Evaluation of Variable Advisory Speed Limits in Congested Work Zones

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ABSTRACT

The effectiveness of variable ‘advisory’ speed limit (VASL) systems in congested urban work zones was investigated. Except for one publication, all previous studies focused on regulatory speed limit systems. This study used a comprehensive set of performance measures to investigate VASL effectiveness. Four congested work zones with lanes reduced from 4 to 3 lanes on Interstate 270 in St. Louis were selected for empirical and simulation analysis. The empirical analysis showed that VASL were effective in slowing down drivers gradually as they approached the work zone, thus reducing any sudden speed changes. Simulation analysis showed that operationally, the use of VASL resulted in: a 39% to 53% decrease in average queue length, a 7% to 11% reduction in throughput, a 4% to 8% increase in travel time. The use of VASL achieved a decrease in the standard deviation of speeds at the taper and 1-mile upstream of the work zone. The maximum speed differences also decreased up to 10 mph with VASL. A new VASL algorithm investigated in the study showed significant improvements in mobility and safety performance compared to the original field algorithm. The new algorithm made promising improvements in safety – a 30% reduction in rear end conflicts and a 20% reduction in lane changing conflicts as compared to the without VASL condition. The new VASL algorithm also decreased the queue length, further improving the overall safety in congested work zones. Thus, it is possible to design a VASL system that improves traffic and safety in congested work zones.

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INTRODUCTION

Variable speed limit (VSL) systems, which include both regulatory VSL and advisory VSL (VASL), have been implemented in several states for improving traffic safety and mobility. The major difference between regulatory and advisory VSL is that the regulatory VSL is enforceable whereas advisory VSL is not. Previous implementations can be categorized into three application types: hazardous weather, recurring congestion and work zones. Robinson (2000) reports that some states use VSL systems during hazardous weather or poor visibility conditions. For example, New Jersey has been using VSL on the New Jersey Turnpike since the 1960s to alert drivers of hazardous road conditions. Recently, there has been a growing interest in varying the speed limits in urban areas to alleviate recurring traffic congestion. For example, a VSL system was deployed on I-270 in urban St. Louis, Missouri, from 2008 to 2011. Figure 1 (a) shows the VSL sign used to display the speed limit. A detailed discussion of such deployments for recurring congestion in the U.S. and Europe can be found in Kianfar et al. (2013). A few states have also deployed VSL systems in work zones. Michigan, Utah, and Virginia, have tested regulatory VSL systems while Minnesota tested an advisory VSL (VASL) system. Although Section 2B.13 of the MUTCD (FHWA 2009), paragraph 18, allows the use of VSL, it does not provide specific guidance on placement and operation of these signs.

The focus of this paper is on the third type of VSL application: work zones. A brief review of the work zone VSL evaluations is in order. A VSL system was used in a work zone on I-96 in Lansing, Michigan. Lyles et al. (2004) reported that the effects of VSL on 85th percentile speeds and speed variance were inconsistent or undetectable. However, the percentage of vehicles exceeding certain speed thresholds decreased when VSL was in operation indicating a desirable safety effect. Operationally, lower travel times through the work zone were reported when VSL was in operation. A VASL system was deployed at an I-494 work zone in Twin Cities, Minnesota, for a three-week period. The system evaluation conducted by Kwon et al. (2007) showed a 25-35% decrease in speed variance, a 7% increase in throughput, and an increase in speed limit compliance during the morning peak period. Riffkin et al. (2008) investigated a VSL system in a work zone on I-80 near Wanship, Utah. Data was collected for two VSL scenarios: 1) VSL sign posted at 65 mph during day and night, and 2) VSL sign display varying between 55 mph during the day and 65 mph at night. The base case scenario consisted of a static 65 mph speed limit sign. When compared to the base case, VSL produced lower average speeds, lower speed variance, and higher compliance. Fudala and Fontaine (2010) evaluated a VSL system in a work zone on a congested portion of the Washington D.C. Beltway. A limited field evaluation showed inconclusive results in terms of operational effects. A simulation study was conducted to study various aspects of system configuration, the control algorithm, and sign placement. The simulation results showed that a properly designed VSL system could provide mobility and safety benefits in a work zone as long as the demand does not significantly exceed capacity. In summary, some previous work zone VSL evaluations have reported modest safety and mobility benefits.

The current study complements the existing body of knowledge on VSL systems by using a comprehensive set of performance measures. A list of performance measures used in the literature and the current study are shown in Table 1. With the exception of the Minnesota deployment (Kwon et al. 2007) all other VSL deployments in work zones were regulatory. The current study found that advisory VSL could improve safety and mobility in congested work zones, a finding similar to the effect of regulatory VSL (Fudala and Fontaine 2010), sans the need for enforcement. Specifically, the study accomplished three objectives:

1. Conducted empirical analysis of the safety effectiveness of VASL in congested work zones using field data.
2. Evaluated the mobility and safety impact of VASL in congested work zones using a set of performance measures more comprehensive than those used in previous studies (last row of Table 1). This objective was achieved using analysis conducted on calibrated simulation models.
3. Investigated the work zone performance of a field-implemented VASL algorithm on a freeway corridor in Missouri, documented its strengths and weaknesses, and proposed improvements to address limitations of the algorithm.

EMPIRICAL ANALYSIS OF VASL EFFECTIVENESS

The I-270 corridor in St. Louis, Missouri, had permanent VASL signs deployed between July 2011 and November 2013. The advisory signs varied the speed limits based on prevailing traffic conditions. Figure 1 (b) shows a schematic of the advisory sign. A yellow background is used for the advisory sign with white letters for displaying the speed limit. The work zones within the I-270 corridor provided an opportunity for investigating the performance of VASL. The Missouri DOT’s VASL algorithm used had the following characteristics:

- All detectors in the I-270 VASL corridor average vehicle speeds every 30 seconds across all lanes (weighted by volume).
- The speed displayed for the VASL 1 mile upstream of congested area is the speed measured at the beginning of taper rounded up to the next 10 mph increment as shown in Table 2. The maximum speed limit is 60 mph.
- The speed displayed for the VASL 2 miles upstream of congested area should be 10 mph higher than the VASL 1 mile upstream, up to the regular speed limit of 60 mph (see Table 2).
- VASL is updated in 5 minute intervals using the most recent 30-second average speed.

The Missouri DOT’s algorithm has some similarities with the speed-based algorithm used in the Minnesota VASL deployment (Kwon et al. 2007). The algorithm used in the Woodrow Wilson Bridge Project in Virginia (Fudala and Fontaine 2010) used volume, occupancy as the parameters to determine the posted speed limit while the Michigan deployment (Lyles et al. 2004) used traffic flow and operating speeds to determine the speed limit.

Description of Work Zones

Work zones in the northbound direction of I-270 between I-44 and Route 100 generated congested conditions at certain times during the day. Traffic conditions were defined as congested when vehicle speeds dropped below 30 mph. All work zones involved the rightmost lane closure (4 lanes reduced to 3 lanes). There were also instances when the VASL signs were not operational with work zone in place, thus allowing for comparison with and without VASL traffic conditions. After reviewing the traffic data from several work zones, four datasets were chosen. Due to Missouri DOT’s policy of avoiding scheduling work zones during peak periods so as to minimize the impact of work zones on traffic, it was challenging to obtain work zones that generated congestion. The four work zones selected were the best available congested work zones on I-270 during the 2012 construction season. These work zones were independent of each other i.e., it was not the same activity moving in phases on I-270. Traffic data was available for 5-min aggregation intervals for all datasets. Vehicle classification data was not available, thus the analysis was conducted for all vehicles combined. The four datasets are:

Dataset 1 (VASL was operational): Work zone was deployed from mile markers 7.3 to 10.0 on I-270 NB on June 6th, 2012. Congestion lasted for one hour from 1:15 pm to 2:15 pm. Figure 2(a) shows the work zone layout including locations of work zone taper, congested area, VASL, and speed detectors for this dataset. The locations of speed detectors are named A, B, and C. Location A is the furthest upstream from location C which is the congested area location and location B is between locations A and C. Each detector is about 1 mile apart. One VASL sign was deployed 0.2 mile upstream of location B.

Dataset 2 (VASL was operational): Work zone was deployed from mile markers 5.7 to 10.0 on I-270 NB on June 25th, 2012. Congestion lasted for one hour from 9:20 am to 10:20 am. The layout of the work
zone and other locations can be found in Figure 2(b). Each detector is about 1 mile apart. One VASL was deployed at location B and another VASL was deployed 0.8 mile upstream of location A.

Datasets 3 and 4 (no VASL/VSL): Work zone deployed from mile marker 5.7 to 10.0 on I-270 NB on June 28th, 2012. Congestion lasted 45 minutes from 9:45 am to 10:30 am in dataset 3 and from 1:20 pm to 2:05 pm in dataset 4. The work zone layout for datasets 3 and 4 are shown in Figure 2(c), including locations of work zone taper, congested area, static speed limits, and speed detectors. The static speed limit on the I-270 study segment is 60 mph. Each detector is about 1 mile apart.

Figure 3 compares vehicles speeds, aggregated in 5-minute intervals, and the speed limit displayed by the VASL for Datasets 1 and 2 where VASL was active. The speeds were measured downstream from the VASL, after drivers have seen the VASL. Location A in dataset 1 did not have a VASL upstream within its vicinity, thus only location B plot is shown in Figure 3 (a). Figure 3(b) and (c) are the plots at both location A and location B in dataset 2.

**Speed-based Measures of Effectiveness**

For each work zone, the location where the speeds were the lowest was identified as the ‘congested area’. Typically, congestion in work zones occurs at the taper due to the lane drop, when demand exceeds the reduced capacity. However, work activity and intensity inside the work zone may also create congestion. It is not uncommon for traffic to slow down near the activity area due to the presence of workers and work equipment. With the exception of dataset 2 for which the congested area was at the taper, congestion occurred inside the work zone for other three work zones. One objective of VASL is to encourage drivers to reduce speeds gradually while approaching a congested area, thus preventing any unsafe sudden changes in speeds. To investigate this objective, speeds at three locations were recorded, at the congested area (location C) and two upstream locations (location A and location B).

The reduction of average speed from location A to location B was compared with the reduction of average speed from location B to location C. The ratio of the average speed reduction from location A to location B to the average speed reduction from location B to location C was calculated for each dataset. The ratio is computed as:

\[
\text{Speed reduction ratio} = \frac{\text{avg. speed at location A} - \text{avg. speed at location B}}{\text{avg. speed at location B} - \text{avg. speed at location C}} \tag{1}
\]

The speed reduction ratio is only computed when there is a reduction in the average speed from A to B and from B to C. A ratio higher than or equal to 1.0 is desirable as it means the drivers are decelerating earlier rather than later when they approach the congested area. A ratio lower than 1.0 is not desirable since it indicates higher vehicle speeds approaching a congested area. The ratios for all four datasets were computed. The speed reduction ratios for dataset 1 and dataset 2 with VASL turned on are 1.32 and 0.77 compared to 0.14 and 0.57 for the dataset 3 and dataset 4 with VASL turned off. Thus, VASL were effective in slowing down drivers gradually as they approached the work zone bottleneck, thus reducing any sudden speed changes.

Since individual vehicle speeds were not available, absolute compliance to speed limits could not be computed. One surrogate compliance measure adopted from Kwon et al (4) is the correlation coefficient between the average speeds and the posted speed limits (shown in Figure 3) for work zone VSL applications. The correlation coefficients computed in this study were 0.841 for location B in dataset 1, and 0.423 and 0.865 for location A and location B in dataset 2. The high positive correlations between the speed and the speed limit, especially at location B, indicate that average speeds and posted speed limits follow similar trends. Such a high correlation could indicate a high level of driver compliance. The compliance measure was not computed for datasets 3 and 4 because the congested traffic conditions meant that the operating speeds were always below the static speed limit of 60 mph.
SIMULATION ANALYSIS OF ADDITIONAL VASL SCENARIOS

Comparison of VASL, VSL, and Static Speed Limit Scenarios

Traffic simulation was used to perform additional analysis of the effectiveness of VASL in work zones. Simulation complements empirical analysis by exploring scenarios not captured by the field studies. Field data was not available to quantify the mobility impacts of VASL, thus simulation provided a medium to assess the mobility impacts. For example, measures such as delay times were challenging if not impossible to calculate using archived traffic data of flow, speed, and density. Simulation was used to evaluate variable speed limits in work zones by Yadlapati and Park (2004) for a case study in Virginia and by Mitra and Pant (2005) for an interchange work zone in Florida. This study used the same simulation software, VISSIM, as used by Yadlapati and Park (2004), and Mitra and Pant (2005). Two simulation models were created: one with VASL and one with static speed limit (i.e. without VASL). In all simulation models, the process of queue build-up and congestion were simulated on a 6.3 miles segment of I-270 in St. Louis, Missouri, from mile marker MM 3.7 to MM 10.0 (same as the work zone described in dataset 2 earlier). The work zone started from MM5.7 and ended at MM10.0. Two VASLs were set up at 1 mile and 2 miles upstream from the work zone taper. Data was recorded at three sensor locations: 1) work zone taper, 2) VASL 1, and 3) VASL 2. VISSIM’s Component Object Model (COM) server was used to program the Missouri DOT VASL algorithm described earlier. The network layout of the model with static speed limit is the same as the model with VASL except the two VASL signs were replaced with static speed limits signs, respectively.

The simulation model was calibrated to match observed capacity from the field by adjusting driver behavior parameters: headway time (CC1), following variation (CC2), and safety distance reduction factor (SRF). The default values of CC1, CC2 and SRF are 0.9 seconds, 4 ft, and 0.6. A capacity value of 2366 veh/hour/lane was obtained for the I-270 segment during morning peak hour for normal traffic conditions without the work zone. Field data obtained from the traffic detectors on I-270 was used to generate speed distributions that were inputted into the model. The calibrated parameters are CC1 = 1.5 seconds, CC2 = 13 ft, and SRF = 0.6.

Simulation time was set to 3900 seconds (> one hour) for both models with and without VASL. The first 300 seconds were used to warm up and the remaining 3600 seconds were used for data collection. In order to build up queue and congestion, the input volumes exceeded the work zone capacity. The previously determined capacity of 2,366 veh/hour/lane was used as an upper bound for the work zone capacity. The chosen input volumes gradually approached capacity (2,366 x 3 = 7,098 vehicles for 3 lanes), exceeded capacity for a certain duration, and fell below capacity. The input volume distribution used in the simulation is displayed in Figure 4.

The desired speed distributions of input vehicles and vehicles going past the posted speed limit signs were obtained from field data measured from another work zone site on I-70 in Missouri with similar road characteristics. Two desired speed distributions, one for speed limit compliant vehicles and one for non-compliant vehicles were inputted into the model. For compliant vehicles’ speed distribution, the maximum speed was the posted speed limit. For non-compliant vehicles’ speed distribution, the minimum speed was set as the posted speed limit. Four compliance rates, 25%, 50%, 75%, and 85% were investigated for the “VASL” scenario. One can argue that, in simulation, the 85% compliance VASL scenario is analogous to a regulatory VSL (if it is assumed that the compliance to regulatory speed limits is 85%). Thus, the VASL with 85% compliance rate will be referred to as VSL scenario. For the static speed limit scenario, compliance rate with respect to static speed limits was also assumed to be 85%, based on the assumption that the speed limit is set according to recommended engineering practice of 85th percentile speeds. Given the urban setting of I-270 in St. Louis, a truck percentage of 10% was used for all scenario evaluations. To account for the stochastic nature of simulation models, each study scenario was simulated 20 times with a different random seed each time and the results averaged across the simulations.
Several performance measures, relevant to work zone mobility and safety, were used to evaluate the effectiveness of VASL. The mobility measures include average queue length, work zone throughput, average number of stops, and average travel time. The safety measures include average 1-minute speed standard deviation, average 1-minute maximum speed differential between adjacent locations of speed limit signs, number of rear end conflicts, and number of lane changing conflicts. The conflict measures were extracted using the surrogate safety assessment model (SSAM) (Gettman and Head 2003; Kim et al. 2007) that post-processes the simulated vehicle trajectories. One measure was the time-to-collision (TTC) which was based on the current location, speed, and trajectory of two vehicles at a given instant. Another measure was the post-encroachment-time (PET), or the time between when the first vehicle last occupied a position and the time when the second vehicle arrived at that position afterwards. The SSAM further identifies conflicts with TTC less than 1.5 seconds, PET less than 5 seconds, and conflict angle less than 30 degrees as rear-end conflicts. A lane changing conflict occurs if the TTC is less than 1.5 seconds, PET is less than 5 seconds, and conflict angle ranges from 30 to 85 degrees.

Results of Operational Performance Measures

Several evaluation scenarios were generated by varying the compliance rate. The results of these scenarios are presented in this section with mobility measures presented first followed by the safety measures. The changes in performance resulting from VASL and their statistical significance are shown in Table 3. A “+” sign means increase and “-” sign means decrease in average queue length due to VASL and VSL. The percentage change in a performance measure due to VASL and VSL was computed as:

\[
\% \text{ change} = 100 \times \frac{\text{With VASL (or VSL) value} - \text{Static Speed Limit value}}{\text{Static Speed Limit value}}
\]  

(2)

Average Queue Length

The average queue length values for all scenarios were computed and are plotted in Figure 5. The queues started at the beginning of work zone taper. The average queue lengths with VASL and VSL were lower than those with the static speed limit. The VASL scenarios with higher compliance rates and VSL resulted in lower values for average queue length. T-tests were performed to test the statistical significance, and the results indicated that they were all statistically significant at a 95% confidence level. The values in Table 3 (the second column) show that the VASL was able to significantly reduce the average queue length, with the reductions ranging from 39.5% to 53.5%.

Work zone Throughput

The vehicle throughput, measured at the work zone taper, for all scenarios are plotted in Figure 6. The throughput values with VASL and VSL were lower than the throughput with the static speed limit. And the differences were all statistically significant. The third column in Table 3 shows the percentage decrease in throughput with VASL ranged from 6.9% to 10.9%.

Average number of stops

The average number of stops for the five scenarios are shown in Figure 7. With the exception of VASL with 75% compliance, all other compliance rates produced fewer stops than the static speed limit scenario. The fourth column in Table 3 showed the percentage change in average number of stops resulting from VASL and VSL. The reduction of 1.3% for the VSL scenario was not statistically significant; all other percentage changes were statistically significant.

Average Travel Time

The average travel times for the 5.3-mile segment measured from 1 mile upstream of the taper to the end of work zone were compared in Figure 8. The maximum queue length was 0.5 mile of taper, well within 1
mile upstream of taper. The average travel time at 25% compliance was lower than the average travel
time with static speed limit (see Table 3). However, the travel times for higher compliance rates (50%,
75%, and VSL) exceeded the average travel time with static speed limit, perhaps due to more vehicles
slowing down in response to the lower VASL speed limits.

**Results of Safety Performance Measures**

**Average 1-minute Standard Deviation of Speeds**

For every minute, the standard deviation of speeds at the taper, 1 mile upstream and 2 miles upstream of
the taper were extracted. The means of the average speed standard deviation across multiple simulation
runs are displayed in Figure 9. The 1-minute standard deviation was deemed to be a better safety measure
than the standard deviation computed over a longer time interval (such as 5 minutes or an hour). The
safety of a vehicle at a freeway location is usually not affected by events happening at that location much
later after the passing of the vehicle. Thus, a small time window of 1-minute duration was selected for
computing standard deviation of speeds. See, for example, MacCarley (2011) for a discussion on short-
term aggregated metrics of accident risk and severity.

As can be seen in Figure 9, the standard deviation of speeds at the taper decreased due to VASL.
The standard deviation values decreased 1-mile upstream as well, however the magnitude of decrease was
smaller than those at the taper. The standard deviation further upstream at the 2-mile location increased
due to VASL, the increases were minor for higher compliance rates. For example for a 50% compliance
rate, the standard deviation decreased by 1.8 mph at the taper, decreased by 0.4 mph at 1 mile upstream,
and increased by 1.8 mph at 2 mile upstream. On the balance, VASL improved safety by decreasing the
standard deviation at more locations, and those being closer to the work zone. Statistical tests were
performed to test the differences between VASL and without VSL results. They were all statistically
significant except for a compliance rate of 25% at 1 mile upstream.

**Average Maximum Speed Difference**

While the standard deviation measure captures the temporal variation of speeds at each of the three
locations (taper, 1 mile, 2 miles upstream), the maximum speed difference captures the spatial correlation
of speeds between two adjacent locations. Higher values of speed differences may indicate need for
excessive braking. Kwon et al. (2007) have used the maximum speed difference measure in the VSL
evaluation they conducted in Minnesota. For each vehicle, speed differences were computed for taper
versus 1 mile upstream, and 1 mile upstream versus 2 miles upstream. The maximum of those two speed
differences was then used to compute the average value for the entire sample. The means of the average
maximum speed difference across all simulation runs is shown in Figure 10. The maximum speed
differences always occurred between the taper and 1-mile upstream location. The results in Figure 10
clearly show that VASL and VSL had smaller average maximum speed differences than without VASL.
This was true for all compliance rates. Even with just 25% compliance, the speed differences with VASL
were 16.0 mph compared to 24.4 mph without VASL. The maximum speed differences were even lower
for higher compliance rates. T-tests for pair-wise comparisons of difference VASL scenarios versus the
without VASL scenario were all statistically significant.

**Rear End and Lane Changing Conflicts**

Vehicle trajectories were extracted from simulations and used as input to the SSAM program. As
previously discussed, SSAM uses certain threshold values for these three measures to identify rear end
and lane changing conflicts. The rear end and lane changing conflict types were believed to be
appropriate for a freeway work zone because of the lane changes occurring at the lane drop, the
possibility of queuing near the work zone and the decreased speeds near the work zone. The crossing
conflict type is not applicable since there is not a defined crossing movement. The results of rear end and
lane changing conflicts are shown in Figure 11.
The rear end conflicts shown in Figure 11 indicate that the VASL and VSL produced a higher number of rear end conflicts than the static speed limit. The differences between VASL and static speed limit scenarios were all statistically significant at the 95% confidence level. The results of lane changing conflicts were also similar to the rear end conflicts, the number of conflicts with VASL were higher than without VASL.

The number of conflicts without the work zone, i.e. normal conditions, were also computed for comparison purposes. The study segment was simulated without the work zone for the same demand and the resulting vehicle trajectories were processed using SSAM to determine the number of conflicts. There were 306 lane change conflicts and 42 rear end conflicts without the work zone. As expected, these numbers are lower than the conflicts observed with the work zone in place (both with and without VASL). Without the work zone, the demand was always below capacity and therefore there was no need for vehicles to make any mandatory lane changes, thus decreasing the potential for any conflicts.

**Summary of Performance Measures**

In summary, two out of four operational measures (queue length, stops with one exception) improved due to VASL whereas the other two measures became slightly worse (work zone throughput and travel time). Speed measures, with the exception of standard deviation 2-miles upstream, showed an improvement due to VASL. Higher numbers of rear end and lane changing conflicts were witnessed during VASL use. The mixed results of the effects of VASL on operational and safety measures led to the further investigation of the algorithm used for VASL control. Specifically, the research team confronted the following question: “Can the VASL algorithm used in the field be improved to achieve improvements in all operational and safety measures when compared to no-VASL conditions?” This question is addressed in the next section.

**VASL ALGORITHM PERFORMANCE ENHANCEMENT**

The VASL algorithm implemented by MoDOT in the I-270 corridor was previously described. Two variations of the MoDOT field algorithm were developed and performance evaluated. Traffic simulation was used to compare the performance of these two algorithms (called Proposed 1 min. and Proposed 5 min.) with the current MoDOT algorithm (called the field algorithm). The characteristics of the first algorithm (Proposed 1 min) are as follows:

- All detectors in the I-270 VASL corridor average vehicle speeds every one minute (weighted by volume).
- The recommended speed limit for VASL 1 mile upstream of taper is derived from Table 4 (a) using the speed measured at the taper area. The maximum speed limit is 60 mph.
- The recommended speed for VASL 2 miles upstream of taper is derived from Table 4 (b) using the average speed measured 1-mile upstream of taper. The maximum speed limit is 60 mph, and the minimum speed limit is 45 mph.
- Once a VASL is changed, it cannot be changed until one minute has elapsed.

There are a few differences between the Proposed 1 min. algorithm and the field algorithm. First, the average speeds are computed over a 1-minute interval instead of a 30-second interval. This was done to smooth the oscillations in speeds, if any. Second, interval sizes for measured speeds at taper (Table 4 (a) column 1) were changed to from 10 mph to 5 mph to allow for more speed limit values. Third, the second VASL sign (VASL 2) was updated using speeds measured at the VASL 1 (Table 4 (b)) instead of the displayed speed limit at VASL 1. The second algorithm (Proposed 5 min.) is similar to the Proposed 1 min. algorithm except the VASL signs are updated every five minutes, still averaging speeds over the most recent one minute. This update interval is the same as the one used in the field algorithm. All other parameters of the Proposed 5 min. algorithm are exactly same as those of the Proposed 1 min. algorithm.

In Table 4, the last rows for both 1-mile and 2-miles upstream locations show a minimum speed limit of 35 mph and 45 mph, respectively. These minimum values were chosen based on simulation observations of the field algorithm. While observing the VASL simulations, there were instances where
the upstream congestion lasted for a long time after the downstream congestion had cleared. This was possibly due to the effect of time lag between the speed limit updates. Thus, a minimum upstream speed limit was applied to alleviate some of this congestion. Note that in simulation, the minimum speed limit is only relevant when vehicles can operate at that speed limit or higher speeds. If congestion causes vehicles to slow down below the minimum speed limit, the vehicle speeds are controlled by congestion and not by the minimum speed limit. The minimum speed limit only aids the flow recovery process and may delay the onset of upstream congestion. In this study, queue length in the simulations never exceeded 0.5 miles. However, if longer queues are observed (e.g., 1 mile or longer), lower minimum speed limit values may be chosen for upstream locations to aid in warning approaching traffic of the back of the queue.

Comparing Performance of Three VASL Algorithms

The results of the two proposed VASL algorithms were compared with the performance of the field algorithm and shown in Table 5. The comparisons are made for 75% compliance rate. The second column in the table ranks the three algorithms (F: field, P1: proposed 1-minute, P5: proposed 5-minute) for each performance measure. For example, for the work zone throughput measure, the field algorithm had the lowest throughput while the P5 had the highest. The best of the three algorithms for each measure is shown in the third column. Upon reviewing the results shown in the third column, the P5 algorithm outperformed the field algorithm across more measures than P1. Thus, the P5 algorithm was chosen for comparison with the no-VASL conditions across all chosen measures. The fourth column in the table shows the percentage difference in the results of P5 and no-VASL, computed as:

\[
\text{% difference} = 100 \times \frac{P5 \text{ value} - \text{Static Speed Limit value}}{\text{Static Speed Limit value}}
\]

A negative percentage value indicates that the corresponding measure’s value was lower for P5 as compared to no-VASL. Negative values are desirable for average queue length, number of stops, travel time, standard deviation of speed, maximum speed difference, and both rear end and lane changing conflicts. Positive percentage values are desirable for work zone throughput.

The proposed 5-minute algorithm (P5) made some important improvements in performance when compared to the field algorithm. First, the work zone throughput for the field algorithm was up to 6.9% lower than static speed limit throughput, while the throughput with P5 is only 1.0% lower than the static speed limit throughput. Second, the static speed limit travel times were up to 6.4% lower than the field algorithm travel times as compared to 2.1% lower than the P5 algorithm travel times. Third, the rear end conflicts for field algorithm were greater than those of static speed limit, while the number of rear-end conflict for P5 was 30% lower than static speed limit. Similarly, the lane changing conflict for P5 was 20% lower than the static speed limit conditions (note that the 23% reduction shown in Table 5 is for P1 algorithm which slightly outperformed P5 for this measure). Thus, the proposed 5-minute VASL algorithm addressed the safety shortcomings of the field algorithm, improved the performance on throughput and travel times, and outperformed static speed limit on all other measures.

The results shown in Table 5 can also be used to conduct analysis with different weights assigned to performance measures. For example, if a transportation agency is primarily interested in the mobility benefits of VASL it is reasonable to assign higher weights to operational measures than safety measures. Considering queue length, throughput, number of stops, and travel time, the P5 algorithm slightly outperforms the field algorithm.

CONCLUSIONS AND FUTURE RESEARCH

Work zones in high traffic volume urban areas often create bottlenecks. Transportation agencies are faced with the challenge of alleviating congestion at these bottlenecks and improving safety. The I-270 corridor in St. Louis carries the highest volumes among all freeways in Missouri with daily volumes exceeding
180,000 at some locations. An active traffic management strategy employing variable speed limits on I-270 corridor was deployed by Missouri DOT to address the congestion and safety concerns. Thus, work zones on this corridor provided a rare opportunity to test the effectiveness of VASL in a congested urban area. The empirical analysis of the VASL system found that the VASL were effective in slowing down drivers as they approached a work zone bottleneck, thus reducing any sudden changes in speeds. Correlation between traffic speeds and posted speed limits showed medium to high compliance to the advisory speed limits.

The simulation analysis showed that the VASL algorithm implemented in the field decreased queue length and number of stops but slightly worsened throughput and travel time. Most speed-based measures improved due to VASL. The effect of the field VASL algorithm on rear end and lane change conflicts was not consistent. A new VASL algorithm investigated in the study showed significant improvements in mobility and safety performance compared to the algorithm implemented in the field. The new algorithm made promising improvements in safety – a 30% reduction in rear end conflicts and a 20% reduction in lane changing conflicts as compared to the without VASL condition. Rear end and lane change crashes typically occur at congested work zones due to the queuing conditions. The new VASL algorithm also decreased the queue length, further improving the overall safety in congested work zones.

This study offered a robust evaluation using ten performance measures for assessing benefits of advisory VSL in work zones. The study findings for safety benefits were similar to the findings of regulatory VSL documented in other studies. A comparison between the effects of regulatory and advisory speed limit systems in work zones could be investigated in the future using empirical studies. Since detectors did not provide vehicle type information, speed data was aggregated for all vehicle types. The study was conducted in an urban setting, thus most of vehicles are passenger cars.

The interaction among locations of VASL, detectors, and work zones could be studied in the future assuming a DOT is willing to change the traffic control during work zone deployments. Also, more informative sources of data are becoming available in contrast to point detection data. Travel time data from smart phones and other location-based devices could be used in the future to analyze travel times through work zones. With field studies it is not always feasible to study the same work zone with and without VASL occurring during the same time of day. If possible, future research should explore opportunities where VASL and static speed limits are deployed on the same work zone during the same time of day on different days in order to account for confounding factors.

Although the VASL algorithms analyzed in this paper were for a specific location in Missouri, some of the findings are transferable to other locations. Many major cities in the US have one or more interstates that carry traffic volumes similar to I-270 in Missouri. Thus, lessons learned from the proposed algorithm on I-270 could be useful for other locations considering VASL deployment. First, the interval size for averaging traffic speeds was increased from 30 seconds (the field algorithm) to 1-minute. The higher aggregation interval size helped smooth the oscillations in speeds. Second, it is recommended that the speed limit at the second VASL sign (two miles upstream of the taper) be determined based on the average prevailing speeds one mile upstream of the taper instead of the displayed speed limit at the first VASL sign.

The VASL algorithms studied in this paper, those implemented in the field and those that were proposed, were aimed at improving safety. This study took a holistic approach of comparing the performance of VASL with static speed limit across several safety and mobility performance measures. Algorithms specifically geared towards improving specific performance measures, such as mobility, could be explored in future research. However, it is noted that research on VSL applications for recurring traffic congestion have been inconclusive in capacity improvements (Mirshahi et al., 2007, Papageorgiou et al., 2008, Weikl et al., 2013, Kianfar et al., 2013).

In the simulation analysis, the ‘advisory’ aspect of the VASL was modeled using the compliance to posted speed limit. In future research, other alternatives to modeling the ‘advisory’ nature of VASL may be investigated. The travel times with VASL were larger than without VASL for most compliance levels. The higher the compliance level, the higher was the travel time. This finding means that the increase in travel time due to lower speed limits (VASL is always less than or equal to the static speed
limit of 60 mph on the study corridor) is not offset by the decrease in delay resulting from shorter queue lengths that were observed. In future research, the effects of lower speed limits and queue reduction on travel time can be investigated.

ACKNOWLEDGMENT

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REFERENCES


### Table 1. Performance measures for VSL evaluation

<table>
<thead>
<tr>
<th>Study</th>
<th>Type of VSL</th>
<th>Performance Measures (Field)</th>
<th>Performance Measures (Simulation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lyles et al. (2004)</td>
<td>Regulatory</td>
<td>Average speed, speed difference, travel time, 85(^{th}) percentile speed, speed variance, higher speed vehicle percentage</td>
<td></td>
</tr>
<tr>
<td>Yadlapati and Park (2010)</td>
<td>Regulatory</td>
<td></td>
<td>Travel time, throughput, minimum safety distance, crash surrogate</td>
</tr>
<tr>
<td>Kwon et al. (2007)</td>
<td>Advisory</td>
<td>Maximum speed difference, throughput, compliance</td>
<td></td>
</tr>
<tr>
<td>Riffkin et al. (2008)</td>
<td>Regulatory</td>
<td>Speed distribution, mean and standard deviation of speed, compliance</td>
<td></td>
</tr>
<tr>
<td>Fudala and Fontaine (2010)</td>
<td>Regulatory</td>
<td></td>
<td>Mean speed, lane changes, queue length, stops</td>
</tr>
<tr>
<td>This paper</td>
<td>Advisory</td>
<td>Speed reduction ratio, compliance</td>
<td>Queue length, stops, travel time, throughput, standard deviation of speed, maximum speed difference, rear end conflicts, lane changing conflicts</td>
</tr>
</tbody>
</table>

### Table 2. VASL algorithm deployed in the field by Missouri DOT

<table>
<thead>
<tr>
<th>Average speed measured at taper (mph)</th>
<th>Speed limit displayed on VASL 1 mile upstream based on speeds measured at taper (mph)</th>
<th>Speed limit displayed on VASL 2 miles upstream based on speed limit displayed at VASL 1 mile upstream (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥50</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>≥40-50</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>≥30-40</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>≥20-30</td>
<td>30</td>
<td>40</td>
</tr>
</tbody>
</table>
Table 3. Percentage changes in the performance measures resulting from VASL and VSL

<table>
<thead>
<tr>
<th></th>
<th>Queue length</th>
<th>Throughput</th>
<th>Stops</th>
<th>Travel time</th>
<th>Speed Std. Dev.</th>
<th>Maximum Speed Difference</th>
<th>Rear End Conflicts</th>
<th>Lane Changing Conflicts</th>
</tr>
</thead>
<tbody>
<tr>
<td>VASL 25%*</td>
<td>-40.9%*</td>
<td>-7.6%*</td>
<td>-9.7%*</td>
<td>-1.8%*</td>
<td>-16.7%*</td>
<td>-34.4%*</td>
<td>52.1%*</td>
<td>53.5%*</td>
</tr>
<tr>
<td>VASL 50%*</td>
<td>-39.5%*</td>
<td>-10.9%*</td>
<td>-13.7%*</td>
<td>4.4%*</td>
<td>-21.4%*</td>
<td>-38.1%*</td>
<td>44.1%*</td>
<td>49.7%*</td>
</tr>
<tr>
<td>VASL 75%*</td>
<td>-53.5%*</td>
<td>-6.9%*</td>
<td>8.0%*</td>
<td>6.4%*</td>
<td>23.8%*</td>
<td>-45.5%*</td>
<td>50.1%*</td>
<td>0.60%</td>
</tr>
<tr>
<td>VSL</td>
<td>-52.6%*</td>
<td>-7.8%*</td>
<td>-1.30%</td>
<td>7.6%*</td>
<td>26.2%*</td>
<td>-44.3%*</td>
<td>52.9%*</td>
<td>9.2%*</td>
</tr>
</tbody>
</table>

* Statistically significant at the 95% confidence level
# Speed limit compliance rate

Table 4. Proposed 1 min and 5 min algorithm characteristics

<table>
<thead>
<tr>
<th>Average speed measured at taper (mph)</th>
<th>VSL 1 mile upstream based on speeds measured at taper (mph)</th>
<th>VSL 2 miles upstream based on speed measured at 1 mile upstream of taper (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥50</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>≥45-50</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>≥40-45</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>≥35-40</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>≥30-35</td>
<td>40</td>
<td>45</td>
</tr>
<tr>
<td>&lt;30</td>
<td>35</td>
<td>45</td>
</tr>
</tbody>
</table>
Table 5. Performance of the three VASL algorithms for 75% compliance

<table>
<thead>
<tr>
<th>Performance measure</th>
<th>Best performing algorithm</th>
<th>Proposed 5-minute algorithm vs Static speed limit</th>
<th>Proposed 1-minute algorithm vs Static speed limit</th>
<th>Field algorithm vs Static speed limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average queue length</td>
<td>F</td>
<td>-38.4%</td>
<td>-37.2%</td>
<td>-53.5%</td>
</tr>
<tr>
<td>Work zone throughput</td>
<td>P5*</td>
<td>-1.0%</td>
<td>1.7%</td>
<td>-6.9%</td>
</tr>
<tr>
<td>Number of stops</td>
<td>P5*</td>
<td>-27%</td>
<td>-20.1%</td>
<td>+8%</td>
</tr>
<tr>
<td>Travel time</td>
<td>P5*</td>
<td>+2.1%</td>
<td>+5.4%</td>
<td>+6.4%</td>
</tr>
<tr>
<td>Standard deviation of speeds</td>
<td>Taper: F</td>
<td>Taper: -10%</td>
<td>Taper: -16%</td>
<td>Taper: -24%</td>
</tr>
<tr>
<td></td>
<td>1-mi u/s: P5</td>
<td>1-mi u/s: -22%</td>
<td>1-mi u/s: -24%</td>
<td>1-mi u/s: -21%</td>
</tr>
<tr>
<td></td>
<td>2-mi u/s: P5*</td>
<td>2-mi u/s: +16%</td>
<td>2-mi u/s: +21%</td>
<td>2-mi u/s: +26%</td>
</tr>
<tr>
<td>Maximum speed difference</td>
<td>P1*</td>
<td>-57%</td>
<td>-62%</td>
<td>-45%</td>
</tr>
<tr>
<td>Rear end conflicts</td>
<td>P5*</td>
<td>-30%</td>
<td>-5%</td>
<td>+50%</td>
</tr>
<tr>
<td>Lane changing conflicts</td>
<td>P1*</td>
<td>-23%</td>
<td>-30%</td>
<td>+0.5%</td>
</tr>
</tbody>
</table>

Note: F: field VASL algorithm, P1: proposed 1-minute VASL algorithm, P5: proposed 5-minute VASL algorithm
* Statistically significant at 95% confidence level when compared with the field algorithm (F)
Figure 1. Regulatory and Advisory VSL Signs
Figure 2. Work zone layouts for Datasets 2, 3, and 4.
Figure 3. Temporal variation of vehicle speed and speed limits.
Figure 4. Input volume distribution.

Figure 5. Average queue length (in feet).

Figure 6. Work zone throughput (veh/hr).
Figure 7. Average number of stops.

Figure 8. Average travel time (in seconds).

Figure 9. Average standard deviation of speeds (in mph).
Figure 10. Means of average maximum speed difference (in mph).
a. Number of rear end conflicts

![Bar chart showing rear end conflicts]

b. Number of lane changing conflicts

Figure 11. Rear end and lane changing conflicts.