Development and Field Evaluation of Variable Advisory Speed Limit System for Work Zones

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A practical methodology to reduce traffic conflicts at work zones was developed and evaluated in the field. The proposed system uses variable advisory speed limits that are determined with a two-stage speed reduction scheme. The system is designed to lower the speed of the upstream traffic approaching the work zone bottleneck to the same level as the downstream flow. The system was implemented at one of the I-494 work zones in the Twin Cities, Minnesota, for a 3-week period in 2006. Data collected from the field indicated a 25% to 35% reduction of the average 1-min maximum speed difference along the work zone area during the 6:00 to 8:00 a.m. morning peak periods after the system was implemented. The reduction in speed difference also resulted in an approximate 7% increase of the total throughput volume measured at the downstream work zone boundary during the 6:00 to 7:00 a.m. periods. The volume increase during the 7:00 to 8:00 a.m. periods was not significant. Estimation of the driver compliance rate, by comparing the speed differences upstream and downstream of the advisory speed limit signs, showed 20% to 60% correlation levels during the morning peak periods.

Improving safety and operational efficiency of traffic flows at work zones has been one of the major challenges in traffic engineering. While variable speed limit (VSL) control has long been recognized as one of the most promising tools for managing work zone traffic flows, the lack of efficient online methodologies that can determine optimal speed limits in real time and the difficulties in enforcing VSLs in the field have resulted in few operational VSL systems for work zones. To be sure, most variable speed control systems currently in operation in the United States and other countries are for non-work zones and are intended to provide safe speed limits under the prevailing traffic and environment conditions, without explicit consideration of mitigating traffic conflicts caused by downstream bottlenecks (*1–3*). Recently, several research groups have explored the potential effectiveness of VSL control in improving operational efficiencies on freeways. Hegyi et al. (*4*) showed the benefit of VSL coordination for suppressing shock waves in freeway traffic, by applying a model-based predictive control (MPC) approach. Recently, Lu et al. (*5*) expanded the MPC approach to implement a VSL control through in-vehicle systems. In both cases, a macrosimulation model was used to estimate the effectiveness of their proposed VSL control methods. A model-based optimization approach with VSL was also tried by Lin et al. (*6*), who showed the potential benefit of a work zone VSL control in maximizing throughput while minimizing delay. Another simulation-based study, done by Abdel-Aty et al. (*7*), reported that a VSL control on I-4 in Florida reduced both crash likelihood and travel times.

Developing an efficient VSL system that can optimally manage the traffic speed levels under dynamically changing traffic conditions is critically important in improving safety and managing congestion at work zones. In this study, a variable advisory speed limit system for work zones (VASLS-WZ) was developed and evaluated in the field. The proposed system adopts an efficient, two-stage speed reduction approach that does not employ traffic flow models in determining the time-variant advisory speed limit values. By providing advisory speed levels to drivers approaching a congested work zone segment, the system tries to minimize the potential for rear-end collision and mitigate the negative impacts of shock waves. The system was implemented for a 3-week period in February to March 2006 at one of the I-494 work zones in the Twin Cities, Minnesota, and its effectiveness in reducing traffic conflicts and improving operational efficiency was evaluated with data collected from the field. The rest of this paper summarizes the methodology of the proposed system, field implementation, and performance evaluation results.

DETERMINATION OF VSL FOR TWO-STAGE SPEED REDUCTION

Figure 1 shows the general layout of the proposed two-stage VASLS-WZ, which uses real-time measurements at both downstream and upstream of a given work zone. It tries to reduce the speed of the upstream flow sequentially to the same level as that of the downstream traffic, by using two variable advisory speed limit signs. Let $U_{a,t}$ and $U_{b,t}$ be the upstream and downstream speed levels measured at time *t*, respectively. Then

$$\Delta_{a,t} = \alpha_{a,t}\left(U_{a,t} - S_{a,t}\right) \tag{1}$$

$$\Delta_{b,t} = \alpha_{b,t}\left[\left(U_{a,t} - \Delta_{a,t}\right) - S_{b,t}\right] \tag{2}$$

where

$\Delta_{i,t}$ = actual speed reduction at location *i* due to $S_{i,t}$, posted advisory speed limit;

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Transportation Research Record: Journal of the Transportation Research Board, No. 2015, Transportation Research Board of the National Academies, Washington, D.C., 2007, pp. 12–18.
DOI: 10.3141/2015-02

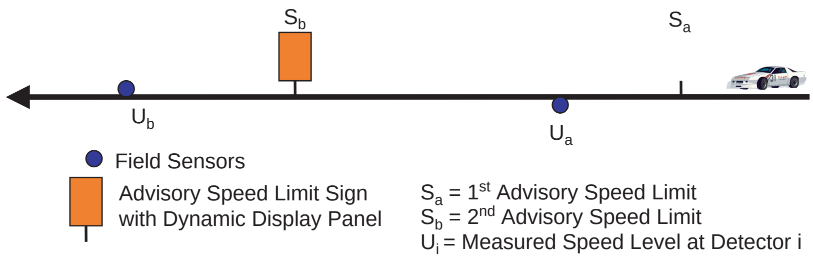

FIGURE 1 General layout of two-stage variable advisory speed limit system.

$\alpha_{i,t}$ = driver compliance rate at location *i;* and
$U_{a,t} \geq U_{b,t}$.

The objective of the system is to reduce $U_{a,t}$ to $U_{b,t}$, by using $S_{a,t}$ and $S_{b,t}$, that is,

$$\Delta_{a,t} + \Delta_{b,t} = U_{a,t} - U_{b,t} \tag{3}$$

Let $S_{b,t} = U_{b,t}$ and $\alpha_t = \alpha_{a,t} = \alpha_{b,t}$. Rearranging Equation 3 for $S_{a,t}$ with Equations 1 and 2,

$$S_{a,t} = \left[(\alpha_t - 1)U_{a,t} + U_{b,t}\right]/\alpha_t \tag{4}$$

Therefore, if α_t can be estimated, the advisory speed limit at time *t* at the upstream location can be determined as a function of both upstream and downstream speed levels. Figure 2 shows the general pattern of $S_{a,t}$ with respect to different combinations of upstream and downstream speed levels for $\alpha_t = 0.7$.

Further, $S_{a,t} > 0$, and $\alpha_t > 0$, then from Equation 4,

$$\alpha_t > 1 - U_{b,t}/U_{a,t} \tag{5}$$

where $U_{a,t} \geq U_{b,t}$.

Equation 5 defines the required level of the driver compliance level for the proposed variable advisory speed limit system to be effective.

FIELD IMPLEMENTATION OF VASLS-WZ AT I-494 WORK ZONE

The two-stage speed reduction methodology was implemented, and its performance was evaluated with the data collected from the site. Figure 3 shows the schematic layout of the VASLS-WZ that was installed at the I-494 southbound work zone near the Wakota Bridge in the Twin Cities. That section, approximately 2.5 mi long, starts from the Lake Road interchange and ends at the west end of the Wakota Bridge. The current posted speed limit of the entire section is 55 mph. For this study, the following devices were installed at the site:

- Five sets of radar sensors for speed and volume measurements;
- Three advisory speed limit warning signs with light-emitting diode (LED) panel for variable speed display;
- Three sets of Doppler radar sensors for speed measurements at the advisory speed sign locations; and
- One set of web-based wireless communication system for data collection, processing, and speed limit determination.

As noted in Figure 3 that in this evaluation, to prepare for the possible detector malfunction situations, multiple detectors were installed to measure both upstream and downstream speed levels. Also, one additional variable advisory speed limit sign was installed near the downstream bottleneck location to ensure system redundancy. The two downstream signs, S1 and S2, show the same advisory speed limit values that are determined with the downstream

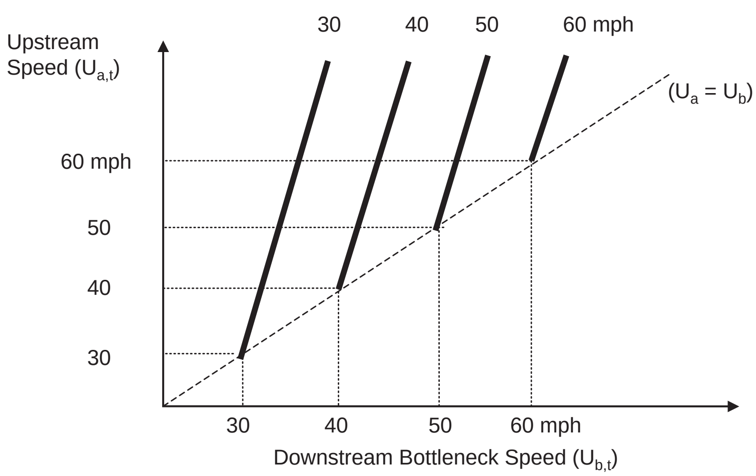

FIGURE 2 General pattern of $S_{a,t}$ with $(U_{a,t}, U_{b,t})$ for $\alpha = 0.7$.

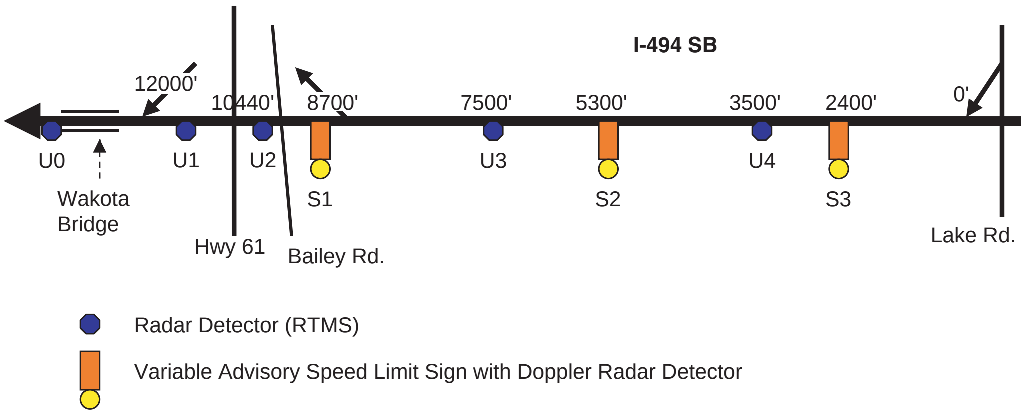

FIGURE 3 Layout of I-494 work zone variable advisory speed limit system.

bottleneck speed levels, while the speed limit of the upstream sign, S3, is calculated with both upstream and downstream speed measurements following the two-stage reduction method. In this project, the advisory speed limit signs were manufactured and installed by engineers in the Metro District, Minnesota Department of Transportation (DOT), whereas all the other devices were rented from a private vendor.

Variable Advisory Speed Limit Algorithm for Field Implementation

In this study, it was determined that the advisory speed limit would be varied every 1 min in 5-mph increments. Further, the upper limit of the advisory speed limit at the upstream sign was set to 50 mph, while that of the two downstream signs was set to 45 mph to reflect the current posted advisory speed limit for the existing curve section. Figure 4 shows the discretized version of the two-stage speed reduction method in determining the advisory speed limit at the first upstream sign, S3. The algorithm for signs S1 and S2 is shown in Figure 5. These algorithms were coded into the web server, which determined the advisory speed limit values for all three signs using the speed measurements uploaded from each detector station every 30 s through a wireless communication network. The resulting advisory speed limit values were downloaded into each speed sign through the same wireless communication system (*8*). In this study, the speed limit values at each sign were updated every 1 min using the previous 90-s measurements.

Format of Variable Advisory Speed Limit Sign

Figure 6 shows the format of the variable advisory speed limit sign specifically designed for this research in cooperation with engineers at the Minnesota DOT Metro District. In this study, a total of three such signs were manufactured and installed by the Metro District maintenance personnel at the I-494 work zone site. The LED display panel was provided by the private vendor as part of the web-based communication system used for this project. Figure 7 shows one of the downstream signs, S1, installed near the Highway 61 interchange. The LED panel and all the detection and communication devices used in this field evaluation were powered by solar panels, which were installed at each sign and detector location. It can be noted that a rectangular shape was used in this study to improve conspicuity of the variable advisory speed sign at the test work zone site, where numerous diamond warning signs were already in place.

DATA COLLECTION AND PERFORMANCE EVALUATION OF VASLS-WZ

The VASLS-WZ was installed at the I-494 work zone on February 20, 2006, and data collection for the before condition started on February 21, 2006. After a 3-week testing period under the shadow operation mode, the system was finally activated at approximately 10:00 a.m. on March 15, 2006, and data for the after period were collected until April 4, 2006. Types of data collected include the following: lane-by-lane speed and volume for every 30 s at five loca-

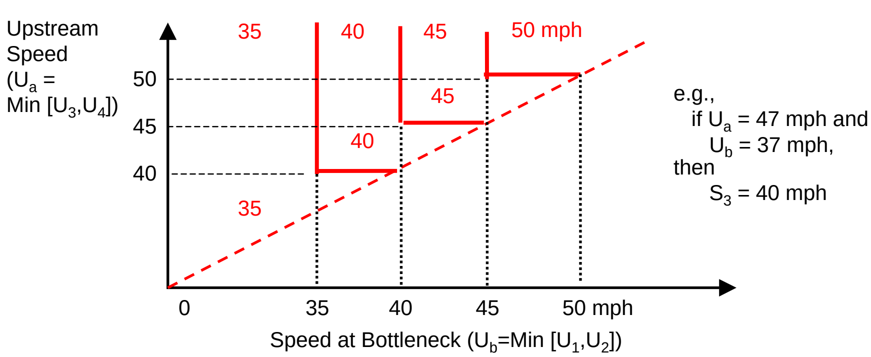

FIGURE 4 Variable speed limit algorithm for S3 at I-494 work zone.

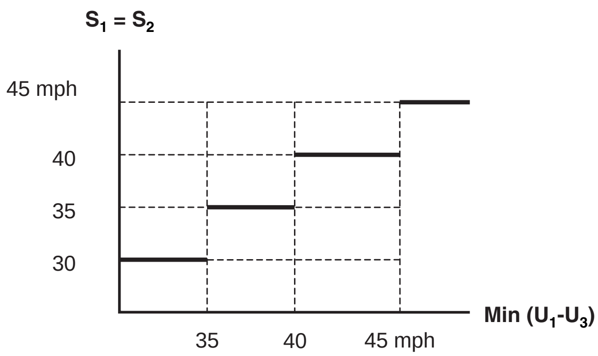

FIGURE 5 Algorithm for determining speed limit at S1 and S2 at I-494 work zone.

3.0" Radius, 1.3" Border, 0.8" Indent, Black on Orange;
"WATCH" E: "FOR" E: "SLOW" E: "TRAFFIC" E: "AHEAD" E:
2.3" Radius, 0.9" Border, 0.6" Indent, Black on Orange;
"MPH" D:

FIGURE 6 Format and dimension of variable advisory speed limit sign.

FIGURE 7 Variable advisory speed limit sign installed near Highway 61 interchange.

tions with remote traffic microwave sensors (RTMS); and posted speed limit values every 1 min at each sign.

Speed and volume data were archived and used for evaluating performance of the system after field testing was completed. Specifically, the following issues were addressed with the morning peak-period data collected during the before-and-after periods of the system being activated:

- Speed variations within the work zone section,
- Total throughput variations at the downstream boundary of the work zone site, and
- Traffic response to posted advisory speed limit values.

During the before-and-after data collection periods, no unusual weather or incident conditions occurred at the test site, except for the morning of March 16, when there was heavy snow.

Speed Variations Within Work Zone

First, the effectiveness of the VASLS-WZ in reducing the speed difference within the work zone area was studied. For every 1-min interval, all speed measurements from detectors in the work zone were compared, and a maximum speed difference was determined for each 1-min period. Figures 8 and 9 show the average maximum speed differences during morning peak periods of typical weekdays before and after the system was implemented. As mentioned, the system was activated at approximately 10:00 a.m. on March 15. During the week of March 6, a malfunctioning detector did not produce any data. Therefore, only those days with the same number of working detectors were used for this comparison. Further, data from March 16

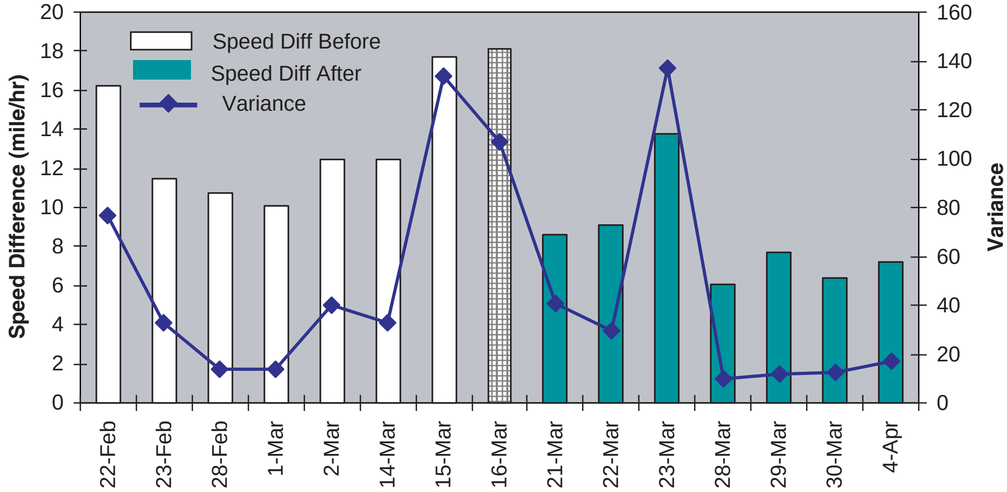

FIGURE 8 Average maximum speed difference comparison (6:00 to 7:00 a.m.).

were not included in this comparison, since there was heavy snow that day, where no comparable snow condition was observed during the before period. Therefore, a total of 7 before and 7 after weekdays were used in this analysis. As noted in Figures 8 and 9, the maximum speed difference within the work zone during the morning peak periods was decreased after the system was activated. Specifically, during the periods of 6:00 to 7:00 a.m. on weekdays, the average 1-min maximum speed difference within the work zone was reduced from 13.0 mph to 8.4 mph (–35%) after the VASLS-WZ became operational. The statistical test shows the significance level of $\alpha = 7\%$. For the periods of 7:00 to 8:00 a.m., the average difference was reduced from 18.4 mph to 14.1 mph (–23%), with the statistical significance level at 1%. In regard to variance in the maximum 1-min speed differences, the 7:00 to 8:00 a.m. periods show clear reduction after the system was activated, while the differences were not significant for the 6:00 to 7:00 a.m. periods. The before-and-after comparison of the two consecutive detection points in the test site showed that during the weekday morning peak periods, the average maximum speed difference was reduced from 10.4 mph to 6.3 mph ($\alpha = 2\%$) for the 6:00 to 7:00 a.m. periods, and from 14.8 mph to 12.9 mph ($\alpha = 1\%$) during 7:00 to 8:00 a.m. periods. As described, the before-and-after data comparison clearly indicates that the VASLS-WZ was effective in reducing the longitudinal speed differences along the work zone during the morning peak periods.

Total Throughput Volume Comparison at Downstream Boundary

Effects of the longitudinal speed difference reduction on the operational efficiency of the work zone area were investigated. Figures 10 and 11 show the total hourly volume and speed comparisons at the downstream boundary of the I-494 work zone during the weekday morning peak periods before and after the VASLS-WZ was activated. As indicated in Figure 10, the average total throughput between 6:00 and 7:00 a.m. was increased by 7.1%, from 3,595 to 3,852 vehicles, while the increase in the total volume from 5:00 to 9:00 a.m. was 2.2%. Speed levels at the downstream boundary during the same time periods clearly show the increase from 47.2 mph to 48.5 mph at $\alpha = 1\%$. The before-and-after comparisons for the

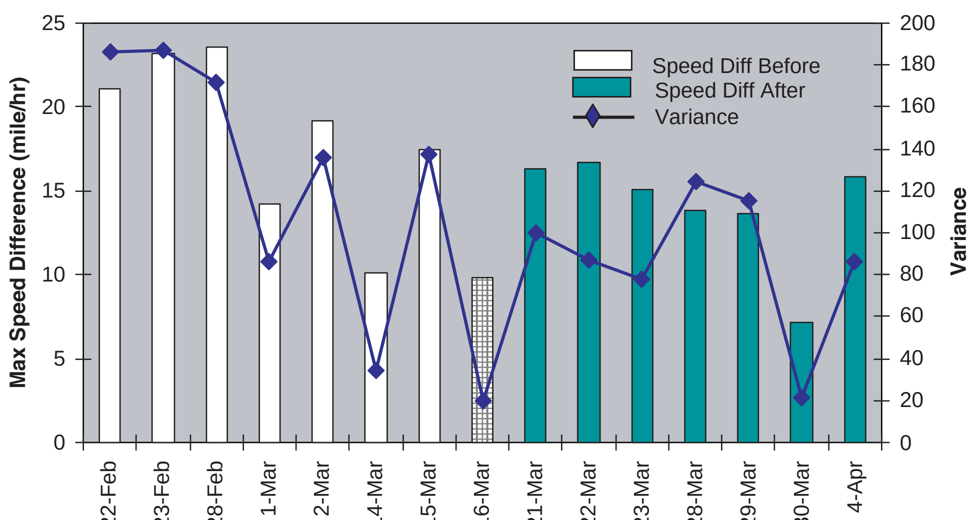

FIGURE 9 Average maximum speed difference comparison (7:00 to 8:00 a.m.).

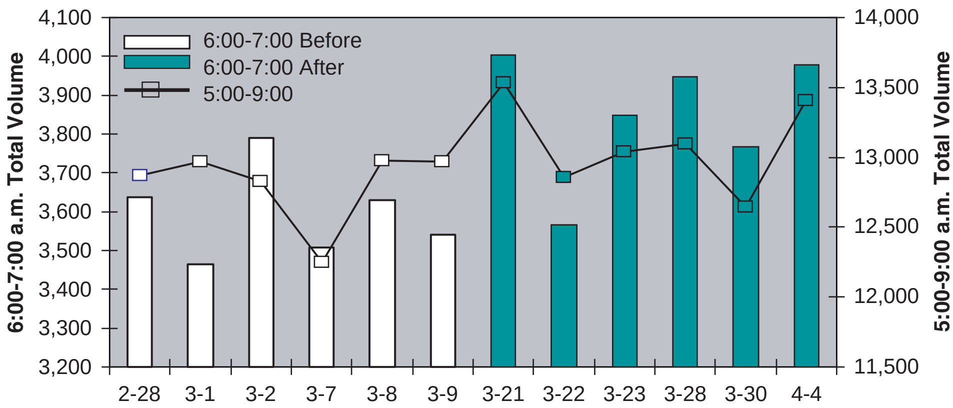

FIGURE 10 Peak-hour total throughput comparison (6:00 to 7:00 a.m.).

7:00 to 8:00 a.m. periods in regard to total throughput and speed levels at the downstream boundary did not show significant differences. The foregoing results indicate that during the 6:00 to 7:00 a.m. periods, reduction of the longitudinal speed differences in the work zone clearly contributed in improving the speed levels at the downstream boundary, thus increasing the total throughput of the work zone.

Assessment of Driver Compliance

To evaluate the level of the driver compliance for the VASLS-WZ, the correlations between the following quantities were studied in this analysis. They are the difference between U4, the speed level of the flow approaching the sign S2 and the posted advisory speed limit value of S2; and the difference between U4, the speed level of the approaching flow, and U3, the speed level measured at the downstream of the speed limit sign S2.

If all the drivers comply with the posted speed limit, the two values mentioned should be very similar, that is, the correlation between two differences is close to 1.0. Figure 12 shows the plot of those two quantities from the data collected on March 22 during the 6:00 to 8:00 a.m. period, which has the correlation coefficient of 0.5. Of interest is that the level of correlation becomes lower as the difference between the posted speed limit value and the speed level of the approaching flow increases. Figure 13 shows the variations of the correlation coefficients at two sign locations on different weekdays. As indicated in this figure, the level of correlation varies between 0.2 and 0.6, and it shows promising possibilities of operating the VASLS-WZ on a regular basis.

CONCLUSIONS

Optimal speed management of traffic flows approaching a work zone area is critically important in improving the safety and efficiency of the work zone operation. In this research, a two-stage variable advisory speed limit system was developed and implemented at the I-494 work zone. Data collected from the field during the before-and-after periods clearly indicate the effectiveness of the system in reducing the longitudinal speed differences along the work zone area during the 6:00 to 8:00 a.m. peak periods on weekdays—that is, a 25% to 35% reduction in regard to the average 1-min maximum speed difference. This resulted in an approximately 7% increase of total throughput measured at the downstream work zone boundary during the 6:00 to 7:00 a.m. periods, while the increase during the 7:00 to 8:00 a.m. periods was not significant. Estimation of the driver compliance level by correlating the speed differences upstream and downstream of the speed limit signs also showed promising results—that is, a 20% to 60% level, even though posted speed values were the advisory limits. The simplicity of the speed control strategy developed in this study and the flexibility of the hardware and software system used for field implementation indicate the possibility of adopting the proposed variable advisory speed limit system as one of the regular tools for work zone management.

Future recommendations include the design of a simpler speed sign format through driver perception and simulation studies, more frequent updates of speed limit values in real time (e.g., 30-s updates), and adoption of different non-intrusive detection technologies. Further, the long-term effects of VSL control on drivers' compliance levels need to be studied.

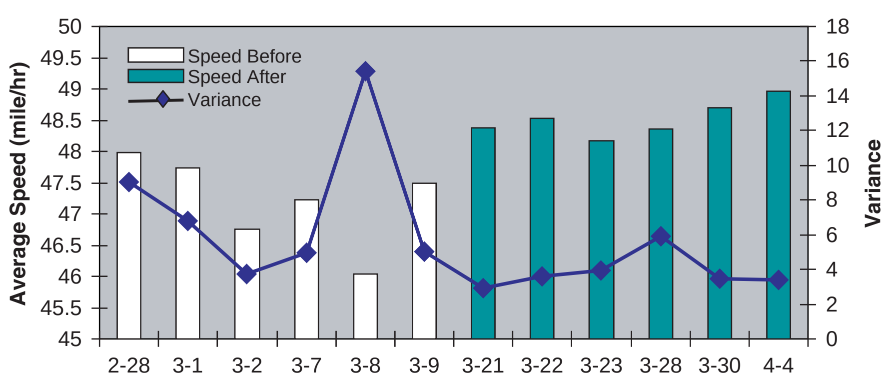

FIGURE 11 Average speed comparison at downstream boundary (6:00 to 7:00 a.m.).

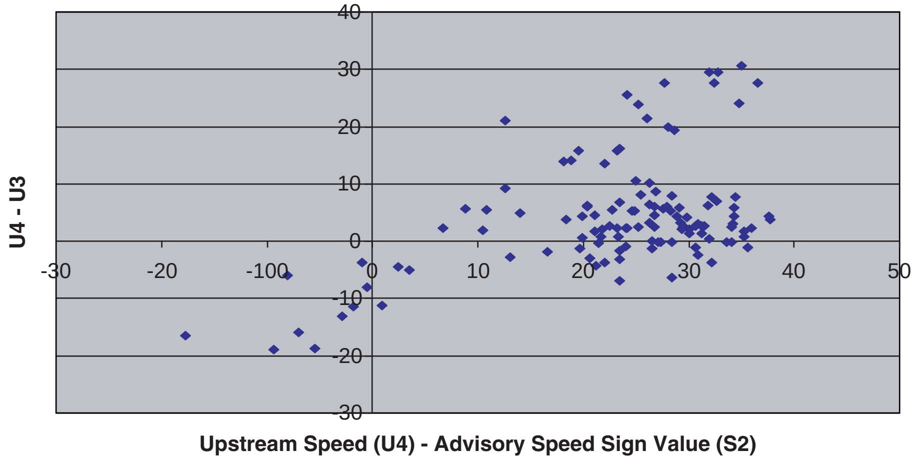

FIGURE 12 Speed difference correlation at second sign location on March 22 (6:00 to 8:00 a.m.).

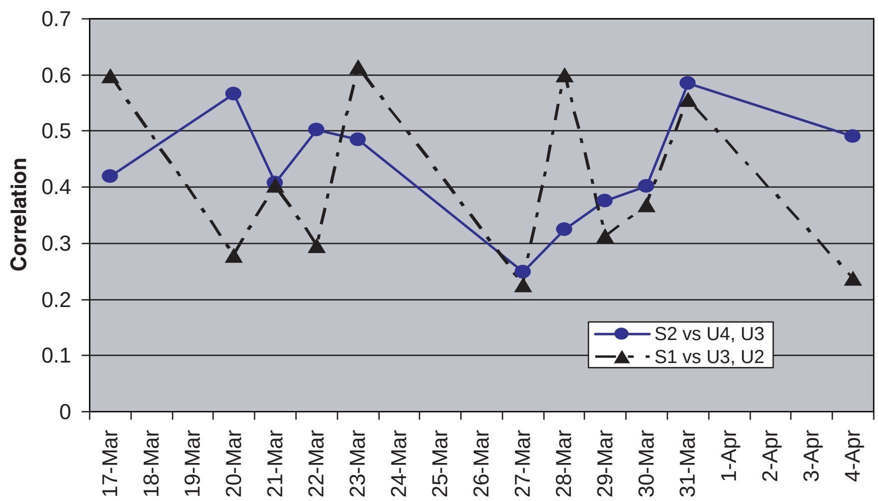

FIGURE 13 Estimation of driver compliance level during morning peak periods (6:00 to 8:00 a.m.).

ACKNOWLEDGMENTS

This project was financially supported by the Minnesota Department of Transportation. The cooperation of the traffic and construction personnel in Metro District, including Mike Engh and Eric Embacher, was critical for the completion of the study. Finally, the variable advisory speed limit signs were manufactured and installed by the Metro Sign Shop and Maintenance Group.

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The Work Zone Traffic Control Committee sponsored publication of this paper.