FIELD EVALUATION OF A VARIABLE ADVISORY SPEED LIMIT SYSTEM FOR REDUCING TRAFFIC CONFLICTS AT WORK ZONES

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Abstract

A practical methodology to reduce the 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. It is designed to lower the speed of the upstream traffic approaching the work zone bottleneck to the same level as the current downstream flow. The system was implemented at one of the I-494 work zones in the Twin Cites, Minnesota, for a three week period in 2006. The data collected from the field indicates 25-35 % reduction of the average 1-minute maximum speed difference along the work zone area during the 6:00-8:00 a.m. morning peak periods after the system was implemented. The reduction in speed difference also resulted in approximately 7% increase of the total throughput volume measured at the downstream work zone boundary during the 6:00-7:00 a.m. periods, while the volume increase during 7:00-8:00 a.m. periods was not significant. The 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.

Introduction

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 on-line methodologies that can determine optimal speed limits in real time and the difficulties in enforcing variable speed limits in the field have resulted in very few operational VSL systems for work zones. To be sure, most variable speed control systems currently in operation in the U.S and other countries are for non-work zones and 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, 2, 3). Recently several research groups have explored the potential effectiveness of the VSL control in improving operational efficiencies on freeways. Hegyi et. al. showed the benefit of VSL-coordination for suppressing shock waves in freeway traffic by applying a model-based predictive control (MPC) approach (4). Recently Lu, et. al. expanded the MPC approach to implement a VSL control through in-vehicle systems (5). In both cases a macro-simulation 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 the delay. Another simulation-based study 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 variable speed limit system that can optimally manage the traffic speed levels under the dynamically changing traffic conditions is of critical importance 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 the 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 three-week period in February-March 2006 at one of the I-494 work zones in Twin Cities, Minnesota, and its effectiveness in reducing traffic conflicts and improving operational efficiency was evaluated with the data collected from the field. The rest of the paper summarizes the methodology of the proposed system, field implementation and performance evaluation results.

Determination of Variable Speed Limits 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 and tries to reduce the speed of the upstream flow sequentially to the same level as that of the downstream traffic 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

$$\Delta_{a,t} = \alpha_{a,t} (U_{a,t} - S_{a,t}), \quad (1)$$
$$\Delta_{b,t} = \alpha_{b,t} [(U_{a,t} - \Delta_{a,t}) - S_{b,t}], \quad (2)$$

where, $\Delta_{i,t}$ = Actual speed reduction at location i due to $S_{i,t}$, the posted advisory speed limit,
$\alpha_{i,t}$ = Driver compliance rate at location i,
$U_{a,t} \geq U_{b,t}$

The objective of the system is to reduce $U_{a,t}$ to $U_{b,t}$ using $S_{a,t}$ and $S_{b,t}$, i.e.,

$$\Delta_{a,t} + \Delta_{b,t} = U_{a,t} - U_{b,t} \quad (3)$$

Let $S_{b,t} = U_{b,t}$ and $\alpha_t = \alpha_{a,t} = \alpha_{b,t}$

Rearranging (3) for $S_{a,t}$ with (1) and (2),

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

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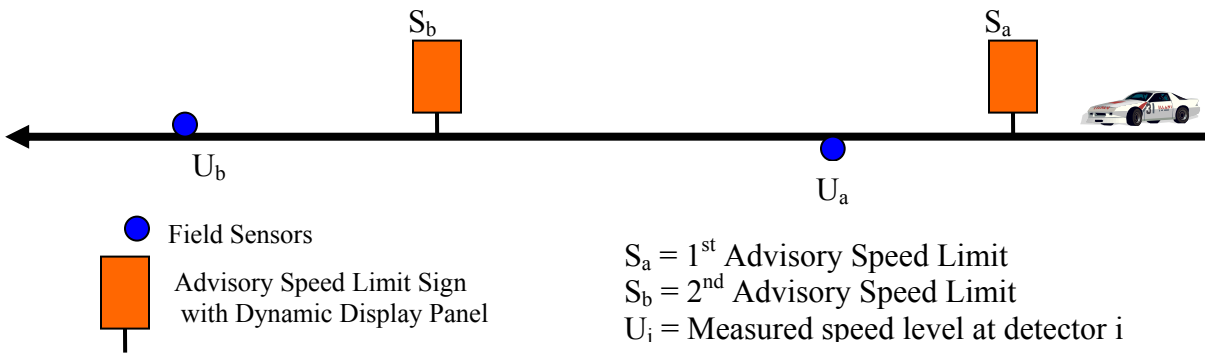

Figure 1. General Layout of a Two-Stage Variable Advisory Speed Limit System

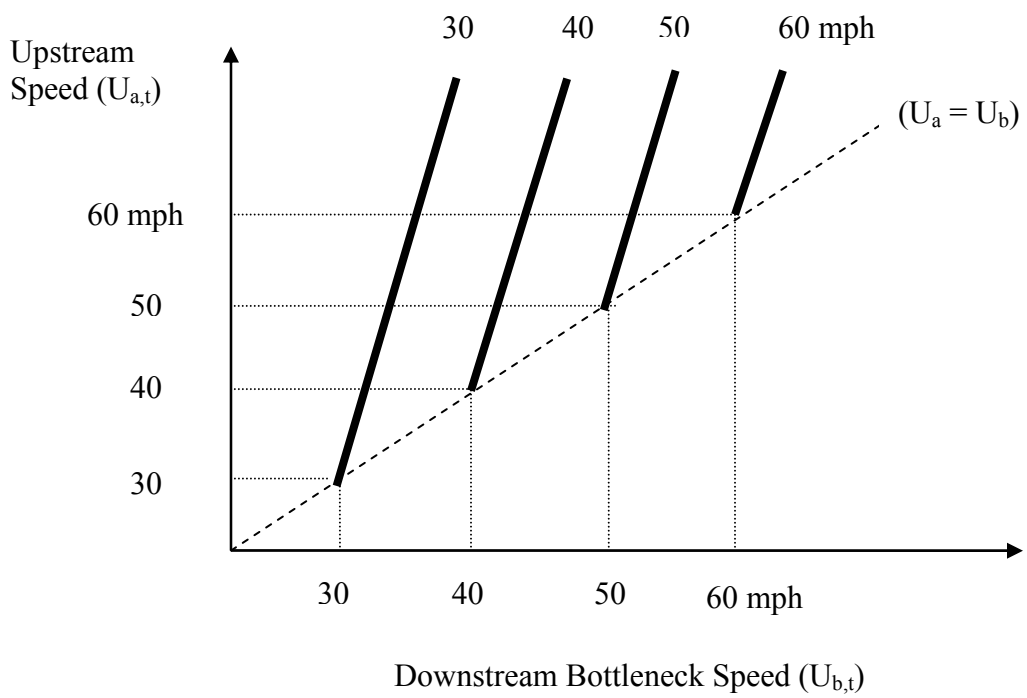

Figure 2. General pattern of $S_{a,t}$ with respect to ($U_{a,t}$, $U_{b,t}$) for $\alpha = 0.7$

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 α_t = 0.7.

Further, $S_{a,t} > 0$, and $\alpha_t > 0$

then from (4), $\alpha_t > 1 - U_{b,t}/U_{a,t}$ where, $U_{a,t} \geq U_{b,t}$ (5)

The 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 the VASLS-WZ at I-494 Work Zone

The two-stage speed reduction methodology developed in the previous section was implemented and its performance was evaluated with the data collected from the site. Figure 3 shows the schematic layout of the VASL-WZ that was installed at the I-494 Southbound Work Zone near the Wakota bridge in the Twin Cities, Minnesota. This section, approximately 2.5 miles 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. The following devices were installed at the site for this study:

- 5 sets of radar sensors for speed and volume measurements
- 3 Advisory Speed Limit warning signs with LED panel for variable speed display
- 3 sets of Doppler radar sensors for speed measurements at the advisory speed sign locations
- 1 set of web-based wireless communication system for data collection, processing and speed limit determination.

It can be 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. Further, one additional variable advisory speed limit sign was also installed near the downstream bottleneck location to ensure the system redundancy. The downstream two signs, S1 and S2, show the same advisory speed limit values that are determined with the downstream 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

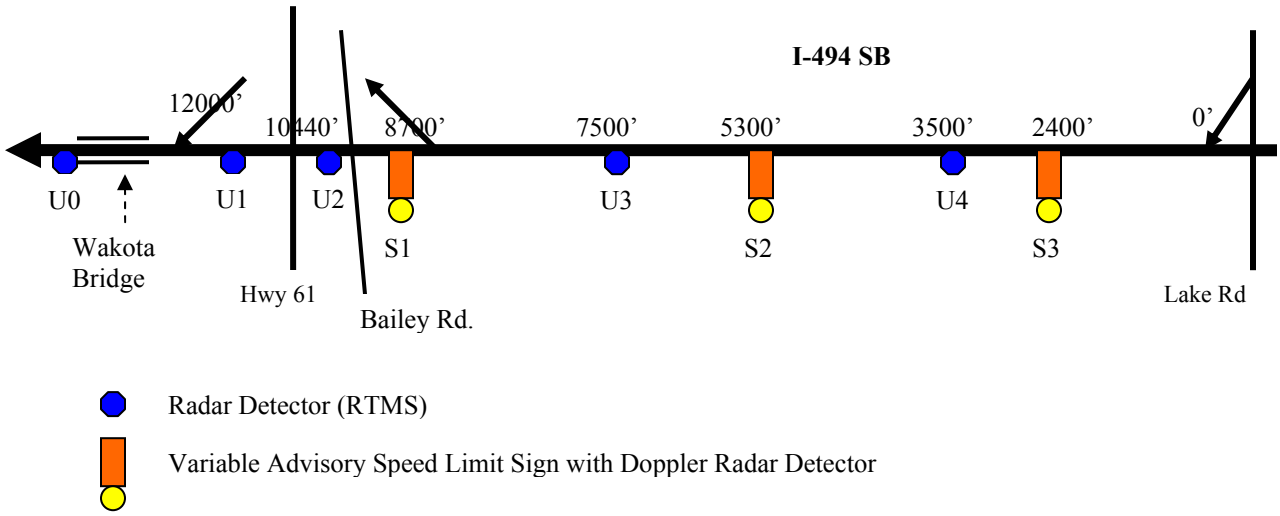

Figure 3. Layout of the I-494 Work Zone Variable Advisory Speed Limit System

signs were manufactured and installed by the engineers in the Metro District, Minnesota Department of Transportation (Mn/DOT), while 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 minute 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 downstream two 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 the 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 seconds 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 minute using the previous 90-second 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 the engineers at the Mn/DOT Metro District. In this study, a total of 3 such signs were manufactured and installed by the Mn/DOT 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/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 the conspicuity of the variable advisory speed sign at the test work zone site, where numerous diamond warning signs were already in place.

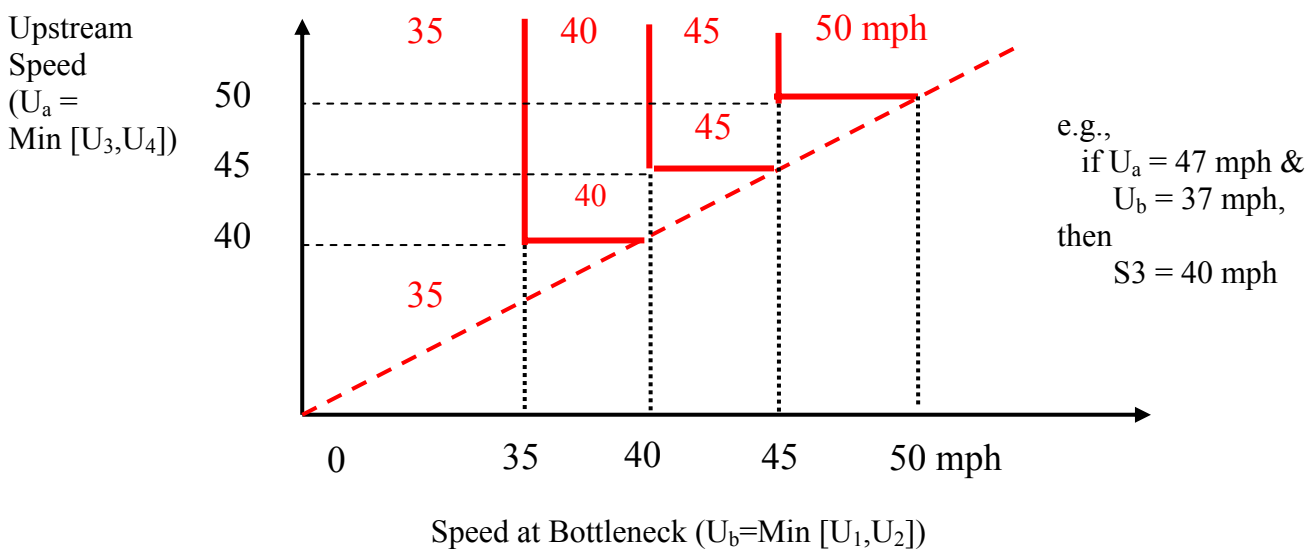

Figure 4. Variable Speed Limit Algorithm for S3 at I-494 Work Zone

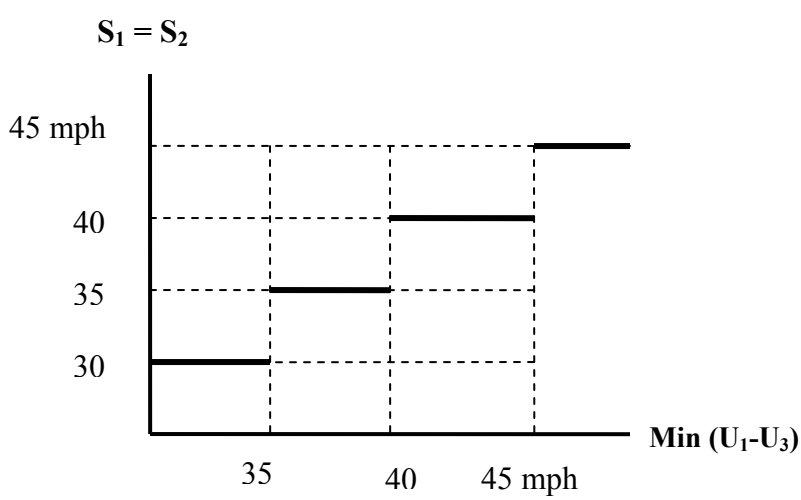

Figure 5. Algorithm for determining Speed Limit at S1 and S2 at I-494 Work Zone

Figure 6. Format and Dimension of the Variable Advisory Speed Limit Sign

Figure 7. Variable Advisory Speed Limit Sign installed near Highway 61 interchange

Data Collection and Performance Evaluation of VASLS-WZ

The VASL-WZ was installed at the I-494 work zone on February 20, 2006, and the data collection for the 'before' condition was started from 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 the data for the 'after' period was collected until April 4, 2006. The types of the data collected include:

- Lane by Lane Speed and Volume for every 30 seconds at 5 locations with RTMS radar sensors,
- Posted speed limit values every 1 minute at each sign.

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

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

It needs to be noted that during the before and after data collection periods, no unusual weather or incident conditions occurred at the test site, except the morning of March 16, when there was a heavy snow.

Speed Variations within Work Zone

First, the effectiveness of the VASL-WZ on reducing the speed difference within the work zone area was studied. For every one minute interval, all the speed measurements from the detectors in the work zone were compared and a maximum speed difference was determined for each 1 minute period. Figures 8 and 9 show the average maximum speed differences during the morning peak periods of typical weekdays before and after the system was implemented. As mentioned earlier, the system was activated at approximately 10:00 a.m. on March 15. It needs to be noted that in the week of March 6, there was a malfunction detector that did not produce any data, therefore only those days with the same number of working detectors were used for this comparison. Further, the data from March 16 was not included in this comparison, since there was a heavy snow on this day while no comparable

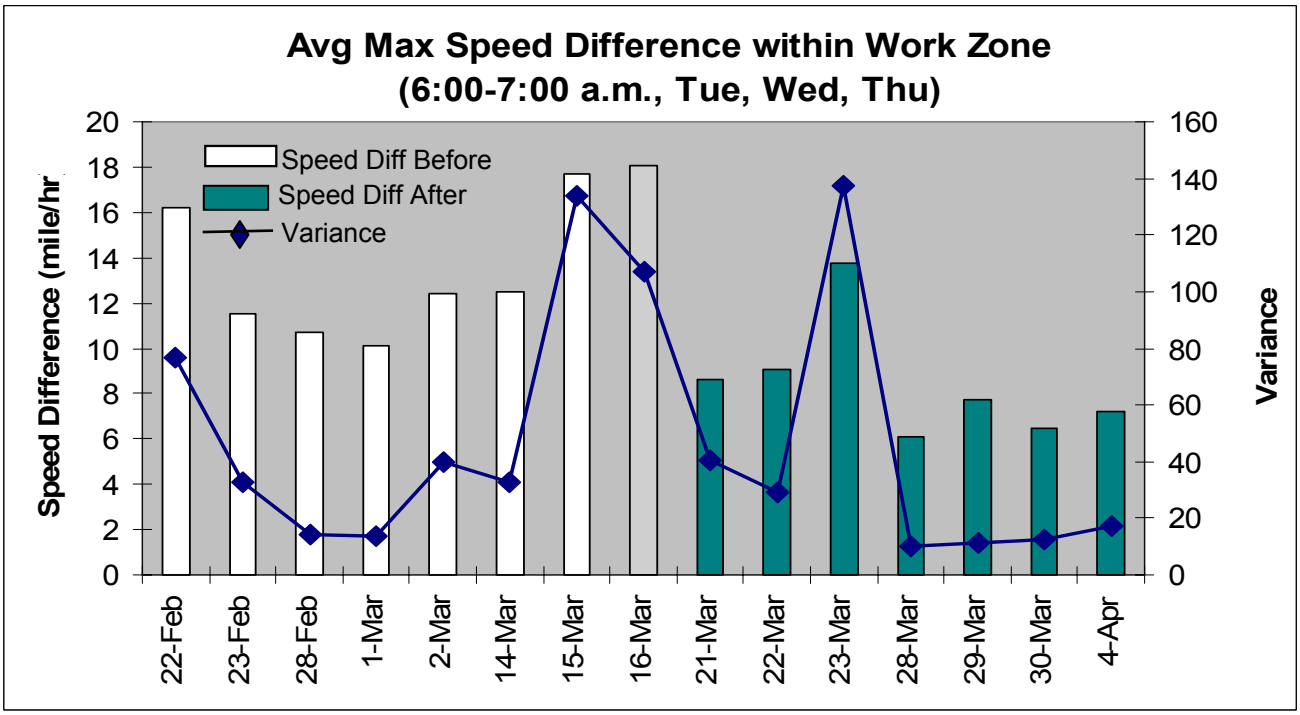

Figure 8. Average Maximum Speed Difference Comparison (6:00-7:00 a.m.)

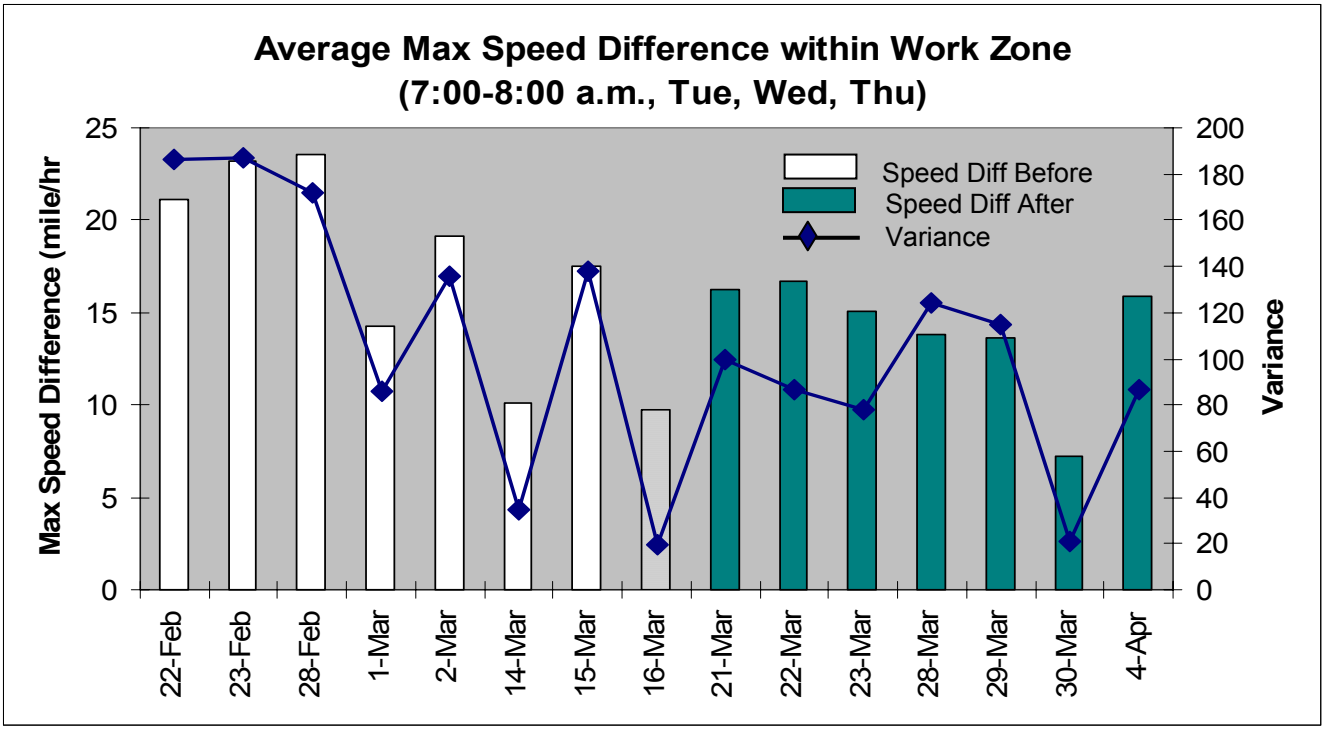

Figure 9. Average Maximum Speed Difference Comparison (7:00-8:00 a.m.)

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 these figures, the maximum speed difference within the work zone during the morning peak periods was decreased after the system was activated. Specifically, during the period of 6:00-7:00 a.m. on weekdays, the average 1-minute maximum speed difference within the work zone was reduced from 13.0 mph to 8.4 mph (-35%) after the VASL-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 terms of the variance in the maximum 1-minute speed differences, the 7:00-8:00 a.m. periods show clear reduction after the system was activated, while the differences were not significant for the 6:00-7:00 a.m. periods. The before – after comparison between 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 6:00-7:00 a.m. periods, and from 14.8 mph to 12.9 mph ($\alpha = 1\%$) during 7:00-8:00 a.m. periods. As described above, the before and after data comparison clearly indicates that the VASL-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

In this section, the 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 VASL-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 3595 to 3852 vehicles, while the increase in the total volume from 5:00 to 9:00 a.m. was 2.2%. The 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 7:00-8:00 a.m. periods in terms of total throughput and speed levels at the downstream boundary did not show significant differences. The above results indicate that during the 6:00-7:00 a.m. periods, the 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.

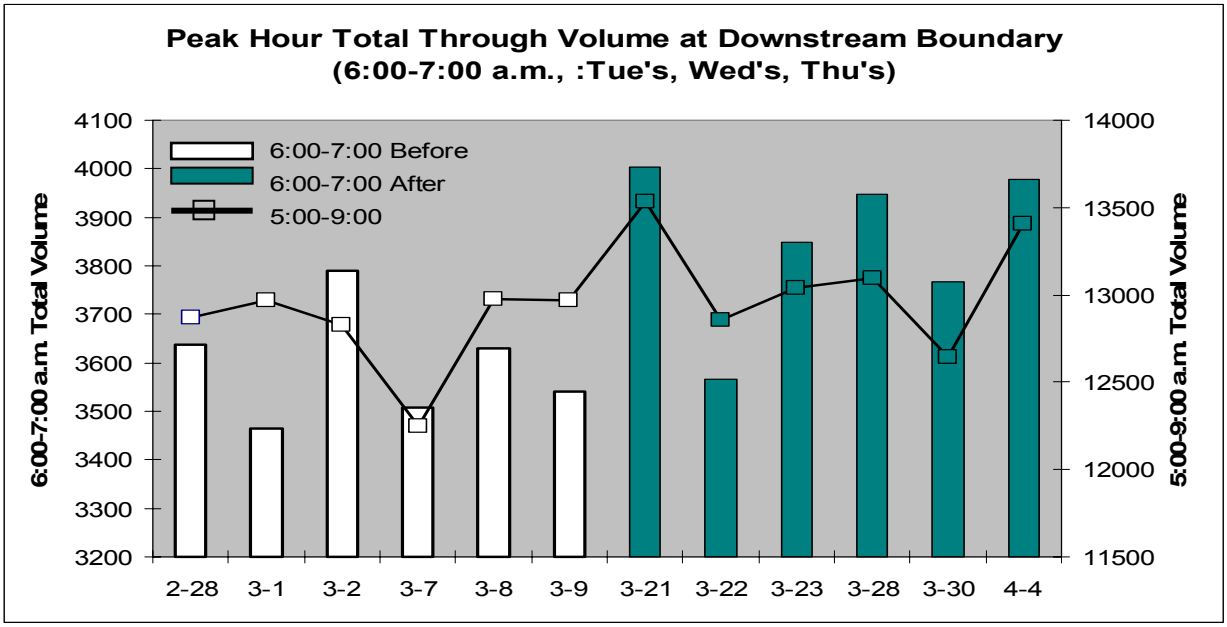

Figure 10. Peak-hour Total Throughput Comparison (6:00-7:00 a.m.)

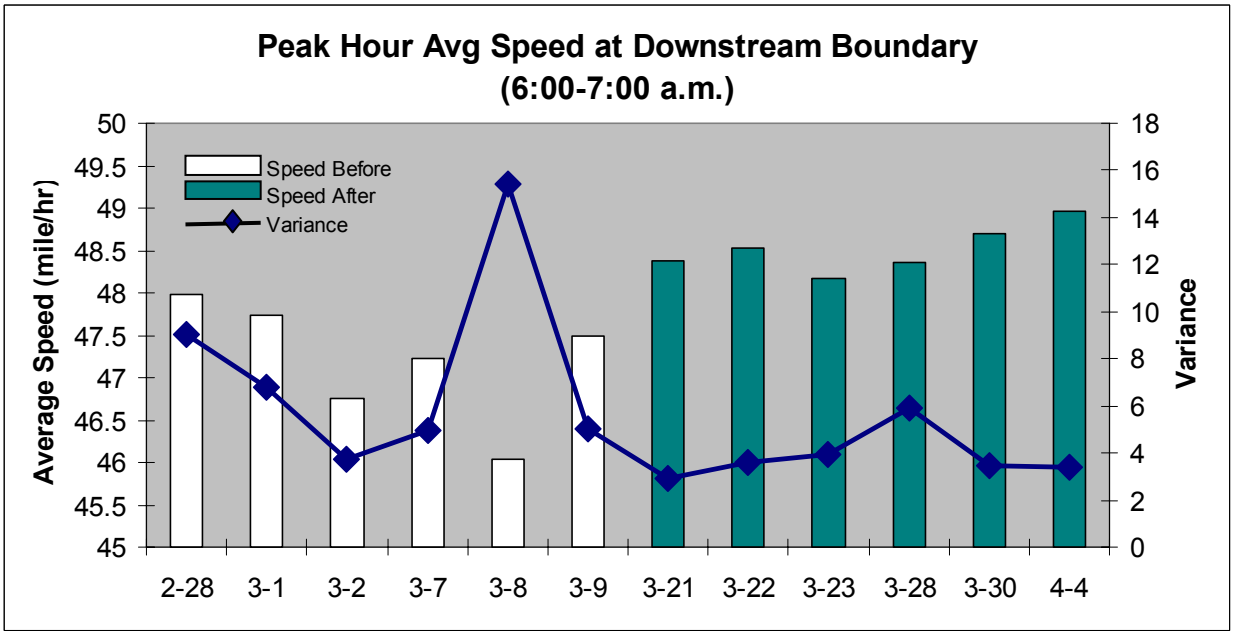

Figure 11. Average Speed Comparison at Downstream Boundary (6:00-7:00 a.m.)

Driver Compliance Assessment

To evaluate the level of the driver compliance for the VASL-WZ, the correlations between the following quantities were studied in this analysis, i.e.,

- Difference between U4, the speed level of the flow approaching the sign S2, and the posted advisory speed limit value of S2,
- 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 to the posted speed limit, the above two values should be very similar, i.e., 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 6:00-8:00 a.m. period, which has the correlation coefficient of 0.5. It is interesting to note 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 week days. As indicated in this figure, the level of correlation varies between 0.2 and 0.6, and it shows promising possibilities of operating the VASL-WZ on a regular basis.

Conclusions

Optimal speed management of the traffic flows approaching a work zone area is of critical importance 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. The data collected from the field during the before and after periods clearly indicates the effectiveness of the system in reducing the longitudinal speed differences along the work zone area during the 6:00-8:00 a.m. peak periods on weekdays, i.e., 25-35 % reduction in terms of the average 1-minute maximum speed difference. This resulted in approximately 7% increase of the total throughput measured at the downstream work zone boundary during the 6:00-7:00 a.m. periods, while the increase on the 7:00-8:00 a.m. periods was not significant. The estimation of the driver compliance level by correlating the speed differences upstream and downstream of the speed limit signs also showed promising results, i.e., 20 to 60% level, even though the posted speed values were the advisory limits. The simplicity of the speed control strategy developed in this study and the flexibility of the hardware/software system used for the field implementation indicate the possibility of adopting the proposed variable advisory speed limit system as one of the regular tools for work zone management.

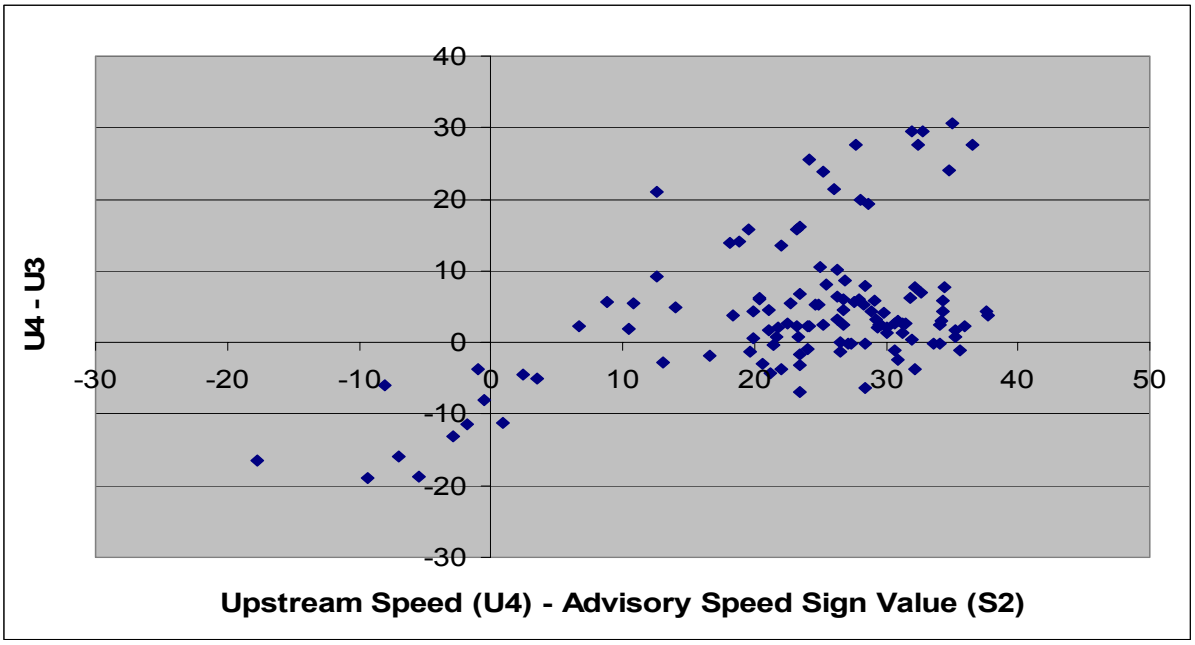

Figure 12. Speed Difference Correlation at the 2nd sign location on March 22 (6:00-8:00 a.m.)

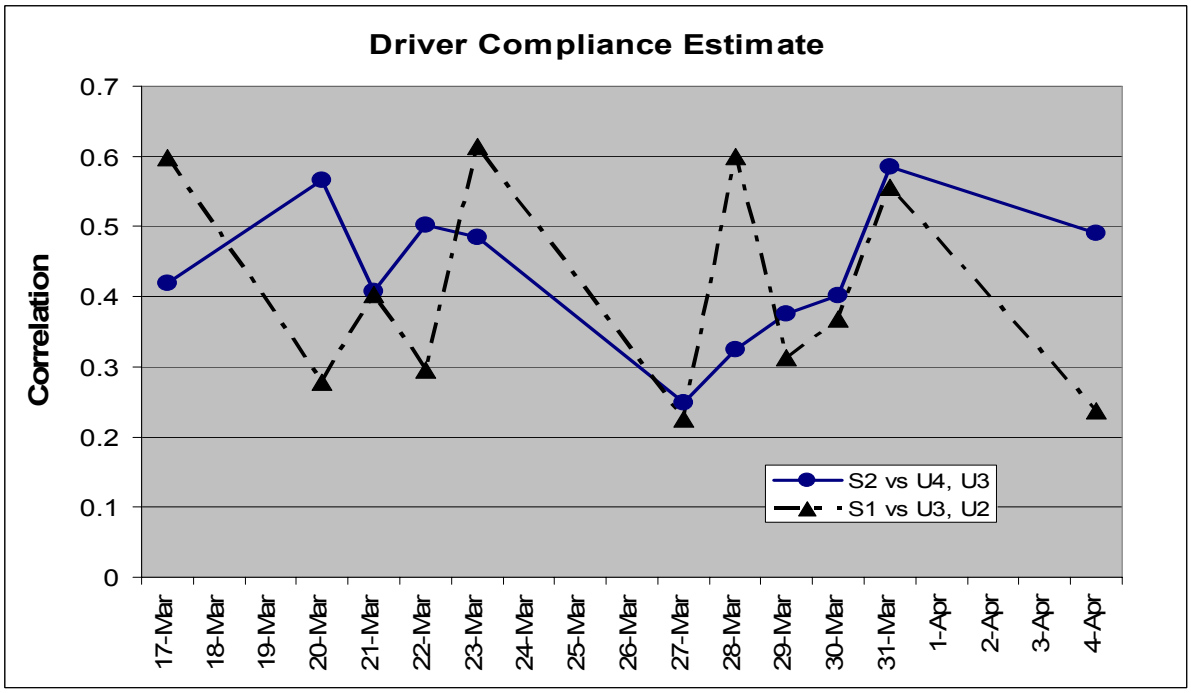

Figure 13. Estimation of Driver Compliance Level during Morning Peak Periods (6:00-8:00 a.m.)

Future recommendations include the design of a simpler speed sign format through driver perception and simulation studies, more frequent updates of the speed limit values in real time, e.g., 30 second updates, and the adoption of different non-intrusive detection technologies. Further, the time-variant effects of variable speed limit control on drivers' compliance levels need to be studied by implementing the proposed system in a long-term work zone site.

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