Evaluation of Variable Advisory Speed Limits in Work Zones

Final Report
August 2013

SWZDI
Smart Work Zone Deployment Initiative

Mizzou
University of Missouri - Columbia

Sponsored by
Smart Work Zone Deployment Initiative
(TPF-5(081))
Federal Highway Administration
(InTrans Project 06-277)

About SWZDI

Iowa, Kansas, Missouri, and Nebraska created the Midwest States Smart Work Zone Deployment Initiative (SWZDI) in 1999 and Wisconsin joined in 2001. Through this pooled-fund study, researchers investigate better ways of controlling traffic through work zones. Their goal is to improve the safety and efficiency of traffic operations and highway work.

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16. Abstract

Variable advisory speed limit (VASL) systems could be effective at both urban and rural work zones, at both uncongested and congested sites. At uncongested urban work zones, the average speeds with VASL were lower than without VASL. But the standard deviation of speeds with VASL was higher. The increase in standard deviation may be due to the advisory nature of VASL. The speed limit compliance with VASL was about eight times greater than without VASL. At the congested sites, the VASL were effective in making drivers slow down gradually as they approached the work zone, reducing any sudden changes in speeds. Mobility-wise the use of VASL resulted in a decrease in average queue length, throughput, number of stops, and an increase in travel time. Several surrogate safety measures also demonstrated the benefits of VASL in congested work zones. VASL deployments in rural work zones resulted in reductions in mean speed, speed variance, and 85th percentile speeds downstream of the VASL sign. The study makes the following recommendations based on the case studies investigated:

1. The use of VASL is recommended for uncongested work zones to achieve better speed compliance and lower speeds. Greater enforcement of regulatory speed limits could help to decrease the standard deviation in speeds.
2. The use of VASL to complement the static speed limits in rural work zones is beneficial even if the VASL is only used to display the static speed limits. It leads to safer traffic conditions by encouraging traffic to slow down gradually and by reminding traffic of the reduced speed limit.

A well-designed VASL algorithm, like the P5 algorithm developed in this study, can significantly improve the mobility and safety conditions in congested work zones. The use of simulation is recommended for optimizing the VASL algorithms before field deployment.

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EVALUATION OF VARIABLE ADVISORY SPEED LIMITS IN WORK ZONES

Final Report - August 2013

Praveen Edara, Ph.D., P.E., PTOE; Carlos Sun, Ph.D., P.E., J.D.; Yi Hou, M.S.
University of Missouri-Columbia edarap@missouri.edu (573) 882-1900

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This research was conducted under the Midwest Smart Work Zone Deployment Initiative (SWZDI) and Federal Highway Administration (FHWA) Pooled Fund Study TPF-5(081), involving the following state departments of transportation:

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EXECUTIVE SUMMARY

The effectiveness of variable speed limit (VSL) systems in work zones was investigated in this study. While the majority of the VSL deployments in the past pertained to hazardous weather conditions or recurring congestion applications, very few states deployed VSL systems in work zones. Michigan, Utah, and Virginia tested regulatory VSL systems while Minnesota tested an advisory VSL (VASL) system. A survey questionnaire inquiring about the use of VSL in work zones conducted in the study revealed four other states, Washington, Virginia, Ohio, and New Hampshire, using or planning to use VSL in work zones. Limited studies on work zone VSL evaluations have reported safety and mobility benefits. The current study contributes to the limited body of knowledge by performing extensive evaluations at work zones in Missouri. This study used a more comprehensive set of performance measures than previous evaluations. The study scope included both urban and rural work zones and uncongested and congested sites. The study had three main objectives: 1) to conduct field studies to investigate the effectiveness of VASL on traffic safety in work zones, 2) to evaluate the mobility and safety impact of VASL in congested work zones, and 3) to investigate the work zone performance of an existing VASL algorithm used in Missouri and to make algorithm improvements. Appropriate statistical techniques were applied to achieve the three main objectives.

The uncongested work zone treatment site was located on northbound I-270 between I-44 and Route 100. At this site the VASL was always on when the work zone was in place, thus there was no data available without VASL. A control site, without VASL, was located on westbound I-70 between I-270 and Route 94. The treatment and control sites were similar in terms of work zone configuration, terrain, geometrics and volumes. The compliance rates, as shown in Figure E1, were much higher with VASL than without it.

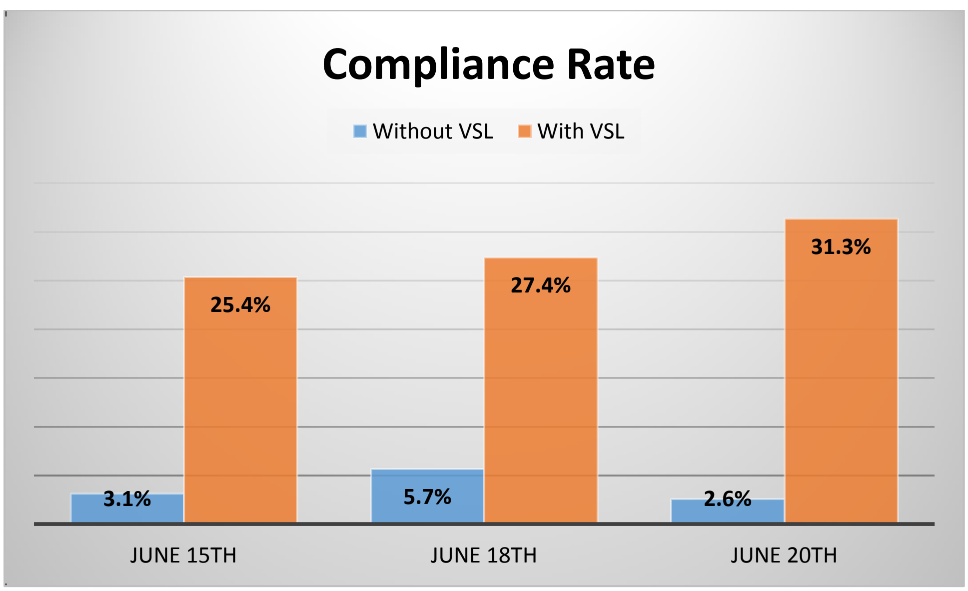


Figure E1. Compliance rates with and without VASL

The congested work zone was on northbound I-270 between I-44 and Route 100. Because there were times when the VASL signs were not on with the work zone in place, the site served both as the treatment (with VASL on) and control (with VASL off).Two work zone periods with VASL (cases 1 and 2) and two work zone periods without VASL (cases 3 and 4) were analyzed.

For investigating safety, two points upstream from the bottleneck were defined: location 1 and location 2. Location 1 was between 1 and 1.6 miles upstream from location 2, and location 2 was between 1 and 1.6 miles upstream from the bottleneck. Speeds were analyzed as vehicles proceeded from location 1 to location 2 and then to the bottleneck. The average speed reduction from location 1 to location 2 was compared to the reduction from location 2 to the bottleneck. If the ratio of the two speed reductions was greater than or equal to 1.0, then drivers decelerated earlier rather than later when they approached the bottleneck. A ratio lower than 1.0 was not desirable, since it represented higher vehicle speeds near the bottleneck. The speed reduction ratios for cases 1 and 2 (with VASL turned on) were 1.32 and 0.77 compared to 0.14 and 0.57 for cases 3 and 4 (with VASL turned off).

In summary, urban field studies demonstrated some trade-offs in the deployment of VASL. For the uncongested sites, the average speeds with VASL were found to be lower than without VASL. On average, a reduction of 2.2 mph was observed. However, the standard deviation of speeds with VASL was higher by 4.4 mph on average than without VASL. The increase in standard deviation may be due to the advisory nature of VASL. Since they are not enforceable, some drivers comply while others do not, thus increasing the standard deviation. The compliance rates inside the work zone were low with or without VASL. Still, the compliance with VASL was about eight times greater than without VASL. For the congested sites, VASL were effective in slowing drivers down gradually as they approached the work zone, thus reducing sudden changes in speeds. The average speeds and the posted advisory speed limits with VASL had similar trends, with correlation coefficients ranging between 0.42 and 0.86. The visual inspection of average speeds versus variable speed limits showed that drivers complied with VASL.

Two case studies of work zones in rural areas were conducted. The first work zone was located on southbound US 54 between Route D and Route E, and the second work zone was located on northbound US 63 near Route H. With traffic conditions not warranting the lowering of advisory speed limits, the case studies instead focused on evaluating the effect of VASL as static digital speed limit signs. The VASL sign was in addition to the existing static speed limit signage, thus acting as reinforcement to the static speed limit. For the US 54 site, the mean speed and 85th percentile speeds with VASL were about 2 mph lower than without VASL. In terms of effect size, the 2 mph difference was small. The difference in variance in speeds at the downstream location was not significant. At the taper the 85th percentile speeds were very close to the posted speed limit indicating vehicles slowed down between the VASL and taper locations. The decrease in the mean speeds from VASL to the taper location indicates that the drivers lowered their speeds with VASL (by 2.8 mph) compared to without VASL (by 7.7 mph). In terms of effect size, this approximately 5 mph difference was large. The variance of this speed reduction was also lower with VASL. For the US 63 site, the mean speed downstream of the VASL sign was 1.5 mph lower with VASL than without VASL. The 85th percentile speed also was lower with VASL (by 2 mph). In summary, both rural case studies showed reductions in mean speed, speed variance, and 85th percentile speed downstream from the VASL sign. The speed reduction from the VASL sign to the taper was significant when VASL was deployed, at the US 54 site. Thus, VASL could complement static speed limit signage at a rural work zones. VASL deployments result in safer traffic conditions by reminding traffic of the reduced speed limit as they approach the work zone.

Traffic simulation was used to complement field studies by exploring scenarios not captured by the field studies. Two work zone simulation models were created: congested work zone with VASL and without VASL. By varying the compliance rate and truck percentages, ten different evaluation scenarios were generated. The use of VASL resulted in a 40% to 58% decrease in average queue length, a 6% to 13% reduction in throughput, a 20% to 29% decrease in number of stops and a 1.5% to 10% 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 standard deviation of speeds slightly increased 2 miles upstream of the taper with VASL. The maximum speed differences also decreased by up to 10 mph with VASL. The effect of VASL on predicted number of rear end and lane changing conflicts varied based on the proportion of trucks in the traffic stream. The number of conflicts increased with VASL when the traffic stream consisted of 10% trucks, but decreased for 15% trucks. The traffic simulation produced mixed results with both positive and negative mobility and safety results.

The mixed results of the effects of VASL on operational and safety measures led to the refinement of the existing algorithm. Two variations of the VASL field algorithm were developed. One of the proposed algorithms, the 5-minute algorithm (P5), made some important improvements in performance compared to the field algorithm. First, throughput improved by 11.5%. Second, travel times improved by 1.5%. Third, rear end conflicts were reduced by approximately 31% and 20% for 10% and 15% trucks, respectively. Similarly, lane changing conflicts were also lowered. Thus, the proposed 5-minute VASL algorithm improved both the safety and the mobility performance.

The study makes the following recommendations based on the case studies investigated:

1. The use of VASL is recommended for uncongested work zones to achieve better speed compliance and lower speeds. Greater enforcement of regulatory speed limits could help to decrease the standard deviation in speeds. The use of VASL in congested work zones results in drivers reducing their speeds while approaching the work zone. However, it was not possible to distinguish the effect of VASL with that of traffic congestion in reducing speeds.
2. The use of VASL to complement the static speed limits in rural work zones is beneficial even if the VASL is only used to display the static speed limits. It leads to safer traffic conditions by encouraging traffic to slow down gradually and by reminding traffic of the reduced speed limit.
3. A well-designed VASL algorithm, like the P5 algorithm developed in this study, can significantly improve the mobility and safety conditions in congested work zones. The use of simulation is recommended for optimizing the VASL algorithms before field deployment.

INTRODUCTION

Variable speed limit (VSL) systems have been implemented in several states for improving traffic safety and mobility. 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 2010. 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.

The focus of this research project 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. They also mention that the VSL benefits during uncongested conditions are unknown and further research may be needed to address that question. In summary, some previous work zone VSL evaluations have reported modest safety and mobility benefits.

The current study contributes to the limited existing body of knowledge on VASL systems by performing extensive evaluations at work zones in Missouri. This study used a more comprehensive set of performance measures than previous evaluations. The study scope included both urban and rural work zones and uncongested and congested sites. The study has three main objectives:

1. To conduct field studies to investigate the effectiveness of VASL in terms of safety measures such as compliance to posted speed limits and other speed characteristics.

2. To evaluate the mobility and safety impact of VASL in congested work zones. Mobility measures such as average queue length, work zone throughput, and average travel times are investigated. Safety measures researched include, speed variance, maximum spatial speed difference and rear end and lane changing conflicts based on time to collision and conflict angle surrogate measures. This objective is achieved using analysis conducted on calibrated simulation models.
3. To investigate the work zone performance of an existing VASL algorithm being used on a freeway corridor in Missouri, to document its strengths and weaknesses, and to make improvements to address limitations of the algorithm.

To achieve the above study objectives three tasks were conducted. Task 1 was a survey of state DOT on VASL practices in work zones. Task 2 was an analysis of the effectiveness of VASL in work zones in urban and rural areas. Task 3 was a simulation analysis of additional 'what if' scenarios that could not be evaluated in field studies.

The results of each of these tasks are presented in this report. First, the results of the state of practice survey are presented. Second, the characteristics of field studies of urban and rural VASL deployments are presented followed by a discussion of the results. Simulation analysis of additional VASL scenarios is then provided. The report concludes with a discussion of the key findings and recommendations for future VASL deployments.

STATE-OF-THE-PRACTICE SURVEY

A survey questionnaire was prepared and administered via a web service. The survey inquired about the use of regulatory or advisory VSL in work zones, devices used to display VSL, the basis for changing speed limits, type of traffic detection used, placement of VSL signs, and measures of effectiveness for evaluating VSL deployments. A copy of the survey can be found in Appendix A. The survey participation request was sent to appropriate DOT personnel (such as work zone coordinators) in all 50 states in May, 2011. Survey reminders were also sent one week and two weeks after the initial request.

Overall, 29 DOTs responded to the survey. Table 1 lists the states that responded. Only four state DOTs, Washington, Virginia, Ohio, and New Hampshire, said they have used VSL in work zones. As reported in the previous section, three other states, Michigan, Utah, and Minnesota also deployed VSL in work zones. A summary of the responses of states using VSL in work zones is provided.

Table 1. State DOTs using VSL in work zones

	State	Use VSL in Work Zones
1	Alaska	No
2	Arizona	No
3	Arkansas	No
4	California	No
5	Delaware	No
6	Georgia	No
7	Idaho	No
8	Indiana	No
9	Iowa	No
10	Kansas	No
11	Kentucky	No
12	Louisiana	No
13	Maine	No
14	Michigan	No*
15	Mississippi	No
16	Missouri	No
17	Montana	No
18	Nebraska	No
19	New Hampshire	Yes
20	New Jersey	No
21	New York	No
22	North Dakota	No
23	Ohio	Yes
24	Pennsylvania	No
25	Rhode Island	No
26	Texas	No
27	Vermont	No
28	Virginia	Yes
29	Washington	Yes

* Lyles et al. (2004) reported using VSL in a work zone in Michigan

Washington DOT (WDOT)

WDOT uses both regulatory and advisory VSL in work zones. Dynamic message signs (or permanent changeable message signs) are used to display the variable speed limits. One PCMS sign for each direction of travel is used to advise motorists of the speeds in addition to the standard speed reduction signing. Speeds inside the work zone measured using loop detectors or microwave detectors are used to determine the speed limit. Other factors such as a history of speeding at a particular location are also considered. At problematic locations, coordination with state highway patrol, off peak lane closures, and appropriate advance warning signs are also considered.

VSL signs are typically placed at the beginning of the work zone so drivers understand the need for the speed reduction in coordination with the warning signs. When asked about the factors considered in deploying VSL signs at a particular site, all listed factors were chosen (average queue length, presence of diversion route, work activity type and intensity, average speeds, number of lanes). In terms of evaluation of VSL deployments, average speed, speed variance, volume, deceleration rate, lane change distance and crash frequency were used.

Virginia DOT (VDOT)

VDOT has used regulatory VSL in work zones. Although VSL is not routinely used in work zones, when used the speed limits are displayed using custom variable speed limit display devices. The Beltway project discussed in the previous section was mentioned as the only work zone VSL deployment by VDOT. The speeds inside the work zone measured using microwave detectors are used to update speed limits. Type of work activity and intensity, and number of lanes were listed as the factors considered in the deployment of VSL signs at a work zone site. Three measures of effectiveness are considered in evaluating VSL deployments – average speeds, speed variances, and crash frequency.

Ohio DOT (ODOT)

ODOT has uses regulatory VSL in work zones. Portable post-mounted signs are used to display the variable speed limits. The number of devices deployed at a site varies based on speed, length and number of speed zones at each work zone. The speed limits are predetermined for different times of day and not determined using real-time measured speeds. Factors such as average queue length, proximity of work activity to traffic, mobile versus stationary activity are taken into consideration while determining the placement of VSL signs. ODOT plans to embark on an evaluation of the effectiveness of VSL systems soon.

New Hampshire DOT (NHDOT)

NHDOT uses regulatory VSL in work zones. When used, up to two variable speed limit display devices are used to post the speed limits. The speeds inside the work zone are used to update speed limits. The placement of signs varies with the geographical limits of work zone. Type of work activity and intensity, and the number of lanes were listed as the factors considered in the deployment of VSL signs at a work zone site. No measures of effectiveness have been established to evaluate VSL deployment in work zones.

EMPIRICAL ANALYSIS OF VASL EFFECTIVENESS

In this section, two sets of case studies are presented. One set involves congested and uncongested urban work zones in St. Louis, Missouri. Another set involves rural work zones in rural central Missouri.

Urban Case Studies

The I-270 corridor in St. Louis, Missouri, has permanent VASL signs deployed since 2010. The advisory signs reduce the speed limits based on the prevailing traffic conditions. The work zones within the I-270 corridor provided an opportunity for investigating the performance of VASL. Work zones in uncongested segments of I-270 and congested segments of I-270 were selected as case studies for analyzing VASL effects. The algorithm used to update the speeds on VASL signs is provided next.

The I-270 VASL Algorithm

The MoDOT's VASL algorithm used in the field had the following characteristics:

- All detectors in the I-270 VASL corridor average vehicle speeds every 30 seconds.
- The speed displayed for the VASL 1 mile upstream of taper is the speed measured at the taper area rounded up to the next 10 mph increment as shown in Table 2(a). The maximum speed limit is 60 mph.
- The speed displayed for the VASL 2 miles upstream of taper should be 10 mph higher than the VASL 1 mile upstream, up to the regular speed limit of 60 mph as displayed in Table 2(b).
- Once a VASL is changed, it cannot be changed until 5 minutes have elapsed.

Table 2. VASL algorithm deployed in the field

a. VASL 1 mile upstream of taper

Average speed measured at taper	Speed limit displayed on VASL 1 mile upstream
>50	60
40-50	50
30-40	40
20-30	30
10-20	20
<10	10

b. VASL 2 miles upstream of taper

Speed limit displayed on VASL 1 mile upstream	Speed limit displayed on VASL 2 miles upstream
60	60
50	60
40	50
30	40
20	30
10	20

Uncongested Sites

One work zone site on northbound I-270 between I-44 and Route 100 operated under uncongested conditions and was selected as the treatment site. Because the VASL was always operational when the work zone was in place, the site did not allow for collecting any data without VASL. Thus, another work zone site without VASL and only static speed limits had to be selected as a control site for assessing the effects of VASL. Since the entire I-270 corridor had VASL deployed, the control sites had to be selected from other freeways in the region to capture similar driver population. One such work zone site was found on westbound I-70 between I-270 and Route 94.

The I-70 site was the best control site available considering the many similarities with the treatment site. Both work zones involved the closure of rightmost lane, had similar terrain, geometrics, hourly volume (4,509 vph on I-270 and 4,336 vph on I-70), and the same work zone reduced speed limit of 50 mph. The days of work activity were also the same at both sites (in June 2012). One difference between the two sites was the I-270 work zone had three lanes open to traffic whereas the I-70 work zone had four lanes open to traffic with the work zone in place. The layout of traffic detectors, speed limit signs (static and VASL), and work zone starting (taper) and ending points are shown in Figures 1 and 2 for I-270 and I-70, respectively. For both sites, two detectors were deployed at or immediately downstream of the two static speed limit signs within the work zone. Thus, these detectors measured average speeds of vehicles that were aware (or reminded) of the reduced work zone speed limit. For the I-270 site (Figure 1), one permanent VASL sign was present upstream of the second detector (detector 2) and immediately downstream of the static speed limit sign. Thus, detector 2 captured the response of drivers in reaction to VASL.

Figure 1. Layout of the I-270 work zone (uncongested treatment)

Figure 2. Layout of the I-70 work zone (uncongested control)

Speeds averaged over one minute intervals were collected for each detector location. This was the smallest resolution data that was available from the data archive provided by Missouri DOT. The speed data were collected from 11:00 am to 5:00 pm on three days with work zones at both sites on June 15th, 18th and 20th, 2012. For the duration of the work zone, the VASL displayed 50 mph on June 15th and 20th, and 40 mph on June 18th. Thus, the VASL was same as the static speed limit of 50 mph on the 15th and the 20th and 10 mph lower than the static speed limit on the 18th. These were the only speeds displayed on the VASL during the entire work zone period for uncongested conditions. As will be later discussed the VASL display was updated dynamically based on traffic levels for congested conditions; however, this was not the case for uncongested work zones.

Descriptive statistics of the speed data are shown in Table 3. The average speeds reported by detector 1 were significantly higher than the posted speed limit of 50 mph on all three days (Table 3). The average speeds at detector 2 at the VASL site were always lower than those at the control site, but still higher than the posted speed limit. The average speeds dropped from detector 1 to detector 2. The speed drop was more predominant at the VASL site. However, this drop may not be entirely due to VASL as the distance between detector 1 and 2 at the VASL site is 1.2 miles compared to 0.7 miles at the control site. The standard deviation of speeds at detector 2 was higher with VASL on all three days. F-test results for these differences were significant at the 95% confidence level. This finding may be attributed to the advisory nature of the VASL. Since the VASL are not enforceable, some drivers may have slowed down while others did not, thus increasing the standard deviation during each measurement interval.

Table 3. Descriptive statistics of speeds at uncongested treatment and control sites

Date	Scenario	Detector 1			Detector 2		
		Average speed	Standard deviation	Traffic count	Average speed	Standard deviation	Traffic count
June 15th	With VASL	63.4	2.42	31434	58.2	7.56	28600
	Without VASL	62.4	3.48	25842	59.6	2.91	28658
June 18th	With VASL	61.9	6.49	28000	57.6	8.07	25920
	Without VASL	61.9	3.34	22308	59.8	4.35	24532
June 20th	With VASL	63.5	2.32	28678	57.4	7.66	26642
	Without VASL	61.8	3.07	22694	60.3	2.84	24860

Note: Standard deviation is the standard deviation of 1-min interval average speeds

Compliance to Posted Speed Limit

Compliance of drivers to the posted speed limits in a work zone is a good measure of effectiveness of any speed limit policy. In a recent study, the authors (Hou et al., 2013) compared the driver compliance to different reduced speed limits in Missouri. As demonstrated in that study, individual vehicle speeds are necessary to compute the compliance rates for a given policy. Unfortunately, the traffic data collected by point detectors (e.g. loop detectors) only report average values of traffic variables averaged over certain time intervals (as low as 10 seconds). Further, for archiving purposes, the data is aggregated into 1-minute, 5-minute, 15-minute or even larger time intervals. Thus, it is challenging to compute true compliance rates using point detector data. However, that was the only form of traffic monitoring available for the treatment and control sites. Instead of true compliance rate, a pseudo compliance rate (from now referred to as compliance rate) was defined as the '*percentage of 1-minute average speeds below the posted speed limit*'. The average speeds at detector 2 were used for comparing the compliance rate for work zones with and without VASL since it was located immediately downstream of the speed limit signs (static, VASL). The compliance rates computed for the three work zone days are shown in Figure 3. The compliance rates were much higher with VASL than without it: compliance to VASL was about 8 times, 4 times, and 12 times higher than that of static speed limit, on June 15th, 18th, and 20th, respectively.

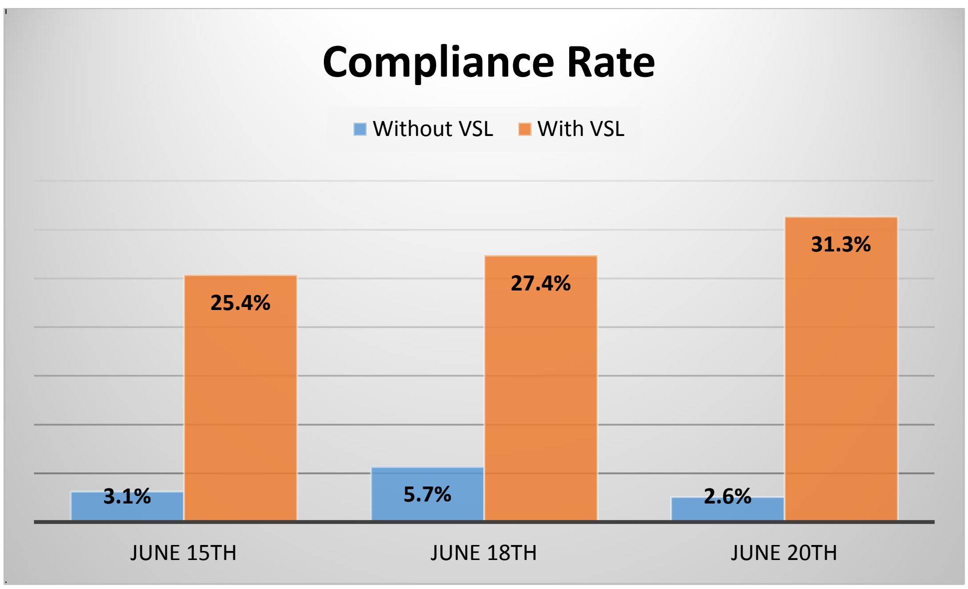
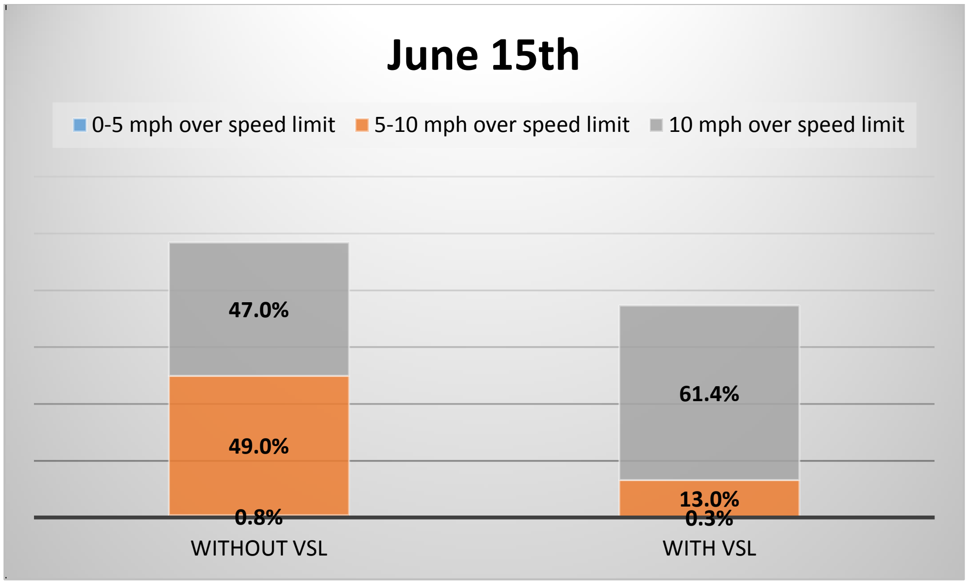
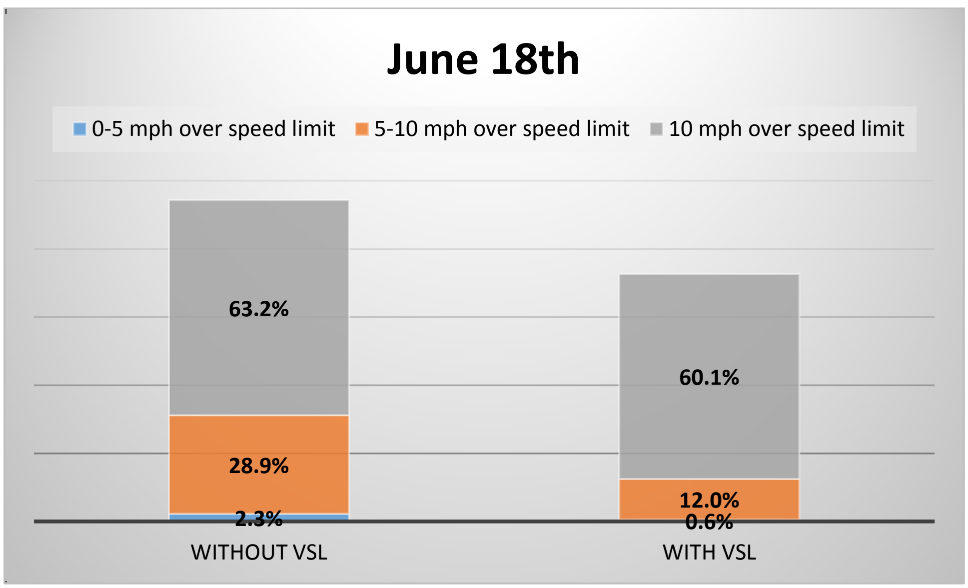


Figure 3. Compliance rates with and without VASL

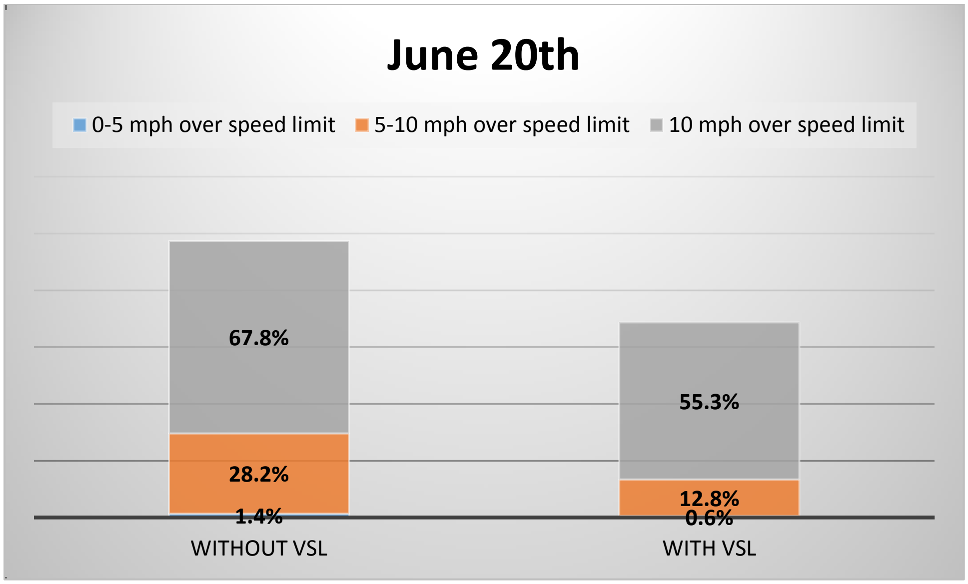
For noncompliance, the percentage of 1-minute average speeds exceeding the speed limit by less than 5 mph, between 5 mph to 10 mph, and over 10 mph were also computed and are shown in Figure 4. Earlier it was found that the overall compliance rate was significantly higher with VASL. From Figure 4, the degree of violation of the posted speed limit is shown. One trend that is evident from Figure 4 is that the relative percentage of violations over 10 mph were high for both with and without VASL. Previously from Figure 3, one troubling finding for without VASL static speed limits was the extremely low compliance rates of 3.1%, 5.7% and 2.6%. The implication of this finding is further exacerbated by the fact that of the non-compliant observations 49%, 67%, and 70% violated the speed limit by over 10 mph on the three days. Thus, use of VASL is recommended for improving compliance rates inside a work zone.


June 15th
0-5 mph over speed limit
5-10 mph over speed limit
10 mph over speed limit
47.0%
49.0%
0.8%
61.4%
13.0%
0.3%
WITHOUT VSL
WITH VSL

(a)


June 18th
0-5 mph over speed limit
5-10 mph over speed limit
10 mph over speed limit
63.2%
28.9%
2.3%
60.1%
12.0%
0.6%
WITHOUT VSL
WITH VSL

(b)



(c)

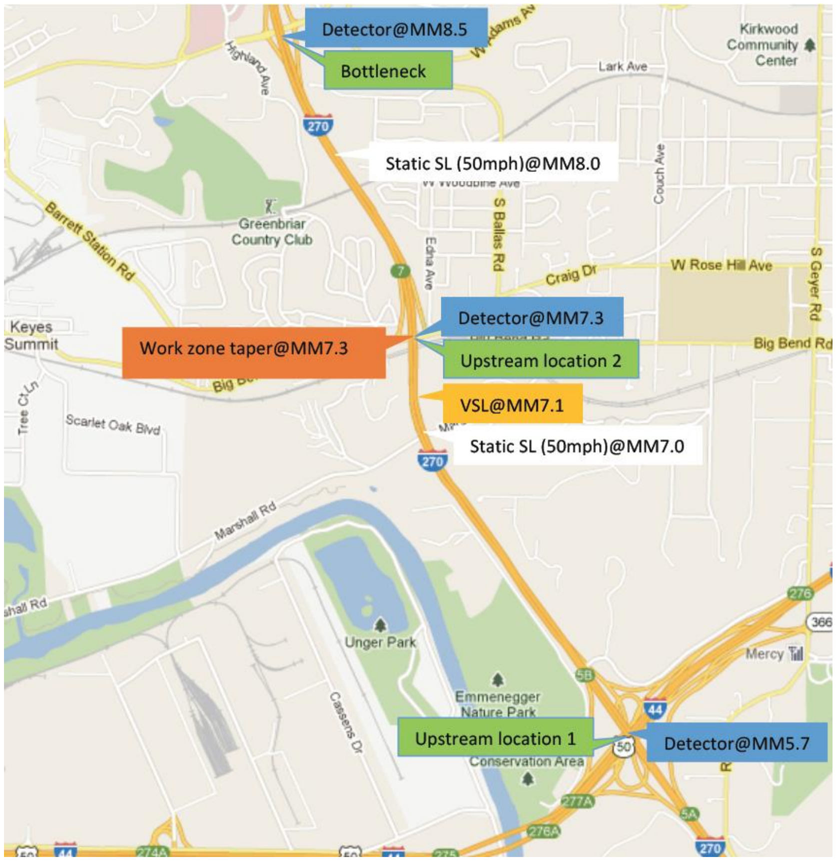
Figure 4. Percentage of speeds exceeding the speed limit by less than 5 mph, between 5 mph to 10 mph, and over 10 mph

Congested Sites

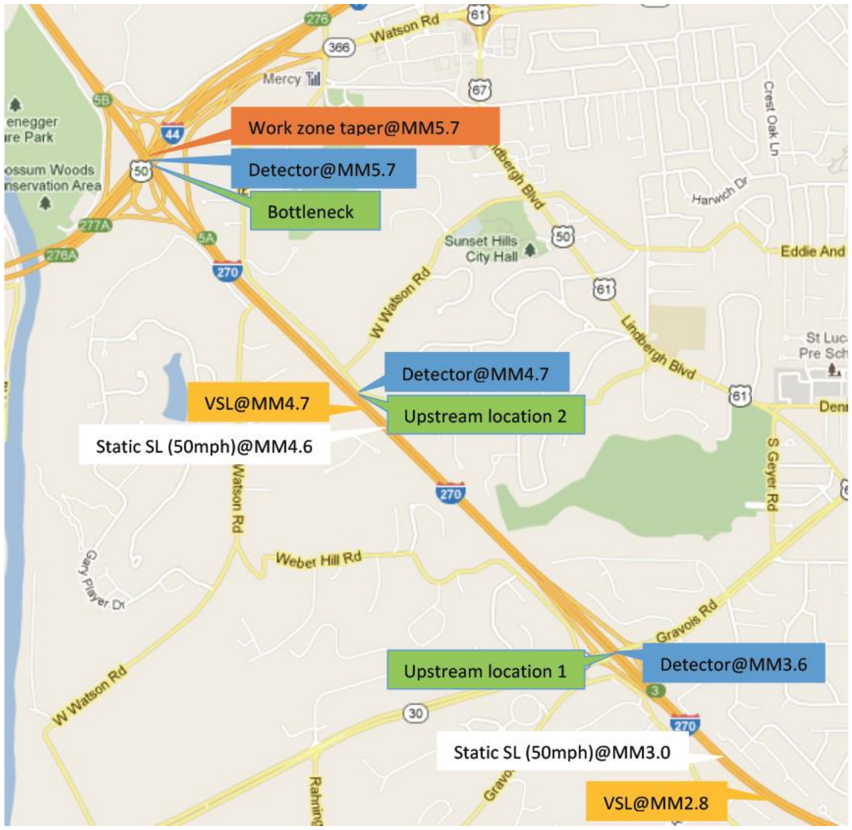
Work zones in the northbound direction of I-270 between I-44 and Route 100 generated congested conditions at certain times during the day. All work zones involved the rightmost lane closure (5 lanes reduced to 4 lanes). There were also instances when the VASL signs were not operational with work zone in place, thus allowing for comparison of with and without VASL traffic conditions. After reviewing the traffic data from several work zones, the following four work zones (referred to as Cases) were chosen.

Case 1: Work zone deployed from mile markers 7.3 to 10.0 on I-270 NB on June 6th, 2012. Congestion lasted 1 hour from 1:15 pm to 2:15 pm. VASL were ON.
Case 2: Work zone deployed from mile markers 5.7 to 10.0 on I-270 NB on June 25th, 2012. Congestion lasted 1 hour from 9:20 am to 10:20 am. VASL were ON.
Case 3: 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. VASL were OFF.
Case 4: Work zone deployed from mile marker 5.7 to 10.0 on I-270 NB on June 28th, 2012. Congestion lasted 45 minutes from 1:20 pm to 2:05 pm. VASL were OFF.

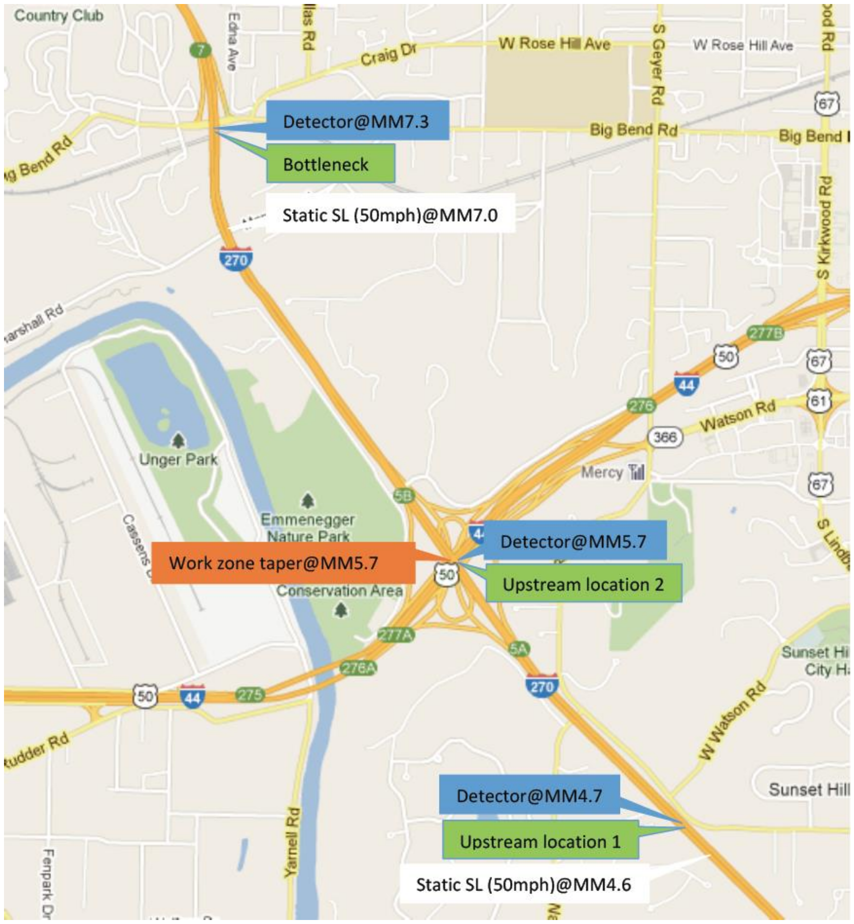
For each work zone, the location where the speeds were the lowest was identified as the bottleneck. With the exception of case 2 for which the bottleneck was at the taper, bottlenecks were located inside the work zone for all work zones. One objective of VASL is to encourage drivers to reduce speeds gradually while approaching a bottleneck, thus preventing any unsafe sudden changes in speeds. To investigate if this objective was met, speeds at three locations were recorded, at the bottleneck location and two upstream locations (upstream location 1 and upstream location 2. Figure 5 shows the layout for each work zone including locations of work zone taper, bottleneck, VASL, static speed limit signs, and speed detectors. In case 1, one VASL was deployed 0.2 mile from location 2. In case 2, one VASL was deployed at upstream location 2 and another VASL was deployed 0.8 mile upstream from location 1. For all congested work zone locations, traffic data was available at 5-min aggregation intervals (unlike the uncongested sites for which 1-min data was available). The distances between upstream locations and the bottleneck are shown in Table 4. The speed statistics are shown in Table 5.



a. Case 1


Work zone taper@MM5.7
Detector@MM5.7
Bottleneck
Detector@MM4.7
VSL@MM4.7
Upstream location 2
Static SL (50mph)@MM4.6
Upstream location 1
Detector@MM3.6
Static SL (50mph)@MM3.0
VSL@MM2.8

b. Case 2



c. Cases 3 and 4

Figure 5. Layout of VASLs and detectors upstream the bottleneck

Table 4. Distances between upstream study locations and bottleneck

Scenarios	**Upstream location 1 to Upstream location 2 (mile)**	**Upstream location 2 to bottleneck (mile)**
Case 1	1.6	1.2
Case 2	1.1	1.0
Case 3	1.0	1.6
Case 4	1.0	1.6

Table 5. Speed statistics

	Scenarios	Upstream location 1		Upstream location 2		Bottleneck	
		Average speed	Std. deviation	Average speed	Std. deviation	Average speed	Std. deviation
With VASL	Case 1	60.0	2.46	48.7	18.19	40.1	24.46
	Case 2	52.9	17.40	34.8	22.47	11.4	5.55
Without VASL	Case 3	59.9	1.34	58.8	2.81	50.7	14.02
	Case 4	59.5	2.05	54.3	8.37	45.0	18.19

Note: Standard deviation is the standard deviation of 5-min interval average speed.

The reduction of average speed from upstream location 1 to upstream location 2 was compared with the reduction of average speed from upstream location 2 to bottleneck. Figure 6 shows the average speeds at upstream locations and bottlenecks for cases with and without VASL. The ratio of the average speed reduction from upstream location 1 to upstream location 2 to the average speed reduction from upstream location 2 to bottleneck was calculated for each case. 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 bottleneck. A ratio lower than 1.0 is not desirable since it indicates higher vehicle speeds approaching a bottleneck. The ratios for all four cases were computed and shown in Figure 7. The speed reduction ratios for case 1 and case 2 with VASL turned on are 1.32 and 0.77 compared to 0.14 and 0.57 for the case 3 and case 4 with VASL turned off.

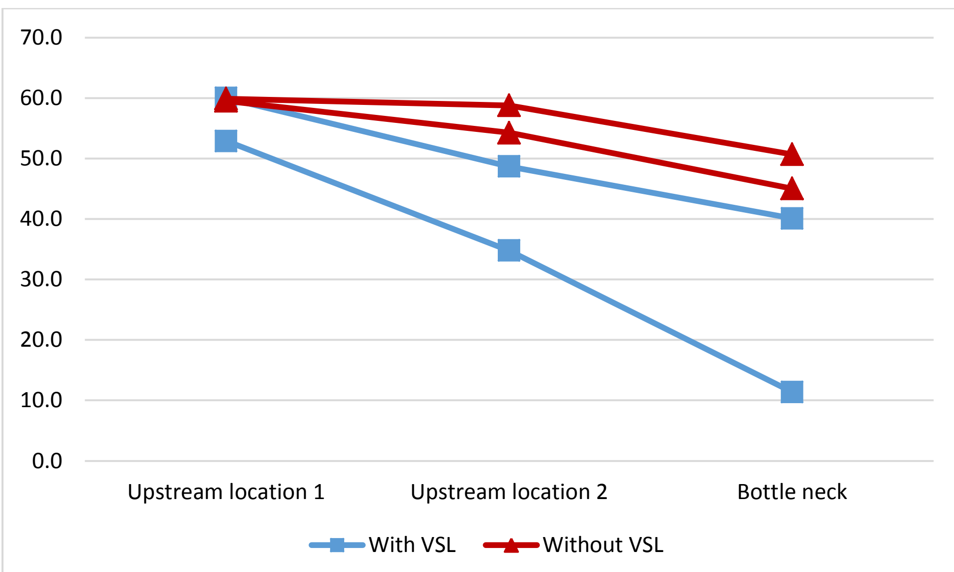


Figure 6. Average speeds at upstream locations and bottlenecks

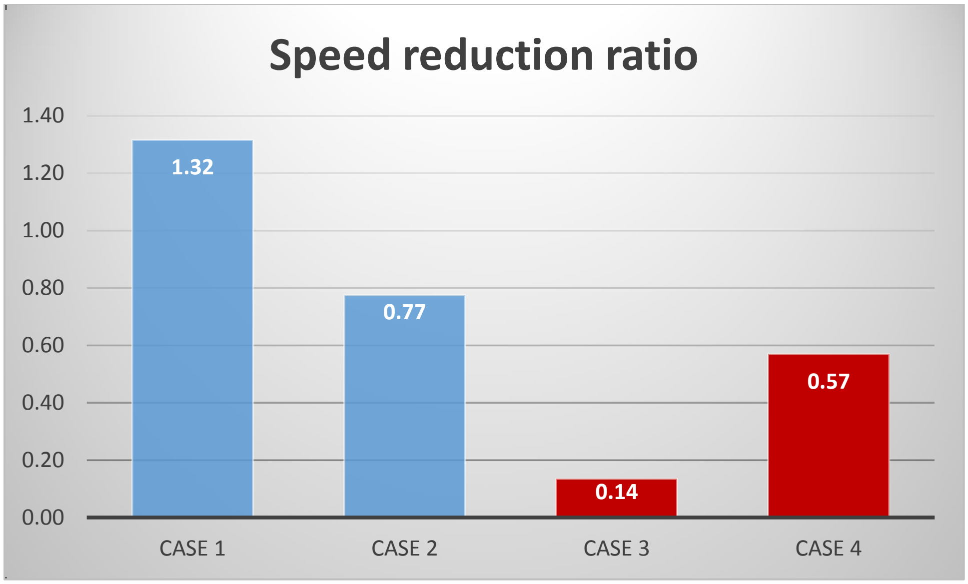
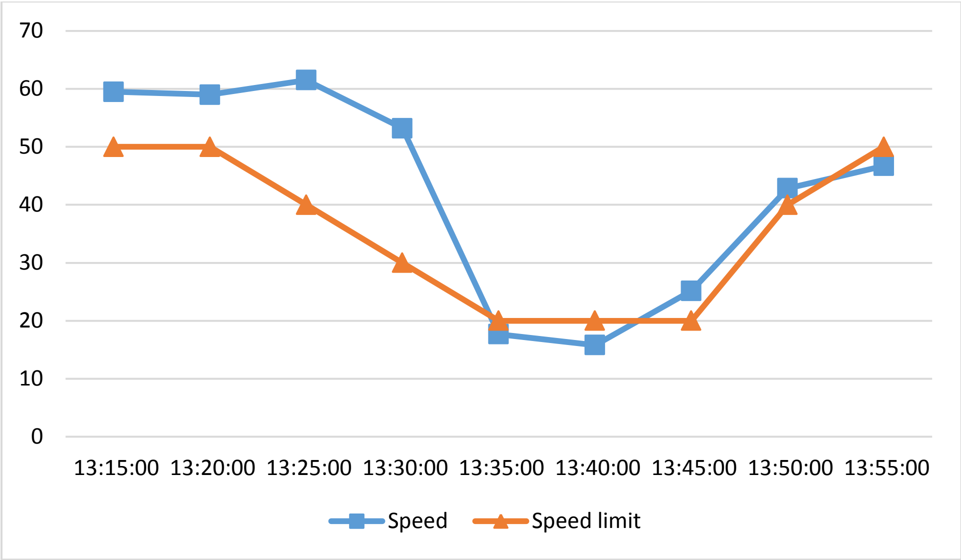


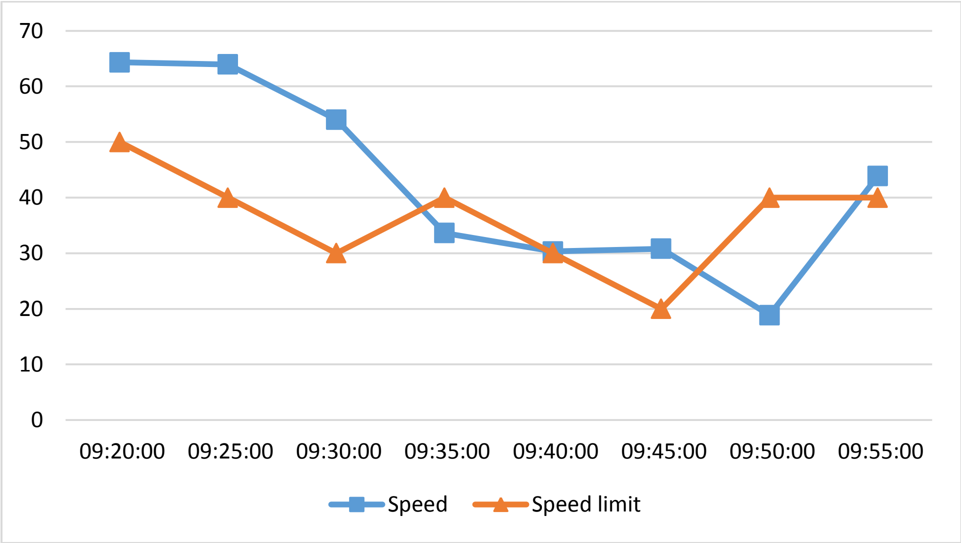
Figure 7. Average speed reduction ratios

Previously, for uncongested work zones a pseudo compliance rate was computed as the '*percentage of 1-minute average speeds below the posted speed limit*'. It was not possible to compute this measure for congested work zones due to two reasons: 1) the 5-min time interval data did not generate a sufficiently large sample – only 12 average speed values in one hour, and 2) unlike the uncongested sites the VASL speed limits varied during the observation period and computing compliance to different posted speed limits was not possible due to even lower sample sizes. Consequently, alternative methods for evaluating compliance had to be applied for the congested work zones.

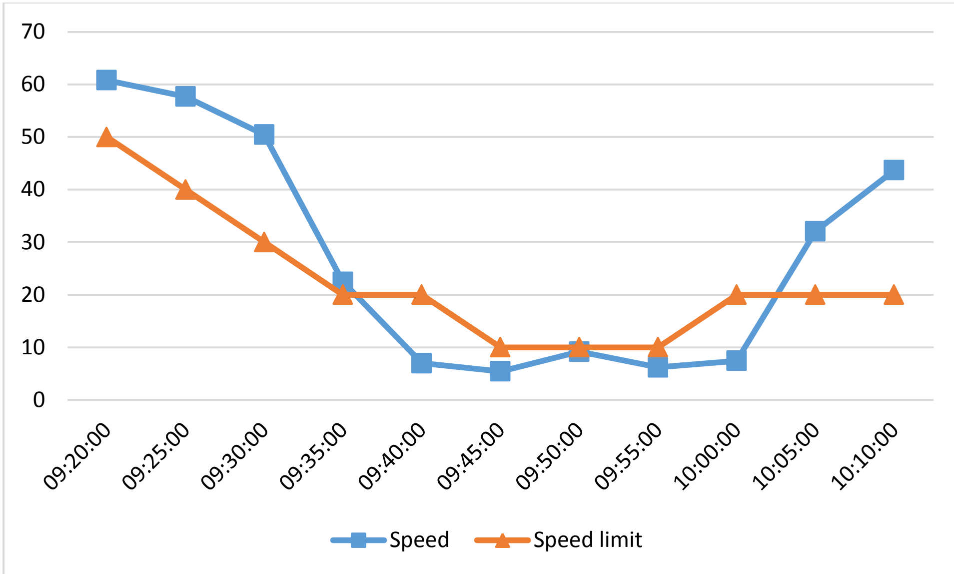
One method is to plot the average speeds and VASL posted speed limits together and visually identify compliance issues. For example, Figure 8(a) shows plots of average speed and VASL speed limits for upstream location 2 in case 1 (the downstream detector location closest to VASL signs. Similarly, Figures 8(b) and 8(c) show plots for case 2 locations 1 and 2 since there are two sets of VASL signs within close proximity upstream of the work zone. The compliance plots are not generated for cases 3 and 4 because the congested traffic conditions meant that the operating speeds were below the static speed limit of 60 mph. The range of time intervals shown on the X-axis of Figures 8(a) to (c) do not exactly match the entire observation period reported earlier for each case. The missing time intervals mean that the posted speed limit on VASL was not available at those times. Figures 8(a) to (c) show the average speeds were higher than the VASL speed limit during majority of the time intervals. The trend in average speeds was similar to the trend in the posted advisory speed limits: speeds decreasing with reduced speed limits and vice versa. A second method adopted from Kwon et al (2007) computes the correlation coefficient between the average speeds and the posted speed limits. The correlation coefficients were 0.841 for upstream location 2 in case 1, and 0.423 and 0.865 for upstream location 1 and location 2 in case 2. The high positive correlations between the speed and the speed limit, especially at location 2, indicate that average speeds and posted speed limits follow similar trends. Such a high correlation could indicate a high level of driver compliance.



a. Upstream location 2 in case 1



b. Upstream location 1 in case 2



c. Upstream location 2 in case 2

Figure 8. Speed versus speed limit plots

In summary, urban field studies demonstrated some trade-offs in the deployment of VASL. For the uncongested sites, the average speeds with VASL were found to be lower than without VASL. On average, a reduction of 2.2 mph was observed. However, the standard deviation of speeds with VASL was higher, by 4.4 mph on average, than without VASL. The increase in standard deviation may be due to the advisory nature of VASL. Since they are not enforceable, some drivers comply while others do not, thus increasing the standard deviation. The compliance rates inside the work zone were low with or without VASL. Still, the compliance with VASL was about eight times greater than without VASL.

For the congested sites, it was found that the VASL were effective in making drivers slow down gradually as they approached the work zone, thus reducing sudden changes in speeds. The average speeds and the posted advisory speed limits with VASL had similar trends, with correlation coefficients ranging between 0.42 and 0.86. The visual inspection of average speeds versus variable speed limits showed that that there was compliance over time.

Rural Case Studies

The case studies of I-270 work zones presented in the previous section are from an urban area in St. Louis, Missouri. Some segments on the I-270 corridor carry as high as 150,000 vehicles per day. Highways in rural areas differ from those in urban areas. For example, rural highways have lower ADT, tend to have higher truck percentage in the traffic stream, fewer number of lanes, and the posted speed limits are also often higher. Thus, it was important to measure the effect of VASL at rural highway work zones. To this end, two case studies of work zones in rural areas were conducted.

The first work zone was located on southbound US 54 between Route D and Route E, south of Jefferson City, Missouri. The ADT on US 54 is 14,255 with most of the traffic either commuting to and from Jefferson City or tourists traveling south to the Lake of the Ozarks. US 54 was being resurfaced in both directions with lane closures occurring during different times of day. The normal speed limit was 65 mph which was lowered to 55 mph when the work zone was in place. During the work activity only one of the two lanes in one direction was open to traffic. The westbound work zone was monitored on September 21, 2011. Speeds were recorded with the VASL turned off from 4:30 pm to 5:30 pm and from 5:30 pm to 6:30 pm with the VASL turned on. A VASL algorithm was developed that lowered speed limits based on observed 1-minute average speed and density values. The algorithm was then coded as a computer program and different threshold values for speed and density were used to determine the posted speed limit. The program was installed on a laptop computer, which was then used in the field. One observer continuously entered the speeds displayed on the radar gun (this was feasible given the relatively low traffic flow) into the program, which outputted the speed limit to be displayed. The speed limits were posted on VASL using a web-based interface.

Unfortunately, traffic conditions at the site never met the threshold values to lower the speed limit below 55 mph (the posted work zone speed limit). Thus, the VASL displayed a speed limit of 55 mph during the entire observation period. With traffic conditions not warranting the lowering of advisory speed limits, the case study instead focused on evaluating the effect of a digital advisory speed limit sign. The VASL sign was in addition to the existing static speed limit signage, thus acting as a reinforcement to the static speed limit.

The placement of signs and traffic monitoring devices can be found in Figure 9. The VASL sign was placed 284 ft. downstream from the 'Road Work Ahead' sign. One radar gun and a video camera were placed 250 ft. downstream from the VASL, followed by the second radar gun and another camera at the work zone taper. This setup allowed camera 1 to record speeds of vehicles after they had time to react to the VASL, and camera 2 capturing the sustained effect of VASL at the taper.

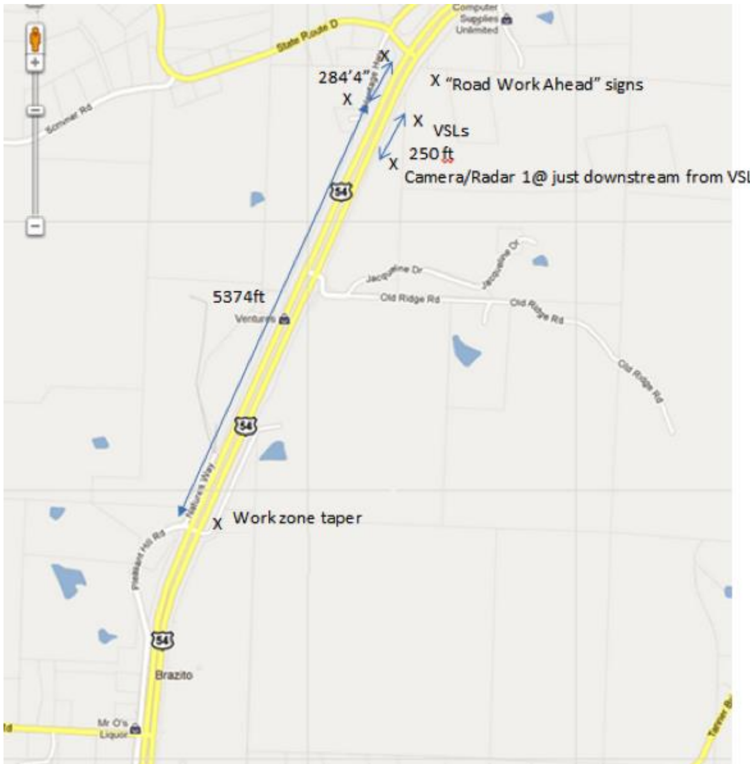


Figure 9. Rural case study 1 – US 54 work zone

The second work zone was located on northbound US 63 near Route H, south of Columbia, Missouri. The ADT on US 63 is 26,000 with significant commuting traffic between Columbia and Jefferson City. Work on the new overpass at the Route H interchange necessitated closing one of the two northbound lanes of US 63 during different times of day. The work zone was monitored on March 13, 2012. Speeds were recorded from 1:00 pm to 2:00 pm with VASL turned on and 2:00 pm to 3:12 pm with VASL turned off. Similar to the US 54 case study, the traffic conditions did not warrant reducing the speed limits than what was posted on the static speed limit signs. Thus, the VASL displayed 60 mph during the entire observation period.

The placement of signs and traffic monitoring devices is shown in Figure 10. The VASL sign was placed 528 ft upstream from the radar gun and camera. The work zone taper was 1 mile downstream from the VASL sign.

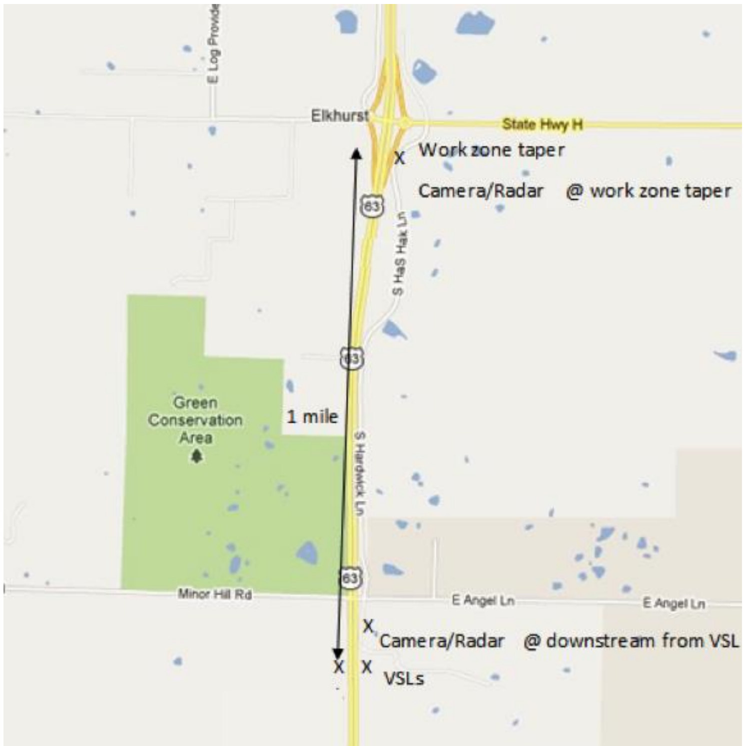


Figure 10. Rural case study 2 – US 63 work zone

Three speed statistics were computed using the raw speeds processed from radar guns. They were the mean, variance, and 85th percentile speeds. The statistical significance of the 85th percentile speeds was computed according to (Hou et al., 2012). The results are shown in Table 6 for the US 54 case study and in Table 7 for the US 63 case study. Table 6(a) shows results at the location downstream of VASL. The mean speed and 85th percentile speeds with VASL were about 2 mph lower than without VASL. If 85th percentile speeds are indicative of the posted speed limit (of 55 mph) then speeding occurred both with and without VASL. The difference in variance in speeds at the downstream location was not significant. At the taper (Table 6 (b)), the 85th percentile speeds were very close to the posted speed limit indicating vehicles slowed down between the VASL and taper locations. The decrease in the mean speeds from VASL to the taper location shown in Table 6 (c) indicates that the drivers lowered their speeds with VASL (by 2.8 mph) compared to without VASL (by 7.7 mph). The variance of this speed reduction was also lower with VASL.

An effect size is a measure of the strength of the relationship between the with VASL speed and the without VASL. In other words, it helps to explain the magnitude of mean speed differences between with and without VASL conditions. One common effect size measure is Cohen's d (Cohen, 1988). It is computed as:

$$d = \frac{\bar{x}_1 - \bar{x}_2}{s}$$

where:
d is the effect size in terms of Cohen's d statistic
$\bar{x}_1$ and $\bar{x}_2$ are the two sample means that are being compared
s is the pooled sample standard deviation.

The effect size for the mean speeds downstream of VASL was 0.43 (Table 6(a)) which is relatively small since the speed difference was only around 2 mph and the pooled standard deviation was 4.57. However, the effect size of the mean speed difference (Table 6(c)) was 2.21 which is significant.

Table 6(a). US 54 speed measures downstream of VASL

	With VASL	Without VASL	p-value
Mean	55.1	57	<0.001
Variance	10.9	21.4	0.14
85th Percentile	60	62	<0.001

Table 6(b). US 54 speed measures at the taper

	With VASL	Without VASL	p-value
Mean	52.2	49.3	<0.001
Variance	20.2	35.7	<0.001
85th Percentile	56	55	0.006

Table 6(c). US 54 speed difference between downstream and taper locations

	With VASL	Without VASL	p-value
Mean	2.8	7.7	<0.001
Variance	2	8	<0.001

For the US 63 case study, the mean speed downstream of the VASL sign was 1.5 mph lower with VASL than without VASL (Table 7). The 85th percentile speed also was lower with VASL (by 2 mph). Similar to the finding in the US 54 case study, the 85th percentile speeds past the VASL sign were higher than the posted speed limit of 60 mph.

Table 7. US 63 speed measures downstream of VASL

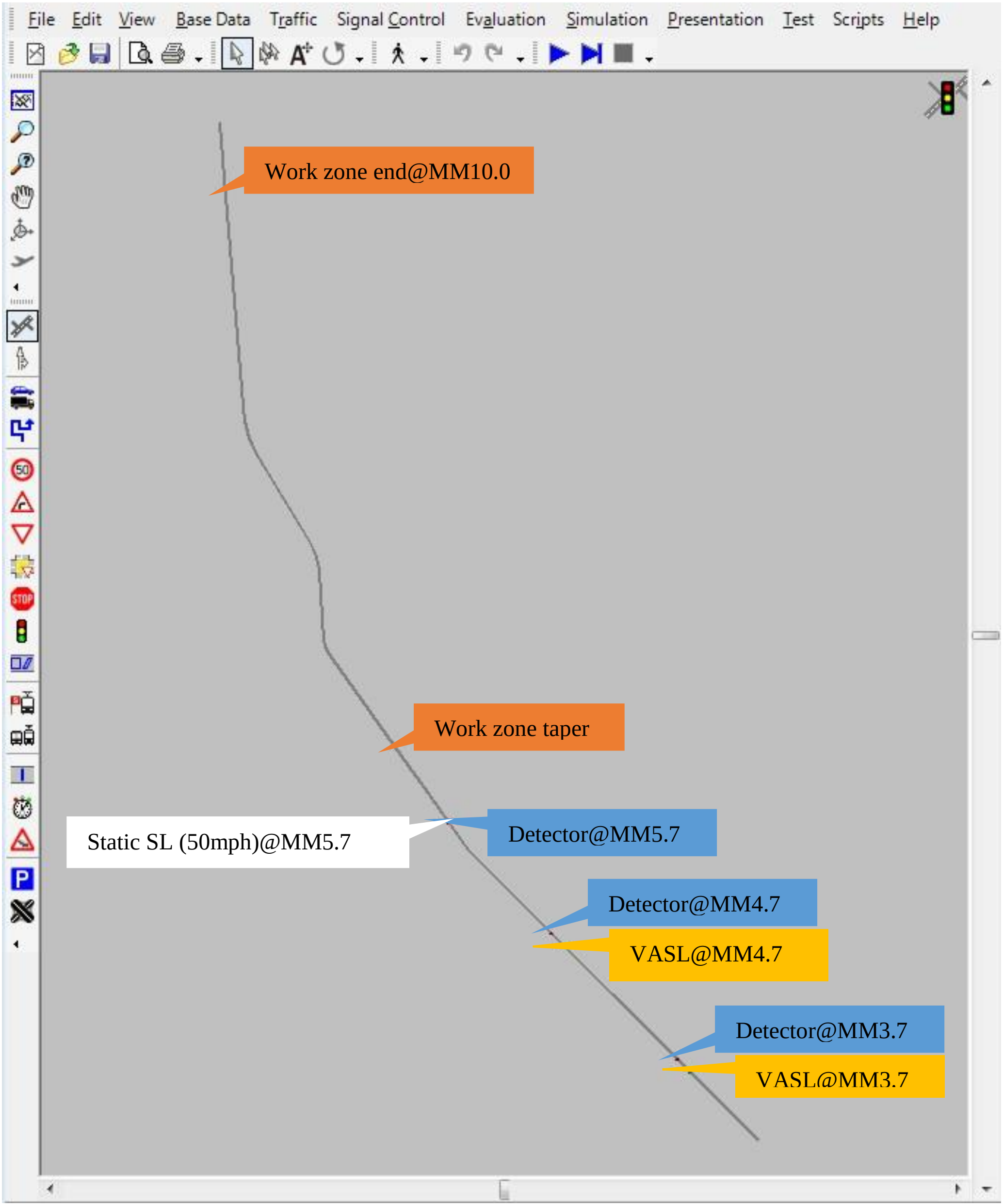
	With VASL	Without VASL	p-value
Mean	58.6	60.1	<0.001
Variance	32	32.4	0.4
85th Percentile	64	66	

In summary, both rural case studies showed reductions in mean speed, variance, and 85th percentile speed downstream from the VASL sign. The speed reduction from the VASL sign to the taper was significant when VASL was deployed, at the US 54 site. Thus, VASL could complement static speed limit signage at a rural work zones. VASL deployments result in safer traffic conditions by reminding traffic of the reduced speed limit as they approach the work zone.

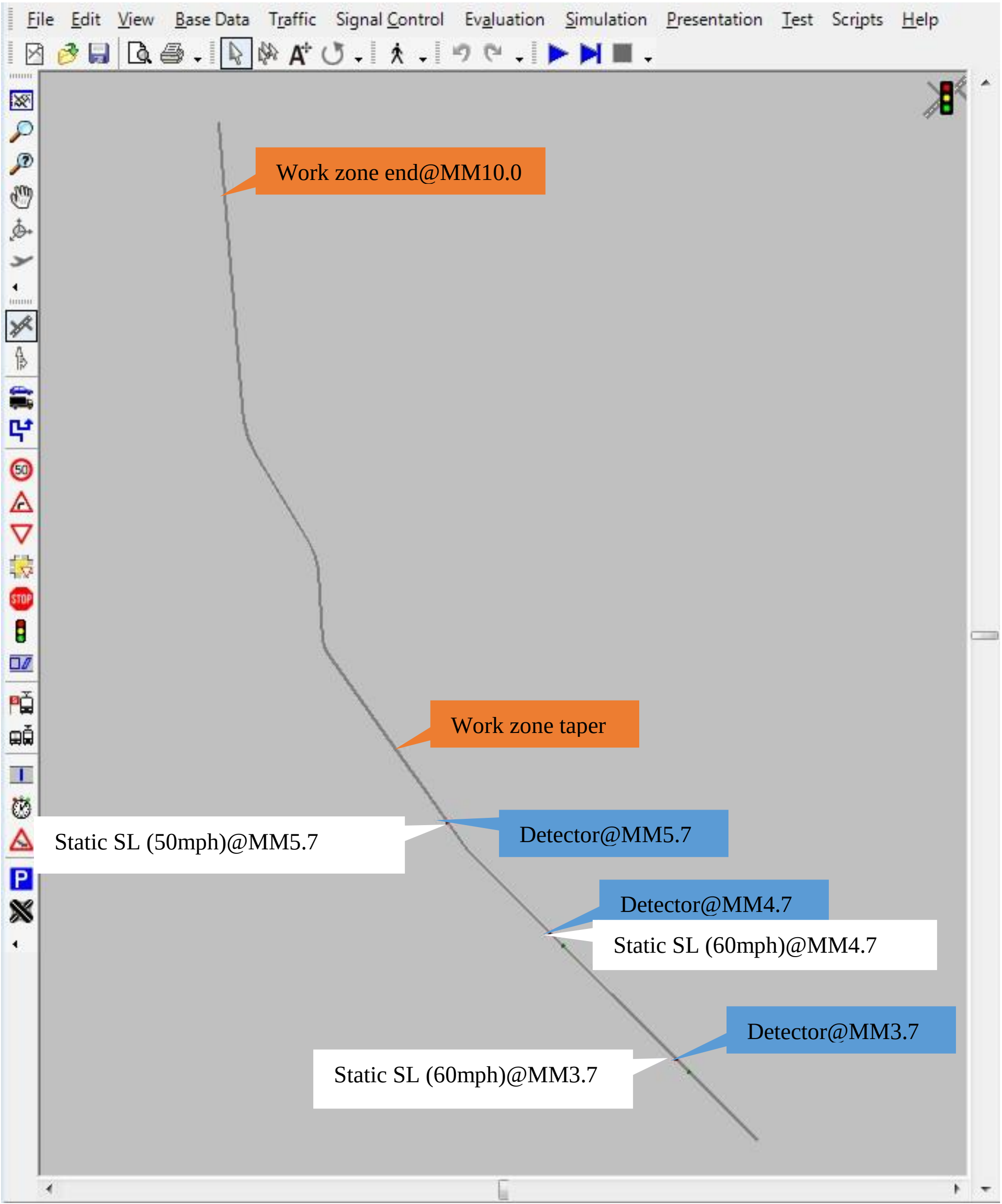
SIMULATION ANALYSIS OF ADDITIONAL VASL SCENARIOS

Comparison of VASL and No-VASL Scenarios

Traffic simulation was used to perform additional analysis of the effectiveness of VASL in work zones. Simulation complements field studies by exploring scenarios not captured by the field studies. 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, and Mitra and Pant. Two simulation models were created: one with VASL and one without it. In both 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. The work zone involved closure of the rightmost lane, reducing the number of lanes from 4 to 3 in the northbound direction from MM 5.7 to MM 10.0. As shown in Figure 11(a), 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. The layout of the model without VASL is shown in Figure 11(b). It is the same as the model with VASL except the two VASL signs were replaced with static speed limits signs displaying 60 mph.



a. VISSIM model with VASL



b. VISSIM model without VASL

Figure 11. Layout of VISSIM model of the I-270 work zone

Simulation Model Input and Calibration

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). 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 shown in Table 8.

Table 8. Calibrated parameters

Parameters	Value
CC1	1.5 seconds
CC2	13 feet
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 as shown in Table 9.

Table 9. Vehicle input

Period (sec)	Flow rate (veh/hr)
0-300	6600
300-600	6800
600-900	7000
900-1200	7200
1200-1500	7400
1500-1800	7600
1800-2100	7400
2100-2400	7200
2400-2700	7000
2700-3000	7000
3000-3300	6800
3300-3600	6800
3600-3900	6800

Simulation Scenarios

The desired speed distributions of input vehicles and vehicles going past the posted speed limit signs were obtained from field data measured upstream of the work zone. Two desired speed distributions, one for speed limit compliant vehicles and one for non-compliant vehicles were inputted into the model. Four compliance rates, 25%, 50%, 75% and 100%, were investigated for the "with VASL" scenario. For the "without VASL" scenario, compliance rate with respect to static speed limits were set at 85%, based on the assumption that the speed limit is set according to recommended engineering practice. Given the urban setting of I-270 in St. Louis, realistic truck percentages of 10% and 15% were evaluated for both "with VSL" and "without VSL" scenarios. The MoDOT's VASL algorithm previously described was also coded in the simulation program. To account for the stochastic nature of simulation models, each study scenario was simulated 20 times and the results averaged.

Measures of Effectiveness for Scenario Evaluations

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 definitions of these measures and the means used to collect them from the simulation are presented next.

- Average queue length (ft): the average of queue length measured from work zone taper to 1 mile upstream every simulation time step (of 0.2 seconds) for the total simulation period using the *queue counter* feature in VISSIM.
- Work zone throughput (veh/hr): number of vehicles passing through the work zone taper in one hour collected using *data collection points* in VISSIM.
- Average number of stops (stops/veh): average number of stops for each vehicle traveling from 2 mile upstream of work zone taper to the end of work zone measured using the *node evaluation* in VISSIM.
- Average travel time (sec): average travel time from 1 mile upstream of the work zone taper to the end of work zone (a total length of 5.3 miles) measured using *travel time sections* in VISSIM.
- Average 1-minute speed standard deviation (mph): average value of the standard deviation of speeds measured every minute at three locations (taper, 1-mile upstream of taper, and 2 miles upstream of taper) for the total simulation period using *data collection points* in VISSIM.
- Average 1-minute maximum speed difference between adjacent locations (mph): the average maximum difference between average speeds of two adjacent detectors measured every minute for the total simulation period. The differences were computed for taper versus 1-mile upstream location, and the 1-mile upstream location versus 2 miles upstream location. The greatest of the two differences was chosen in every interval.
- Rear end conflicts: The conflict measures were extracted using the surrogate safety assessment model (SSAM) 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. The rear-end conflicts were identified throughout the network shown in Figure 11.

- Lane changing conflicts: SSAM identifies a lane changing conflict if the TTC is less than 1.5 seconds, PET is less than 5 seconds, and conflict angle ranges from 30 to 85 degrees. The lane changing conflicts were collected for the entire network.

Results of Operational Performance Measures

Different evaluation scenarios were generated by varying the compliance rate and truck percentage values. For 'with VASL' conditions, four compliance rates and two truck percentages were combined to generate eight scenarios. For 'without VASL' conditions, two truck percentages resulted in two different scenarios. The results of these ten scenarios are presented in this section with mobility measures presented first followed by the safety measures. The percentage change in a performance measure due to VASL was also computed as

$$\%\ change = 100x\,\frac{With\ VASL\ measure\ value - no\ VASL\ measure\ value}{no\ VASL\ measure\ value}$$

Average Queue Length

The average queue length values for all ten scenarios are presented in Figure 12. For both 10% and 15% truck percentages, the average queue lengths with VASL for all compliance rates were lower than without VASL. Higher compliance rates resulted in lower values for average queue length. T-tests were performed to test the statistical significance, and the results are shown in Table 10. The results indicate that they were all statistically significant at a 95% confidence level. The percentage change in average queue length resulting from VASL are shown in Table 11. A "+" sign means increase and "-" sign means decrease in average queue length due to VASL. The values in Table 11 show that the VASL was able to significantly reduce the average queue length, with the reductions ranging from 39.5% to 58.7%.

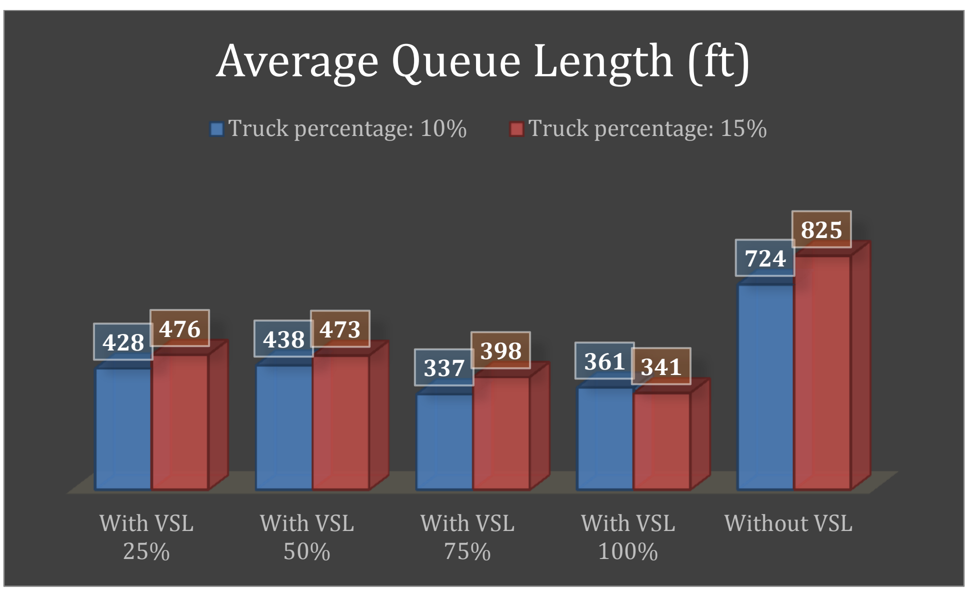


Figure 12. Average queue length

Table 10. Results of t-tests for average queue length (Q)

Hypothesis	P-value	Significant at 95% confidence interval?
$Q_{With\ VSL\ 25\%}^{10\%} < Q_{Without\ VSL}^{10\%}$	<0.0001	Yes
$Q_{With\ VSL\ 50\%}^{10\%} < Q_{Without\ VSL}^{10\%}$	<0.0001	Yes
$Q_{With\ VSL\ 75\%}^{10\%} < Q_{Without\ VSL}^{10\%}$	<0.0001	Yes
$Q_{With\ VSL\ 100\%}^{10\%} < Q_{Without\ VSL}^{10\%}$	<0.0001	Yes
$Q_{With\ VSL\ 25\%}^{15\%} < Q_{Without\ VSL}^{15\%}$	<0.0001	Yes
$Q_{With\ VSL\ 50\%}^{15\%} < Q_{Without\ VSL}^{15\%}$	<0.0001	Yes
$Q_{With\ VSL\ 75\%}^{15\%} < Q_{Without\ VSL}^{15\%}$	<0.0001	Yes
$Q_{With\ VSL\ 100\%}^{15\%} < Q_{Without\ VSL}^{15\%}$	<0.0001	Yes

Table 11. Percentage changes of average queue length resulting from VASL

Truck percentage	Driver compliance	Percentage change (with VASL – without VASL)
10%	25%	-40.9%
	50%	-39.5%
	75%	-53.5%
	100%	-50.2%
15%	25%	-42.3%
	50%	-42.6%
	75%	-51.8%
	100%	-58.7%

Work Zone Throughput

The throughput of vehicles passing through the taper area of the work zone for all scenarios is reported in Figure 13. Figure 13 shows the throughput with VASL was less than the throughput without VASL for all scenarios. This finding was found to be statistically significant for all scenarios as shown in Table 12. Table 13 shows the percentage decrease in throughput with VASL ranged from 6.9% to 13%. Higher VASL compliance rates resulted in lower throughputs with 100% compliance resulted in the lowest throughput value of all the scenarios. This may seem counterintuitive to the expectation of higher uniformity with VASL. Thus, increased compliance to an inefficient strategy (in terms of throughput alone) will reduce throughput.

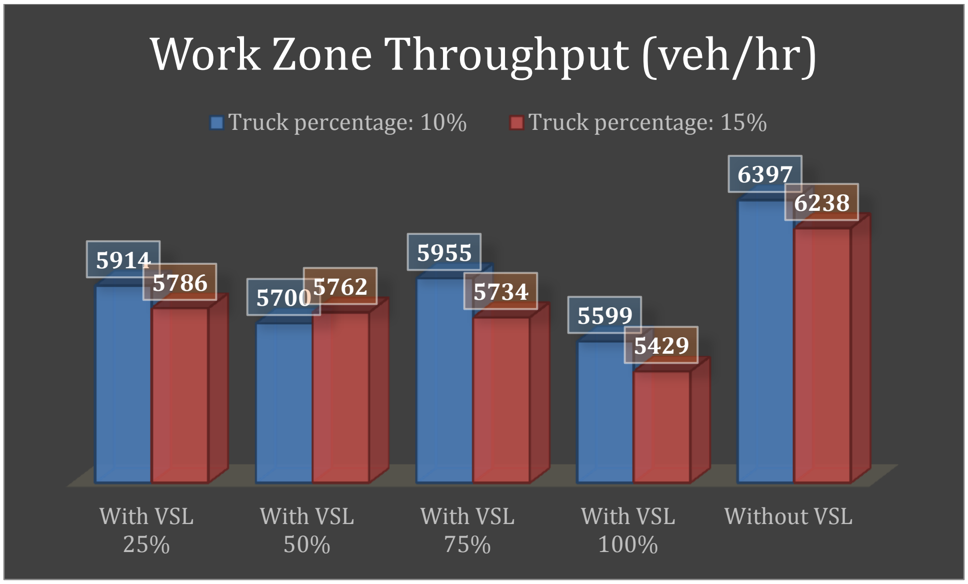


Figure 13. Work zone throughput

Table 12. Results of t-tests for throughput

Hypothesis	**P-value**	**Significant at 95% confidence interval?**
$TP^{10\%}_{With\ VSL\ 25\%} < TP^{10\%}_{Without\ VSL}$	<0.0001	Yes
$TP^{10\%}_{With\ VSL\ 50\%} < TP^{10\%}_{Without\ VSL}$	<0.0001	Yes
$TP^{10\%}_{With\ VSL\ 75\%} < TP^{10\%}_{Without\ VSL}$	<0.0001	Yes
$TP^{10\%}_{With\ VSL\ 100\%} < TP^{10\%}_{Without\ VSL}$	<0.0001	Yes
$TP^{15\%}_{With\ VSL\ 25\%} < TP^{15\%}_{Without\ VSL}$	<0.0001	Yes
$TP^{15\%}_{With\ VSL\ 50\%} < TP^{15\%}_{Without\ VSL}$	<0.0001	Yes
$TP^{15\%}_{With\ VSL\ 75\%} < TP^{15\%}_{Without\ VSL}$	<0.0001	Yes
$TP^{15\%}_{With\ VSL\ 100\%} < TP^{15\%}_{Without\ VSL}$	<0.0001	Yes

Table 13. Percentage changes of throughputs resulting from VASL

Truck percentage	**Driver compliance**	**Percentage change**
10%	25%	-7.6%
	50%	-10.9%
	75%	-6.9%
	100%	-12.5%
15%	25%	-7.2%
	50%	-7.6%
	75%	-8.1%
	100%	-13.0%

Average Number of Stops

The average number of stops for all scenarios are presented in Figure 14. Table 14 shows the T-test results of the statistical significance of the differences between with VASL and without VASL. The differences for 25%, 50%, and 75% compliance rates and 10% trucks were not statistically significant. For the remaining VASL scenarios, the average numbers of stops with VASL were lower than without VASL. The percentage changes of average number of stops resulting from VASL are reported in Table 15. A "+"sign means increase and "-" sign means decrease in stops due to VASL. Of those changes that were significant, the percentage reductions ranged from 19.8% to 29.0%.

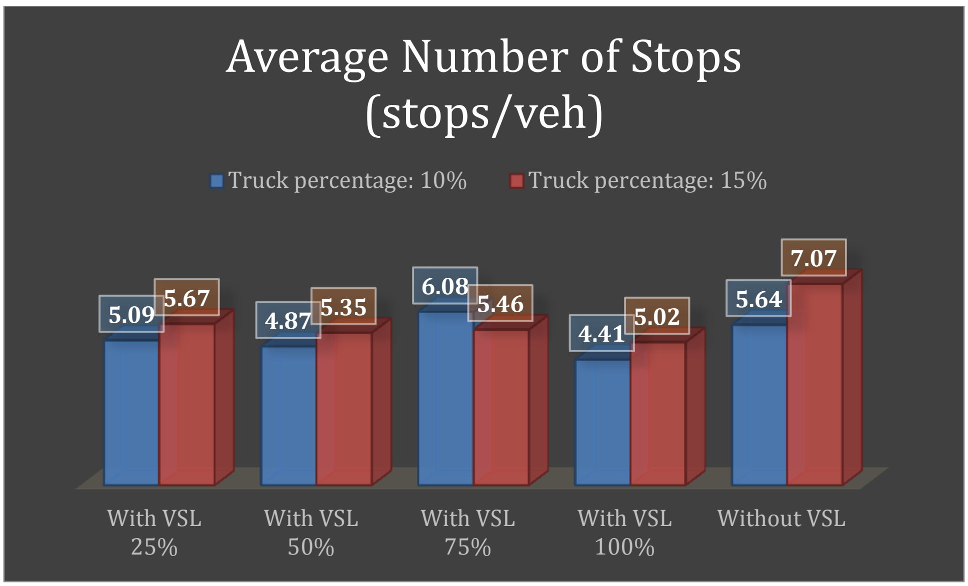


Figure 14. Average number of stops

Table 14. Results of t-tests for average number of stops

Hypothesis	P-value	Significant at 95% confidence interval?
$S^{10\%}_{With\,VSL\,25\%} < S^{10\%}_{Without\,VSL}$	0.2207	No
$S^{10\%}_{With\,VSL\,50\%} < S^{10\%}_{Without\,VSL}$	0.1116	No
$S^{10\%}_{With\,VSL\,75\%} > S^{10\%}_{Without\,VSL}$	0.2149	No
$S^{10\%}_{With\,VSL\,100\%} < S^{10\%}_{Without\,VSL}$	0.0472	Yes
$S^{15\%}_{With\,VSL\,25\%} < S^{15\%}_{Without\,VSL}$	0.0135	Yes
$S^{15\%}_{With\,VSL\,50\%} < S^{15\%}_{Without\,VSL}$	0.0027	Yes
$S^{15\%}_{With\,VSL\,75\%} < S^{15\%}_{Without\,VSL}$	0.0045	Yes
$S^{15\%}_{With\,VSL\,100\%} < S^{15\%}_{Without\,VSL}$	0.0032	Yes

Table 15. Percentage changes of average number of stops resulting from VASL

Truck percentage	Driver compliance	Percentage change
10%	25%	-9.7% (not statistically significant)
	50%	-13.7% (not statistically significant)
	75%	+8.0% (not statistically significant)
	100%	-21.8%
15%	25%	-19.8%
	50%	-24.3%
	75%	-22.8%
	100%	-29.0%

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 are presented in Figure 15. The average travel times without VASL were similar to those with VASL at lower compliance rates. However, the travel times increased with the increase in compliance to VASL, perhaps due to more vehicles slowing down in response to the lower VASL speed limits and thus experiences higher travel times. With 100% VASL compliance the average travel times for the VASL were 10% and 7.9% higher than without VASL (see Table 16). The statistical significance of the differences in travel times with and without VASL is reported in Table 17.

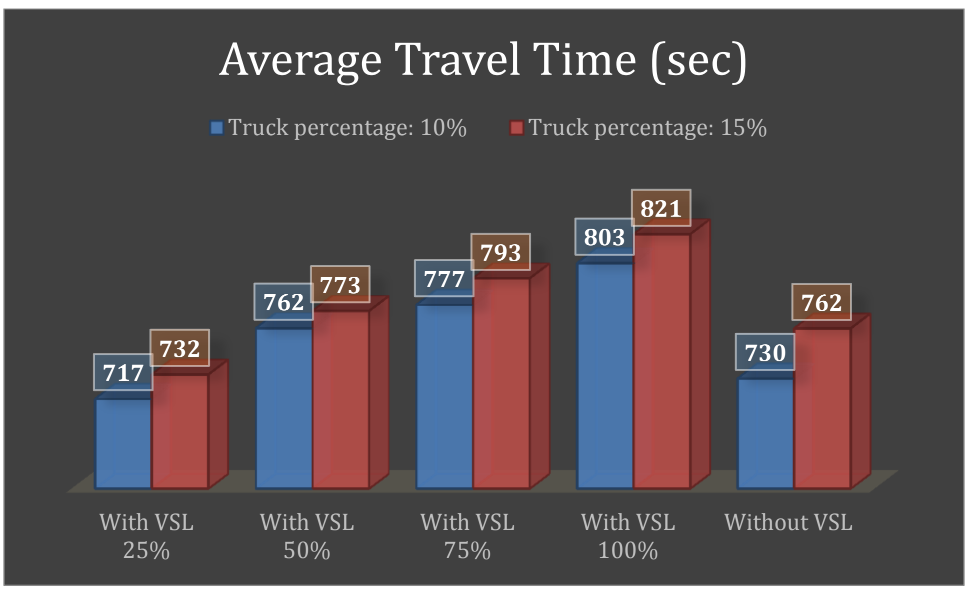


Figure 15. Average travel time

Table 16. Percentage changes of average travel time resulting from VASL

Truck percentage	Driver compliance	Percentage change
10%	25%	-1.8%
	50%	+4.4%
	75%	+6.4%
	100%	+10.0%
15%	25%	-3.8%
	50%	+1.5%
	75%	+4.2%
	100%	+7.9%

Table 17. Results of t-tests for average travel time

Hypothesis	P-value	Significant at 95% confidence interval?
$TT^{10\%}_{With\,VSL\,25\%} < TT^{10\%}_{Without\,VSL}$	0.0210	Yes
$TT^{10\%}_{With\,VSL\,50\%} > TT^{10\%}_{Without\,VSL}$	<0.0001	Yes
$TT^{10\%}_{With\,VSL\,75\%} > TT^{10\%}_{Without\,VSL}$	<0.0001	Yes
$TT^{10\%}_{With\,VSL\,100\%} > TT^{10\%}_{Without\,VSL}$	<0.0001	Yes
$TT^{15\%}_{With\,VSL\,25\%} < TT^{15\%}_{Without\,VSL}$	<0.0001	Yes
$TT^{15\%}_{With\,VSL\,50\%} > TT^{15\%}_{Without\,VSL}$	0.0569	No
$TT^{15\%}_{With\,VSL\,75\%} > TT^{15\%}_{Without\,VSL}$	0.0001	Yes
$TT^{15\%}_{With\,VSL\,100\%} > TT^{15\%}_{Without\,VSL}$	<0.0001	Yes

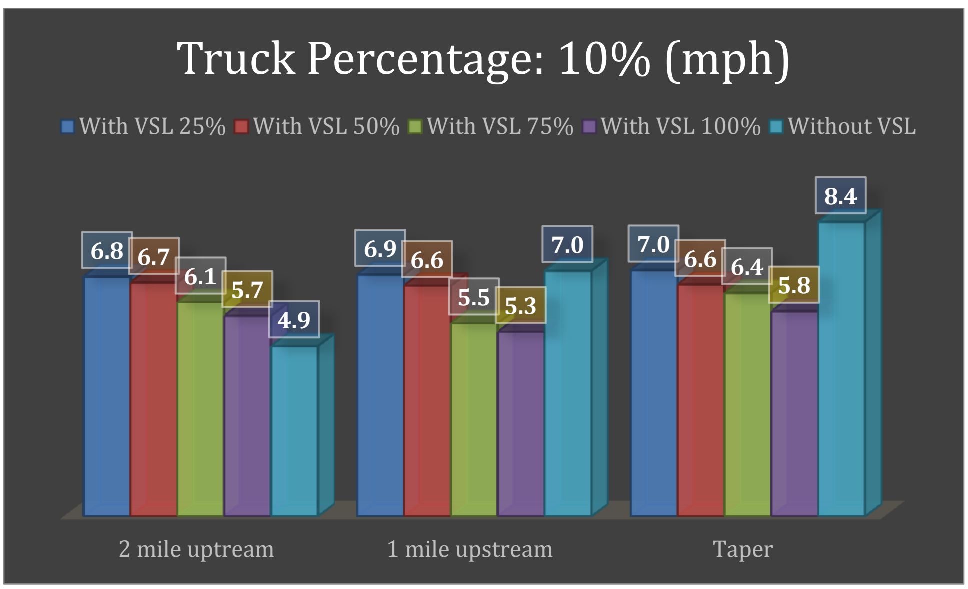
In summary, the use of VASL in oversaturated work zones produced mixed mobility results. VASL did not improve the vehicle throughput through the work zone. The average travel times through the work zone also increased due to the use of VASL. The use of VASL, however, did result in shorter queue lengths. As a result, the average number of stops per vehicle was also fewer with VASL than without it. Thus, if the goal is to improve the throughput or reduce travel times, the two-stage speed-based VASL algorithm tested in this study did not accomplish that goal. If the goal is to reduce the queue length upstream of taper area and the average number of stops then the VASL algorithm was successful in accomplishing that goal. The queue length also has safety implications, in terms of rear end and lane changing conflicts and speed differentials. The safety measures will be explored in the next section and the results correlated with the queue length measure.

Results of Safety Measures

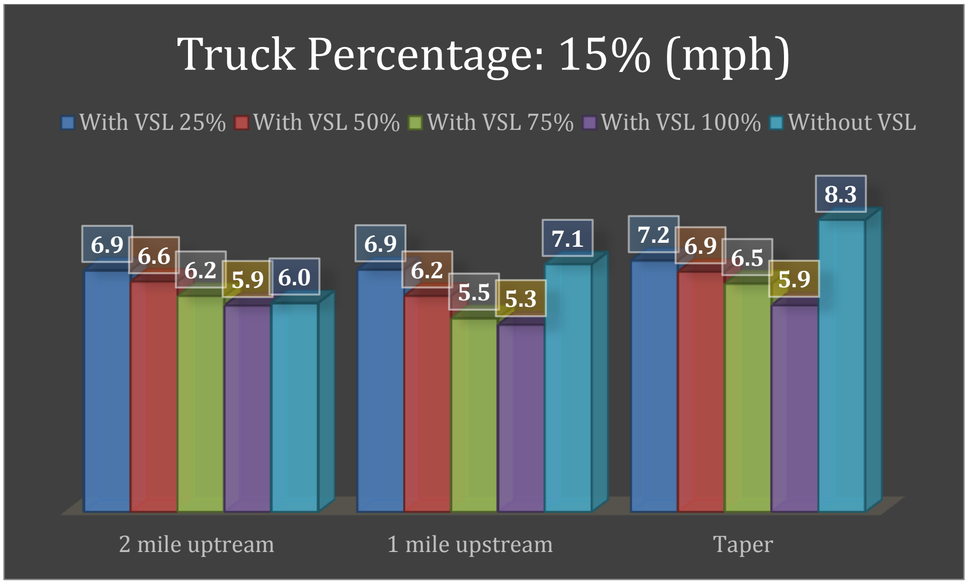
The four safety measures previously defined, average 1-minute standard deviation, average 1-minute maximum speed differential between adjacent, rear end conflicts, and lane changing conflicts will be discussed in the following sections.

Average One-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. For each simulation run, the average speed standard deviation was computed by averaging the 1-minute standard deviations for the entire simulation period. The means of the average speed standard deviation across multiple simulation runs are displayed in Figure 16. 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.



(a)



(b)

Figure 16. Average standard deviation of speeds

The standard deviation of speeds at the taper decreased significantly due to VASL. Figure 16 shows the standard deviation values and Table 18 reports the results of t-test for various pairwise comparisons of with and without 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, assuming a 10% truck percentage. If a 15% truck percentage is assumed, the standard deviation decreased by 1.4 mph at the taper, decreased by 0.9 mph at 1 mile upstream, and increased by 0.6 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.

Compliance towards VASL decreased the standard deviation of speeds. As the compliance increased from 25% to 100% the standard deviation fell at all three locations and for both truck percentages. Since lower standard deviations are associated with safer conditions, measures to improve the compliance to VASL will be worthwhile. For example, a state may consider investing in enforcement to increase compliance with the regulatory speed limit even though the dynamic speed limit is advisory only.

T-tests were performed to test the statistical significance and the results are shown in Table 18. They were all statistically significant except for a compliance rate of 100% with a truck percentage of 15% at 2 miles upstream, and a compliance rate of 25% with truck percentages of 10% and 15% at 1 mile upstream.

Table 18. Results of t-tests for average speed standard deviation

a. 2 Miles Upstream

Hypothesis	P-value	Significant at 95% confidence interval?
$SD^{10\%}_{With\,VSL\,25\%} > SD^{10\%}_{Without\,VSL}$	<0.0001	Yes
$SD^{10\%}_{With\,VSL\,50\%} > SD^{10\%}_{Without\,VSL}$	<0.0001	Yes
$SD^{10\%}_{With\,VSL\,75\%} > SD^{10\%}_{Without\,VSL}$	<0.0001	Yes
$SD^{10\%}_{With\,VSL\,100\%} > SD^{10\%}_{Without\,VSL}$	<0.0001	Yes
$SD^{15\%}_{With\,VSL\,25\%} > SD^{15\%}_{Without\,VSL}$	<0.0001	Yes
$SD^{15\%}_{With\,VSL\,50\%} > SD^{15\%}_{Without\,VSL}$	<0.0001	Yes
$SD^{15\%}_{With\,VSL\,75\%} > SD^{15\%}_{Without\,VSL}$	0.0151	Yes
$SD^{15\%}_{With\,VSL\,100\%} < SD^{15\%}_{Without\,VSL}$	0.2150	No

b. 1 Miles Upstream

Hypothesis	P-value	Significant at 95% confidence interval?
$SD^{10\%}_{With\,VSL\,25\%} < SD^{10\%}_{Without\,VSL}$	0.1796	No
$SD^{10\%}_{With\,VSL\,50\%} < SD^{10\%}_{Without\,VSL}$	0.0036	Yes
$SD^{10\%}_{With\,VSL\,75\%} < SD^{10\%}_{Without\,VSL}$	<0.0001	Yes
$SD^{10\%}_{With\,VSL\,100\%} < SD^{10\%}_{Without\,VSL}$	<0.0001	Yes
$SD^{15\%}_{With\,VSL\,25\%} < SD^{15\%}_{Without\,VSL}$	0.1436	No
$SD^{15\%}_{With\,VSL\,50\%} < SD^{15\%}_{Without\,VSL}$	<0.0001	Yes
$SD^{15\%}_{With\,VSL\,75\%} < SD^{15\%}_{Without\,VSL}$	<0.0001	Yes
$SD^{15\%}_{With\,VSL\,100\%} < SD^{15\%}_{Without\,VSL}$	<0.0001	Yes

c. Work Zone Taper

Hypothesis	P-value	Significant at 95% confidence interval?
$SD^{10\%}_{With\,VSL\,25\%} < SD^{10\%}_{Without\,VSL}$	<0.0001	Yes
$SD^{10\%}_{With\,VSL\,50\%} < SD^{10\%}_{Without\,VSL}$	<0.0001	Yes
$SD^{10\%}_{With\,VSL\,75\%} < SD^{10\%}_{Without\,VSL}$	<0.0001	Yes
$SD^{10\%}_{With\,VSL\,100\%} < SD^{10\%}_{Without\,VSL}$	<0.0001	Yes
$SD^{15\%}_{With\,VSL\,25\%} < SD^{15\%}_{Without\,VSL}$	<0.0001	Yes
$SD^{15\%}_{With\,VSL\,50\%} < SD^{15\%}_{Without\,VSL}$	<0.0001	Yes
$SD^{15\%}_{With\,VSL\,75\%} < SD^{15\%}_{Without\,VSL}$	<0.0001	Yes
$SD^{15\%}_{With\,VSL\,100\%} < SD^{15\%}_{Without\,VSL}$	<0.0001	Yes

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. Differences were computed for taper versus 1 mile upstream, and 1 mile upstream versus 2 miles upstream. The maximum of those two speed differences is the final measure. For each simulation run, the average maximum speed difference was computed by averaging the 1-minute maximum speed differences for the entire simulation period. The means of the average maximum speed difference across all simulation runs is shown in Figure 17. The maximum speed differences always occurred between the taper and 1-mile upstream location. The results in Figure 17 clearly show that VASL 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 and 15.2 mph for 10% and 15% trucks, respectively compared to 24.4 mph and 18.4 mph without VASL. The maximum speed differences were even lower for higher compliance rates. Table 19 shows that pair-wise comparisons of difference VASL scenarios versus the without VASL scenario were statistically significant.

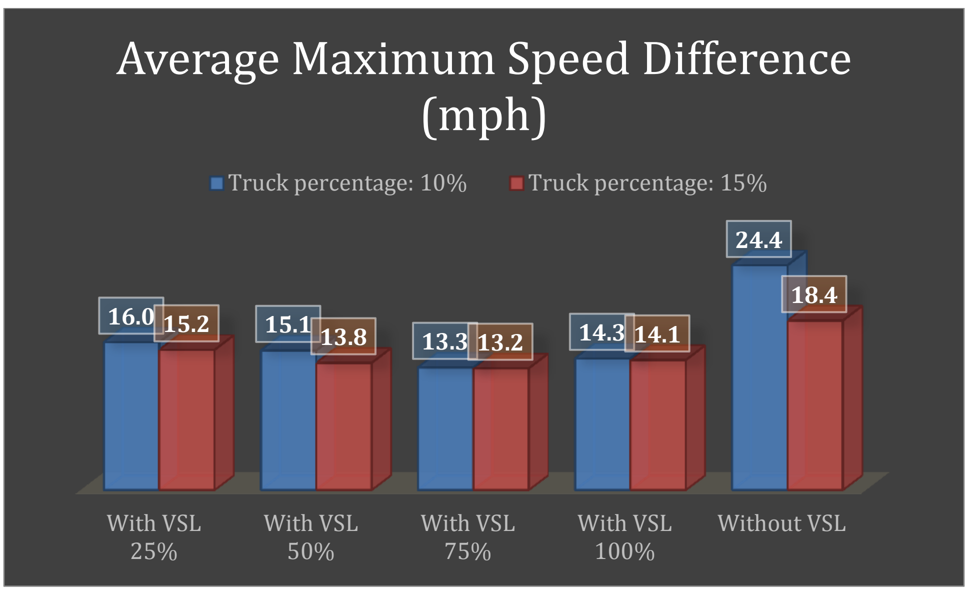


Figure 17. Means of average maximum speed difference

Table 19. Results of t-tests for average maximum speed difference

Hypothesis	P-value	Significant at 95% confidence interval?
$\Delta S_{With\,VSL\;25\%}^{10\%} < \Delta S_{Without\,VSL}^{10\%}$	<0.0001	Yes
$\Delta S_{With\,VSL\;50\%}^{10\%} < \Delta S_{Without\,VSL}^{10\%}$	<0.0001	Yes
$\Delta S_{With\,VSL\;75\%}^{10\%} < \Delta S_{Without\,VSL}^{10\%}$	<0.0001	Yes
$\Delta S_{With\,VSL\;100\%}^{10\%} < \Delta S_{Without\,VSL}^{10\%}$	<0.0001	Yes
$\Delta S_{With\,VSL\;25\%}^{15\%} < \Delta S_{Without\,VSL}^{15\%}$	0.0006	Yes
$\Delta S_{With\,VSL\;50\%}^{15\%} < \Delta S_{Without\,VSL}^{15\%}$	<0.0001	Yes
$\Delta S_{With\,VSL\;75\%}^{15\%} < \Delta S_{Without\,VSL}^{15\%}$	<0.0001	Yes
$\Delta S_{With\,VSL\;100\%}^{15\%} < \Delta S_{Without\,VSL}^{15\%}$	<0.0001	Yes

Rear End and Lane Changing Conflicts

Vehicle trajectories were extracted from simulations and used as input to the SSAM program. Three surrogate safety measures were obtained from the SSAM program: the time to collision (TTC), post encroachment time (PET), and conflict angle. As previously discussed, SSAM uses certain threshold values for these three measures to identify rear end and lane changing conflicts. A rear end conflict is assumed when TTC is less than 1.5 seconds, PET is less than 5 seconds, and conflict angle is less than 30 degrees. And, a lane changing conflict is assumed when TTC is less than 1.5 seconds, PET is less than 5 seconds, and conflict angle is between 30 and 85 degrees.

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 conflict analysis was performed on the entire network shown in Figure 11. The results of rear end and lane changing conflicts are shown in Figures 18 and 19 respectively.

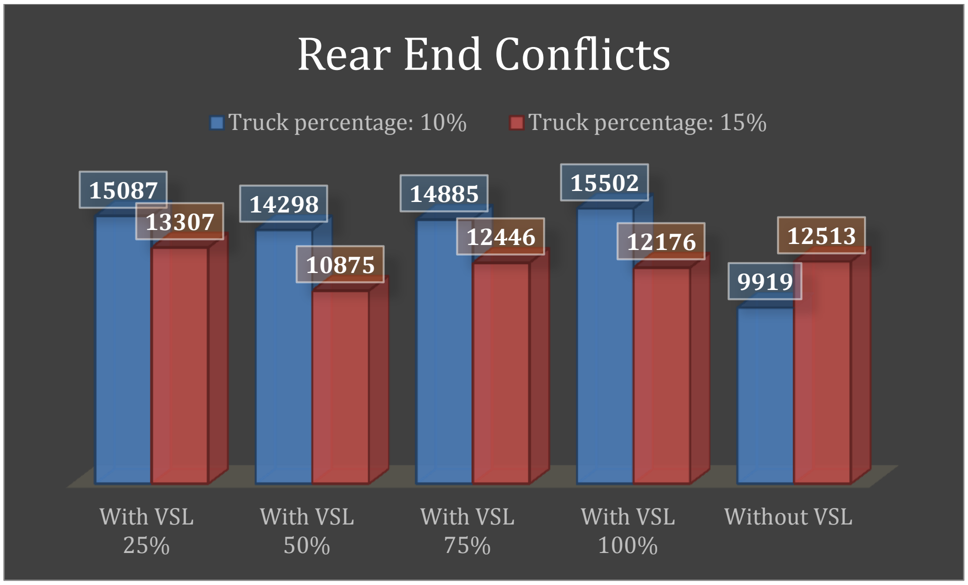


Figure 18. Number of rear end conflicts

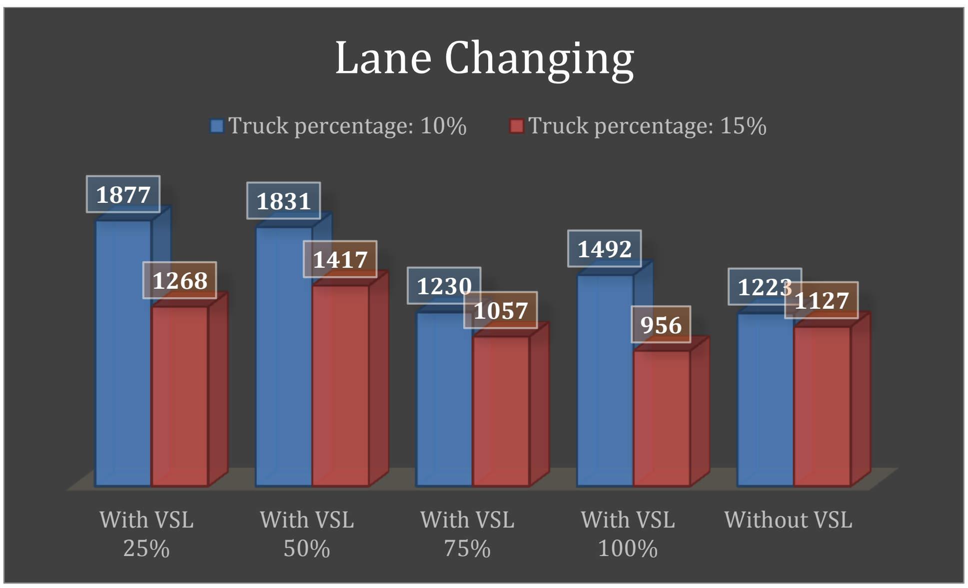


Figure 19. Number of lane changing conflicts

The number of rear end and lane changing conflicts with VASL varied with the truck percentage. For 10% truck, there were fewer rear end and lane changing conflicts when VASL was not used. The opposite was true for 15% truck where VASL decreased the number of rear end conflicts at medium (50%) to high compliance rates (>75%). Thus VASL could provide greater safety benefits at higher truck percentages.

Summary of Performance Measures

The results of operational and safety performance measures can be summarized as follows. Operationally, the use of VASL in the I-270 work zone resulted in: a 40% to 58% decrease in average queue length, a 6% to 13% reduction in work zone throughput, a 20% to 29% decrease in number of stops per vehicle and a 1.5% to 10% increase in work zone travel time.

In terms of safety, 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 standard deviation of speeds slightly increased 2 miles upstream of the taper after VASL. The maximum speed differences also decreased, by up to 10 mph, with VASL. The effect of VASL on predicted number of rear end and lane changing conflicts varied based on the proportion of trucks in the traffic stream. The number of conflicts increased due to VASL when the traffic stream consisted of 10% trucks. For 15% trucks however, the number of conflicts with VASL were lower than without VASL.

Thus, two out of four operational measures (queue length, stops) 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. And, rear end, lane changing conflicts increased at 10% trucks but decreased at 15% trucks after 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 with 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. 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 new algorithm (Proposed 1 min) are as follows:

- All detectors in the I-270 VASL corridor average vehicle speeds every 1 minute.
- The recommended speed limit for VASL 1 mile upstream of taper is derived from Table 20 (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 20 (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.

Table 20. Proposed 1 min algorithm characteristics

a. VASL 1 mile Upstream Taper

Average speed measured at taper	Speed displayed on VASL 1 mile upstream taper
>50	60
45-50	55
40-45	50
35-40	45
30-35	40
<30	35

b. VASL 2 mile Upstream Taper

Average speed measured 1 mile upstream of taper	Speed displayed on VASL 2 miles upstream taper
>50	60
45-50	55
40-45	50
<40	45

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 20 (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 20 (b)) instead of the displayed speed limit at VASL 1. The goal was to address previously identified shortcomings of the field algorithm.

The second algorithm (Proposed 5 min.) is similar to the Proposed 1 min. algorithm except the VASL signs are updated every five minutes instead of every 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.

Comparing Performance of Three VASL Algorithms

The results of the two new VASL algorithms were compared with the performance of the field algorithm. The detailed bar charts illustrating the differences among algorithms for the different performance measures can be found in Appendix B. The major findings from each of these bar charts were extracted and summarized in Table 21. 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. The main motivation of researching the two new VASL algorithms, P1 and P5, was to address the shortcomings of the field algorithm with respect to the no-VASL conditions. Therefore, the extent to which the shortcomings are addressed by the new algorithms were computed. 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

$$\% \, difference = 100x \, \frac{P5 \; measure \; value - no \; VASL \; measure \; value}{no \; VASL \; measure \; value}$$

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.

Table 21. Performance of the three VASL algorithms

Performance measure	Relative performance of algorithms	Best performing algorithm	Proposed 5-minute algorithm vs No-VASL	
			10% Trucks	15% Trucks
Average queue length	P1>P5>F	F	-47%	-40%
Work zone throughput	F<P1<P5	P5	-1.5%	-1.6%
Number of stops	F>P1>P5 (10% trucks) P1>P5>F (15% trucks)	P5, F	-26%	-18%
Travel time	F>P1>P5	P5	+8.5%	+1%
Standard deviation of speeds	P5>P1>F (at taper) P1~P5~F (at 1-mile and 2 miles upstream of taper)	F	Taper: -12% 1-mi u/s: -27% 2-mi u/s: +12%	Taper: -11% 1-mi u/s: -27% 2-mi u/s: 0%
Maximum speed difference	F>P5>P1	P1	-61%	-53%
Rear end conflicts	F>>P1>P5 (10% trucks) F>P1>P5 (15% trucks)	P5 P5	-31%	-20%
Lane changing conflicts	F>P5>P1 (100% compliance, 10% trucks) P5>P1>F (100% compliance, 15% trucks)	P1 F	-20%	-3%

A few inferences can be drawn from the results shown in Table 21 and the shortcomings of the field algorithm reported in the previous section. 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 13% lower than no-VASL throughput, while the throughput with P5 is only 1.5% lower than the no-VASL throughput. Second, the no-VASL travel times were up to 10% lower than the field algorithm travel times as compared to 8.5% lower than the P5 algorithm travel times. Third, the rear end conflicts for 10% trucks for field algorithm were greater than those of no-VASL, while the number of rear-end conflicts for P5 were 31% and 20% lower than no-VASL for 10% and 15% truck proportions, respectively. Similarly, the lane changing conflicts for P5 were 20% and 3% lower than the no-VASL conditions for 10% and 15% truck proportions, respectively. 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 no-VASL on all other measures.

CONCLUSIONS

The use of variable advisory speed limits in work zones in Missouri was investigated in this study. The investigation included both urban and rural as well as uncongested and congested work zones. Field studies were conducted to investigate the effectiveness of VASL in terms of safety measures such as compliance to posted speed limits, average speed, and speed variance. Additional analysis was conducted for congested work zones using calibrated simulation models. Both mobility and safety impacts of VASL in congested work zones were analyzed. Mobility measures such as average queue length, work zone throughput, and average travel times were investigated. Safety measures included, speed variance, maximum spatial speed difference, rear end and lane changing conflicts based on time to collision and conflict angle surrogate measures. The following are the major findings of the study:

VASL in Urban Uncongested Work Zones (I-270 Case Studies)

1. The average speeds with VASL were lower by 2.2 mph, than without VASL. The standard deviation of speeds with VASL was higher, by 4.4 mph, than without VASL. The increase in standard deviation is possibly due to the advisory nature of VASL. Since they are not enforceable some drivers complied while others did not.

2. For the I-270 work zones, the compliance rates inside the work zone were not high with or without VASL. Still, the compliance with VASL was about eight times greater than without VASL.

The use of VASL is recommended inside uncongested work zones to achieve higher compliance and lower average speeds. Better enforcement of regulatory speed limits could help to decrease the standard deviation in speeds.

VASL in Urban Congested Work Zones (I-270 Case Studies)

1. Work zones in high travel demand areas typically result in bottlenecks. The field studies on I-270 found that the VASL were effective in making drivers slow down as they approached the work zone, thus reducing sudden changes in speeds.

2. The average speeds and the posted advisory speed limits with VASL had similar trends, with correlation coefficients ranging between 0.42 and 0.86. Correlation between traffic speeds and the posted speed limits has been used as a surrogate for compliance in other studies.

The use of VASL in congested work zones results in drivers reducing their speeds while approaching the work zone. However, it was not possible to distinguish the effect of VASL with that of traffic congestion in reducing speeds.

VASL in Rural Work Zones (Hwy. 54 and Hwy. 63 Case Studies)

1. The uncongested traffic conditions at both work zone sites did not warrant varying the speed limits, thus the VASL displayed the work zone speed limit and complemented the existing static speed limits.
2. Both sites showed reductions in mean speed, variance, and 85th percentile speed downstream of the VASL sign indicating that drivers paid attention to the advisory speeds. The speed reduction from the VASL sign to the taper was gradual when VASL was deployed, at the US 54 site.

Using VASL to complement the static speed limits in rural work zones is suggested even if the VASL is only used to display the static speed limits. It leads to safer traffic conditions by encouraging traffic to slow down gradually and by reminding traffic of the reduced speed limit.

VASL in Congested Sites – Additional Simulation Analysis (I-270)

1. The effect of VASL at an oversaturated work zone location on I-270 was investigated. The MoDOT VASL algorithm used on the I-270 corridor was implemented in simulation. The results indicated that VASL decreased the average queue length (up to 58%) and decreased the average number of stops per vehicle (up to 29%). However, the vehicle throughput decreased (up to 13%) and the average travel time through the work zone increased (up to 10%).

2. In terms of safety, VASL decreased the standard deviation of speeds at the taper and 1 mile upstream of the work zone. The standard deviation of speeds increased slightly at 2 miles upstream. VASL also decreased the maximum speed differences by up to 10 mph. The effect of VASL on predicted number of rear end and lane changing conflicts varied based on the proportion of trucks in the traffic stream. The number of conflicts increased due to VASL when the traffic stream consisted of 10% trucks but decreased for 15% trucks.

3. Thus, two out of four operational measures (queue length, stops) improved due to VASL whereas the other two measures became slightly worse (work zone throughput, travel time). Speed measures, with the exception of the standard deviation at 2 miles upstream, showed an improvement due to VASL. And, rear end, lane changing conflicts increased at 10% trucks but decreased at 15% trucks with VASL.

4. A new VASL algorithm was tested to improve VASL performance on throughput, travel time, and conflicts at low truck percentages. The proposed 5-minute algorithm (P5) made some important improvements in performance when compared to the current field algorithm. First, the work zone throughput was improved by 12.5% percent over the field algorithm. Second, the travel times also slightly improved as compared to the field algorithm. The travel times were within 8.5% of the travel times without VASL. Third, the number of rear-end conflicts for P5 were 31% and 20% lower than without VASL for 10% and 15% truck proportions, respectively. Similarly, lane changing conflicts for P5 were 20% and 3% lower than the no-VASL conditions for 10% and 15% truck proportions, respectively. Thus, the proposed 5-minute VASL algorithm addressed the

safety shortcomings of the field algorithm, increased the performance on throughput and travel times, while still outperforming the without VASL conditions on all other measures.

A well-designed VASL algorithm, like the P5 algorithm, can significantly improve the mobility and safety conditions in congested work zones. The use of simulation is recommended to conduct trials of different VASL algorithms before deploying them in the field.

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APPENDIX A

Survey of the use of Variable Speed Limits in Work Zones

This survey is being conducted under the auspices of the FHWA Smart Work Zone Deployment Initiative Pooled Fund program by the University of Missouri-Columbia.

There are 10 questions in this 1-page survey. It should take less than 5 minutes of your time to complete the survey. If you are not the contact person for answering this survey, please forward it to the concerned person in your agency. Thank you for your assistance.

If you have questions or concerns about the survey, please contact me at (573) 882 1900 or via email at edarap@missouri.edu.

1. Name of your organization and your position:

2. Does your agency use either advisory or regulatory variable speed limits (VSL) in work zones to notify drivers of work zone speeds?

- A. Yes, advisory VSL only
- B. Yes, regulatory VSL only
- C. Yes, advisory and regulatory VSL
- D. No, you are done. (please skip to the end)

3. What devices are used to display the variable speed limits?

- A. Variable Speed Limit Display
- B. Permanent Changeable Message Signs (also called Dynamic Message Signs)
- C. Portable Variable Message Signs
- D. None

E. Other devices (please specify)

4. On the average, how many devices of each type mentioned in Question 3 are used per site?

5. What is the basis for changing the speed limit?

- A. Speeds near the taper
- B. Speeds inside the work zone
- C. Queues

D. Other (please specify)

6. What types of detectors do you use to measure real-time speeds for setting speed limits?

A. Loops

B. Microwave

C. Infrared

D. Video

E. Magnetic

F. Other devices (please specify)

7. When VSLs are used, how far from the taper area are these signs placed?

8. What factors do you consider in locating the VSL sign(s) at a particular site?

A. Average queue length

B. Location of a potential diversion route

C. Type of work activity

D. Work intensity

E. Average speeds

F. Number of lanes

9. Which of these measures do you use to evaluate the effectiveness of a VSL system?

A. Average speeds before and after VSL sign

B. Speed variances before and after VSL sign

C. Traffic volumes before and after VSL sign

D. Vehicle deceleration rates before and after VSL sign

E. Lane change distance before and after VSL sign

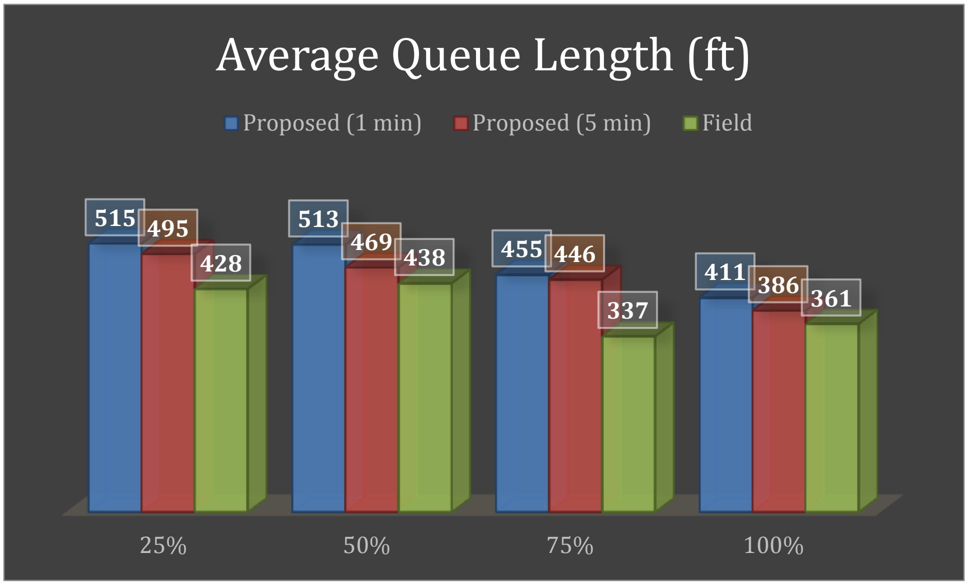
F. Total number of crashes before and after VSL sign

G. Other measures (please specify)

10. Would you like to receive a copy of the survey responses when completed?
If yes, please provide your contact information below

APPENDIX B

Performance of three VASL algorithms



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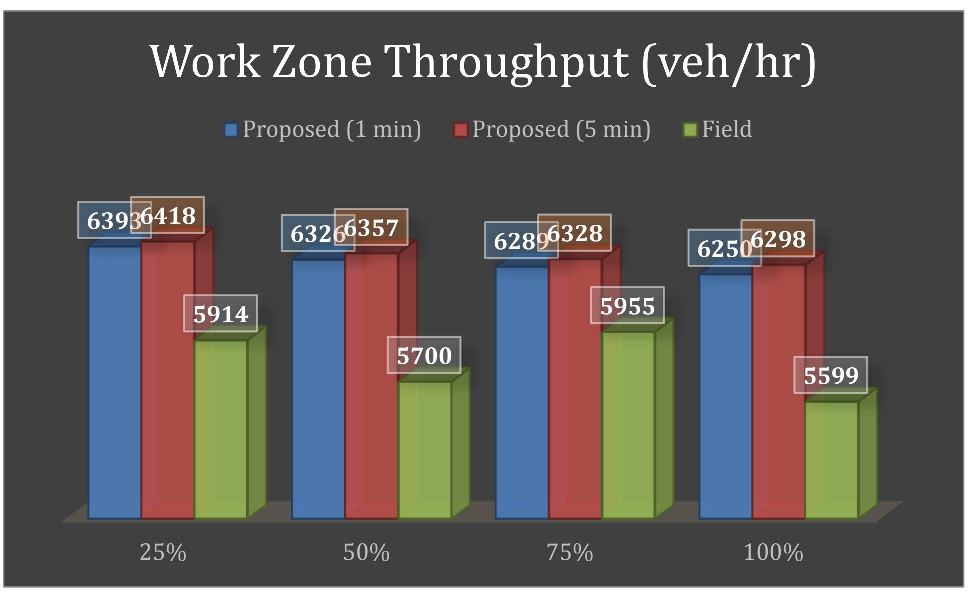

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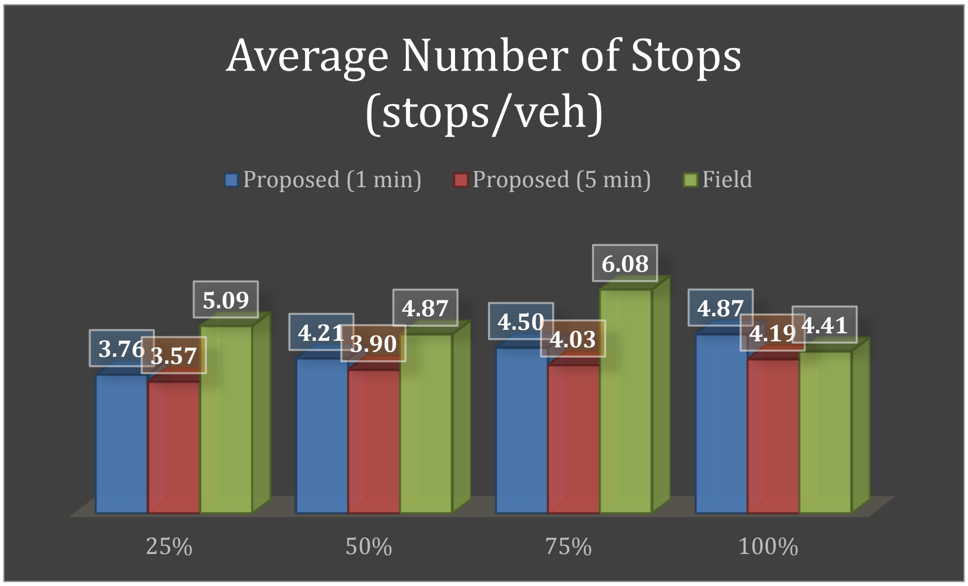

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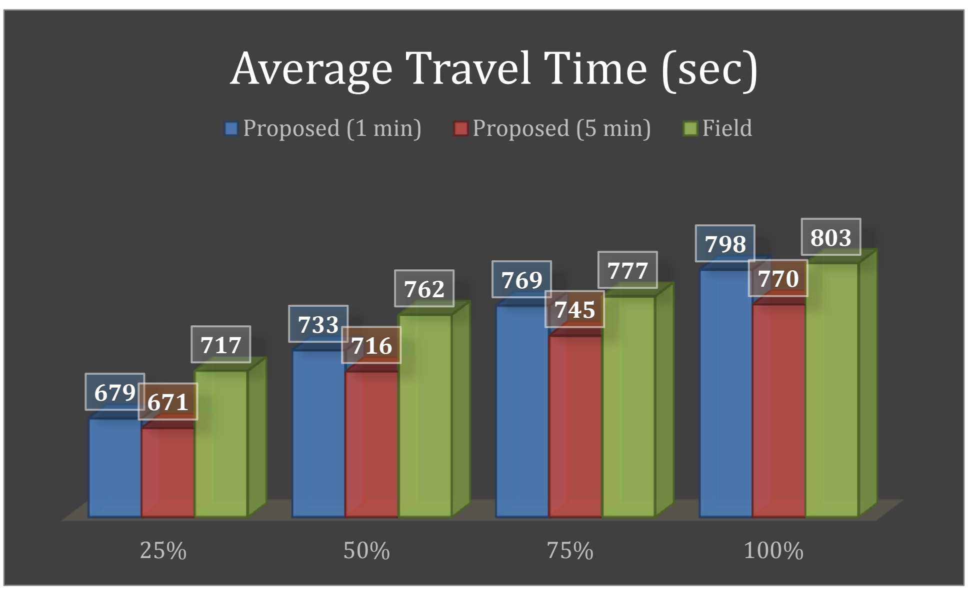

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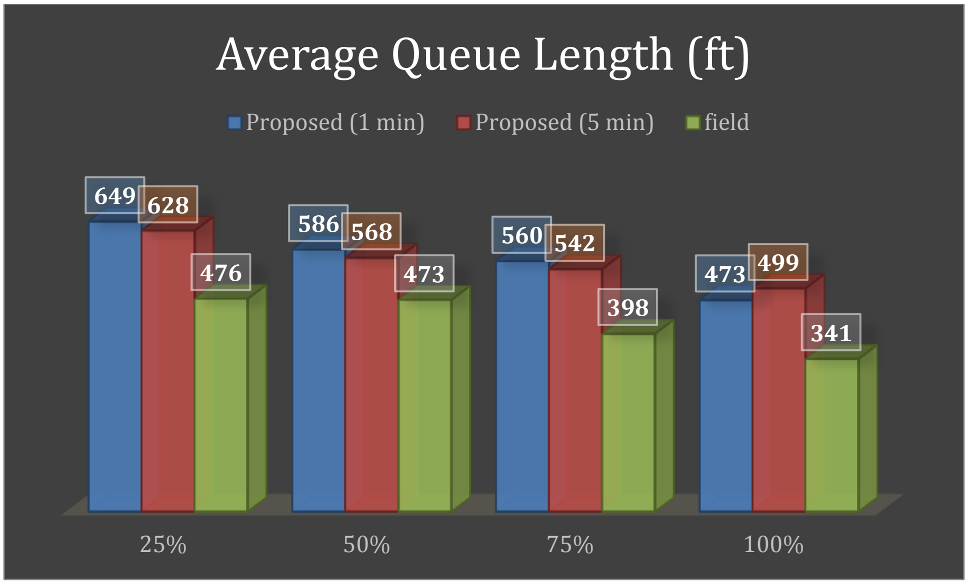
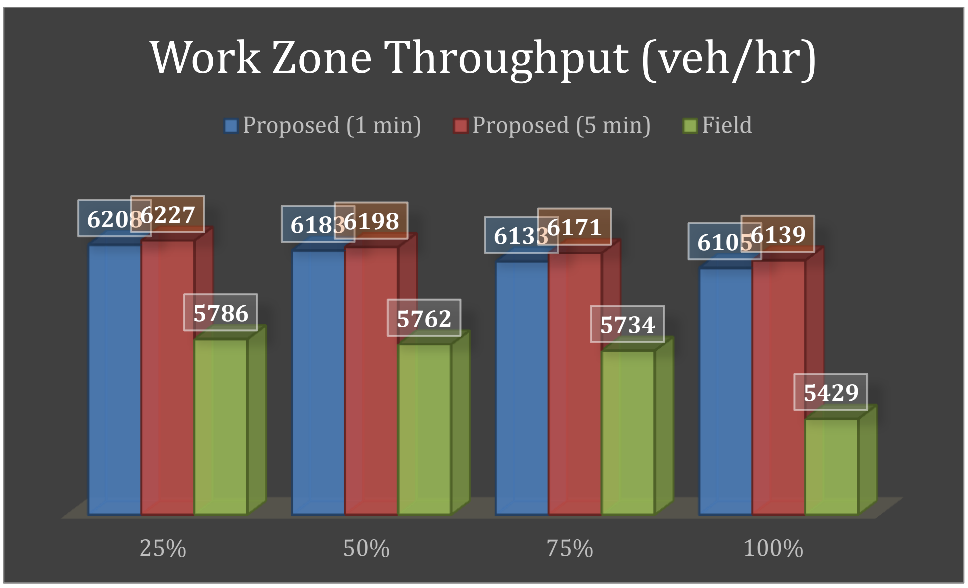
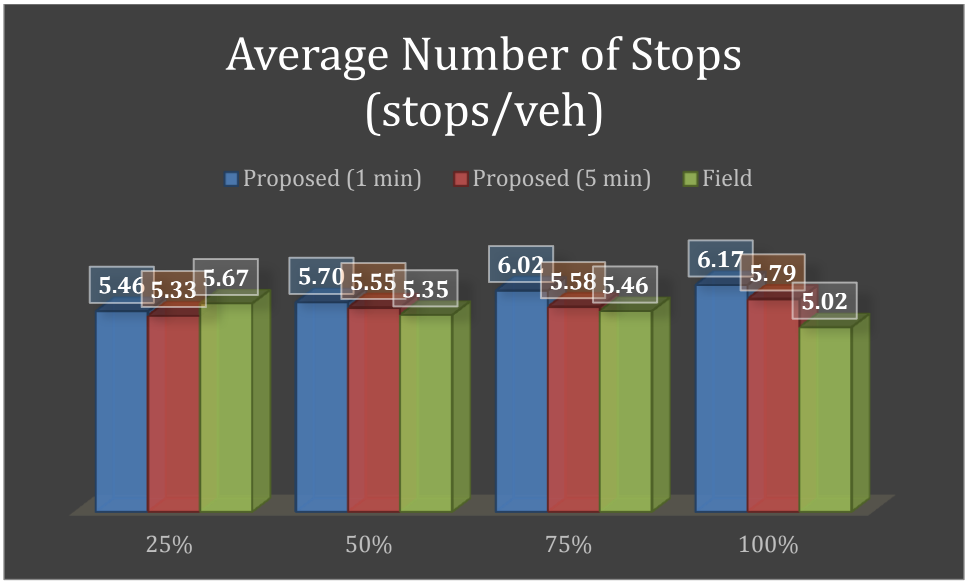
Figure B1. Results of performance measures with 10% of truck percentage


Average Queue Length (ft)
Proposed (1 min)
Proposed (5 min)
field
649
628
476
586
568
473
560
542
398
473
499
341
25%
50%
75%
100%

(a)


Work Zone Throughput (veh/hr)
Proposed (1 min)
Proposed (5 min)
Field
6227
5786
6198
5762
6171
5734
6139
5429
25%
50%
75%
100%

(b)



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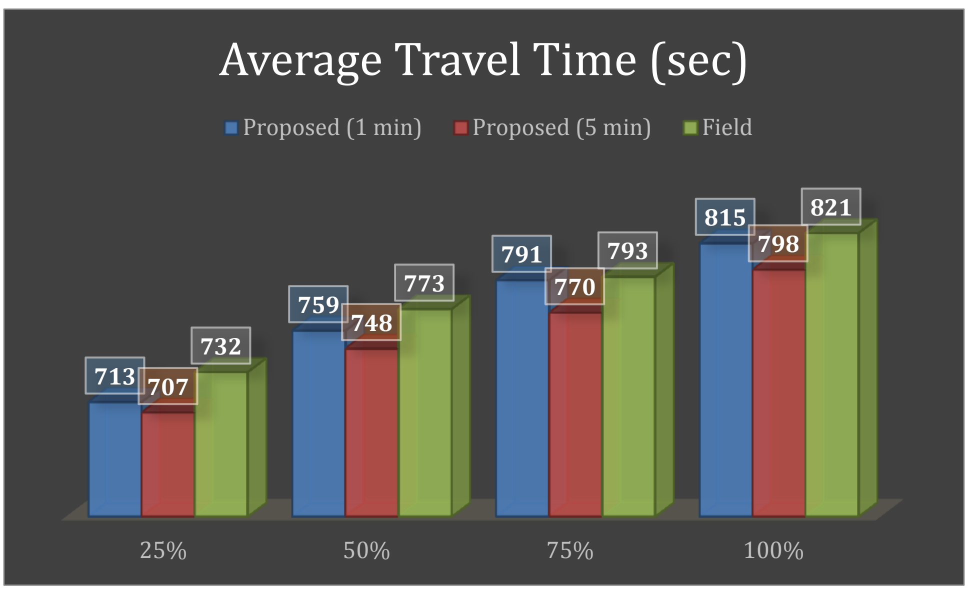
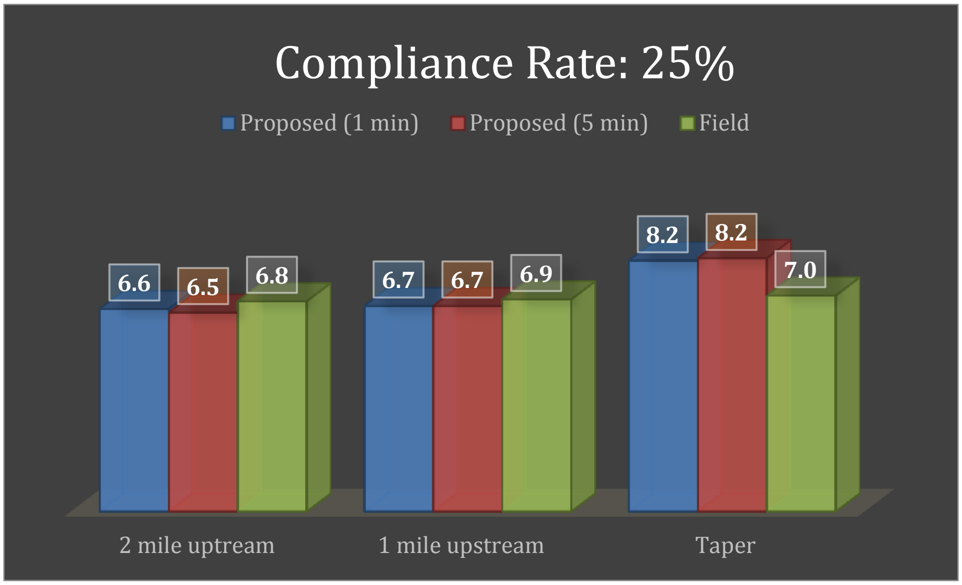
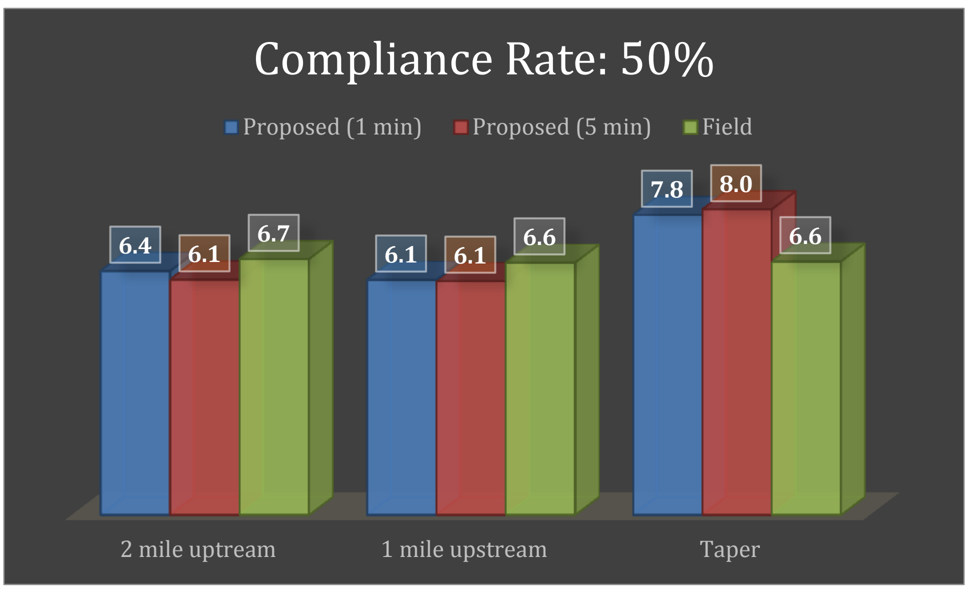


(d)

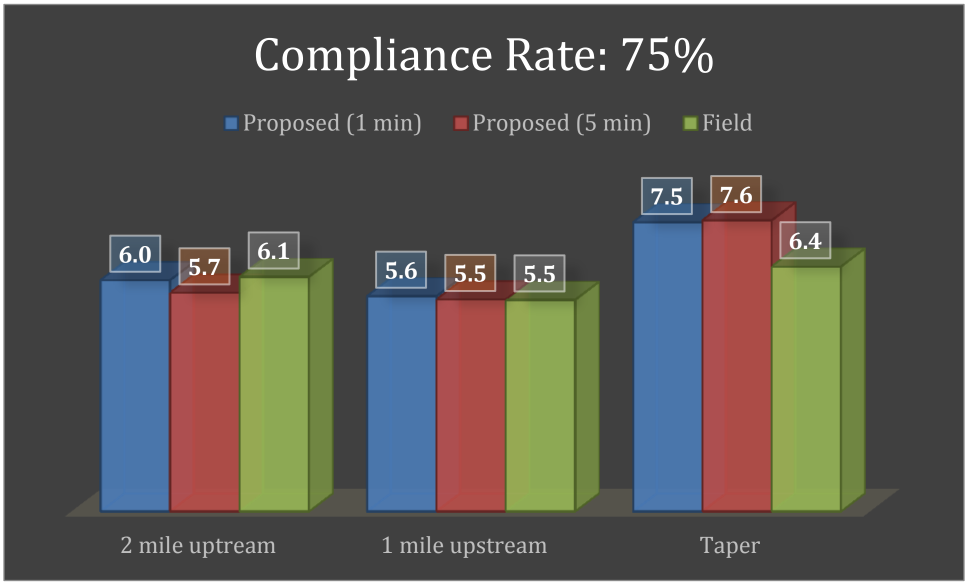
Figure B2. Results of performance measures with 15% of truck percentage


Compliance Rate: 25%
Proposed (1 min)
Proposed (5 min)
Field
6.6
6.5
6.8
6.7
6.7
6.9
8.2
8.2
7.0
2 mile uptream
1 mile upstream
Taper

(a)


Compliance Rate: 50%
Proposed (1 min)
Proposed (5 min)
Field
6.4
6.1
6.7
6.1
6.1
6.6
7.8
8.0
6.6
2 mile uptream
1 mile upstream
Taper

(b)



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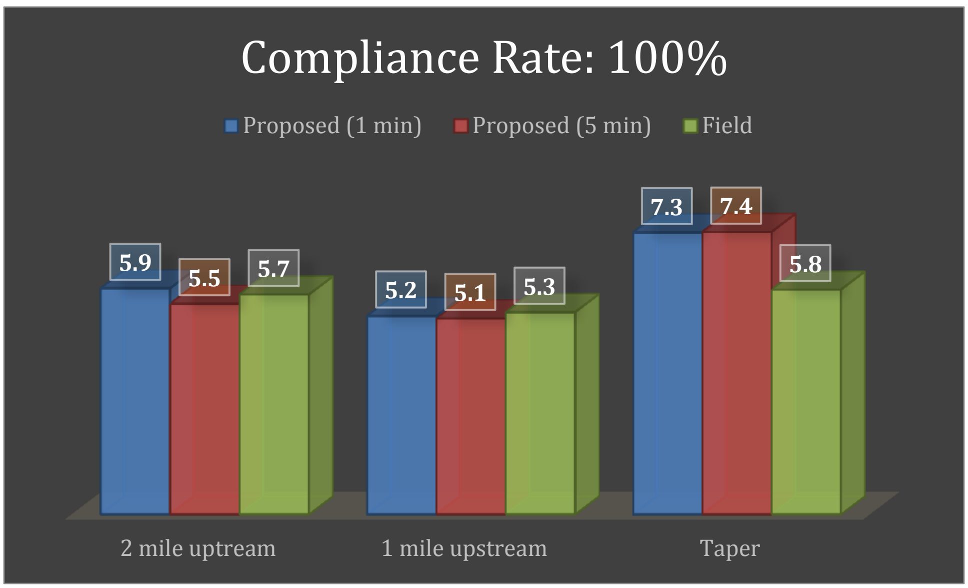
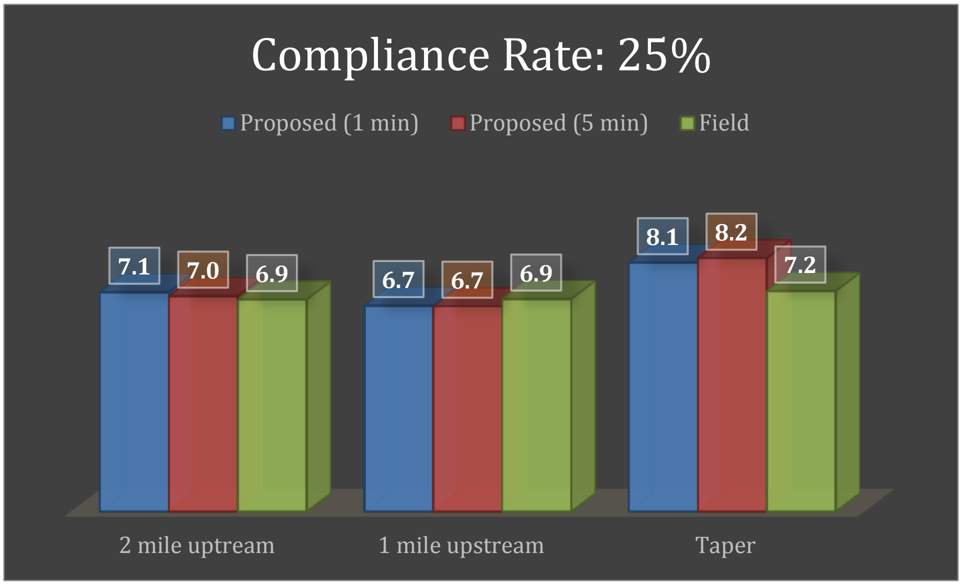
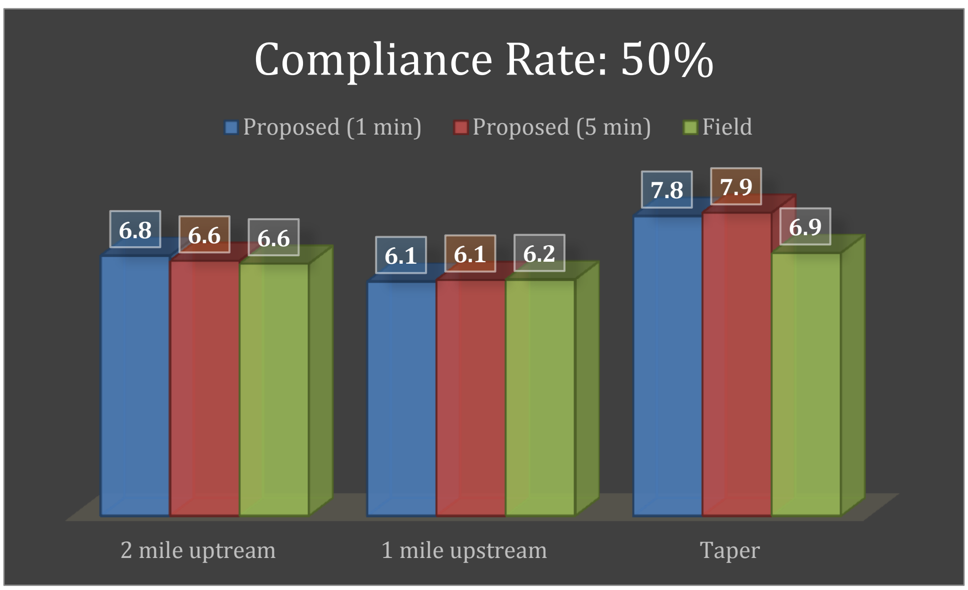


(d)

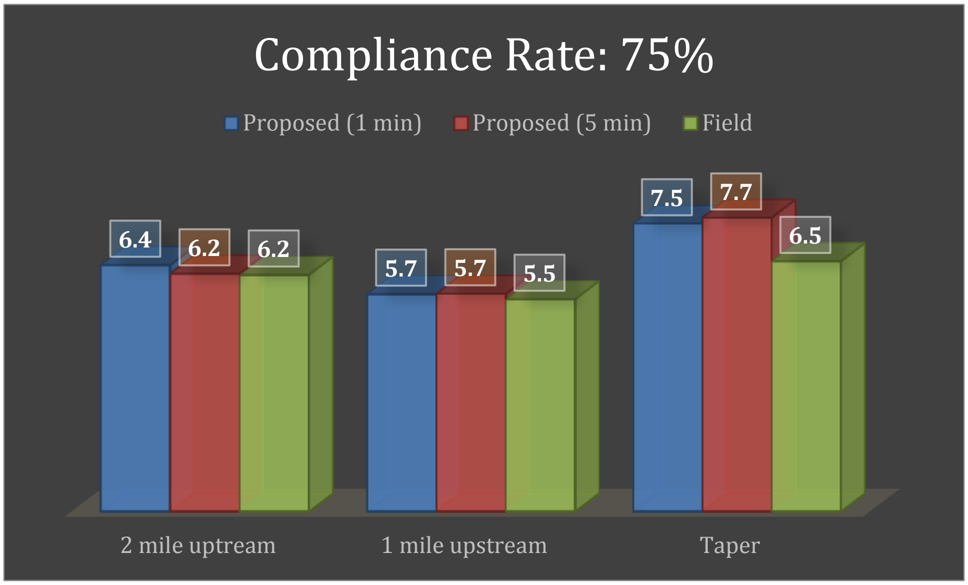
Figure B3. Average one-minute standard deviation of speeds (in mph) with 10% trucks


Compliance Rate: 25%
Proposed (1 min)
Proposed (5 min)
Field
7.1
7.0
6.9
6.7
6.7
6.9
8.1
8.2
7.2
2 mile uptream
1 mile upstream
Taper

(a)


Compliance Rate: 50%
Proposed (1 min)
Proposed (5 min)
Field
6.8
6.6
6.6
6.1
6.1
6.2
7.8
7.9
6.9
2 mile uptream
1 mile upstream
Taper

(b)



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(d)

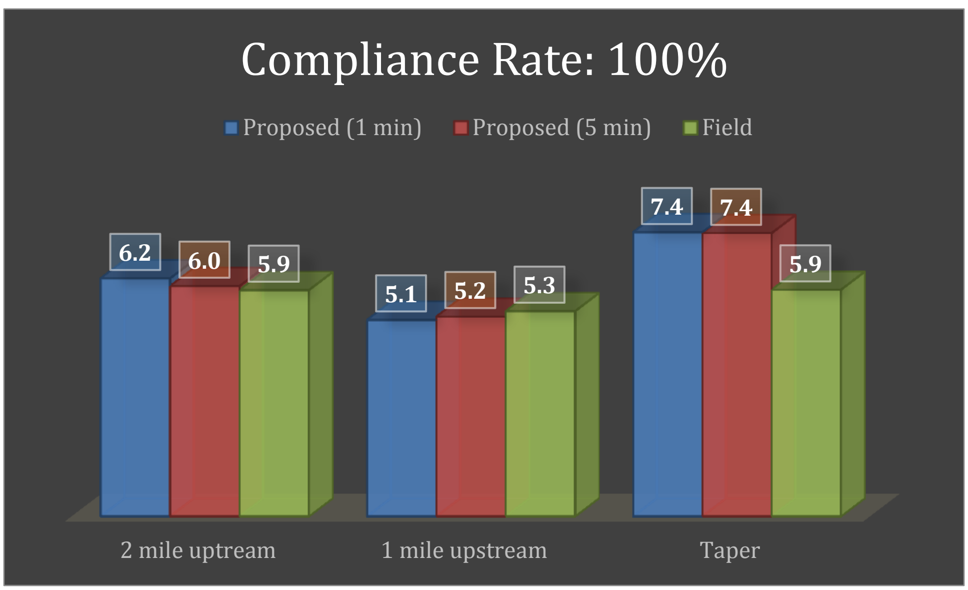
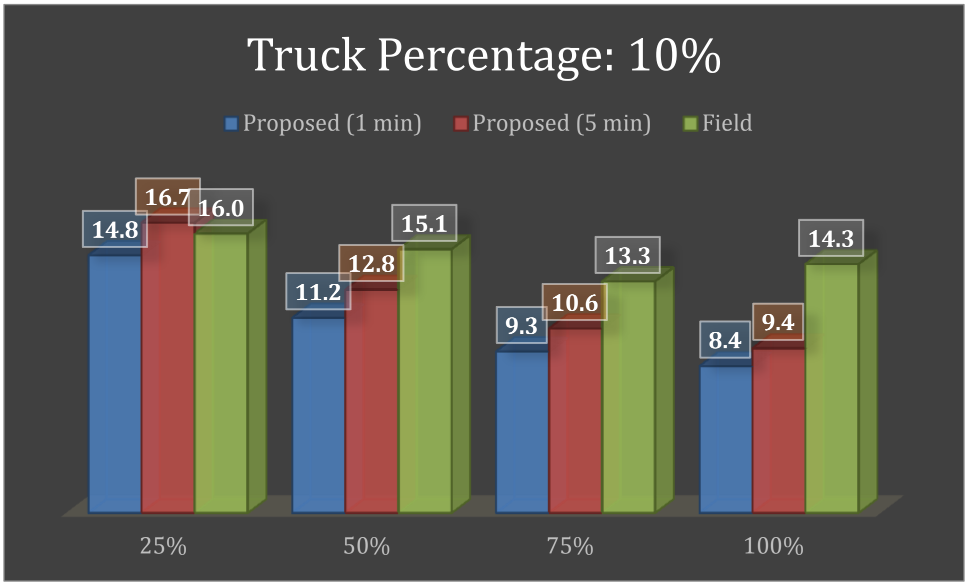


Figure B4. The average one-minute standard deviation of speeds (in mph) with 15% trucks



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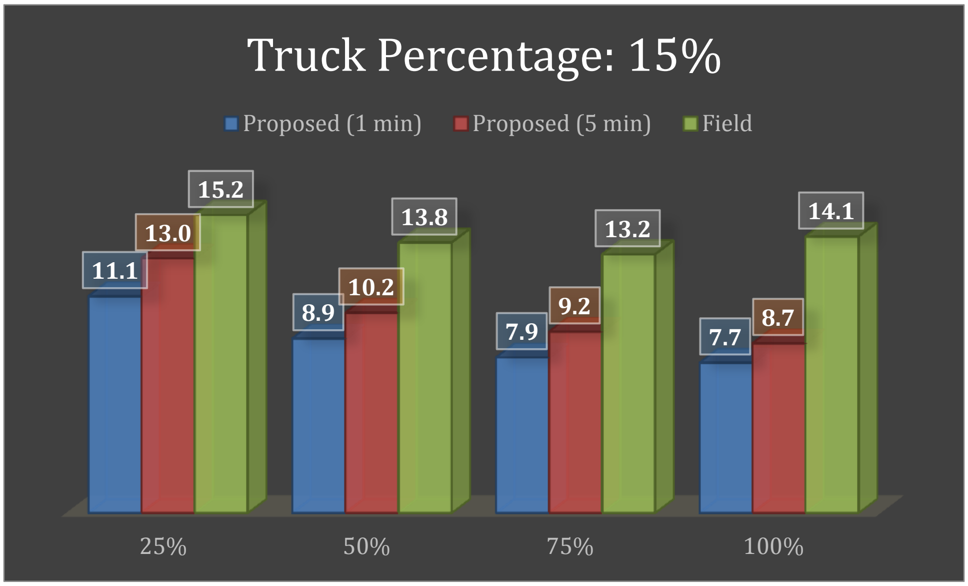
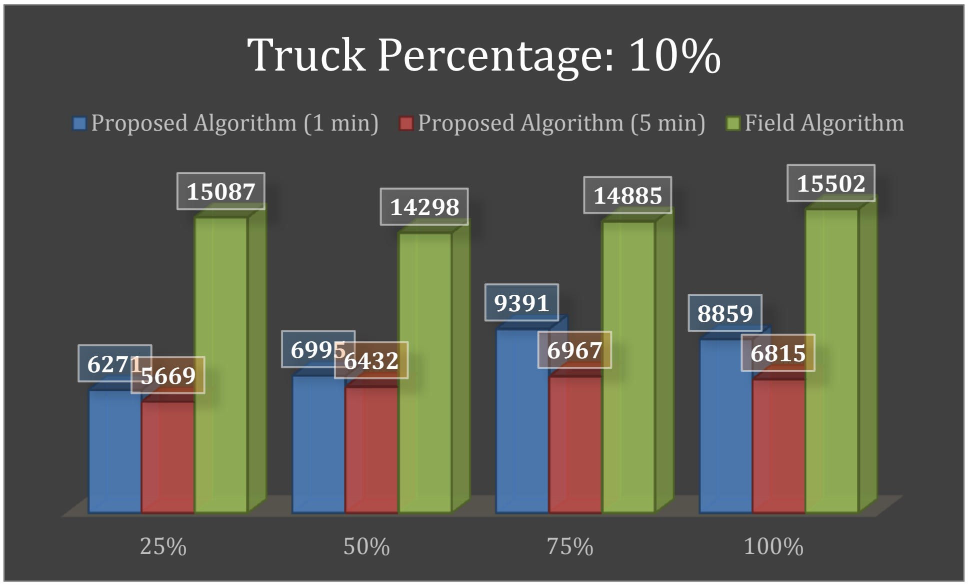


(b)

Figure B5. Average maximum speed difference (in mph)



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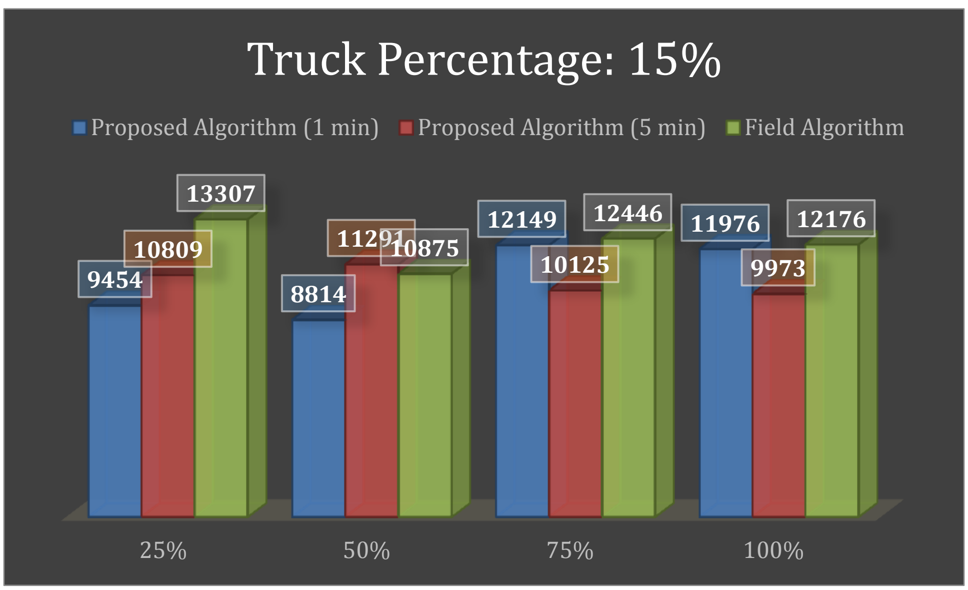
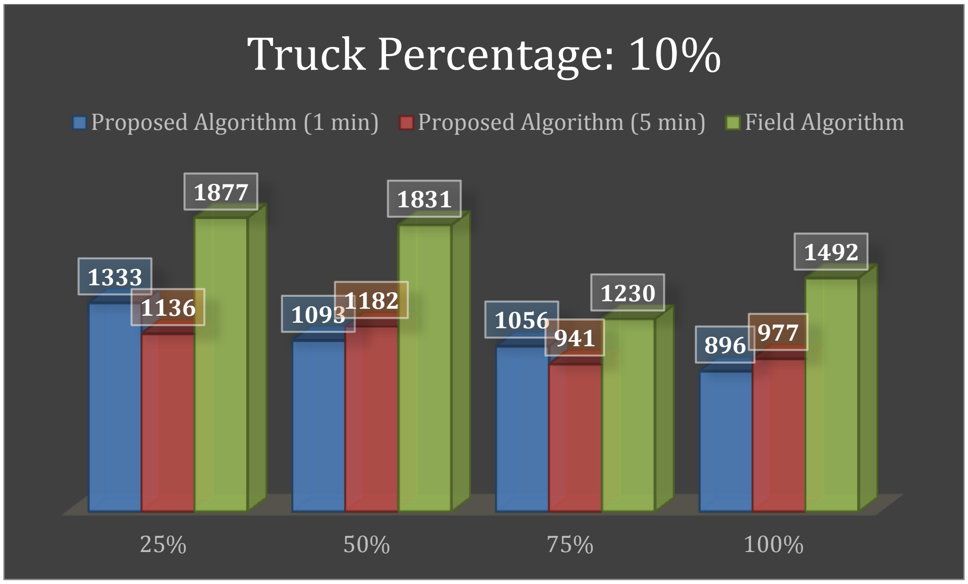


(b)

Figure B6. Number of rear end conflicts



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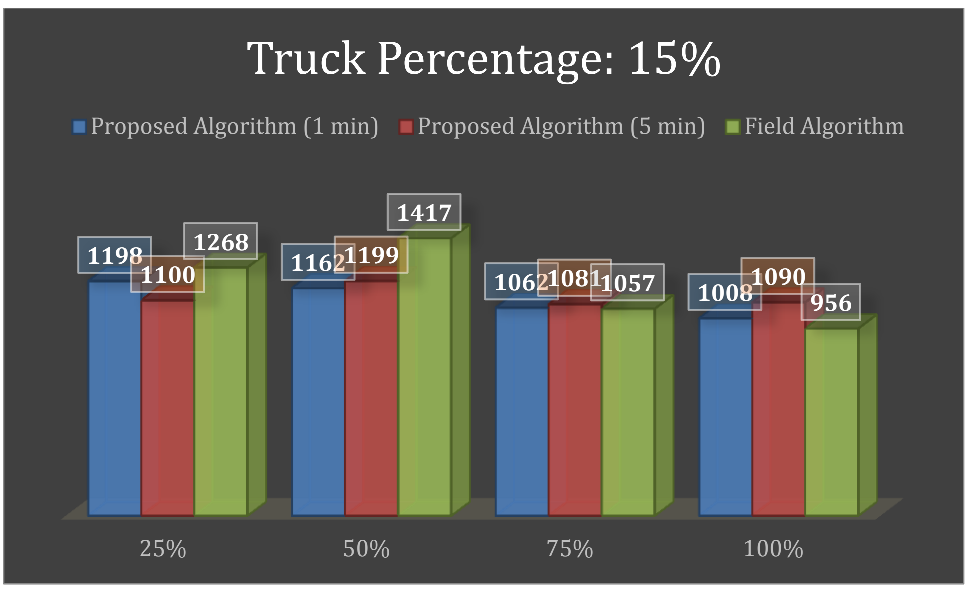

(b)

Figure B7. Number of lane changing conflicts