A Field Test and Evaluation of Variable Speed Limits in Work Zones

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Department of Transportation and Related Agencies Appropriations Bill, 2000

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ABSTRACT

This report describes a field operational test of a variable speed limit (VSL) system in a work zone in Michigan and evaluates the extent to which: speed limit compliance is affected; the credibility of the speed limits is increased; safety is improved; and traffic flow is improved. The system in Michigan was deployed during the summer 2002 in a work zone on I-96 south and west of Lansing, Michigan. Despite operational constraints of the test site, there were positive effects on (increased) average speeds and (decreased) travel time through the VSL deployment area. The percentage of vehicles exceeding certain thresholds (e.g., 60 mph) did, however, decrease when the system was in operation. A review of the crashes in the area showed that most were rear-end collisions, most occurred in the non-VSL direction, and none appeared to be directly associated with the deployment of the system. The VSL system can present far more credible information (realistic speed limits) to the motorist, responding to both day-to-day changes in congestion as well as changes in nature of the roadwork activity and geometry as motorists go through a given zone.

INTRODUCTION

The basic premise of variable speed limits (VSLs) is that in some situations the regulatory speed limit should vary dynamically with conditions encountered on the roadway such as inclement weather, work zones, and congestion. Moreover, speed limits that are perceived to be unreasonably low can lead to low speed-limit compliance rates, and high variance in vehicle speeds. With VSL, the hypothesis is that motorists will respond "better" to realistic speed limits, resulting in higher compliance, lower speed variance, and increased safety. In this context, the US Department of Transportation's Federal Highway Administration (FHWA) solicited applications for field tests of VSL systems in work zones. Michigan was one of several states chosen to undertake the field tests and the first to complete an evaluation.

The basic objectives of this project were to design and deploy a viable VSL system in a work zone and evaluate the extent to which: speed limit compliance is affected; the credibility of the speed limits is increased; safety is improved; and traffic flow is improved. The system used in Michigan was "bench tested," initially field-tested on a local road to confirm that the system was basically operating as expected, and then deployed during the summer of 2002 in a work zone on I-96 south and west of Lansing, Michigan. There were four separate deployments within an 18-mile work zone during which operational data were collected. The data were then analyzed in the context of the operation of the VSL system itself as well as its effects on traffic flow and safety.

VSL SYSTEM SPECIFICATION

The key features of the VSL system (Figure 1) deployed in the Michigan field test include:

- high visibility variable speed signs (although amber lights, rather than white, were used in the display);
- trailer-mounted solar power source, signs, and sensors; vehicle sensing accomplished through remote traffic microwave sensors (RTMS);
- seven trailers with RF communications between sequential trailers;
- fully adjustable operating parameters (e.g., minimum and maximum display speed, configurable display speed look-up table, and multiple configuration settings);
- cell-modem access for checking operation status and for remote data retrieval;
- a weather/moisture detection sensor and a pager system that can be used by enforcement personnel to determine the speed limit displayed by any sign in the system.

The system monitored traffic flow and speed at given locations, calculated necessary speed statistics (e.g., average speed), and displayed a speed limit on a designated VMS according to pre-established logic ("settings files"). Settings files were developed for each specific deployment depending on site conditions (e.g., different files invoked for weekday vs. weekend use and/or when different types of construction were occurring).

Figure 1. Variable speed limit system deployed in Michigan varied the speed limit based on nature of road work activity and traffic conditions.

BASIC VSL DEPLOYMENT IN WORK ZONE

The section of I-96 used is located on the southern and western edges of the City of Lansing, Michigan. A variety of "permanent" and "transient" work activities were included in the overall work zone. At times there was significant congestion through the work zone while at others, traffic ran quite smoothly.

VSL Deployment and Data Collection in the Work Zone

The general framework for the VSL deployment is summarized:

- The VSL was deployed in one direction only and was basically a comparison of VSL system "on" versus "off."
- VSL trailers were placed within "line of sight" of each other with spacing varying from a few hundred yards to 1.0 mile. Spacing was closer than originally planned due to trailer-to-trailer communications problems and geometric factors.
- Some of the VMS displays varied according to logical rules based on prevailing speed while others were constrained by MDOT, based on geometric and other operating considerations. For example, MDOT required that speed limits no higher than 50 mph be posted near some ramp locations. These constraints were established in the "settings" files. The maximum speed limit in the active work zone was never allowed to be higher than 60 mph although the trailer at the end of the work zone was permitted to go as high as 70 mph.
- The displayed speed limits were set at the estimated 85th percentile speed at the next downstream location unless otherwise controlled.
- The presence of enforcement personnel was tested during one deployment. The aspects of enforcement examined/tested were: 1) whether the pager technology used to communicate

the speed limits to law enforcement worked and if the officer(s) present could use it; and 2) the effect of having enforcement personnel present within the VSL deployment area.

- Data for the evaluation came from the sensors on the trailer and from independent traffic data collection devices (e.g., pneumatic tube-based data collection devices) installed by MDOT.

VSL SYSTEM EFFECTIVENESS

The analysis of system effectiveness depended primarily on data collected by the system itself, although traffic data collected by MDOT using road sensors and independent traffic monitoring equipment at those same trailer locations were also used in some analyses. The latter were not used extensively because tube sensors were torn up repeatedly.

Measures of Effectiveness (MOE)

The following MOEs were used:

- average speed at specific trailer locations,
- difference between average speed and displayed speed,
- travel time through the work zone section where the system was deployed,
- 85th percentile speed,
- speed variance, and
- percentage of "higher speed" vehicles (percentage of vehicles in excess of 60 and 70 mph).

A separate analysis was undertaken with and without enforcement personnel present during one deployment. Finally, vehicle crashes that occurred within time windows around the VSL deployment were also examined.

System Deployment and Basic Data Collection Procedure

The basic system deployment and data collection scenario for each deployment was as follows:

1. A potential VSL deployment site within the overall I-96 work zone was selected based on traffic characteristics, whether the speed limit could be varied, length of time the deployment would be available, and an assessment of whether the system could be safely and effectively deployed.
2. MDOT then set constraints on the maximum speed limit that could be posted at each location within the deployment area. Logical rules for setting speed limits up to these maximum values were developed.
3. The VSL system was physically deployed, system operations monitored for 24 hours, and then "before" data collection commenced and continued for a specified period while the VMS were covered with static 50 mph regulatory signs.
4. After collecting "before" data, VMS displays were uncovered and the system was in "full" VSL operation while the "during" data were collected.

Of the four attempted deployments on I-96, only three (the first, third, and fourth) yielded usable data. During the second deployment system problems were encountered at the outset (e.g., erroneous occupancy counts which caused problems with the speed-setting algorithm) and construction work was completed earlier than expected.

Data Analysis Approach and Limitations

The analysis consisted of: descriptive statistics for various MOEs including graphs showing, for example, variation in average speed; simple comparisons of mean speeds (e.g., mean speed at a specific trailer for "before" and "during" conditions); and analysis of variance (ANOVA) which allowed for control of the effects of upstream speeds and volume. Data were analyzed both at specific trailer locations and longitudinally through the VSL deployment area.

Most of the comparisons and analyses were done using data collected by the VSL system. The MDOT data were useful at specific locations for assessing the 85th percentile speed and speed variance. The utility of the MDOT data resulted from the details that were available: the VSL system data were only available in 6-minute aggregations (e.g., the average speed over 6 minutes); while MDOT individual vehicle data were "binned" in either of 2 speed distributions (16 or 30 increments). Unfortunately, not all MDOT data were "binned" the same.

The regulatory speed limit throughout the work zone when the VSL system was not deployed was 50 mph (day and night) versus a normal speed limit of 70 mph when no work zone is present. Mid-way through the overall work zone there are interchanges with I-69 and I-496 which cause congestion at various times. Prevailing speeds through the work zone (when the 50 mph limit was in effect) varied considerably but were typically above 50 mph other than during congested periods when traffic was stop-and-go. For each deployment, motorists were well within the overall work zone (with a speed limit of 50 mph) where the VSL deployment started. The end of the VSL deployment area generally coincided with the end of the overall work zone where the speed limit returned to 70 mph.

Results of VSL Effectiveness Analysis

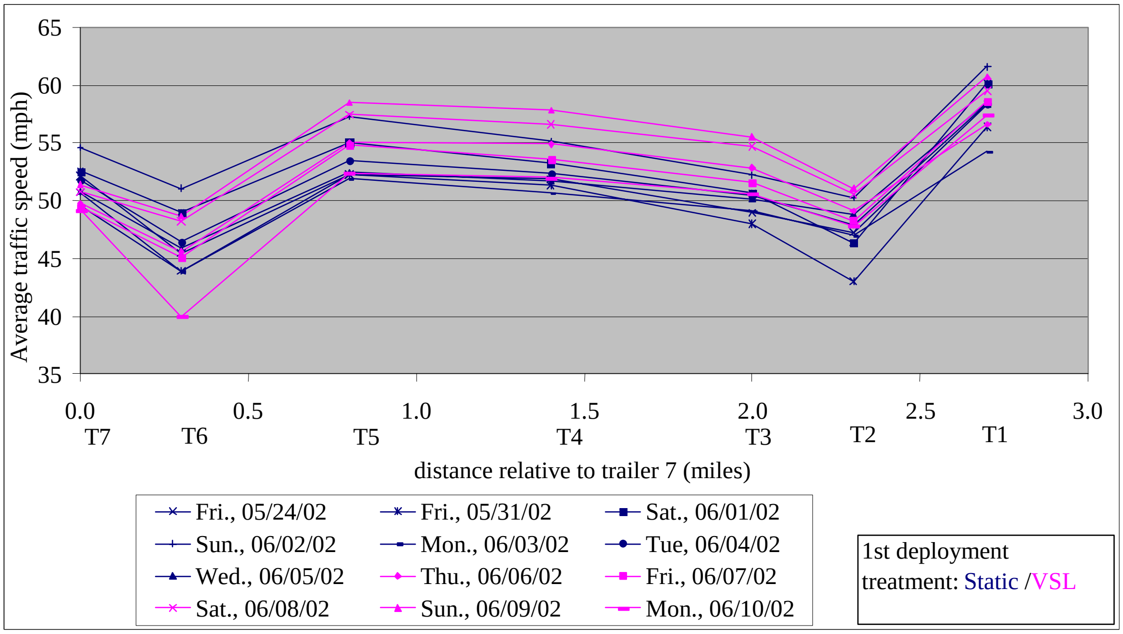
Average Speed, Difference between System-Displayed and Average Speed

As noted, most of the analysis regarding average speed was done using VSL system data. For this analysis, each observation is the average speed over a 6-minute period. The speed at the preceding (upstream) trailer was typically used as a covariate when statistical testing was done. This was essentially a control based on the "entry" speed from the last trailer.

Given that the static speed limit during the "before" period is 50 mph, it was expected that the VSL system would increase speeds through the zone, especially since the before speeds during non-congested times were generally higher than 50 mph.

Figure 2 is typical of the comparisons that were done for "before" and "during" conditions. Based on an *a priori* determination of when VSL effects were expected to be interesting (i.e., in these instances, AM rush and off-peak nighttime periods) and data availability, data from several days from the "before" and "during" periods were selected and plotted. Each line in the figure represents a plot of the 6-minute average speeds averaged over the noted time period (e.g., the speed profiles in Figure 2 shows average speeds calculated over 2+ hours) over the length of the VSL deployment area. Both the distance through the zone and the trailer locations are shown on the horizontal axis in each case. In the figure, motorists are proceeding from left to right, from Trailer 7 toward Trailer 1. Trailer 7 was placed well within the overall construction zone while Trailer 1 is at the eastern end at the point where motorists could resume normal (70 mph) speed.

6:00 – 8:00AM



8:00 – 10:00PM

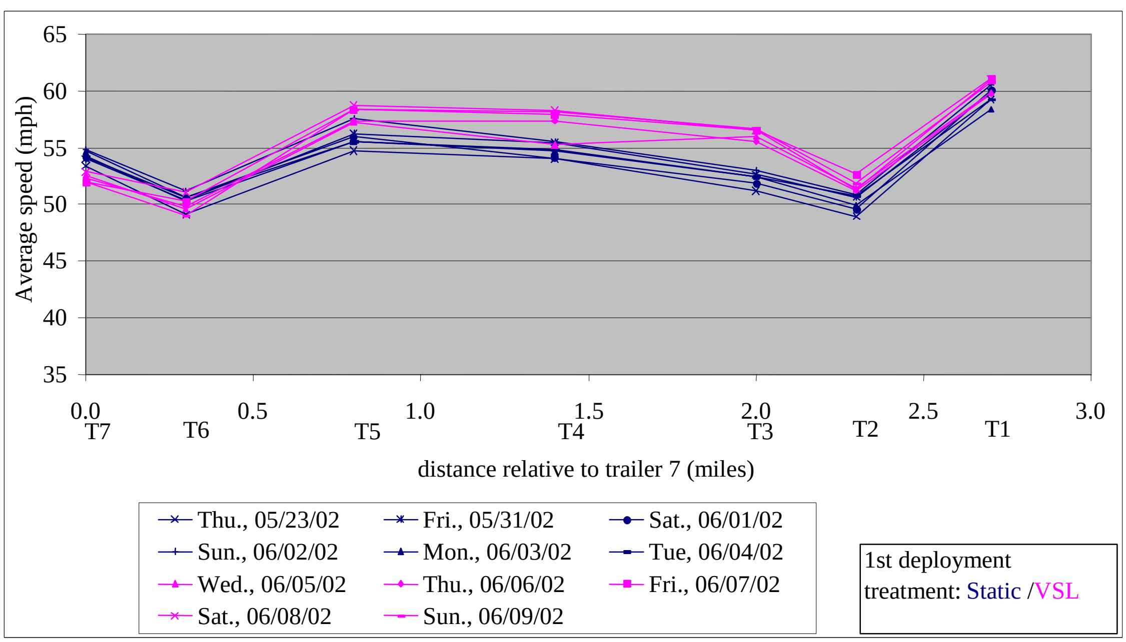


Figure 2. Comparison of average speed profiles for 6:00-8:00am and 8:00-10:00pm, first deployment

Looking at Figure 2 in more detail, the day-to-day variation within "treatment groups" is illustrated as the variation from peak to non-peak time periods. As a general statement, average speeds are somewhat higher when the VSL is in operation ("during") although the differences in the vicinity of the first trailers encountered by the motorist (Trailers 7 and 6) are not as apparent. It should be noted that the displayed speed at Trailers 7 and 2 were limited to 50 mph or less when the system was active, the same as the static speed limit. Data from both weekdays and weekends for the before and during conditions are shown in this comparison.

The information displayed in figure 2 (and others not shown) is summarized and presented in Table 1. Differences in average speeds observed during VSL operation and the static limit are shown for each time period at each trailer location as well as an indication of whether the differences were statistically significant at the .05 level. For the differences in average speed, the cell is shaded if the difference is statistically significant. In addition, the differences in displayed speeds are shown—that is, the differences between the average VSL displayed speeds and the static limit of 50 mph (before period). In the table, for the average speed difference, positive numbers indicate that the average speeds when the VSL was operating were higher than the average speeds when it was not (static). For the displayed speed difference, a positive number indicates that the average VSL system display was higher than 50 mph (the static, before limit).

Table 1. Summary of results of average and displayed speed comparisons, first deployment

time	variable	weekday/ weekend	location 7	6	5	4	3	2	1
6:00AM to 8:30AM	average speed difference (VSL -static)	weekday	0.3	0.7	2.5	3.7	3.7	2.5	0.9
		weekend	-1.3	-0.7	1.9	2.2	2.5	-0.5	-1.1
	displayed speed difference (VSL –static 50)	weekday	0.0	8.5	8.8	8.1	8.1	0.0	
		weekend	0.0	10.0	10.0	10.0	10.0	0.0	
10:30AM to 12:30PM	average speed difference (VSL -static)	weekday	-1.5	-0.7	2.0	2.2	2.5	1.5	0.3
		weekend	-2.4	-1.6	1.9	3.1	3.7	2.5	-0.6
	displayed speed difference (VSL –static 50)	weekday	0.0	9.3	9.0	6.7	6.7	0.0	
		weekend	0.0	10.0	10.0	10.0	10.0	0.0	
4:00PM to 6:00PM	average speed difference (VSL -static)	weekday	-5.4	-3.1	0.7	1.9	3.3	0.8	-0.1
		weekend	-9.1	-6.8	-4.6	-3.7	0.2	2.2	-1.3
	displayed speed difference (VSL –static 50)	weekday	-1.0	8.7	8.5	8.5	8.5	0.0	
		weekend	-1.9	6.3	6.6	8.1	8.1	0.0	
8:00PM to 10:00PM	average speed difference (VSL -static)	weekday	-1.6	-0.2	2.1	1.8	3.8	1.5	0.9
		weekend	-2.0	-0.5	1.9	3.1	4.1	1.6	0.8
	displayed speed difference (VSL -static)	weekday	0.0	10.0	9.4	9.9	9.9	0.0	
		weekend	0.0	10.0	10.0	10.0	10.0	0.0	

NOTES: Shaded cell indicates that the difference is statistically significant at .05; blank cell indicates that data are not available; cell values are the differences in speed in mph

Overall, average speeds were generally higher at trailers further into the VSL deployment area. Conversely, average speeds at the first-encountered trailers were lower when the VSLs were displayed. Based on these figures and the information summarized in Table 1, the following observations are offered regarding average speed for the first deployment:

- Given that the speed limit displayed at Trailer 7 (first one seen by motorists) was always constrained to 50 mph, it appears that motorists responded better to the lighted VMS display since the average speed was closer to the posted speed when the VMS was in operation. This does not, however, appear to hold true at the next trailer where the speed limit displayed increased and average motorist speed decreased or was about the same. An on-ramp from I-69 between Trailers 7 and 6 probably accounts for the speed decrease at this point (a dip in the profile during all time periods).
- At Trailers 5, 4, and 3, the displayed speed limit was generally higher and average motorist speeds were higher during VSL operations and across all time periods. It is interesting to note that in the middle of the VSL deployment area (Trailers 5-2), the VSL results in consistently higher speeds for both weekdays and weekend days during the nighttime period.
- Motorists typically slowed at Trailer 2 where the maximum allowable "during" speed limit was 50 mph because of a median crossover with restrictive geometry. The speed reduction at Trailer 2 was consistently 1-3 mph greater with the VSL in operation than when a static 50 mph limit was displayed, suggesting that the VSL/VMS had more credibility than the static sign.
- Motorists increased their speeds sharply at Trailer 1 (or, more accurately, between Trailers 2 and 1) since they were exiting the work area and it was visually very clear that this was the case.

Similar analyses were undertaken for the 3rd and 4th deployments. For the 3rd deployment, only three time periods (10:30am-12:30pm, 5-6:00pm, and 8-10:00pm) were available and the "before" data were limited to only one day. Third deployment results were similar to those for the first deployment although in almost all instances the "during" speed profiles were higher than the "before" profile. The comparisons were limited because only a few "before" data sets exist (because of short-range modem problems). Because there are several ramps in this deployment area, the allowable speed limit at Trailers 4 and 6 was limited to a maximum of 50 mph and, thus, the speed profiles are flatter than those for the first deployment. Again, at the end of the VSL area, the highway ahead was clear (VSL allowed to go to 70 mph) and speeds increased between the last 2 trailers.

Statistical comparisons (not shown) revealed that the average speeds were about 1-3 mph higher when the VSL was active in both the 10:30am -12:30pm and 8-10:00pm periods and statistically significant in all cases. For the 5-6:00pm period, the "during" average speeds were lower for Trailers 7 through 3 and higher for the last 2 although none of the differences was statistically significant.

For the fourth deployment, during some of the observation periods there was significant congestion at the beginning of the VSL deployment area with average speeds ranging from 25 to about 50 mph. The congestion was due to the work in the area just prior to the VSL area and an on-ramp from I-496 with relatively high volumes. Speeds typically increased as motorists traversed this area of the work zone. At the end of the zone, the last trailer operated separately from the others and showed a constant 70 mph both before and during the deployment (the sign was static before). In this instance, the speed-setting algorithms were different for the daytime (workers present, maximum speed limit of 50 mph) and nighttime (workers not present, maximum speed limit 70 mph).

While definitive conclusions are difficult with respect to average speed through the three VSL deployment areas, where there were no ramps or other mitigating geometric factors, both displayed speed limit and average speeds increased (e.g., in the middle of the first deployment area). There was some evidence that motorists gave more credibility to the lighted, VMS-active speed limit signs than static ones. Finally, there is also some evidence that the responses to the VSL were more consistent during non-peak periods, especially at night.

Travel Time through the Work Zone (VSL deployment area)

If average speeds increase when the VSL is deployed, the corollary is that travel times through the VSL deployment area decreases. Travel time was calculated based on the assumption that the average speed over any "link" between 2 adjacent trailers was the average of the speed observed at the 2 trailers.

For the first deployment, the differences in travel times observed between the VSL and static 50 mph speed limit are shown in Table 2. Not surprisingly, given the average speed results given earlier, travel time decreased for three of the four time periods reviewed. However, travel time increased for the 4-6:00pm period for both weekdays and weekend days.

Table 2. Comparison of travel times through work zone, first deployment

Time	travel time difference (VSL - Static)			
	Weekday		weekend	
	seconds	percent	seconds	percent
6:00AM - 8:30AM	-10.6	-5.4	-2.8	-1.6
10:30AM - 12:30PM	-5.0	-2.6	-5.3	-2.9
4:00PM - 6:00PM	1.8	1.0	20.9	11.3
8:00PM - 10:00PM	-5.2	-2.9	-5.8	-3.2

NOTE: Shaded cell indicates that the difference was significant with 95% confidence

While these changes are statistically significant in all cases, the absolute change was relatively small. In the best-case situation (AM rush hour during the week), average travel times decrease 11 seconds (or 5.4% of the overall travel time)—this benefit is accrued over 2.3 miles of travel. It is not clear that such savings are perceptible to the average motorist. Similar calculations were done for the third and fourth deployments although the savings were not as large or as consistent (e.g., for the fourth deployment, travel time increased 24.5 seconds during the 10:30am-12:30pm period). All savings were less than 6%.

85th Percentile Speed

The 85th percentile speeds were estimated using data obtained from the MDOT pneumatic tube sensors (disaggregating of the data was necessary and could not be done using VSL system data). For a variety of operational reasons (e.g., different aggregation formats, sensor failures), there was considerable variation in the quality and amount of data from the MDOT devices. Notwithstanding these problems, the variation in the 85th percentile speed was examined at specific trailers where data permitted. Overall, the 85th percentile speed was not seen to vary very much between the "before" and "during" conditions or with the displayed speed limits. Because of the data problems and inconsistency (at best) in the findings, no conclusions could be drawn.

Speed Variance

Similar to the examination of the 85th percentile speed, examination of speed variance relied on the data from the MDOT tube-based devices. There was little difference in the variance of vehicle speeds observed before or during VSL operation at some trailers, and at others results were inconsistent.

Percentage of "Higher Speed" Vehicles (%>60 mph, %>70 mph)

The percentages of higher-speed vehicles were examined as a rough measure of speed limit compliance. That is, for example, as the percentage of vehicles traveling over 60 mph increased, compliance with the speed limit clearly decreased. In all instances, the speed limit throughout the entire work area was 50 mph when the VSL system was not displaying the variable limits. The maximum limit when the system was operating varied according to the deployment, time of day, and transient congestion conditions, but never exceeded 60 mph.

Figure 3 is an illustration of the type of comparison that was done. The example is from Trailer 1 in the first deployment at the end of the work zone. It should be noted that it is expected that the "before" data could be on the high side (as much as 4 mph) because of tube-

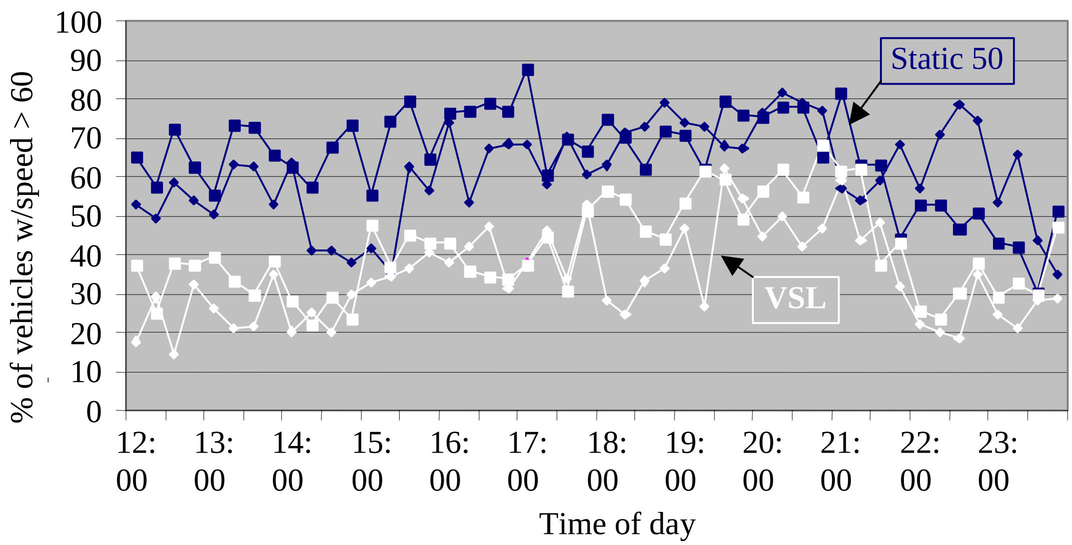


Figure 3. Percentage of vehicles exceeding 60 mph, trailer 1, first deployment

based system difficulties. Even considering a high-side bias, the observed speeds with the static speed limit were considerably higher than “during” VSL operation. A comparison was also done with 70 mph as the criterion. Significantly fewer vehicles exceeded 70 mph in the “during” VSL condition with percentages ranging from 0 to a high of 16% during the “before” condition.

Results for the first deployment are summarized in Table 3 for 3 trailers where data were available. In general, it can be seen that the VSL system results in significantly better speed limit compliance.

Table 3. Summary of “higher speed” traffic for the first deployment

results	trailer			
	speed > 60 mph		speed >70 mph	
	weekday	weekend	weekday	weekend
"During" was slightly higher than "before" half of the time and slightly lower the other half.	3			
"During" was less than 2% lower than "before" most of the time.			7	
"During" was about 5% lower than "before" most of the time.			1(right)	
"During" was about 10% lower than "before" most of the time.	7			1(right)
"During" was about 20% lower than "before" most of the time.		1(right)		
"During" was about 30% lower than "before" most of the time.	1(right)			
Only a few drivers drove faster than 70 mph "before" and "during" the deployment.			3	

NOTES: Numbers in the table are trailer numbers; direction in parentheses next to the trailer number indicates the lane used in the speed comparison; trailers with no parentheses indicate that there was only one lane at those trailers.

While the results from the first deployment were reasonably consistent (even considering potential errors with the tube-based data), the results from the third and fourth deployments were not. In the third deployment, there were instances when the “before” percentages were greater than those “during,” while in others the reverse was true. For the fourth deployment, good data were only available at Trailer 6. At this location, the “during” percentages were higher than the “after” percentages.

Enforcement

The pager used to communicate variable speed limit changes to law enforcement officers successfully received the updated posted speed. On average, it took about one minute after the posted speed was changed for the information to be received by the pager. Although, the pager used by police officers seemed to work adequately, there could be some difficulty identifying which trailer they are using as a speed limit reference (this was solved during the demonstration by marking the back of each display with the trailer number—thus, the officer downstream of the trailer could “look back” and see the number of the trailer and then use the pager to determine the speed that was displayed). The trailer numbering system, while a small item, made it difficult to easily communicate problems—everyone associated with the project made errors from time to time when referring to the "first" (or last) trailer in the system…trailers should be numbered in order of encounter by the motorist.

Crash Analysis

Finally, the crashes that occurred before, during, and after the VSL system was deployed were reviewed. All police-reported crashes that occurred on I-96 in both time and space windows associated with the various VSL deployments were reviewed. The time windows were defined by the length of the VSL deployment and then similar time periods both before and after the deployment period. The spatial windows were defined by the deployment area itself although all crashes that occurred in both directions (i.e., eastbound and westbound) were selected. Once the crashes were identified, copies of the original police report were retrieved so that the sketches of the crash situation could be reviewed.

Conditions in the 2 travel directions (for any given deployment) were different. For example, the first deployment was on the eastbound side. Eastbound motorists had a barrier wall to their left (separating them from westbound traffic), a shoulder area to their right, and no construction workers immediately adjacent to the travel lane. Westbound motorists had the barrier wall to their left but would have had an open median to their right with workers in or on the other side of this median.

During the first deployment time windows, no crashes occurred on the eastbound side where the VSL system was deployed, but, three occurred on westbound I-96, one during the VSL deployment and 2 after.

Seven crashes occurred in the deployment 3 "windows." Deployment 3 was also an eastbound deployment. There were no crashes in either direction during system deployment although there were three crashes before, one of which involved an eastbound motorist. All the rest of the crashes were westbound either during the before or after periods. The one eastbound crash that did occur happened during congestion when there was a traffic back-up. The VSL-displayed limit would have been at the minimum in this situation.

There were nine crashes during the windows for the fourth deployment. This deployment was westbound and the "slow" lane through the deployment area was adjacent to workers with separation by orange work-zone barrels. The left lane was adjacent to a grass median with a conventional shoulder. Seven of the crashes were on the eastbound side (no VSL system) and were almost all rear-end crashes. Of the 2 westbound crashes, one was on an off-ramp while the other was a rear-end in traffic during the active deployment period.

It is clear that more crashes occurred on the "other side" of the freeway from the VSL system deployment and that the "during deployment" periods were relatively safe. However, the "other side" typically had a higher likelihood of congestion due to adjacent workers, at least in the first and third deployments. For the fourth deployment, eastbound traffic was more likely to be slowing down than westbound traffic. It seems apparent, albeit based on sparse data, that the VSL system did not contribute to any crashes. Considerably more data from more deployments would be necessary to determine whether the VSL leads to safer conditions.

Discussion and Summary of VSL System Effectiveness

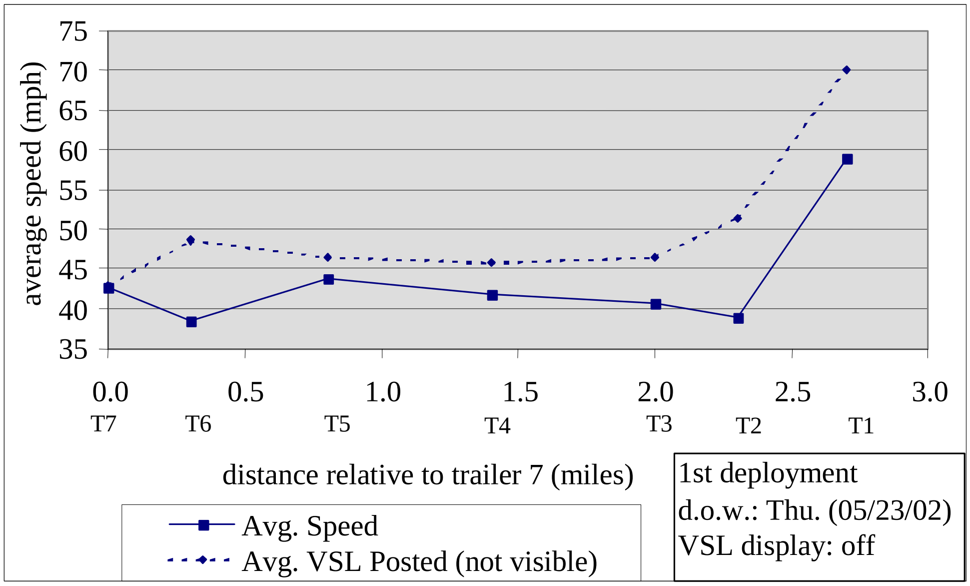
The overall assessment of the VSL system effectiveness was hampered by the lack of consistent and comprehensive data. Neither the VSL system itself nor the MDOT traffic data devices provided data that were sufficient to measure all of the MOEs to the desired degree. The latter were primarily hampered by failures due to sensors being ripped up. Unfortunately, these and some other problems with the MDOT data were not obvious until after any given VSL system deployment was closed down. The VSL system data were simply too aggregated to be used to assess changes in the 85th percentile speed or variance. These problems notwithstanding, several things were learned about the effectiveness of VSLs:

- The **average speed** of motorists appeared to increase through the deployment areas in most instances when the VSL system was operating. This was the case when and where other factors, such as ramps, did not add to congestion or require that speed limits be kept low.
- As a corollary to the increase in average speed, the **travel time** through the VSL deployment areas decreased. However, the time savings are, operationally, small and unlikely to be noticed by the average driver.
- In some instances (e.g., off-peak periods), motorists seemed to respond better to the lighted VMS displays than to standard static speed limit signs mounted on trailers.
- There was some limited evidence that the **percentages of high-speed motorists** decreased when the VSL system was operating.
- While the pager was an effective way to communicate speed limit changes to law enforcement, it took on average of about one minute after the posted speed was changed for the information to be received by the pager.

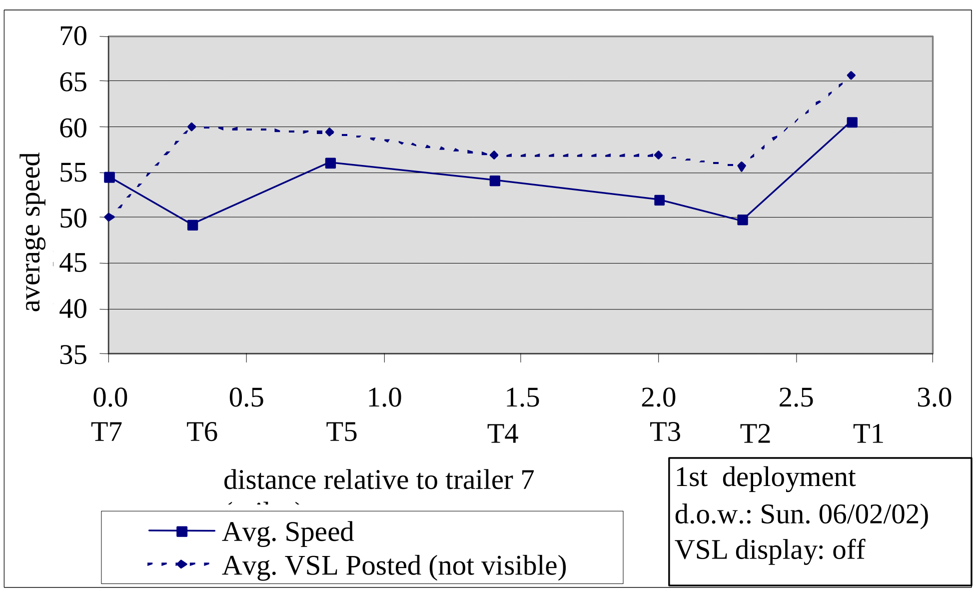
Although the overall effectiveness of the VSL system in the I-96 deployment was somewhat limited in the context of the MOEs measured, there are other advantages to its use. Motorist speeds (and congestion) can vary both by day of the week and longitudinally through the work zone. Static speed limits cannot effectively account for these variations, but the VSL display can change with changing conditions and present more credible limits to the motorists.

An example of the day-to-day variation (for the first deployment) was shown in Figure 2. Average speeds at any given trailer varied as much as 12 mph, while the static posted limit was constant at 50 mph. Data from a congested “slow day” (top graph) and when the traffic is moving better (bottom graph) is reproduced in Figure 4 with overlays (dotted line) of what the VSL system would have displayed (as opposed to a static 50 mph).

These graphs show the responsiveness of the system to day-to-day changes in ambient traffic. It is clear that the posted limit would appear much more realistic (credible) to the motorist. In comparison, Figure 5 is an example of the system’s responsiveness to longitudinal changes in ambient traffic. The VSL system is responsive when ambient traffic conditions vary longitudinally throughout the zone. While this can be seen in Figure 2, it is even more apparent when the situation in the fourth deployment is examined. In this situation, motorists were often coming out of a very congested part of the work zone (average speed of about 25 mph) and traversing an increasingly more “open” work area. The VSL that would have been displayed varied through the deployment area from 40 mph (the minimum speed limit that was allowed) at the congested end through to 70 mph at the “open” end.



Congested



Uncongested

Figure 4. Comparison of observed traffic speed profiles for congested and uncongested days with VSL that would have been displayed (deployment 1)

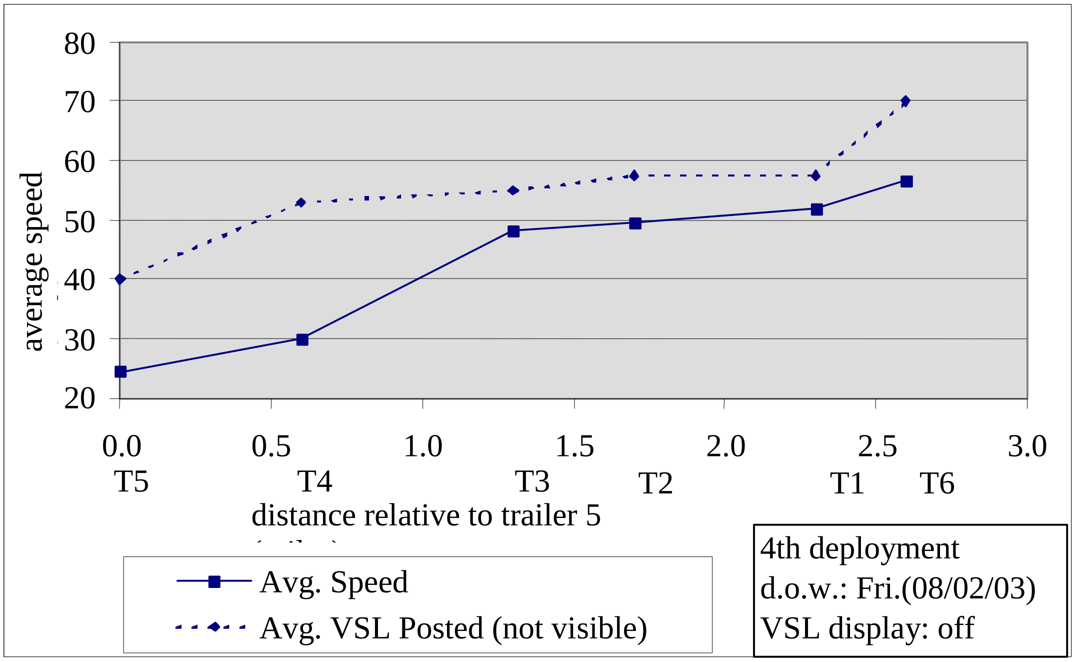


Figure 5. Comparison of observed traffic speed profile with longitudinal variation in congestion with VSL that would have been displayed (deployment 4)

OVERALL SUMMARY, CONCLUSIONS, AND DISCUSSION

From an effectiveness perspective, the VSL system had relatively minor impacts in the work zone in which it was used. As it turned out, the topography of the area and the existence of the ramps and bridges associated with a freeway-to-freeway interchange resulted in significant restrictions being placed on the speed limits that could be used. In addition, the presence of the ramps and the work activity resulted in relatively low speeds under many conditions. These limitations notwithstanding, there were positive effects on (increased) average speeds and (decreased) travel time through the VSL deployment area. Effects on the 85th percentile speed and speed variance were either undetectable or inconsistent. The percentage of vehicles exceeding certain thresholds (e.g., 60 mph) did, however, decrease when the system was in operation. Finally, a review of the crashes in the area showed that most were rear-end collisions, most occurred in the non-VSL direction, and none appeared to be directly associated with the deployment of the system. From this perspective, the VSL system certainly did not seem to create additional safety problems in the deployment areas.

Despite the paucity of usable data, it seems clear that VSL systems will have different applicability in different types of work zone situations. In the case of I-96, what appeared to be a relatively straightforward zone was made difficult (from the experimental perspective) by required limitations on operating speed resulting from geometry, topography, and congestion. The shortened on- and off-ramps (due to maintaining traffic flow) resulted in the need to restrict the maximum speed limit. Overall, the travel speeds (and related measures) were often affected more by the geometry and the weaving traffic within the confines of the freeway-to-freeway interchanges than they were by the posted limits. The point being that even if the system had operated perfectly and more data been available, it seems unlikely that the analysis would have shown more VSL effectiveness. From this, the conclusion is drawn that VSL systems will have potentially more utility in longer and "simpler" work zones (e.g., long zones with short work areas).

These limitations notwithstanding, the VSL system can present far more credible information to the motorist, responding to both day-to-day changes in congestion as well as significant changes in congestion and geometry as motorists go through a given zone.

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