed limits for the work zone over different time periods of a day and achieve a substantial increase in the overall throughput and a reduction in speed variance. The results of numerical analysis with the actual work zone on I-83 SB have confirmed the effectiveness of the proposed TOD SL control. It is notable that the proposed TOD SL control also features its robustness in contending with inevitable variations in the actual volume during each time-of-day period without the extensive use of traffic sensors.

However, it should be noted that the optimal speed limits resulted from the proposed TOD SL model are robust only for the 2–1 work-zone type (particularly, one right-lane closure in a two-mainline highway segment) and during the target TOD periods, since the traffic flow models were developed with traffic flow data from the same work-zone type and the established TOD periods are based on the historical traffic flow data. Thus, if the real-time data during the target TOD period (e.g., work-zone operation period) are significantly different from the historical data, one needs to recompute the speed limits with the proposed model.

To effectively enforce the proposed strategy, responsible highway agencies shall consider providing the TOD SL control information and messages through the website or any other media means to motorists so as to minimize their learning time and increasing their compliance rate. During the initial stage of field implementation, it is also essential that some enforcement strategies (e.g., monitored by traffic police or video cameras) be placed on the work zone.

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Kyeong-Pyo Kang received the B.S. degree in transportation engineering from Hanyang University, Ansan, South Korea, in 1996, and the M.S. degree in urban planning from Seoul National University, Seoul, South Korea, in 1998. He is currently working toward the Ph.D. degree in transportation engineering at the Department of Civil and Environmental Engineering, University of Maryland, College Park.

He is currently working as a Research Assistant at the University of Maryland. His current research interests include advanced work zone control strategies such as variable speed limit (VSL) control, time-of-day speed limit (TOD SL) control, dynamic late merge (DLM) control, and integrated control of VSL and DLM for highway work-zone operations.

Gang-Len Chang received the Ph.D. degree in transportation engineering from the University of Texas at Austin in August 1985. He is a Full Professor at the Department of Civil and Environmental Engineering, University of Maryland, College Park. He is also the Manager of the Applied Technologies and Traffic Analysis Program and the Director for Traffic Safety and Operations Laboratory. He is the Chief Editor for *ASCE Journal of Urban Planning and Development*.

Dr. Chang is a member of American Society of Civil Engineering (ASCE) and a member of the ASCE Transportation and Development Institute Publication Committee.