FIELD TEST OF VARIABLE SPEED LIMITS IN WORK ZONES (IN MICHIGAN)

FINAL REPORT

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Field Test of Variable Speed Limits in Work Zones (in Michigan)
Final Report

Michigan Department of Transportation
Michigan State University

INTRODUCTION

Variable speed limits (VSLs) have had numerous applications over several decades with increasing interest in the last several years. The basic premise of VSLs is that in some situations the normally posted regulatory speed limit should vary dynamically with conditions encountered on the roadway (e.g., inclement weather, work zones, school zones) and/or congestion that may be present. This is in response to the often-stated argument that some invariant static limits are perceived to be "unreasonable" to the average motorist. In turn, speed limits that are perceived to be unreasonable can lead to low speed-limit compliance rates, high variance in vehicle speeds, and unsafe conditions. With VSL, the hypothesis is that motorists will respond "better" to realistic speed limits, resulting in higher compliance, lower speed variance, and safer conditions. From the motorist's perspective, one of the stereotypical situations where unrealistic static limits are often encountered is in construction/work zones—an example being a very long marked work zone (with a low statutory limit) where no actual construction activity is encountered until miles after the start of the zone or such activity occurs only for short sections within the zone. In this context, the US Department of Transportation's (USDOT) Federal Highway Administration (FHWA) solicited applications for field tests of VSL systems in work zones. Michigan was one of three states chosen to undertake the field tests.

The project reported on here is the result of a joint public-private venture led by the Michigan Department of Transportation (MDOT) and includes the participation of the Michigan Department of State Police (MSP), Michigan State University (MSU), and NES Worksafe (Worksafe). International Road Dynamics (IRD) was also actively involved in technology development and deployment through Worksafe.

An extensive literature review is not provided here as reviews have already been done by others and are generally available. Principal among these is that done by researchers at Northwestern University under the auspices of National Cooperative Highway Research Program project 3-59, *Assessment of Variable Speed Limit Implementation Issues*, wherein experience both in the US and abroad is catalogued and a comprehensive list of vendors of various system components is compiled and presented.

The **basic objectives** of this project (as articulated by the FHWA) 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. In this context, VSL is a field application of intelligent transportation system (ITS) technology.

The VSL system used in Michigan was developed and deployed by Worksafe/IRD with direction from MDOT and MSU. The system was "bench tested" by Worksafe/IRD, initially field-tested on a local road (under direction of MSU and MDOT) to confirm that the system was basically operating as designed (and required), and then deployed during the summer (2002) in a work zone on I-96 south and west of Lansing, Michigan. There were four separate and different deployments within the larger (~18-mile) work zone during which operational data were collected. The data were then analyzed in the context of the operations of the VSL system itself as well as its effects on traffic flow.

This report contains the following components: a description of the partnership in place for the demonstration project; information about the legality of VSL in Michigan; a brief description of the VSL system deployed in Michigan; a description of the pre-deployment and testing of the system; information about the overall deployment site; basic system operations; and system effectiveness. The report is concluded with discussion and comments regarding further applications of VSL in work zones. Throughout the report, issues and problems encountered are discussed with resolutions noted. In some instances, references are made to separate documents (e.g., the IRD manual for the system deployed) which are not a formal part of this report. These are available from the original authors of the various documents and reports.

VSL PARTNERSHIP

The VSL demonstration in Michigan involved several different entities with a variety of motivations for involvement. The motivations ranged from attempting to provide a system that would be marketable to state agencies and/or the construction industry to testing a technique that might lead to operational improvements in work zones and documenting the impact of a state-of-the-art technology in work zone traffic control.

As noted, this project was the result of the coordinated efforts of several entities: Worksafe/IRD provided the VSL system and technical support for operation in the field; MDOT provided overall supervision as well as coordination between the project activities and the construction activities; and MSU provided experiment design, data collection plans, and analysis of the operational effects of the system. MSP's role turned out to be somewhat limited, providing enforcement presence during one of the four field deployments. The nature/extent of the interactions among the various partners is described below along with discussion of problems that were encountered.

MDOT/MSP INTERACTION

MDOT and MSP already had a memorandum of understanding (MOU) in place whereby MSP provides "on call" extra/strategic enforcement in work zones around the state. This is an annual agreement under which MSP provides extra surveillance/enforcement activities to work zones where such extra attention is deemed appropriate (typically by the MDOT Transportation Service Center (TSC) for the geographical area in which the work is being done). Under terms of this existing agreement, MSP provided enforcement during the 2002 construction season for the VSL test site when requested by MDOT personnel (including those at the TSC).

The relationship between MDOT and MSP served the project well although MSP was not really a full partner in the project. Given the short-term and dynamic nature of the system deployments, coordination with MSP was somewhat difficult given that, ideally, MSP provides additional work zone surveillance as an overtime activity that officers have to sign up for two weeks in advance. Such advance notice was hard to achieve for this project as the deployment time frames were somewhat unpredictable. Worksafe/IRD provided pagers and instruction in using them to the police officers. While a problem in the short term, if use of the VSL in work zones were to become routine, there would be no problem in coordinating with MSP. The only issue would be use of the technology itself (e.g., use of pagers to retrieve system information) which is discussed later.

MDOT/WORKSAFE INTERACTION

Somewhat similar to the agreement between MDOT and MSP, MDOT also had a renewable contract with Worksafe which, in turn, had a contractual relationship with IRD. The former contract allows MDOT to deploy traffic control devices associated with work zones for various as-needed special purposes and projects. The provision of the VSL system was accomplished via a task order under this existing open-ended contract. Costs incurred in developing, testing, and deploying the VSL system were covered by funds from the project.

While there were some difficulties communicating with Worksafe and IRD on occasion for different purposes, these were basically due to the experimental nature of the project. For example, when the system was being deployed and checked in the field, MSU personnel had no real authority to communicate (or control) Worksafe/IRD personnel. Problems were minimized as a result of good interactions on a personal level. System deployment in the work zone was further complicated since the prime contractor for the construction used a separate (i.e., not Worksafe) sub-contractor for their traffic control. This resulted in some minor problems in coordinating sign/device placement/modification in the field. In routinized deployment, the VSL system would simply be a regular part of the deployed TCDs in a work zone. Communications would be streamlined considerably (assuming that the VSL system is provided by the sub-contractor responsible for other TCDs in the work zone).

MDOT/MSU INTERACTION

The MDOT/MSU relationship was positive and there were no significant problems in communication or chain of command. While MSU personnel had to formally go "through" MDOT to communicate with other partners, there were no problems of any consequence.

MDOT INTERNAL INTERACTIONS AND OTHER PARTNERSHIP ISSUES

There were some minor issues between VSL project personnel (e.g., MDOT and MSU personnel involved in the VSL project) and the MDOT field personnel (at the TSC) during the first deployments on the I-96 site. TSC personnel viewed the VSL demonstration as an additional "task" for an already high-profile project near the state capitol. Eventually, after field personnel were introduced to the VSL equipment (during the pre-deployment testing) and actively engaged in deciding actual deployment locations, MDOT TSC personnel became less concerned and subsequent deployments went smoothly to the point of routine assistance.

Issues/problems with the cooperation between those involved in the VSL project and system deployment in the field were most significant when a fifth deployment was attempted in the spring of 2003. A major reconstruction site had been identified on I-75 north of Flint, Michigan, where VSL could have been deployed. While the MDOT field personnel and their contract managers (a private consulting firm) were very supportive of deployment, problems developed when the prime construction contractor balked at having VSL deployed on the site. The basic issue was one of liability for the "extra" (VSL) traffic control. Although the MDOT TSC offered to cover any additional insurance rider that might be required (within reason), the prime contractor did not obtain a quote for the rider in a timely fashion (well over a month) and the deployment had to be dropped.

FUTURE PARTNERSHIP ISSUES

Whatever communication/partnership problems existed for the demonstration project, it is clear that they would be lessened considerably in a more conventional contractual relationship for a construction job. In this project, the deployment of the VSL system was (reasonably) considered to be an "extra" in terms of the construction project and by every one associated with the actual construction. If use of the VSL technology were a standard procedure (e.g., it was a part of required traffic control in the bidding of the project), the system would presumably be provided by the primary contractor (or a sub-contractor if one is used to provide work zone traffic control) and the lines of communication and responsibility of different entities would be defined by contract. Alternatively, if the VSL is to be provided by the DOT, that provision would likewise be written into the contract documents.

LEGALITY OF VSL IN MICHIGAN

The MDOT and the MSP have the legal authority to set speed limits in work zones within the state. In the past, work zone limits were specified by statute (and fixed)—this was, however, changed in recent years. According to the current edition of the Michigan Vehicle Code, "a person operating a vehicle on a highway, when entering and passing through a designated work area where a normal lane or part of the lane of traffic has been closed due to highway construction, maintenance, or surveying activities, shall not exceed a speed of 45 miles per hour unless otherwise determined and posted by the state transportation department, a county road commission, or a local authority." The final part of the citation is relevant with respect to posting speeds other than 45 mph, variable or not. On many Michigan freeways, the basic (and maximum) speed limit is 70 mph (and this was the case for the site that was used). While "normal" work zone speed limits are generally less than 70 mph (e.g., 60 or 50 mph, 45 in maintenance zones), these typical limits are not established by law. Moreover, while it is MDOT's policy that reductions in the speed limit not occur in greater than 10 mph increments, this is not the law and can be waived. The MSP indicated that VSLs are enforceable, similar to any other speed limit.

VSL SYSTEM SPECIFICATION

For this project, Worksafe/IRD developed a proposal (for MDOT) for the VSL system based on criteria contained in the FHWA solicitation and additional specification by MSU and MDOT. The detailed system proposal is contained in a separate document (not included here) and summarized below. In this specific case, the system was based, as much as possible, on an existing lane-merge system that was being used on an experimental basis in several Michigan work zones. A photograph of a typical VSL trailer is shown in appendix A (additional photographs are available separately). The key features of the VSL system that was deployed as part of this project include:

- ✓ high visibility sign sizes and variable message signs (VMS) as specified by the FHWA although it should be noted that amber lights, rather than white, were used in the deployed VMS display of the variable speed limit;
- ✓ solar-powered;
- ✓ signs, sensors, and power source are trailer-mounted;
- ✓ vehicle sensing accomplished through remote traffic microwave sensors (RTMS);
- ✓ seven trailers with signs, communication equipment, etc.;
- ✓ RF communications between sequential trailers;
- ✓ fully adjustable operating parameters (minimum and maximum display speed, update frequency, maximum speed differential, maximum speed increment, configurable display speed look-up table, and multiple configuration settings based on selectable field conditions);
- ✓ on-site data processing (for speed limit display) and storage (e.g., time log of speed limit displayed);
- ✓ cell-modem access for remote data retrieval for later analysis;
- ✓ a weather/moisture detection sensor;
- ✓ a pager system that can be used by enforcement personnel to determine the speed limit displayed by any sign in the system; and
- ✓ cell-modem access for checking operating status.

As specified, the system monitored traffic flow and speed at a given location (or locations), calculated necessary speed statistics (e.g., average speed), and displayed a speed limit on a designated upstream variable message (speed limit) sign according to pre-established logical statements. These logical statements are contained in "settings files." Pre-determined settings files were developed for each specific deployment. For example, there were different settings files invoked for weekday vs. weekend use and/or when different types of construction were occurring (e.g., workers protected by barrier wall versus barrels).

PRE-DEPLOYMENT TESTING

Prior to full deployment in an active work zone, the system was tested on a local county road. While this deployment was in a "live" traffic situation, the lower traffic volumes provided a considerably safer environment for working with the system at the roadside. In addition, any operating problems encountered impacted only a few motorists. The complete pre-deployment report was submitted as a part of a quarterly report on the project (and is available as a separate document) and is not included here although the basic approach, selected results, and discussion are summarized below.

PURPOSE AND DESCRIPTION

The purpose of the pre-deployment testing was to ensure that the VSL system components worked as expected prior to the deployment in the construction zone. The pre-deployment testing (see appendix A for an outline of the complete procedure) was focused on equipment inspection, testing of functional characteristics of the system, assessment of data collection and processing mechanisms, evaluation of system quality factors, and consideration of system portability. In addition, general familiarity with the system and its operation was gained.

First, the ability of the trailers to communicate with each other was tested, as was the ability of the system to communicate with the pagers and remote computers (and vice versa). Then the ability of the system to accurately collect real-time traffic data and properly process them to determine desirable speed limits was evaluated. While the VSL system was collecting data for use in internal calculations, “independent” data were collected manually (vehicle counts) and using radar (vehicle speeds). Radar was used during these tests since (at this level) there was no concern about the potential bias in motorist behavior introduced by using it—this was merely a test of whether the system was accurate. The “system” and “independent” volume and speed data were then compared to validate system accuracy and determine required system modifications and adjustments.

The system was deployed on Okemos Road, south of I-96 and testing was performed from 4/11/02 to 5/11/02. Okemos Road is situated just south and east of Lansing, Michigan and is a two-way, two-lane county road with 4-6 ft grass shoulders, and a posted speed limit of 55 mph. A “system” of four (of seven) trailers was used during the pre-deployment testing (one master and three slaves). (See figure 1.) The trailers were placed on the shoulder and used in the forward-looking RTMS configuration. The VMS at each trailer was turned off or covered during the test to minimize driver distraction. The master trailer was placed the furthest downstream (south) and is referred to as trailer number 1. (The downstream convention is characteristic of IRD’s system specification.) Upstream of the master trailer was trailer number 2, followed by trailers 3 and 4. The distance between any two consecutive trailers was ~0.5 mile although that was varied as part of the test.

RESULTS

The results of the pre-deployment testing are summarized below.

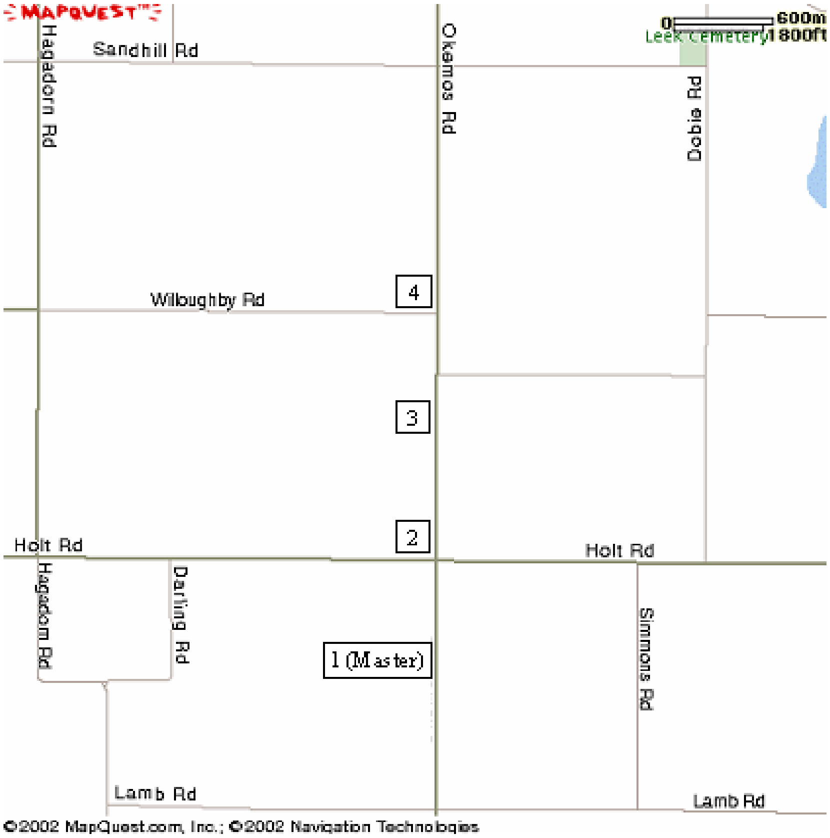
Functional Characteristics

The capability of the system to send out updated VMS display information and reports on system working status via the paging system was tested and confirmed. From the downloaded error log, it was clear that failures were adequately captured. The pager 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.

Data Collection and Processing

In tests performed from 4/11/02 to 5/01/02, the RTMS was used in the forward (upstream)-looking mode. Traffic data collected by the system include volumes, occupancies, and individual vehicle speeds. Information on vehicle length classification was not available. Utilizing the individual vehicle speeds, the system calculates the average speed over a specified aggregation time period. Based on the system specification, this time period can vary from 5 min to 15 min. As part of the test, a successful override of the aggregation period was performed, both on the site and remotely. The system collected data based on the specified time period

Figure 1. Pre-deployment VSL test site



(typically 15-min). Traffic statistics were downloaded both on site and remotely. A review of the downloaded data is presented later.

External Interface

Either the local controller panel or a computer modem can be used to access the system (but not both simultaneously). The tests showed that the system can be configured successfully from either option, although the available configuration menus are a little different from each other.

System Quality

The master trailer was equipped with a weather sensor. There were several rainy days during the pre-deployment test, and the weather monitor picked up this information successfully and reduced the posted speed limit properly in response to the weather conditions. From the data, it was also observed that the weather sensor detected ice on the pavement on several cold nights. In conclusion, the weather sensor works properly.

Based on the specifications, the optimum communication distance between two consecutive trailers is 0.75 mile. Each trailer communicates with the trailer downstream and upstream. Communications were tested using all four trailers (with a spacing of 0.5 miles); the 1st and 3rd (spacing of 1 mile) and the 1st and 4th. It was confirmed that trailers communicated properly at a distance of 0.5 mile, 1 mile, and 1.5 mile.

The accuracy of the traffic data collected by the system was tested by comparison of average speed and traffic volumes with manually collected observations (i.e., counts and speeds collected by radar). Data collection sessions were repeated several times and at different locations within the test sites. When the forward-looking mode was used, the RTMS could not capture the vehicle correctly and a significant undercounting of vehicles by the system was observed.

To improve the accuracy of data collection, adjustments were performed regarding the position of the trailers relative to the traffic lane, the angle at which the sensor "looks down" onto the traffic, and the sensitivity. (The ideal position of the RTMS should be overhead of the traffic lane, which was not the case in the experimental site and is, in general, not practical.) After repeating the experiments it became apparent that the position of the RTMS was not a sufficient explanatory factor for this problem since little improvement was achieved by repositioning the RTMS.

Later, improvements on the software were performed and the deployed configuration was changed to the backward-looking mode (RTMS pointed downstream). Analysis of the data collected under this configuration showed that the detection accuracy improved considerably. Although some differences were still observed between volumes collected and those collected and reported by the system, the differences were clearly smaller than before.

Review of the specifications document provided by IRD and on-site observations revealed that the algorithm used by the system to determine speed limits was based on occupancy. While this may be appropriate for other applications, the concern for this project is an observed-speed-based speed limit. The occupancy thresh-holds “rules” in the algorithms for calculating displayed speeds can be easily manipulated to eliminate occupancy if desired.

Although the VMS was off/covered during this test, the system log recovers the values that would have been displayed. This log was compared manually with the speed that the system should display, given the algorithm and the existing conditions.

In general the speed limits “displayed” by the system were in agreement with those calculated based on local conditions and the algorithm rules, with the exception of speeds at trailer 2. Occasionally, other trailers displayed inaccurate results for one sampling period and then corrected the abnormality in the next period. Several logs were reviewed seeking a pattern or a potential explanation for this behavior, but the problems seemed to occur in a random fashion. These issues were addressed prior and during the actual deployment in the work zone and are addressed later in this report. The continued “adjustment” during the actual field deployment was necessary due to the need to get into the field and because it was thought that the problem was easily remedied.

Portability

It was confirmed that the length of the set up and take down is approximately 10 minutes without calibration. It was also confirmed that the system does not need to be recalibrated if it is turned off and then on at the same site. However, when moving to another location proper calibration is needed to ensure that the RTMS is properly positioned and accurately collects vehicle counts and speeds.

CONCLUSIONS FROM PRE-DEPLOYMENT TESTING

Overall, the communication capabilities of the system proved satisfactory, whereas the data collection and processing mechanisms required additional fine-tuning in order to perform at an acceptable level. It was recommended that the system operation be closely monitored throughout the deployment in the work zone. Thus, the deployment operationally became a continued test of system operations *per se* as well as a test of system effectiveness with respect to traffic flow.

BASIC VSL DEPLOYMENT IN WORK ZONE

After the pre-deployment testing, the system was deployed in a work zone on I-96 south and west of Lansing, Michigan (see figure 2).

Figure 2. General location of the overall I-96 work zone site (from US-127 to Wacousta Road)

GENERAL DESCRIPTION OF OVERALL SITE

As can be seen in figure 2, this section of I-96 skirts the southern and western edges of the City of Lansing (with a metropolitan area population of ~450,000). South and west of the freeway, the adjacent land tends to suburban/rural while north and east of the freeway there is more development. To the unfamiliar motorist, the character of the section is suburban-rural although there is some well-developed land just west of US-127. The overall site consisted of three separate construction operations (although done by one prime contractor) during the 2002 construction season. Summary information about the actual work is provided in table 1. There was significant congestion (at times) through the construction zone during rush periods when traffic is limited to one lane in each direction. At other times, traffic ran quite smoothly.

Because of problems coordinating schedules and some system operating issues, section 1 could not be used for the experiment. The bulk of the work planned for the area was completed before the project team was ready to deploy. The four deployments that were evaluated occurred in sections 2 and 3 (table 1). The overall site provided conditions that ranged from very controlled situations (section 2) where work was intense and continuous although separation between the work activity and the motorists was provided by a median to less controlled sites where motorist/work separation occurred with barrels. Opposing directions of traffic, on one side of the freeway, were separated by a barrier wall. Section 3 offered relatively intense work (concrete patching) with work activities and traffic separated only by barrels. Not all work was underway at the same time although motorists encountered almost continuous activity of one sort or another in sections 2 and 3 during the testing period. The treated zones were typically at the eastern end of section 2 (after section 1 had been completed).

VSL DEPLOYMENT IN THE WORK ZONE

The general framework for the VSL deployment is summarized below. Elements of the original proposal that were changed are also noted and addressed.

- ✓ The VSL was deployed in one direction only. Originally, deployment in both directions (at the same time) was to provide an untreated "control" site which would have had similar conditions to the "treated" site. However, the two directions of traffic had very different conditions primarily due to ramps and other geometric characteristics, and the "control site" idea was abandoned. In addition, unidirectional deployment was done to save on system costs. Th experiment that evolved was basically a "before/after" or "treatment/no treatment" type of comparison.

- ✓ Originally, a warning/informational sign was slated to be placed in advance of the overall work zone to inform motorists that variable speed limits were in effect in the construction zone ahead. After discussion with MDOT personnel and others, the advance sign was not used. The basic arguments were that the system would not always be there; and that motorists did not need the notice (they were already being warned of the work zone) and should heed posted regulatory limits, whether they vary or not.

Table 1. Description of field test site (I-96 from US-127 to Wacousta Road)

	Section 1. I-96 from US-127 to Lansing Road; microsurface and minor bridge repair	**Section 2. I-96 from Lansing Road to M-43; Total reconstruction**	**Section 3. I-96 from M-43 to Wacousta Road; concrete pavement repair (patching)**
approximate start date	June 2002	March/April 2002	August 2002
approximate end date	August 31, 2002	August 31, 2002	September 2002
existing section	2 lanes in each direction with grass median	varies 2-3 lanes in each direction; some median grass, other barrier wall	varies 2-3 lanes in each direction; some median grass, other barrier wall
approximate length of work zone	8 miles	5 miles	5 miles
AADT (commercial AADT)	33,700-43,900 (4,900-5,900)	29,000-52,700 (4,400-6,000)	41,200-47,300 (6,000)
brief description of work to be done	thin new wearing surface and minor work to underside of bridges over freeway	total reconstruction including bridge reconstruction (raising overpass) and ramps at Lansing Road	concrete patching of selected locations throughout project area
nature of operation	some moving operation within lane closure (e.g., one lane closed for 3 weeks with active sites within zone varying day-to-day)	long-term (2 or more months) lane closure	patching with week-or-more lane closures
type of lane closures	one lane open, one closed	lanes closed on one side with traffic cross-over and both directions maintained on one side	1-2 lanes will be closed at one time with traffic maintained on open lane(s)
typical duration of lane closures	one lane may be closed for a month	duration of project (months)	one-two weeks
type of separation of lanes of opposing traffic and/or workers and traffic	barrels separate work from passing motorists	barrier walls separates 2-way traffic on one side; other side has no traffic	barrels separate work from passing motorists
work schedule (e.g., day only, night)	primarily daylight	day and night	primarily daylight
normal speed limit	70 mph	70 mph	70 mph
speed limit if no VSL	50 mph	50 mph	50 mph

- ✓ The VSL trailers were planned to be placed approximately every 1.5-2 miles. However, spacing was typically much closer due to trailer-to-trailer communications problems (discussed later) and geometric factors that **required** a speed limit reduction.

- ✓ The deployments consisted of up to seven trailers placed for one direction of travel. Some of the VMS displays varied as planned (i.e., according to logical rules based on prevailing speed) but 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. The maximum speed in the active work zone was never allowed to be higher than 60 mph although one trailer at the end of the work zone was permitted to go as high as 70 mph (this was basically a sign that was seen by the motorists as they exited the work zone).

- ✓ The speed limits posted/displayed varied with the estimate of the 85^{th} percentile speed at the next downstream location unless otherwise controlled. For some deployments there were different maximum limits depending on whether workers were present (basically a day vs. night rule).

- ✓ The presence of enforcement personnel was used for only one deployment. This was primarily due to the timing that was required to schedule state police to be present in the zone. The only aspects of enforcement that were examined/tested were: 1) whether the technology of the system worked and if the officer(s) present could use it; and 2) the effect of having enforcement personnel present within the VSL deployment area. This was consistent with the original proposal.

- ✓ Data for the evaluation of the system operations and system effectiveness were originally planned to come from the system itself and independent traffic data collection devices (pneumatic tube-based data collection devices) installed by MDOT. While both types of data were collected, the MDOT tube-based data were frequently not available—primarily because the sensors (tubes) were routinely torn up by traffic. In other instances, data could not be collected with the tube-based systems because of safety problems in placing and maintaining the devices.

- ✓ It had been proposed that videotape data collection (using the Autoscope technology) also be used. This turned out to be not possible because of the lack of available sites (usable overpasses) in close proximity to the deployment sites. Sites where initial data were collected (before the construction work started) turned out to be not anywhere near the actual system deployment sites (once the section 1 work was completed).

The four VSL deployments (the second deployment was aborted in the field) in the I-96 work zone are shown in Appendix B and discussed in more detail later in the report.

MEASURES OF EFFECTIVENESS FOR THE VSL SYSTEM

The following is the original list of measures of effectiveness (MOEs) proposed to be used to evaluate the effects of the system deployment. For each MOE, there are comments regarding whether the MOE was, in fact, used and if not, why not.

- ✓ **average speed.** This is a general-purpose MOE used to assess changes in driver behavior. It was used extensively and generally based on data obtained from the VSL system itself. It provided one measure of speed limit compliance.

- ✓ **85th percentile speed.** This is an MOE that is directly related to the traffic engineering rule of thumb for setting speed limits. It could only be approximated for setting the speed limits and could only be estimated when the MDOT pneumatic tube data were available. Incomplete data (tubes were torn up) and differences in the format of the MDOT data (16 vs 30 speed bins) prohibited much analysis from being done with this measure.

- ✓ **speed limit compliance.** This was of interest as speed limit compliance is considered to be more important in work zones than other locations. Compliance could not be determined from the VSL system data since individual vehicle speeds are not reported;. However, MDOT data (when available) could be used to estimate compliance although even these data were reported in speed bins as opposed to individually.

- ✓ **standard deviation and variance of speed.** The standard deviation (or variance) is considered a reasonable indicator of safety where higher variance indicates a higher level of vehicle-to-vehicle interaction. As was the case with compliance, system data did not support this MOE so only limited analysis was done using MDOT data.

- ✓ **average headway.** This was not available from the data collection devices used.

- ✓ **traffic volume.** While this is not an MOE *per se*, it can be used as an independent variable in stratifying samples in making other comparisons and was used in some analyses.

As noted in the proposal, while the original objectives 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,*

examination of the list of MOEs (above) reveals that the concerns about speed limit compliance and traffic flow improvements were to be addressed directly. This was compromised somewhat by the lack of disaggregate data (available only from the MDOT automatic devices which turned out to be inconsistent and unreliable) for reasonable estimation of the 85th percentile speeds as well as standard deviations/variance.

Moreover, it was noted that the original list does not include any direct measures of "safety." However, crashes at the site were monitored and crash data collected (the official crash report, Michigan's UD-10 form) and analyzed.

The remaining objective was increasing the credibility of speed limits. While this is indirectly addressed through compliance and response to posted limits (if motorists comply, they are presumed to think the limits are credible or at least reasonable), credibility seems to be a longer term objective that is not easily addressed by an evaluation at one site. It should also be noted that compliance and credibility are also greatly affected by the level of enforcement that is present. In any event, credibility is perceptual and can most straightforwardly be addressed by ***asking*** motorists if they "think" the VSLs were realistic/credible—this would imply the use of either a motorist survey or focus groups. Neither of these techniques was originally proposed although the former was discussed for the I-75 deployment which did not come to fruition.

REVIEW OF VSL SYSTEM OPERATIONS IN THE I-96 WORK ZONE

As noted above, the deployments of the VSL system in the overall I-96 work zone (see appendix B) addressed both further testing of system operations and the evaluation of the effectiveness of the VSL system in affecting motorist behavior. In this section, system operations are reviewed and discussed. From the outset it should be noted that during the deployments on I-96, system components and software were replaced and/or upgraded in response to failures or operating problems.

RTMS OPERATION

RTMS operation in counting vehicles and calculating their speeds was evaluated in both the pre-deployment trial and the field deployments. Data from the RTMS were compared to manual counts, radar readings, and data from MDOT's automatic pneumatic tube-based traffic data collection devices (referred to here as "tube data"). The latter was the only basis for comparison used in the I-96 deployments.

During the pre-deployment testing, the RTMS was positioned so that oncoming vehicles were being detected (as they approached the trailer/RTMS sensor from upstream) and there were numerous problems with inaccurate vehicle counts as well as some with vehicle speeds. Updated software was installed and resulted in some improvement and the system was modified to use the RTMS to detect vehicles after they had passed the trailer/sensor (i.e., the sensor "looked" downstream). It was also noted that speed accuracy (as compared to radar) varied by trailer location which implied that systematic calibration of the system is required.

During the deployments on I-96, system and volume data were compared to MDOT's "tube data" from their automatic data collection devices. These devices are widely used by MDOT and were installed and monitored by the group charged with traffic data collection for the agency. Although the MDOT devices were monitored in the field, data from them still showed some variation and the tubes were often ripped up so that there were data missing from different trailers at different times. It is suspected that there might have been some variation in tube placement when the original tubes were ripped up and replaced which would result in variation in vehicle speed from one "installation" to the next. There were other instances when the tube data were simply not available—this was sometimes not known for some time as the data were not downloaded from the devices and supplied on a daily basis. The end result is that limited meaningful comparisons could be made between the two data sources.

When there were two lanes of traffic in one direction, the RTMS sometimes appeared to count vehicles in both lanes based on a comparison to the "tube data." The calibration and "aiming" of the RTMS impacts the accuracy and quality of the data obtained and used internally by the VSL system. Summaries of these and other comparisons between the RTMS and "tube" data are shown in tables 2 and 3.

Table 2. Summary of RTMS and pneumatic tube average speed comparison

Results	1st deployment		3rd deployment		4th deploy.
	before	during	before	during	during
RTMS was 1 mph higher than pneumatic tube.		2	5		
RTMS was 0.5 mph higher than pneumatic tube.		1(right)		1(right)	
RTMS was almost the same as pneumatic tube.		5	7	4, 7	
RTMS was 0.5 mph lower than pneumatic tube.		3	4		
RTMS was 1 mph lower than pneumatic tube.			3	3	1
RTMS was 2 mph lower than pneumatic tube.		4	2, 6	6	3
RTMS was 2 mph lower than pneumatic tube, except 3PM-8PM (RTMS was 4 mph higher).					5
RTMS was 4 mph lower than pneumatic tube.	1(right)	7			6(left)
RTMS was 5 mph lower than pneumatic tube.	2, 3, 7			2	
The pneumatic tube data were not available.	4, 5, 6	6	1(right)	5	2, 4

NOTES: the numbers in the table are trailer numbers; (direction) indicates the lane used in the comparison.

Table 3. Summary of RTMS and pneumatic tube 30-minute volume comparison

Results	1st deployment		3rd deployment		4th deploy.
	before	during	Before	During	During
RTMS was 100 % higher than pneumatic tube.	1(right)	1(right)			
RTMS was 30 % higher than pneumatic tube.			5		
RTMS was 10 % higher than pneumatic tube.			7	7	
RTMS was almost the same as pneumatic tube, but varied by time slice because of the interval time variation.	2, 3, 7	2, 3, 5, 7	2, 3, 4, 6	1(right), 2, 3, 4, 6	1, 5
RTMS was 7 % lower than pneumatic tube.		4			
RTMS was 10 % lower than pneumatic tube.					3, 6 (left)
The pneumatic tube data were not available.	4, 5, 6	6	1(right)	5	2, 4

NOTES: the numbers in the table are trailer numbers; (direction) indicates the lane used in the comparison.

With respect to the evaluation of the system effectiveness, data from both sources can be used for different questions. The RTMS data were judged to be consistent over time for any given deployment given that the sensor location and calibration were generally not changed (e.g., the RTMS was not re-aimed, the offset from the travel lane was not changed). Moreover, data were generally available from the system throughout any given deployment. The tube data (which are more disaggregated) can be used, to the extent they are available, for calculations of changes in the 85th percentile speeds and speed variance, especially when it is only differences that are important.

The RTMS data appear to be "reasonably" accurate although certainly not within limits that are generally accepted for speed enforcement (e.g., radar is generally considered to be accurate within one mph). Based on the comparisons that were possible in this project, errors in average speeds calculated by the system could easily be on the order of a 2-3 miles per hour and vary from one installation (trailer) to another. Problems can also occur with picking up vehicles in adjacent lanes (which affects both speed and volumes).

Operationally, there was a problem with the need to have the VSL trailers close to the edge of the lane in order to detect vehicles in the lane. Consequently, MDOT personnel, contractors, and some of those who maintained the system on site felt that they had to be "too close" to the passing traffic when placing, calibrating, or performing routine maintenance on the system.

Another problem with vehicle detection is that the current system can effectively monitor only one lane of traffic (the near one) which is not sufficient in all situations. In the deployments on I-96, at some trailer sites the "near" lane was considerably slower (e.g., because of ramp traffic) than the others. If the speed limit is to be set on the basis of all traffic (or the faster lane), then the system must be able to monitor all lanes; if the limit is to be set based on the "fast" lane, then that lane must be monitored.

These should be relatively easy problems to fix in the context of the next generation of the VSL system. The following criteria for sensor/system accuracy and deployment are suggested:

- ✓ speed calculation should be accurate within 2 mph;
- ✓ volume calculation should be accurate within 10%;
- ✓ available variation in the trailer offset from the lane edge should be from 10 to 25 feet (e.g., so the system could be placed beyond the guardrail on a shoulder);
- ✓ time for calibration of the system should be 10 minutes or less so that the system is truly portable (this may require, for example, a system where a calibration input is "distance to edge of lane");
- ✓ the system should use, if not store, individual vehicle speeds so that better estimates of the 85^{th} percentile speed can be attained; and
- ✓ the system must be flexible enough to allow monitoring of any specified lane or combination of adjacent lanes (i.e., in some instances, only the near lane might need to be monitored; in others, multiple lanes).

COMMUNICATIONS OPERATION

There were several communications problems which occurred during the course of the deployments. These included trailer-to-trailer communications and communications with the system from a remote location.

The communication link between the VSL system on site and remote locations (e.g., a computer dial-up to access data) is accomplished through a cellular link and suffered at times from a weak signal or "dead area" for the cellular connection. While this is a relatively minor problem, it should be noted that the topography in the area is not particularly severe.

The short-range communications between trailers also caused problems. The system breaks down (at least partially) if the trailers cannot "talk to each other" as control messages and data are passed up and down the system from trailer to trailer to the "master" which is the last trailer (encountered by the motorist) in the system. The trailer-to-trailer link was limited by "line of sight" considerations and fixed (in the short term) by installing longer/higher masts on some trailers. A power failure on an intermediate trailer caused the same problem at one point in time. While data are collected at the trailers even if communications break down (except for power failures), data cannot be retrieved remotely and the site and specific trailer must be visited.

While the short-range problems were fairly minimal once the system was deployed, the line-of-sight criterion limited the system's utility. This is because the trailers had to be placed far closer to one another than had been originally planned because of the site topography. While the terrain is not particularly hilly, a relatively sweeping curve in the construction area (see figure 2) and the barriers presented by an interchange and overpasses effectively blocked communications beyond more than a few hundred yards in some instances. At a minimum, telescoping masts should be considered as a future system modification but switching to a better communication system that does not depend on line-of-sight placement of sequential trailers would be a better solution.

Remote communications are also limited to the master trailer which can be a drawback. A system modification that allowed direct communication to any trailer (perhaps via the master trailer) would seem to be advantageous.

SOFTWARE AND SYSTEM OPERATING REGIME

After specifying and working with the software to establish "settings" files to control the system for the several actual deployments (and several others which were not implemented), the following suggestions are made:

- ✓ the procedures and any user guides need to be simplified and made more clear—they are currently too complicated for one-time/first-time users in the field;
- ✓ there needs to be considerably more flexibility in defining the speed-setting algorithms—users need to be able to have trailers operate independently from one another with, for example, different maximum and minimum speeds and different "steps;"
- ✓ dial-up access to all trailers needs to be provided so that operating regimes can be modified remotely and in a straightforward manner;
- ✓ the system needs to have a timing mechanism so that changes in the speed-setting algorithms can be set to automatically switch back and forth at specified times (e.g., be able to switch to a night-time mode of operation at a specified time and back to day-time mode at another);
- ✓ it should be possible to invoke a remotely-changed constant speed limit if the need arises;
- ✓ there needs to be some visual or audible signal (or both) that indicates that the correct system sign-off procedure has been used (in a couple of instances when someone was physically at

the trailer the procedure was incorrectly followed and the system could not be accessed remotely);

- ✓ the procedures for specifying settings files need to be more flexible so that some variables (e.g., occupancy) can be overridden or ignored;

- ✓ although the pager interface for use by police officers seemed to work adequately in the field, officers will have 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 upstream 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); and

- ✓ 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.

CONCLUSIONS REGARDING VSL SYSTEM OPERATION

Given that the VSL system that was deployed was a prototype unit, it operated reasonably well although it required fairly constant attention from Worksafe/IRD to remain operational. Many of the problems encountered with the system would likely be solved with the next generation although performance specifications need to be clearly stated and met. The most important modifications include: better communications with individual trailers and between trailers, better and more flexible vehicle sensors, the ability to monitor (or use) individual vehicle speeds, better and more flexible capability in establishing the algorithms for setting limits, and easier to follow procedures and rules for using the system.

REVIEW OF VSL SYSTEM EFFECTIVENESS

The impact of VSL system operation on motorist behavior was also assessed within the limits allowed by the I-96 deployments and the data that were collected. The original proposal had included proposed comparisons of various MOEs before, during, and after the VSL system was deployed at a given location in addition to comparisons to base (no construction) conditions. The data to be used included those obtained from the VSL system, external data collected by MDOT at trailer locations, and data from Autoscope-monitored locations. The combination of the construction contractor operating very opportunistically and ahead of schedule on simple parts of the project (i.e., section 1, see table 1) and the inability to deploy the VSL system fast enough resulted in all section 1 deployment opportunities being lost. In the end, the exclusion of the section 1 deployment(s) eliminated the ability and need to use Autoscope for data collection. Overpasses in the two other sections of the project were simply not available (or not relevant) for using Autoscope. Thus, the analysis of system effectiveness depended almost entirely on data collected by the system itself and the MDOT-collected data at those same trailer locations.

MEASURES OF EFFECTIVENESS

The following MOEs were used in the analysis:

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

In addition, a separate analysis was undertaken with enforcement personnel present and not present during part of one deployment. Finally, traffic crashes that occurred within the overall work zone were also examined.

Comparisons using the MOEs above were primarily limited to before and during VSL operation.

SYSTEM DEPLOYMENT AND BASIC DATA COLLECTION PROCEDURE

The basic system deployment and data collection scenario for each deployment is described below.

- ✓ A potential VSL deployment within the overall I-96 work zone was selected based on traffic characteristics, whether the speed limit could be varied (an MDOT TSC decision), whether the deployment could be sustained for two or more weeks, and an assessment (jointly by MDOT, MSU, and Worksafe/IRD) of whether the system could be safely and effectively deployed.

- ✓ MDOT TSC then set constraints, if any, on the maximum speed limit that could be posted at any location within the deployment area (e.g., proximity to an on- or off-ramp typically triggered a 50 mph maximum as did the geometry of the median crossover location).

- ✓ The VSL system was deployed on site with the specific location of each trailer being agreed upon by MDOT, MSU, and Worksafe/IRD. Worksafe/IRD then deployed the system (placed the trailers).

- ✓ As soon as possible after the VSL trailers were placed, MDOT data collection devices were set up at the VSL trailer sites.

- ✓ Once deployed, system operation was checked by Worksafe/IRD (basic system functions) and MSU (e.g., would the system display the “right” speed limits according to the algorithm in effect). During this period, the VSL would be fully operational except for the VMS being covered by a static 50 mph speed limit sign).

- ✓ As soon as system operation was confirmed (typically within 24 hours), both VSL and MDOT data collection began and continued for a specified period (the VMS were covered with static 50 mph regulatory speed limit signs). These are noted as “before” data.

- ✓ After the “before” data were collected, the VMS displays were uncovered and the system was in full VSL operation with the VMS displayed. These are noted as “during” data.

- ✓ In some instances, additional data were collected after the system was shut down or the VMS again covered (with static 50 mph signs).

- ✓ Data collection and system operation was monitored throughout each deployment. Data were downloaded at least daily and stored for later analysis.

- ✓ Once the deployment was over, the system was removed from the site by Worksafe/IRD and stored off-site until the next deployment.

Of the four deployments on I-96, only three (the first, third, and fourth) yielded usable data. The second deployment experienced some system problems at the outset (e.g., apparently erroneous occupancy counts caused problems with the speed-setting algorithm) and then construction work was completed far earlier than expected. So, while the system problems were effectively dealt with in short order, the site effectively became unavailable.

DATA ANALYSIS APPROACH AND LIMITATIONS

The analysis that was done on the collected data generally consisted of: simple 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 (e.g., how did the average speed change at trailer X?) and longitudinally through the deployment area (e.g., how did the average speed profile through the area change?).

Most of the comparisons and analyses were done using data collected by the VSL system itself. MDOT “tube data” was sometimes sporadic (e.g., data were not available throughout the deployment period for all trailers—because of tubes getting torn up) and were somewhat inconsistent with the system data. In short, when the two sets of data were available, it was difficult to tell which one represented “truth.” The MDOT data were, however, useful at specific locations for assessing the 85^{th} percentile speed and speed variance. The utility of the MDOT data resulted from the details that were available: the system data were only available in ~6-minute aggregations (e.g., the average speed over six minutes); while MDOT data were “binned” in either of two speed distributions (16 or 30 increments). Unfortunately, not all MDOT data were “binned” the same (the equipment has two different settings). Although the absolute estimates of 85^{th} percentile speeds may have errors, the changes in the MOE should be reasonably accurate as long as the data were collected continuously. Likewise, examination of the variance should be unaffected by an error in calculating the absolute speed.

The analysis of the crash history is basically anecdotal because of the relatively small number of crashes.

RESULTS OF VSL EFFECTIVENESS ANALYSIS

At the outset, the existing conditions in the work zone are reiterated. The regulatory speed limit throughout the work zone when the VSL system was not deployed was 50 mph (day and night). The normal speed limit when no work zone is present is 70 mph. Mid-way through the overall work zone (see figure 2) there is an elongated interchange between I-96 and I-69 and another between I-96 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 was (anecdotally, based on traveling through the work area) typically above 50 other than during congested periods when traffic was stop-and-go. At the east end of the active work zone (e.g., near trailer 1 in the first deployment), the speed limit was 70 (end of active work area). The western ends of all deployments were well within the overall work area so that eastbound traffic would be subject to the 50 mph limit coming into the VSL deployment and westbound traffic would exit the VSL deployment into a 50 mph area.

In all deployments, the VSL system was restricted to displaying a limit of 60 mph or less except when the eastern end of VSL deployment coincided with the end of the work area when it was allowed to go to 70 mph for the last trailer in the sequence. The MDOT TSC placed various restrictions on maximum limits at different points in the system based on ramp locations and/or constraining geometric conditions (e.g., a median crossover at the east end of two deployments). Details of the algorithms for setting speeds at different locations are provided in appendix B.

The results below are organized according to the MOE being considered (that is, results regarding each MOE are presented for all deployments).

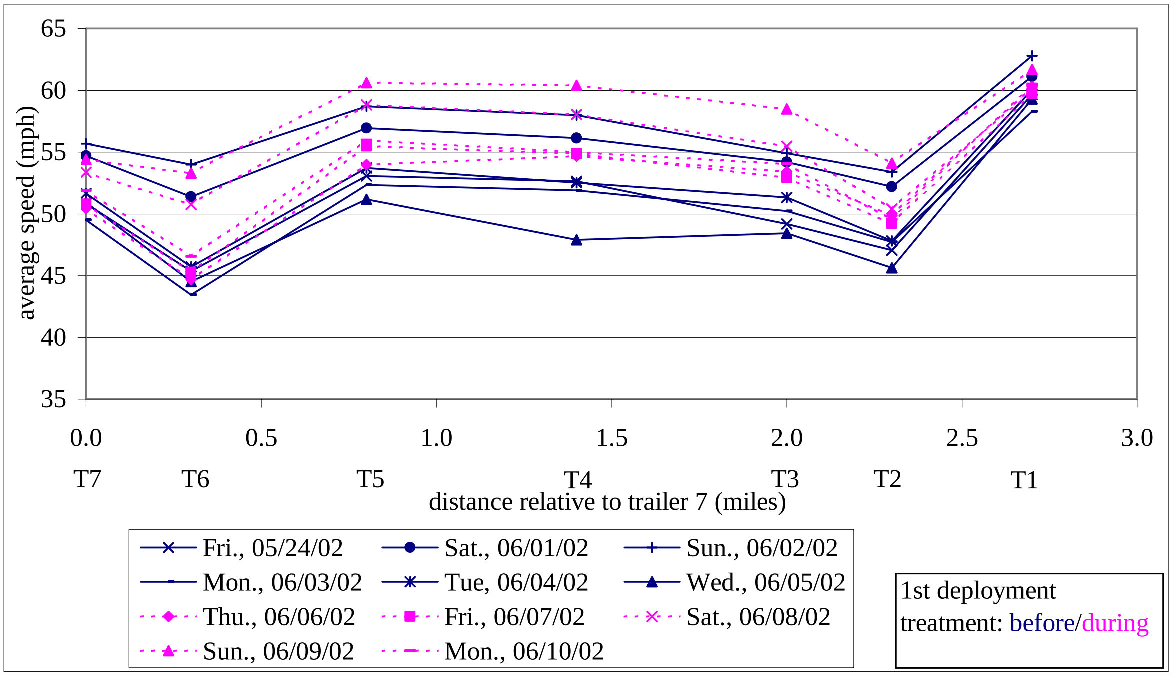
Average Speed, Difference between System-Displayed and Average Speed

As noted, most of the analysis regarding average speed was done using VSL system data. While there may be some errors in estimating the average speed, the data are more consistent throughout the deployment period. Basically, for the analysis, an observation is the average speed over a ~6-minute period. The preceding upstream speed 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 (and the in-zone limit when the VSL system is not in operation) is 50 mph, it was expected that the VSL system would have the effect of increasing speeds through the zone, especially since the before speeds during non-congested times appeared to be generally higher than 50.

Figures 3-6 are 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 this instance, AM and PM rush periods, off-peak daytime, and nighttime periods) and data availability, data from days from the before and during periods were selected and plotted. Each line in the figures represents a plot of the 6-minute average speeds averaged over the noted time period (e.g., figure 3 shows average speeds calculated over 2.5 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 figure 3, motorists are proceeding from left to right (from trailer 7 toward trailer 1).

Figure 3. Average speed profiles for **6:00-8:00 AM**, first deployment



Looking at figure 3 in more detail (as an example), the day-to-day variation both within and between "treatment groups" is also illustrated in these figures. 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 (see appendix B) when the system was active, the same as the static speed limit (i.e., the posted limit for both "before" and "during" conditions was, effectively, 50 mph). A balance of similar days (e.g., weekday and weekend) for the before and during conditions were chosen for the comparison.

In addition to the graphical comparisons, statistical comparisons of the average speeds before and during the deployment were done (and are shown and discussed later). Differences between the VSL-displayed speed limits and the static (before) limits were also examined.

The information displayed in the graphs is summarized and presented in table 4 (after the figures). Differences in average speeds (before and during) 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 (during) were higher than the average speeds when it was not (before). For the displayed speed difference, a positive number indicates that the average VSL system display was that much higher than 50 mph (the static, before limit).

Figure 4. Average speed profiles for **10:30-12:30** AM, first deployment

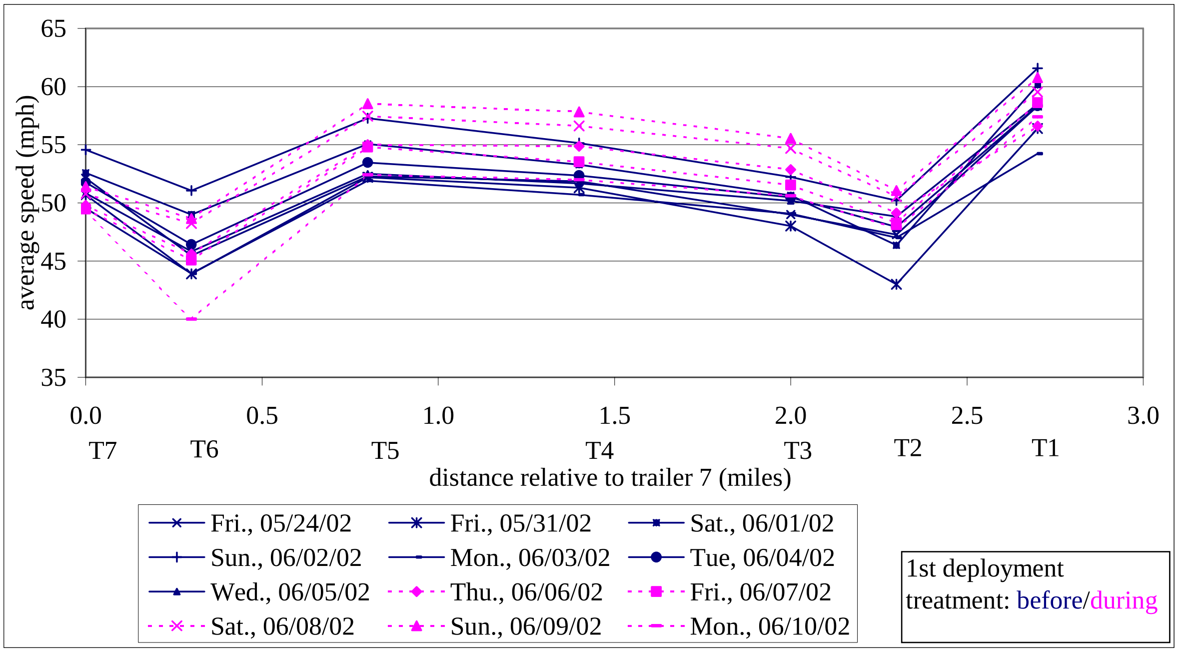


Figure 5. Average speed profiles for **4:00-6:00 PM**, first deployment

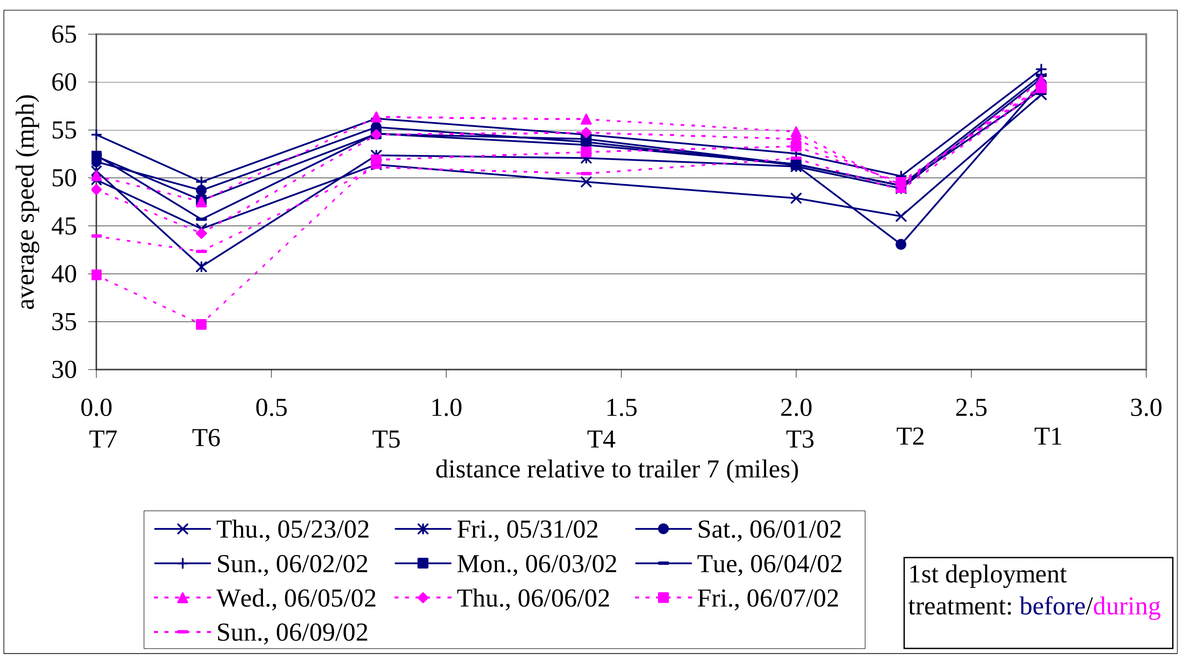
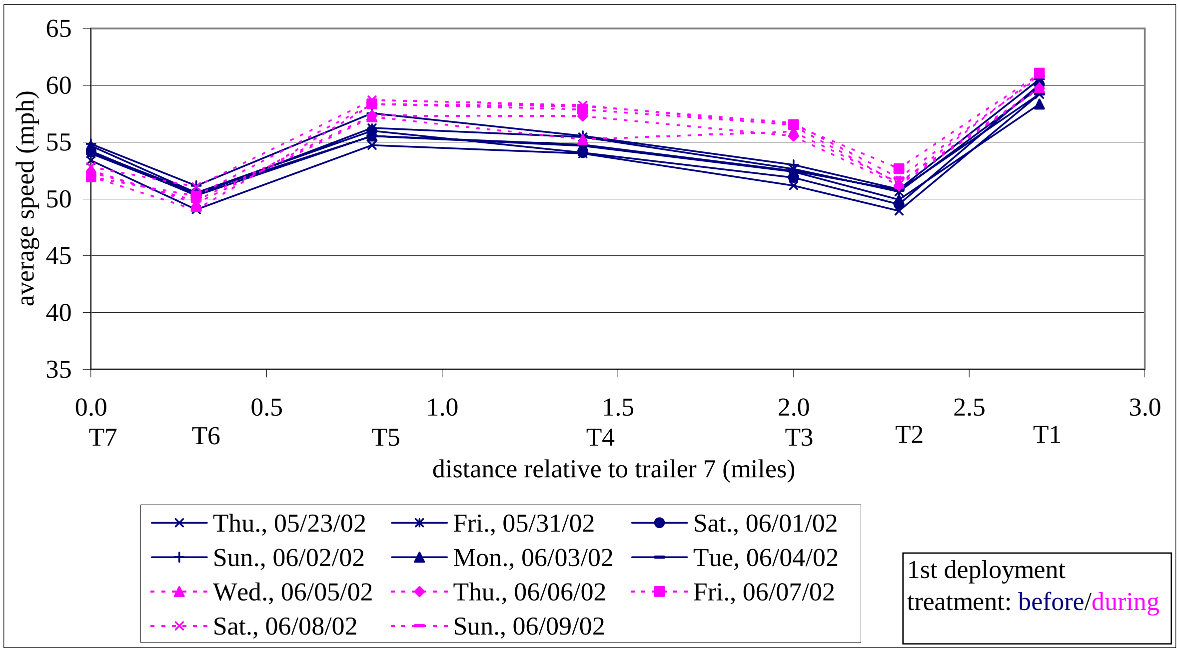


Figure 6. Average speed profiles for **8:00-10:00 PM**, first deployment



Overall, average speeds were generally (although not always) higher at trailers further into the VSL deployment area. Conversely, average speeds at the first trailers encountered were lower when the VSLs were displayed. Based on these figures and the information summarized in table 4, the observations below 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 50 mph (by design), it appears that motorists responded better to the lighted VMS display since the average speed was closer to the posted speed when 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 an interstate 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.

✓ Motorists typically slowed at trailer 2 where the "during" speed limit was no greater than 50 mph in the vicinity of a median crossover with restrictive geometry. Speed reduction at trailer 2 was consistently 1-3 mph greater with the VSL in operation (VMS display on) than when a static 50 mph limit was displayed, suggesting that the VSL had more visibility 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. It is interesting to note that in the middle of the VSL deployment area (trailers 5-2),

Table 4. Summary of results of average and displayed speed comparisons, first deployment

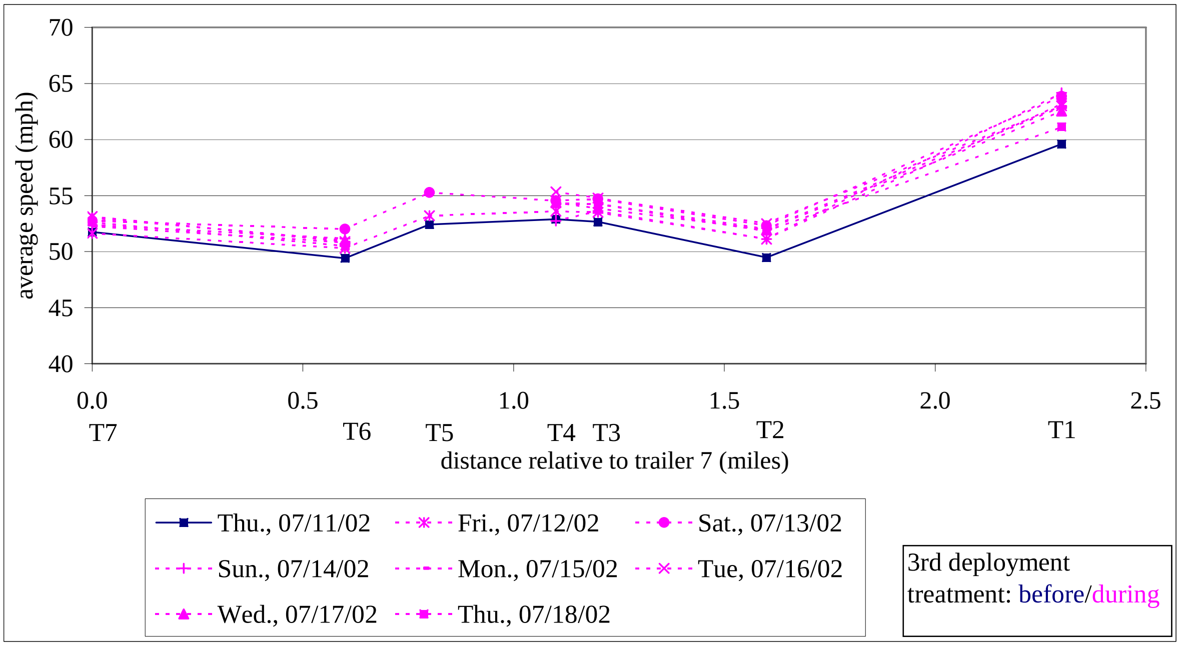
time	variable	weekday/ weekend	location 7	6	5	4	3	2	1
6:00AM to 8:30AM	average speed difference (during - before)	weekday	0.3	0.7	2.5	3.7	3.7	2.5	0.9
		weekend	-1.3	-0.7	1.9	2.2	2.5	-0.5	-1.1
	displayed speed difference (during - before)	weekday	0.0	8.5	8.8	8.1	8.1	0.0	
		weekend	0.0	10.0	10.0	10.0	10.0	0.0	
10:30AM to 12:30PM	average speed difference (during - before)	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 (during - before)	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 (during - before)	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 (during - before)	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 (during - before)	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 (during - before)	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 (or displayed speed, during-before) in mph

the VSL results in consistently higher speeds for both weekdays and weekend days during nighttime periods.

Similar analyses were undertaken for the 3rd and 4th deployments. For the third one, only three time periods (10:30 AM-12:30 PM, 5-6:00 PM, and 8-10:00 PM) were available and the "before" data were limited to only one day. Data from one time period are shown in figure 7.

Figure 7. Average speed profiles for **8:00-10:00 PM**, third deployment



Third deployment results were similar to those for the first deployment although in almost all instances the "during" speed profiles were higher (faster) than the "before" profile. Obviously, the comparison is limited because only a few "before" data sets exist (because of short-range modem problems). Because of the several ramps in the area (see appendix B for layout), the allowable speed limit at trailers 4 and 6 was limited to a maximum of 50 mph thus the speed profiles are a lot flatter (constant) 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 two trailers.

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

For the fourth deployment, during some of the observation periods there was sometimes significant congestion at the beginning of the VSL deployment area so that average speeds ranged 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 with relatively high volumes) and occurred on several days and at a variety of times (e.g., not just rush hour). Speeds typically increased as motorists traversed this area of the work zone. At the end of the zone, the last trailer (#6) 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). The average speed profiles for both daytime (10:30 AM-12:30) and nighttime (8-10:00 PM) are shown in figures 8 and 9, respectively.

Figure 8. Average speed profiles for 10:30 AM-12:30 PM, fourth deployment

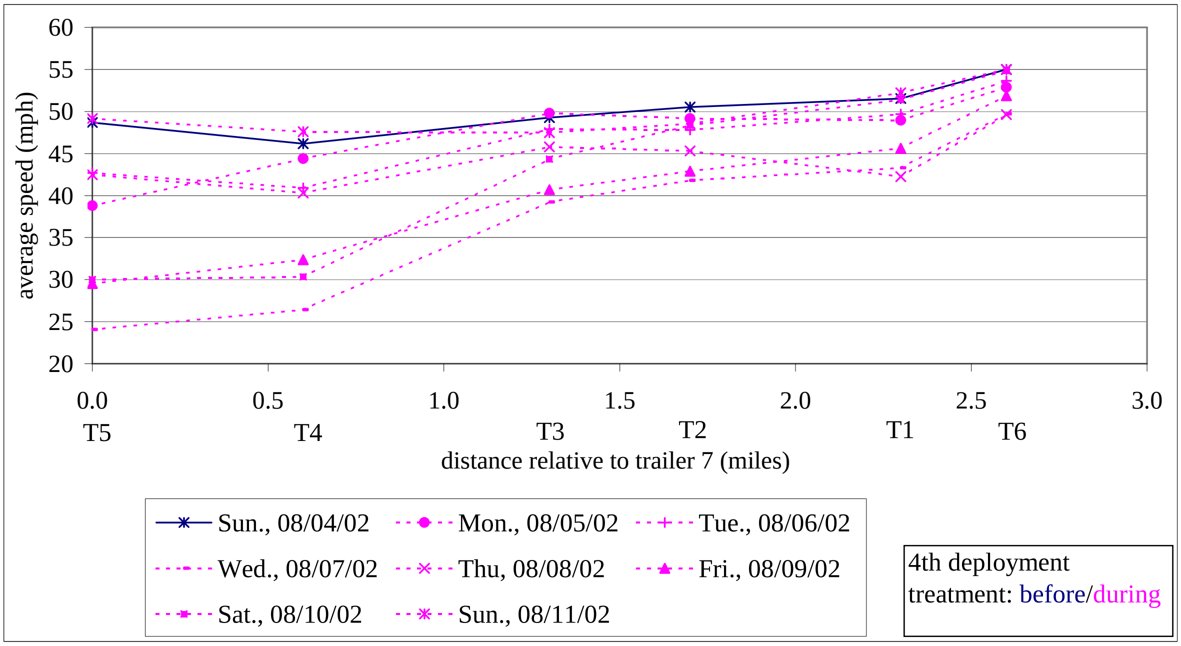
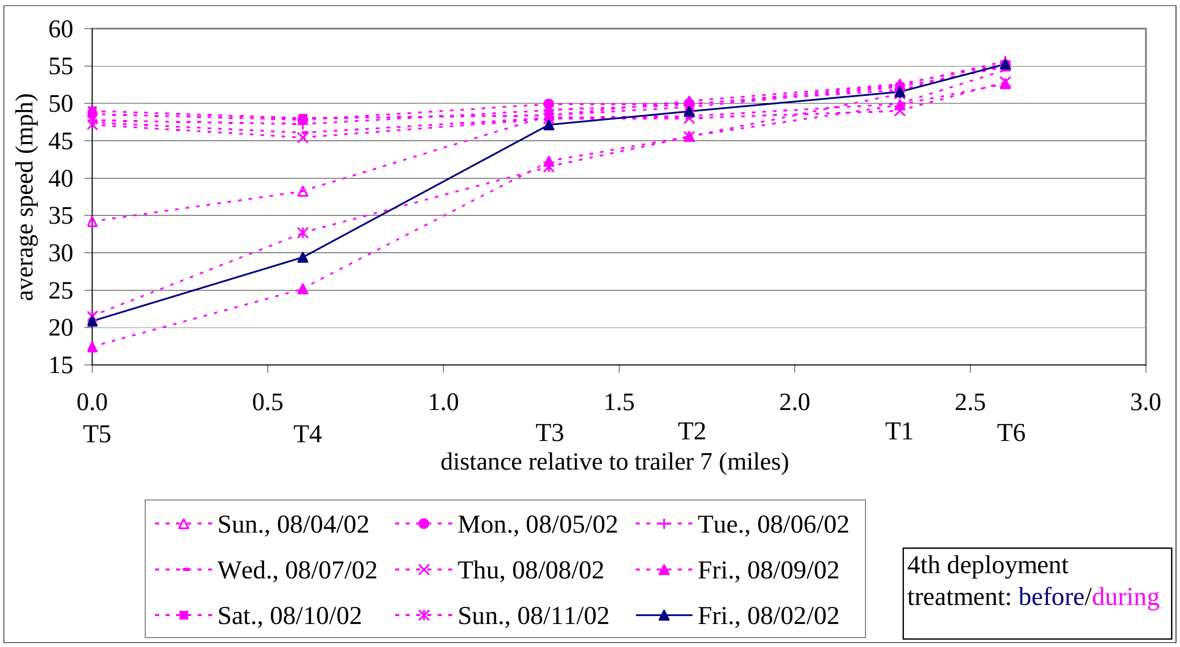


Figure 9. Average speed profiles for 8:00-10:00 PM, fourth deployment



While definitive conclusions are difficult with respect to average speed through the VSL deployment areas (over all deployments), 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 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 Work Zone (VSL deployment area)

If average speeds are expected to increase when the VSL is deployed, the corollary is that travel time through the VSL deployment area would decrease. Given the results for the average speeds at various locations and deployments, there were some mixed results with respect to travel time. Travel time was calculated based on the assumption that the average speed over any "link" between two adjacent trailers was the average of the speed observed at the two trailers.

For the first deployment, the differences in travel times before and during are shown in table 5. Not surprisingly, given the average speed results given earlier, travel time is seen to decrease for three of the four time periods reviewed. However, travel time increases for the 4-6:00 PM period for both weekdays and weekend days.

Table 5. Comparison of travel times through work zone, first deployment

time	travel time difference (during-before)			
	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

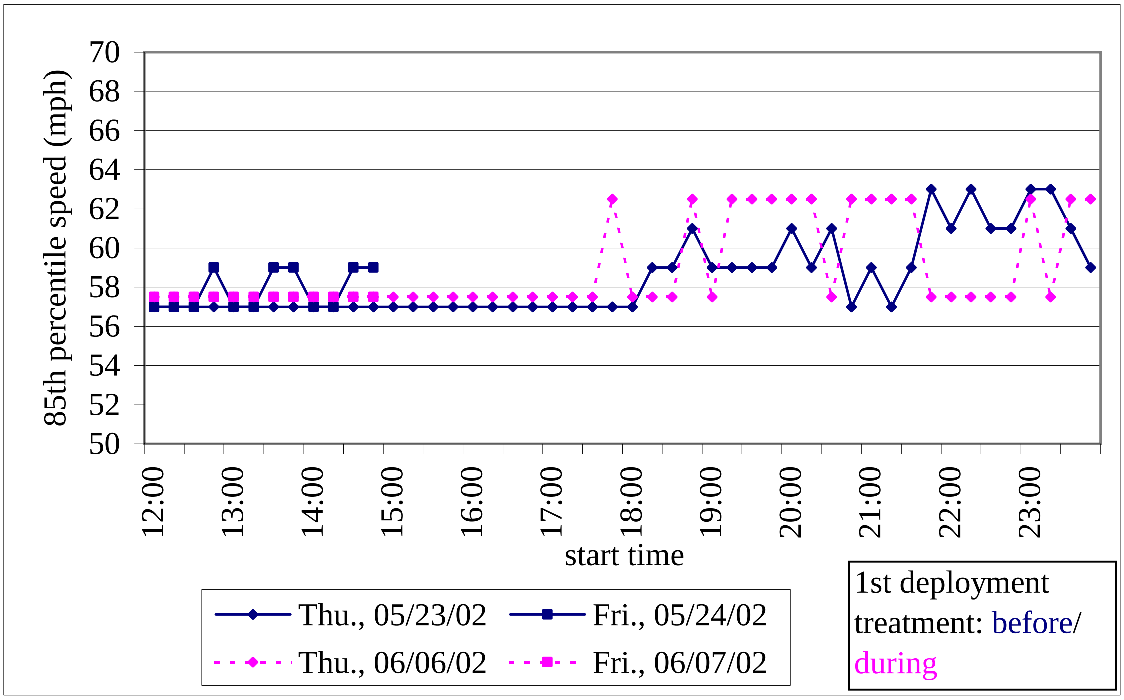
NOTE: shaded cell indicates that the difference was significant with 95% confidence

While these changes are statistically significant in all cases, operational effectiveness is another issue. In the best-case situation (AM rush hour during the week), average travel times are expected to decrease ~11 seconds (or 5.4% of the overall travel time)—this benefit is accrued over 2.3 miles of travel. While the aggregation of such savings over all motorists results in a "significant" amount of total time savings, 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 nor as consistent (e.g., for the fourth deployment, travel time increased 24.5 seconds during the 10:30 AM-12:30 period). All savings were less than 6%.

85th Percentile Speed

The 85th percentile speeds were estimated using data obtained from the MDOT pneumatic tube data (disaggregation of the data was necessary and could not be done using VSL system data). There was considerable variation in the data from the MDOT devices: for the first deployment, before data were in the 30-bin format while during data were in the 16-bin format; for the third deployment, the situation was reversed; and for the fourth deployment only data from the left lane (two lanes of traffic) were available. (For the fourth deployment, the VSL system monitored only the right lane and, hence, speed limits were based on those data.) In addition, there was some evidence that the automatic devices reported "higher" speeds than actually existed in some instances. This was, in part, because the devices were re-set after the tubes were ripped up by traffic. Notwithstanding these problems, the variation in the 85th percentile speed was examined at specific trailers where data permitted. Data from trailer 3 in deployment 1 are shown for four 24-hour periods in figure 10. Problems with availability of data are also illustrated.

Figure 10. 85th percentile speeds at trailer 3, first deployment



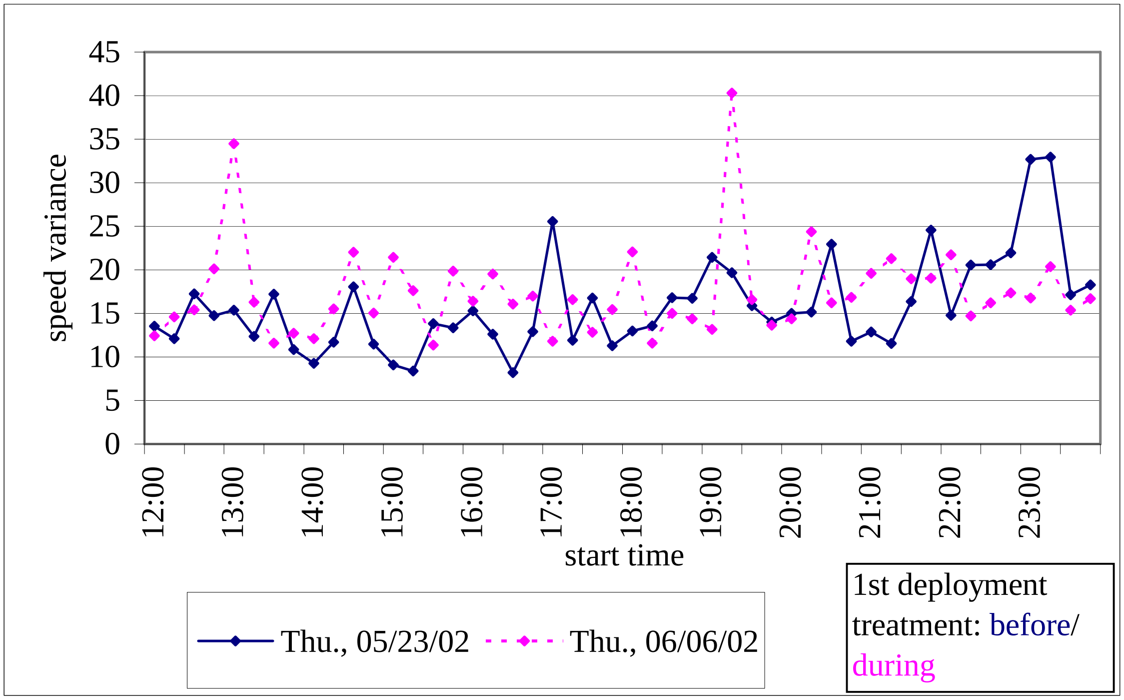
In this particular instance, the 85th percentile speed is seen to vary very little between the before and during conditions. Summaries from several other one-day windows of data for the first, third, and fourth deployments showed that the 85th percentile speed did not vary with the change in displayed speeds. Unfortunately, the reliability of the pneumatic tube-based data is suspect so that findings are inconclusive.

Speed Variance

While the data for examining speed variance are also from the MDOT tube-based devices, they are more usable in this context than for the 85th percentile investigation. Examination of the variance is not affected by the absolute value of the speeds being observed—i.e., even if the speed being measured is incorrect, as long as the error is of the same magnitude from one observation to the next (which it should be), the magnitude of the variance should not vary. However, there were limitations to the amount of data that could be used and the problem with different binning formats also remains.

Figure 11 is an illustration of the fluctuation in speed variance at trailer 3 in the first deployment. This trailer (see appendix B) is in the middle section of the VSL deployment area and before the crossover location. This was an area where average vehicle speeds were somewhat higher "during" the VSL operation. As shown in the figure, with the exception of a couple of "spikes" in the variance, there is little difference between the variance before and during VSL operation. This same sort of result was also observed at trailer 7 (at the beginning of the deployment area).

Figure 11. Speed variance at trailer 3, first deployment



At trailer 1 (at the end of the work area), the variance was typically slightly lower "during" VSL operation.

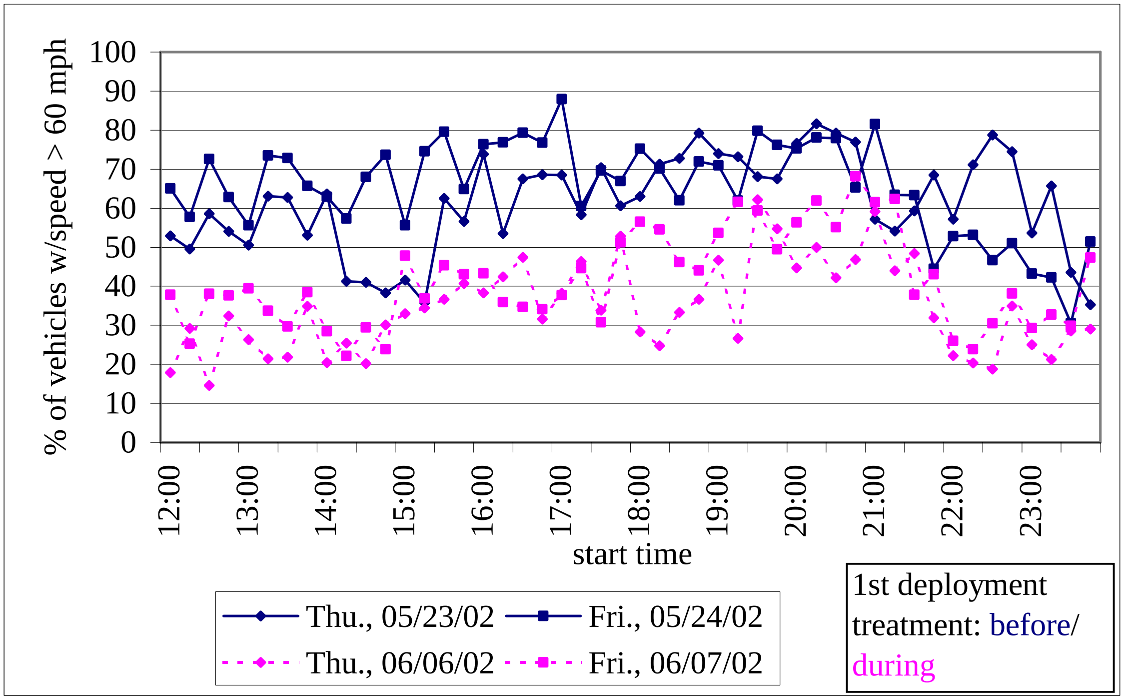
Results were similar for other trailers and other deployments—that is, there was no consistent trend to the speed variance being higher or lower when the system was displaying the speed limit.

Percentage of "higher-speed" vehicles (%>60 mph, %>70 mph)

The percentages of higher-speed vehicles were examined with the idea that these were measures of speed limit compliance. That is, for example, as the percentages of vehicles traveling over 60 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 which deployment is being examined, time of day, and transient congestion conditions.

Figure 12 is an illustration of the type of comparison that was done. The example is from trailer 1 in 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-based system difficulties. Even considering a high-side bias, the "before" speeds were considerably higher than "during" VSL operation.

Figure 12. Percentage of vehicles exceeding 60 mph, trailer 1, first deployment



Such a comparison was also done with 70 mph being the criterion. Significantly fewer vehicles exceeded 70 in the “during” condition with percentages ranging from 0 to a high of 16% during the “before” condition.

Similar results for the first deployment are summarized in table 6 for various trailers. In general, it can be seen that the VSL system seems to result in significantly better speed limit compliance.

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 less convincing. 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 the “percent exceeding” figures showed the opposite results (although good data were only available at trailer 6): “during” percentages were virtually always higher than “after” percentages. Thus, taken across all data that were reviewed, the compliance results are somewhat positive but there were instances when compliance did not appear to be better. The data are, however, limited and subject to some error.

Effect of Enforcement Presence during Fourth Deployment

During the fourth deployment the effect of police presence in the deployment area was also tested. Despite directions which called for police to be stationary, there was some variation

Table 6. Summary of "higher speed" traffic for the first deployment

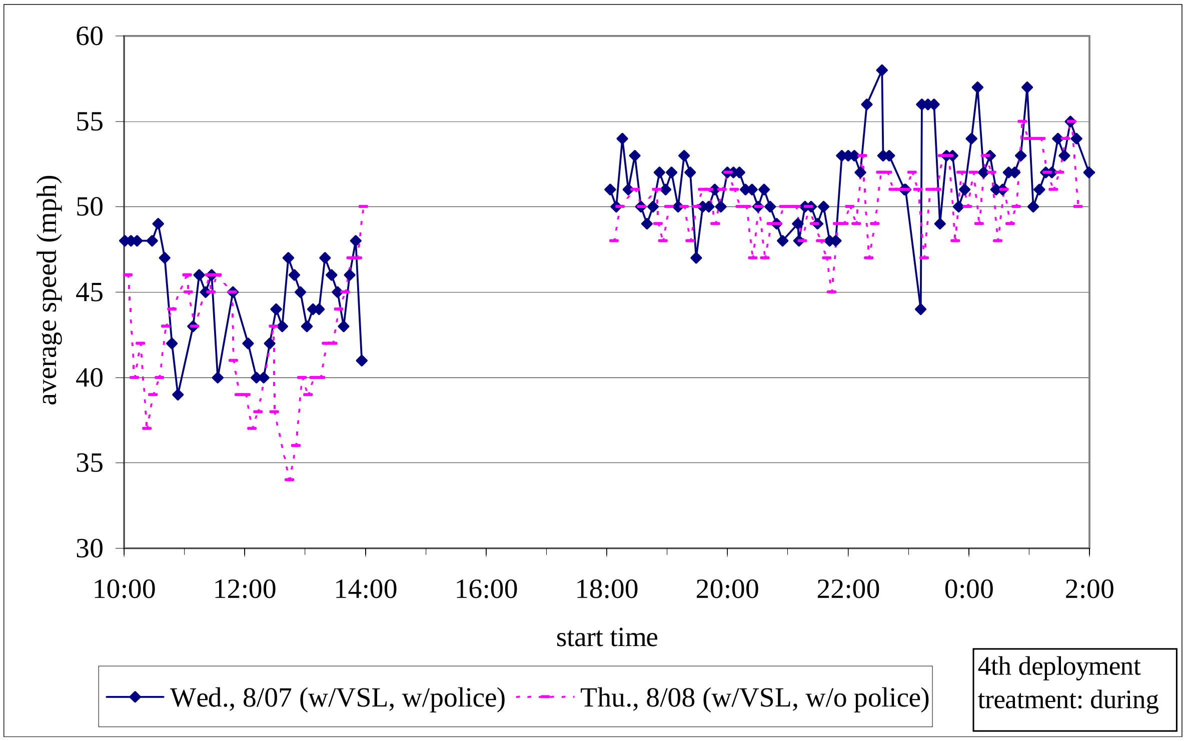
results	trailer			
	speed > 60 mph		speed >70 mph	
	weekday	weekend	weekday	weekend
"During" was slightly higher than "before" half of the time and slightly lower the other half.	3			
"During" was less than 2% lower than "before" most of the time			7	
"During" was about 5% lower than "before" most of 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.

when the police actually went into the field. The approximate locations within the deployment area are shown in appendix B. The police deployment scenario was that the police were supposed to be visible in the deployment area both when the VSL was operating and when it was not. In the fourth deployment, there were two lanes of westbound traffic with the "fast" lane directly adjacent to the median. The construction work occurred in the outside lane which was closed and had workers present during the day. The police were, in general, not supposed to write tickets but merely be present (in the median) and visible with their radar and/or lasers "on" as they would be during normal surveillance/enforcement. Police also used the paging device during the deployment to check on the speed being displayed on the next upstream VSL trailer. The average speeds at trailer 1 are shown in figure 13.

Average speed, speed variance, and percentages of higher speed vehicles were checked at the two trailers nearest the police location. The RTMS data were used for the comparisons of average speeds while the tube-based data were used for speed variance and percentage of higher speed vehicles. Overall, there seemed to be very little effect attributable to the police. At both trailers 1 and 6, average speeds were somewhat higher when the police were present compared to when they were not. Other effects were not as clear. It may well be that motorists simply thought that they were "close enough" to the posted speed limit and that "everyone is going that fast" such that the perceived likelihood of getting pulled over was low.

Figure 13. Average speeds w/ and w/out police presence, trailer 1, fourth deployment



Crash Analysis

Finally, the crashes that occurred when the VSL system was deployed (and before and after) were also reviewed. All (police-reported) crashes that occurred on I-96 in both time and space windows associated with the various VSL deployments were retrieved from the computerized records maintained by MDOT. The time windows were defined by the length of the VSL deployment and then similar time periods both before and after the deployment period. In some instances, the "after" conditions on the road may have changed. The spatial windows were defined by the deployment area itself although all crashes that occurred in both directions (i.e., eastbound and westbound I-96) 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.

Table 7 is a summary of the "time windows" for identifying the crashes while table 8 is a summary of the crashes themselves. In table 8, each crash is sorted by the deployment, the direction in which the VSL was deployed, whether the system was present, a description of the crash, and a determination of whether the crash was related to the VSL

It should be remembered that conditions in the two travel directions (for any given deployment) were somewhat different. For example, during the first deployment the eastbound traffic was "monitored" by the VSL system (that is, eastbound motorists would see the VSL trailers and displays, when active). Eastbound motorists had a barrier wall to their left (separating them from westbound traffic) and a shoulder area to their right. Westbound motorists also had the barrier wall to their left but would have had the median to their right with workers in or beyond the

Table 7. Time "windows" for crash analysis

deployment #	system presence	Time		
		start	end	Length
1	before	Wed., 05/29/02, 3:00PM	Mon., 06/03/02, 11:30AM	4days 20.5hrs.
	during	Wed., 06/05/02, 3:00PM	Mon., 06/10/02, 11:30AM	4days 20.5hrs.
	after	Wed., 06/12/02, 3:00PM	Mon., 06/17/02, 11:30AM	4days 20.5hrs.
3	before	Fri., 07/05/02, 12:30PM	Fri., 07/12/02, 10:00AM	6days 21.5hrs.
	during	Fri., 07/12/02, 12:30PM	Fri., 07/19/02, 10:00AM	6days 21.5hrs.
	after	Fri., 07/19/02, 12:30PM	Fri., 07/26/02, 10:00AM	6days 21.5hrs.
4	before	Sun., 07/28/02, 1:00PM	Sun., 08/04/02, 1:00PM	7days
	during	Sun., 08/04/02, 1:00PM	Mon., 08/12/02, 7:00AM	7days 18hrs.
	after	Mon., 08/12/02, 7:00AM	Mon., 08/19/02, 7:00AM	7days

NOTES:

First deployment: The conditions "before" and "during" deployment were the same. There was a total Reconstruction of the eastbound lanes of I-96. The eastbound traffic was shifted to use one of the westbound lanes. The traffic may have shifted to use the eastbound lane during the "after" condition.

Third deployment: The conditions "before" and "during" deployment were the same. There was a total Reconstruction of the westbound lanes of I-96. The westbound traffic was shifted to use one of the eastbound Lanes. The conditions "after" the deployment were unclear.

Fourth deployment: In the "before" condition, there was concrete patching on the left and middle lanes. Only the right lane was open. In the "during" condition, there was concrete patching on the right and middle lanes. Only the left lane was open. The condition "after" the deployment were unclear.

median. The westbound motorists would have been much more aware of the construction and, in general, be somewhat more prone to congestion simply due to "rubber-necking."

The first three rows in table 8 show the crashes that occurred in the "windows" for the first deployment. All three crashes occurred on westbound I-96, one during the VSL deployment and two after. No crashes occurred on the eastbound side where the VSL system was deployed.

The next seven crashes (rows) occurred in the deployment 3 "windows." Deployment 3 was also an eastbound deployment. There were no crashes in the area (in either direction) during the time that the system was deployed 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 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.

Finally, the last nine crashes (rows) occurred in 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 conventional shoulder. Conditions on the eastbound side of the median were reasonably similar although traffic flow might have been somewhat different (westbound motorists typically were moving from a congested area of the work zone to a less congested area). The eastbound motorists had gone through a congested area (at the extreme western end of the overall work area, then traveled through a relatively smooth-flowing area (nearest the westbound VSL deployment area) and were approaching another congested area. In any event,

Table 8. VSL deployment area crash descriptions (chronological order)

date	time	deploy. #	VSL dir.	system presence	crash description	crash related to VSL
6/7/02	5:15PM	1	EB	during	rear-end in traffic on WB I-96; driver cited for speeding	no
6/12/02	6:59PM	1	EB	after	fixed object on WB I-96; driver was fleeing from the police	no
6/13/02	11:05AM	1	EB	after	rear-end in traffic on WB I-96 at Lansing Rd. ramp; driver of the front vehicle made an abrupt stop because another vehicle cut her off	no
7/6/02	1:55PM	3	EB	before	rear-end in traffic on EB I-96; driver of the front vehicle stopped because of back-up traffic	yes
7/6/02	9:00PM	3	EB	before	rear-end in traffic on WB I-96 at the crossover; driver of the front vehicle slowed down	no
7/8/02	3:50PM	3	EB	before	rear-end in traffic on WB I-96; driver of the front vehicle stopped because of back-up traffic	no
7/19/02	11:45AM	3	EB	after	rear-end in traffic on WB I-96; driver of the front vehicle stopped because of back-up traffic	no
7/19/02	12:50PM	3	EB	after	rear-end in traffic on WB I-96; driver of the front vehicle stopped because of back-up traffic	no
7/19/02	3:10PM	3	EB	after	rear-end in traffic on WB I-96; driver of the front vehicle stopped because of back-up traffic	no
7/21/02	6:00PM	3	EB	after	side-swipe in traffic on WB I-96; lane merge (2 lanes to 1 lane)	no
8/3/02	3:55AM	4	WB	before	rear-end in traffic on EB I-96; vehicle 2 intentionally strike vehicle 1	no
8/6/02	5:30PM	4	WB	during	fixed object on WB I-96 at off ramp to I-69	yes
8/8/02	1:30PM	4	WB	during	angle straight on EB I-96 at on ramp from M43	no
8/9/02	11:15AM	4	WB	during	rear-end on the shoulder of EB I-96; both drivers tried to avoid the stopped vehicle in front	no
8/10/02	2:00PM	4	WB	during	rear-end in traffic on EB I-96	no
8/11/02	2:15PM	4	WB	during	rear-end in traffic on WB I-96	yes
8/13/02	6:30PM	4	WB	after	rear-end in traffic on EB I-96 at on ramp	no
8/14/02	8:00AM	4	WB	after	rear-end in traffic on EB I-96; driver of the front vehicle stopped because of back-up traffic	no
8/16/02	11:48AM	4	WB	after	rear-end in traffic on EB I-96; driver of the front vehicle stopped because of back-up traffic	no

Shaded cell indicates that the accident was not in the area of that deployment work zone.

seven of the crashes were on the eastbound side (no VSL system) and were almost all rear-end crashes in traffic. On the two westbound crashes, one was on an off-ramp while the other was a rear-end in traffic during the active deployment period.

From the summary, 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 as far as crash occurrences were concerned. 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 automatic traffic data collection devices (which use pneumatic tubes as sensors) provided data that were sufficient to measure all of the MOEs to the desired degree. The MDOT devices suffered because the tube sensors were constantly being ripped up by traffic. This resulted in both loss of data and inconsistencies in the data that were obtained because of the "re-setting" of the sensors. Unfortunately, these and some other problems with the MDOT data were not obvious until long after any given VSL system deployment was closed down. The VSL system data were simply too aggregated to be of much use in assessments of changes in the 85th percentile speed or variance. These problems notwithstanding, there were several findings regarding VSL operations. These are summarized below.

- ✓ The **average speed** of motorists appeared to increase through the deployment areas in most instances when the VSL system was operating. This was primarily true 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, it is noted that with such short deployment areas, the time savings is, 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.

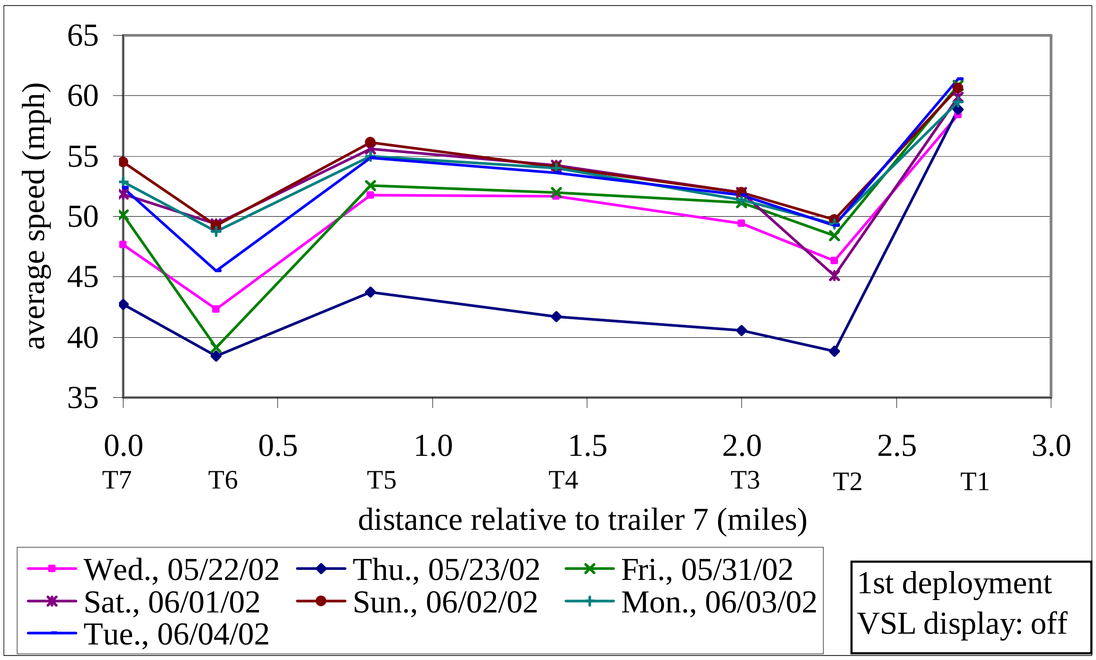
- ✓ While it was not possible to evaluate changes in the **85th percentile speeds** due to VSL system operation, the **speed variance** did not appear to be consistently affected. There was some limited evidence that the **percentages of high-speed motorists** decreased when the VSL system was operating.

- ✓ The addition of **enforcement personnel** in the VSL deployment area seemed to have no effect on average speed, speed variance, or percentages of higher-speed vehicles.

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 would change with changing conditions and present more credible limits to the motorists.

An example of the day-to-day variation (for the first deployment) is shown in figure 14. Average speeds at any given trailer varied as much as 15 mph while the static posted limit was constant at 50 mph. The data from a congested "slow day" (bottom profile) in figure 14 is reproduced in figure 15 with an overlay (dotted line) of what the VSL system ***would have displayed*** (as opposed to a static 50 mph). On the other hand, figure 16 is an illustration of the speed limit that ***would have been displayed*** on a day when the ambient speed was considerably higher.

Figure 14. Typical day-to-day variation in average speeds during 5-6:00 PM period (deployment 1)



A comparison of the speed limit profiles in figures 15 and 16 shows 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 17 is an example of the system's responsiveness to longitudinal changes in ambient traffic.

As illustrated in figure 17, the VSL system is also responsive when ambient traffic conditions vary longitudinally throughout the zone. While this can be seen in figures 15 and 16, 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.

Figure 15. Comparison of speed profile on a **congested** day with VSL that would have been displayed (deployment 1)

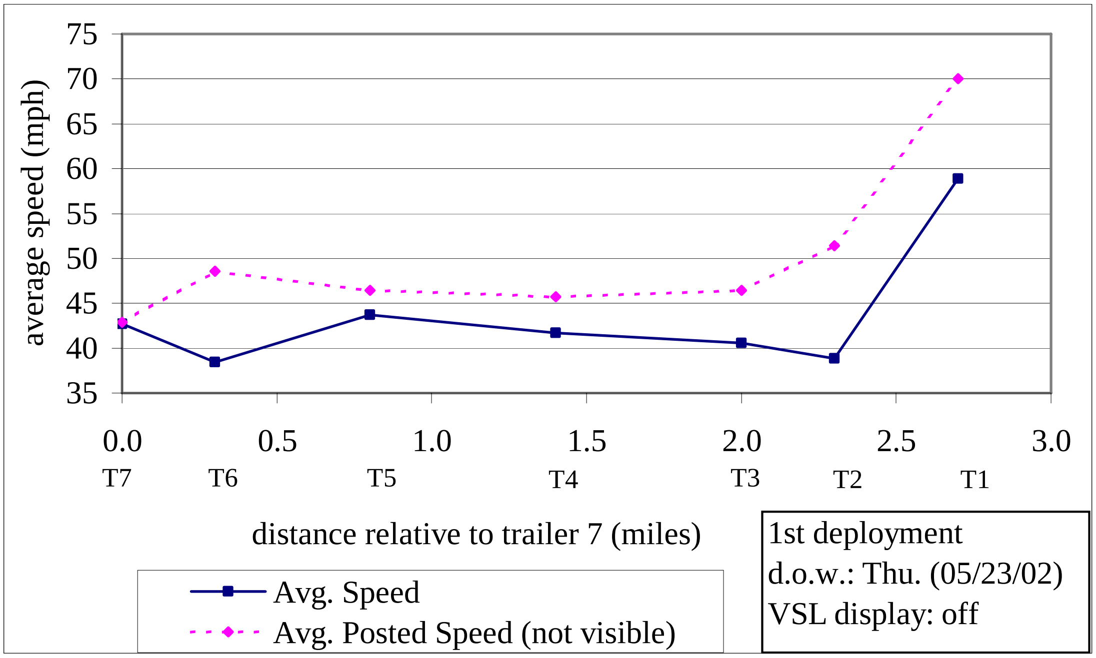


Figure 16. Comparison of speed profile on an **uncongested** day with VSL that would have been displayed (deployment 1)

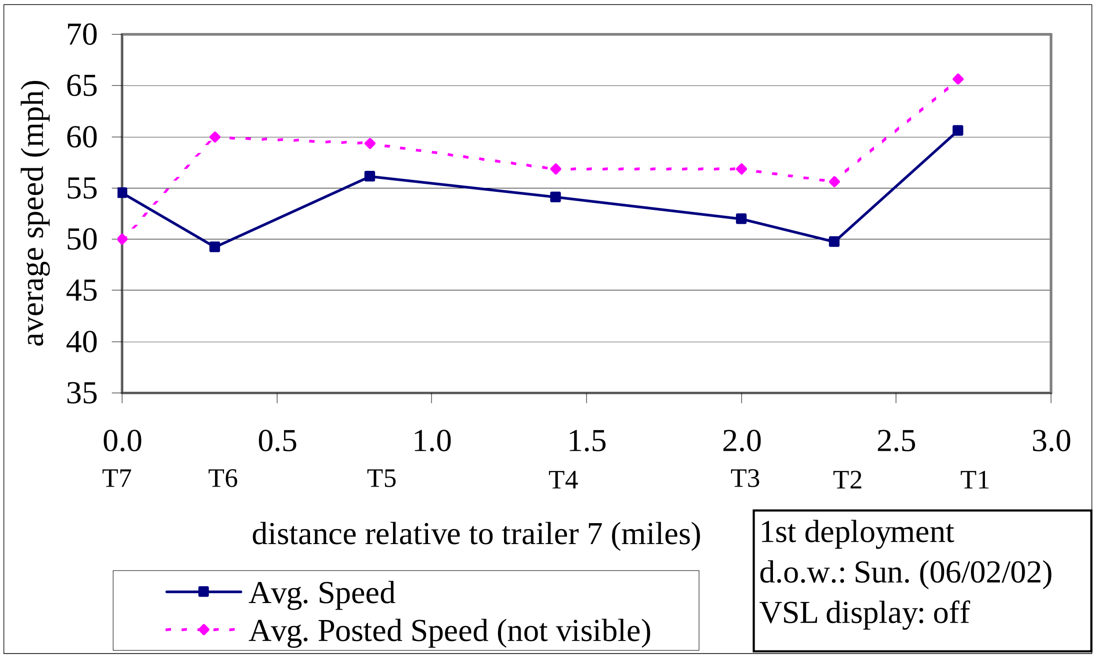
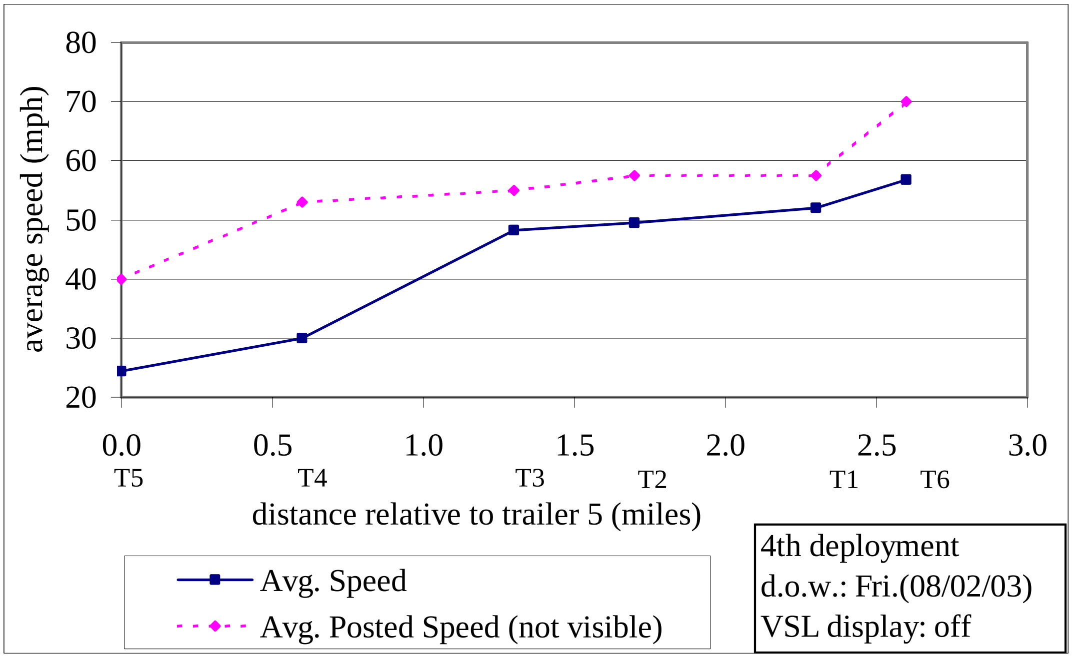


Figure 17. Comparison of speed profile with longitudinal variation in congestion with VSL that would have been displayed (deployment 4)



OVERALL SUMMARY, CONCLUSIONS, AND DISCUSSION

The evaluation of the VSL system implementation in Michigan focused on two basic issues: the operation of the system itself (e.g., did it actually work in the field); and the effectiveness of VSLs with respect to driver behavior in work zones.

Regarding system operation, the system that was tested and deployed in Michigan experienced problems that might be expected of a prototype as opposed to a fully tested and refined system. As deployed, the VSL system required fairly constant attention from the provider although most of these problems should be solved by a second-generation product. The most important modifications include: better communications with individual trailers and between trailers, better and more flexible vehicle sensors, the ability to monitor (or use) individual vehicle speeds, better and more flexible capability in establishing the algorithms for setting limits, and easier to follow procedures and rules for using the system. It should be noted that the ability to monitor, display, and store individual vehicle speeds is likely to be of more interest for researchers and evaluators and may not be necessary for straightforward use although the estimation of the 85th percentile speed may be needed for the speed-setting algorithms. As evaluated, the system suffers from a lack of real portability (due to the reasons just mentioned) which limit its ease of use in the often-restricted work zone environment.

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 average speeds through the VSL deployment area (increased) and travel time (decreased). 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. Apart from the traffic-related MOEs, the presence of enforcement personnel in the deployment area appeared to have no additional or interactive effect. Finally, an anecdotal review of the crashes in the area showed that most crashes were rear-end collisions and none appeared to be directly associated with the deployment of the system. Indeed, most crashes occurred in the non-VSL controlled direction. From this perspective, the VSL system certainly did not seem to create additional safety problems in the deployment areas.

The deployments of the VSL system on I-96 revealed that the system technology needs to be improved before it can be widely used. This can be achieved through manufacturers improving upon the current product, tighter specification of system performance, or some combination of the two.

Despite the paucity of usable data, it is also 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 the contractor's flexible schedule and unforeseen 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 to 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 much more effectiveness. From this, the conclusion is drawn that VSL systems will have more utility in longer and "simpler" work zones. For example, long zones with short areas of actual work. The limited conclusions that can be reached with respect to the original objectives for the demonstration/evaluation project are summarized in table 9 (next page).

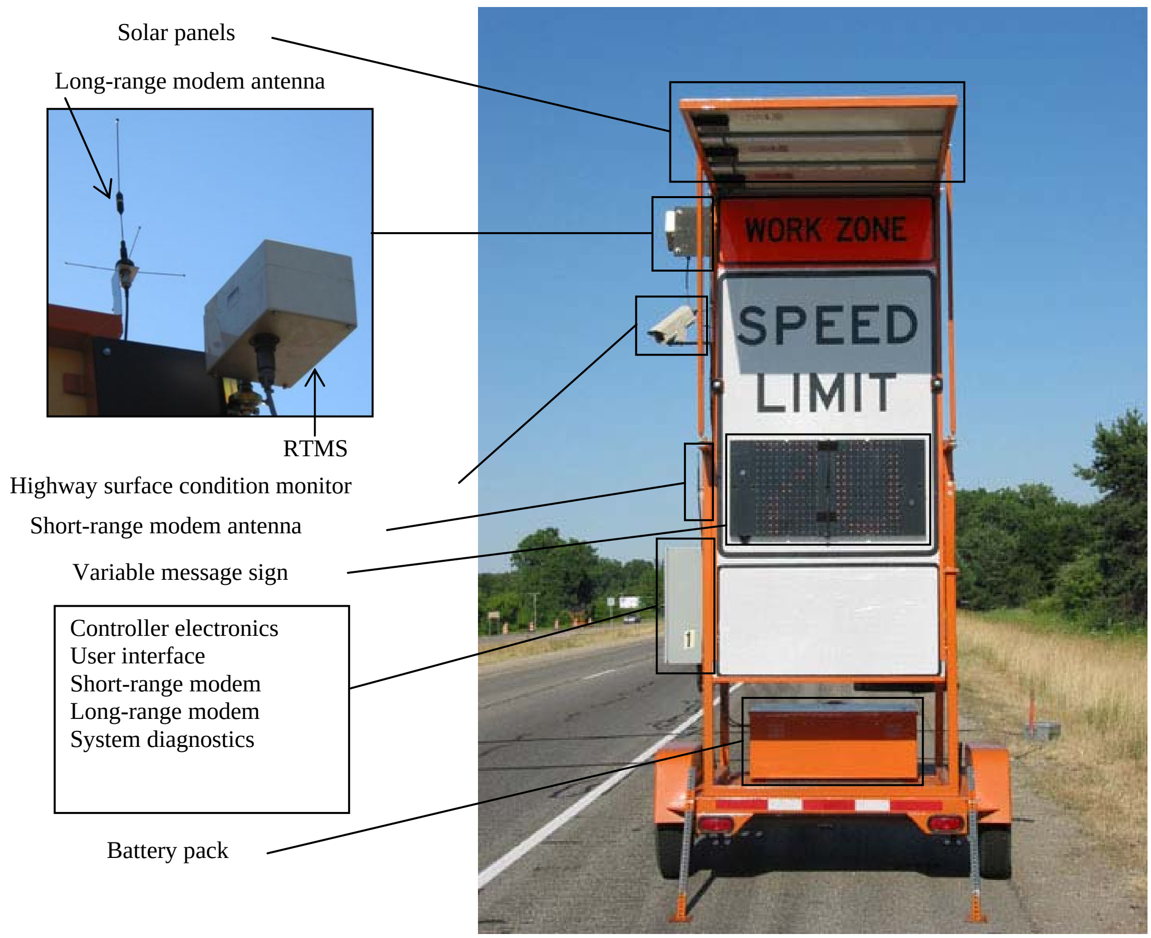
These limitations notwithstanding, it was also seen that the VSL system can present far more credible information to the motorist, responding to both day-to-day changes in congestion as well as significant changes as motorists go through a given zone.

Table 9. Summary of findings and comments regarding original project objectives

objective	finding	comment
increase speed limit compliance	the percentage of vehicles exceeding 60 and 70 mph decreases	as the percentage exceeding decreased, compliance with speed limits increased
increase credibility of speed limits	the VSL system responded well to day-to-day changes in congestion (e.g., different speed limits were displayed in different conditions) and there were positive responses by motorists to these changes	the responsiveness of the VSL system to changing conditions presents more logical/credible speed limits
improve safety	effects of the VSL on speed variance were either undetectable or inconsistent; however, there was no evidence that the VSL system deployment in any way caused additional crashes	the system did not seem to create any safety problems; more data would need to be collected over longer time periods to reach more definitive conclusions regarding safety
improve traffic flow	average speeds through the VSL deployment area increased and travel time decreased (although the latter was small and most likely not noticeable by the average motorist)	the VSL system may have more utility in longer and "simpler" work zones (e.g., long zones with relatively short active work areas)

APPENDIX A
VSL SYSTEM OVERVIEW AND PRE-DEPLOYMENT TESTING PROCEDURE

VSL System Overview



PRE-DEPLOYMENT TESTING PROCEDURE

The following is a brief summary of the various tests that were performed during the pre-deployment testing phase.

1. Testing of Functional Characteristics

Normal conditions

1.1. Ensure that self diagnostics are performed
   a. Test if a call is made to PC terminal or pager to indicate lack of failure
   b. Add a remote display to the system and check for updates of either speed or status,

1.2. Verify that each sensor collects data and transmits data to the controller and the controller communicates with the modem
   a. Traffic sensor performance -Verify that all traffic sensors are collecting data
   b. Wireless communications performance –Verify that the wireless modem performs as expected
   c. Cellular modem - Verify that the cellular modem performs as expected

Failure conditions

1.3. Remove one sensor, run system
   a. Check if system reverts to failure mode and if it displays a default message.
   b. Test if the system is able to recover itself and how long the process takes

2. Data Collection and Processing

2.1. Confirm proper positioning of the RTMS. Measure the mounting height and setback setback (distance from pole to edge of lane 1). Compare with the recommended values (RTMS User Manual, 3.1.2)

2.2. Test if system collects all types of traffic data specified in the documentation (volume, occupancy, average speed and length classification)

2.3. Test the ability to override format specifications (say aggregate data over 15-min). Confirm that the manual override can be done manually, remotely, or both.

2.4. Test manually the functionality of downloading of data on site. Obtain data for the entire testing period

2.5. Test the functionality of remote downloading of data.

2.6. Test if the reporting format is as specified (aggregated over 5-min intervals, in ASCII file)

3. External Interface

3.1. Test the ability to configure the system remotely. Attempt to change settings (i.e., maximum displayed speed limit) by cellular telephone.

3.2. At the master station, switch the system to manual mode. Override the text message to be displayed on the first board and check if it worked.

4. System Quality Factors

4.1. Test volume and speed calculation accuracy

a. Manually collect actual volume data near various trailer locations and compare with volume data provided by the system at the same trailer over the same time period.
b. Collect actual individual vehicle speeds by speed radar near the location of the detection zone of a station. Compare with the speed data transmitted by the station over the same time period.
c. Using the actual speed data above calculate the speed limit to be posted based on the algorithm. Check against the posted speed limit as determined by the system.

4.2. Test the capability to interface with the police pagers

a. Test if the pagers receive the updated speed limit information and how long it takes for the update.
b. Determine if a detailed log of posted speed limits by station can be saved so that police query the system and if it can be transmitted to a PC for future processing.

4.3. Evaluate the effect of equipment placement on detection accuracy

a. Vary the spacing between the stations (0.5, 1.0, 1.5 miles) by skipping one, then two trailers in the sequence. Test if the stations can still communicate with the master.
b. Determine the extent of “background” issues effect. After the system is ready (has incorporated constant signals into the background) perform a volume data collection (for 30 min). Compare actual volumes to the volumes determined by the system over the same data collection period. (RTMS 2.5.1)

5. Evaluate Portability

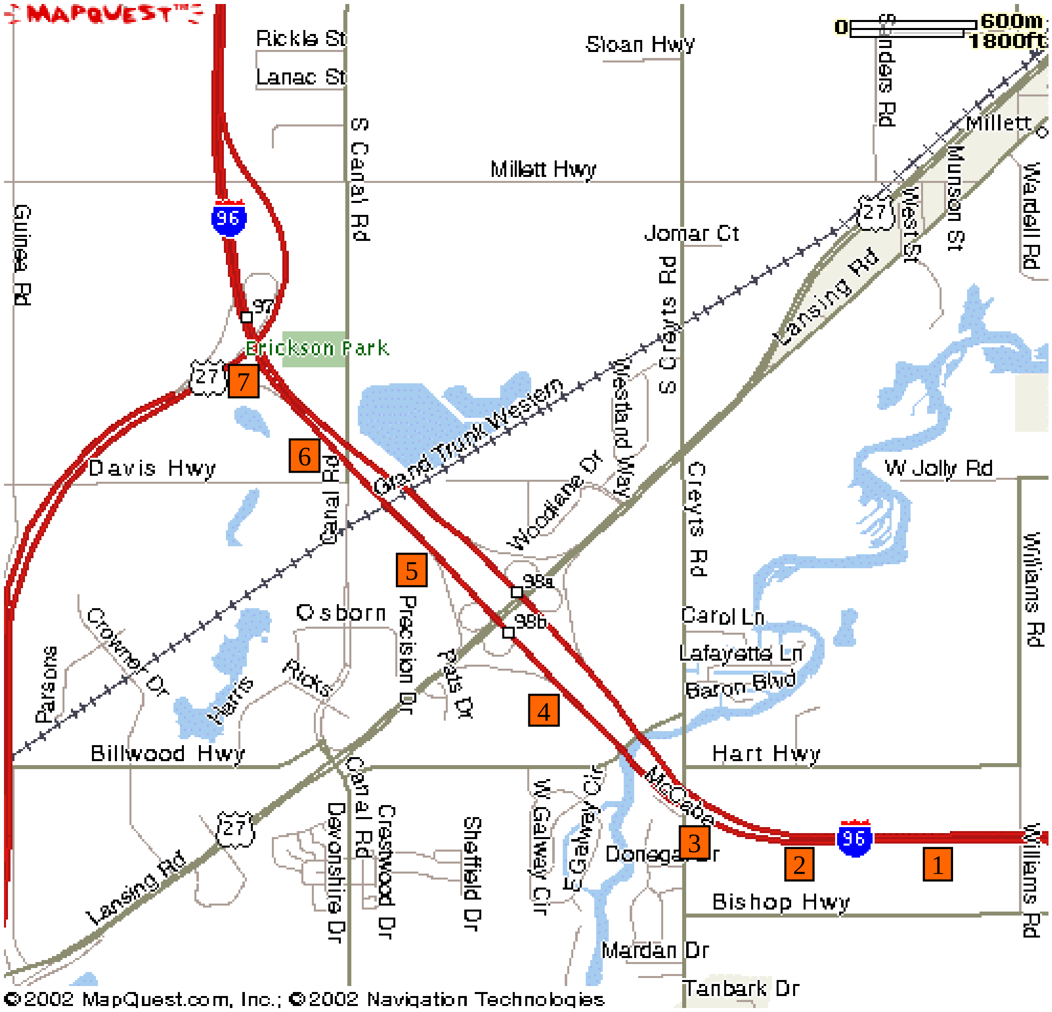
5.1 Determine the length of the set up and take down time

5.2 Test if the system needs to be recalibrated if it is turned off and then on at the same site.

APPENDIX B
VSL System Deployments and Speed Limit Algorithms by Deployment

First Deployment

I-96 Eastbound
Location Map



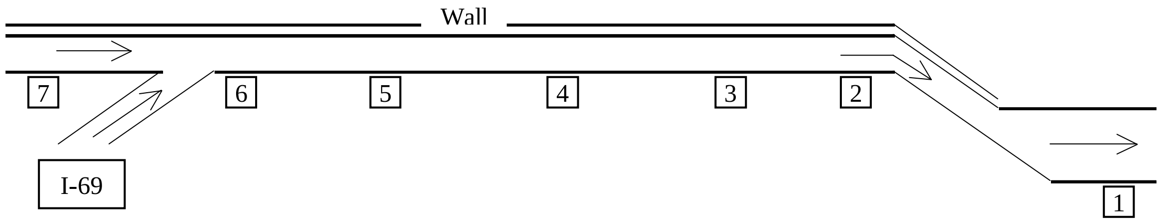
n	VSL trailer

relative sign locations

trailer	distance relative to trailer 7 (mile)	distance to the next trailer (mile)
7	0.0	0.3
6	0.3	0.5
5	0.8	0.6
4	1.4	0.6
3	2.0	0.3
2	2.3	0.4
1	2.7	

FIRST DEPLOYMENT

SIGN LOCATIONS



SPEED DISPLAYS

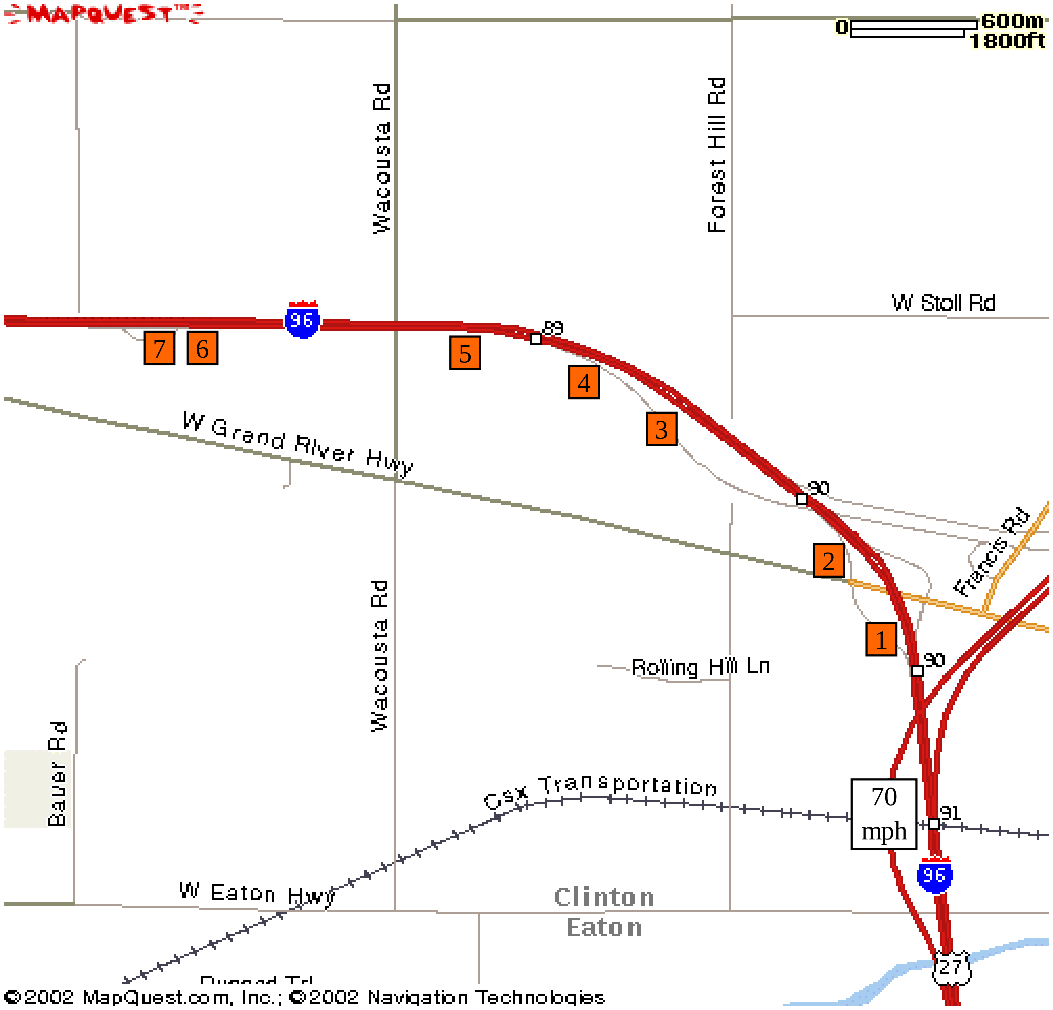
Trailer	Displayed Speed	VSL based on avg. speed at trailer
1	Based on profile 3.	1
2	Based on profile 1.	2
3	Based on profile 2.	3
4	Based on profile 2.	3
5	Based on profile 2.	4
6	Based on profile 2.	5
7	Based on profile 1.	7

SPEED-SETTING PROFILES (ALGORITHM)

PROFILE:	1	2	3
L.O. THRESHOLD - 0%	50	60	70
H.O. THRESHOLD – 90%	40	40	40
MID OCCUPANCY			
$v < 40$	40	40	40
$40 \leq v < 43$	45	45	45
$43 \leq v < 48$	50	50	50
$48 \leq v < 53$	50	55	55
$53 \leq v < 58$	50	60	60
$58 \leq v < 63$	50	60	65
$63 \leq v < 68$	50	60	70
$v \geq 68$	50	60	70

Second Deployment

I-96 EASTBOUND LOCATION MAP



n	VSL trailer

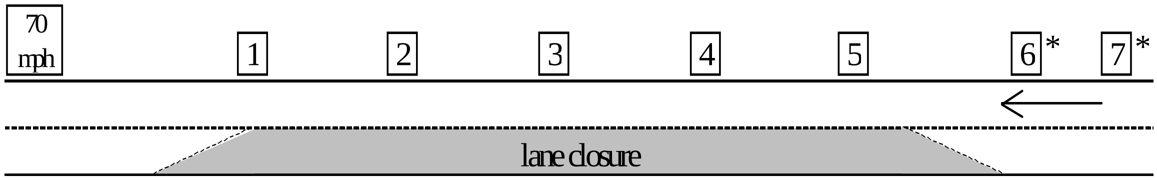
relative sign locations

trailer	distance relative to trailer 7 (mile)	distance to the next trailer (mile)
7	0.0	0.1
6	0.1	0.8
5	0.9	0.4
4	1.3	0.3
3	1.6	0.7
2	2.3	0.3
1	2.6	0.6
70 mph	3.2	

* The lane closure started at 0.2 mile east of trailer 6.

SECOND DEPLOYMENT

SIGN LOCATIONS



***Signs 6 and 7 located at the locations of the 50 mph and 60 mph static signs respectively.

SPEED DISPLAYS

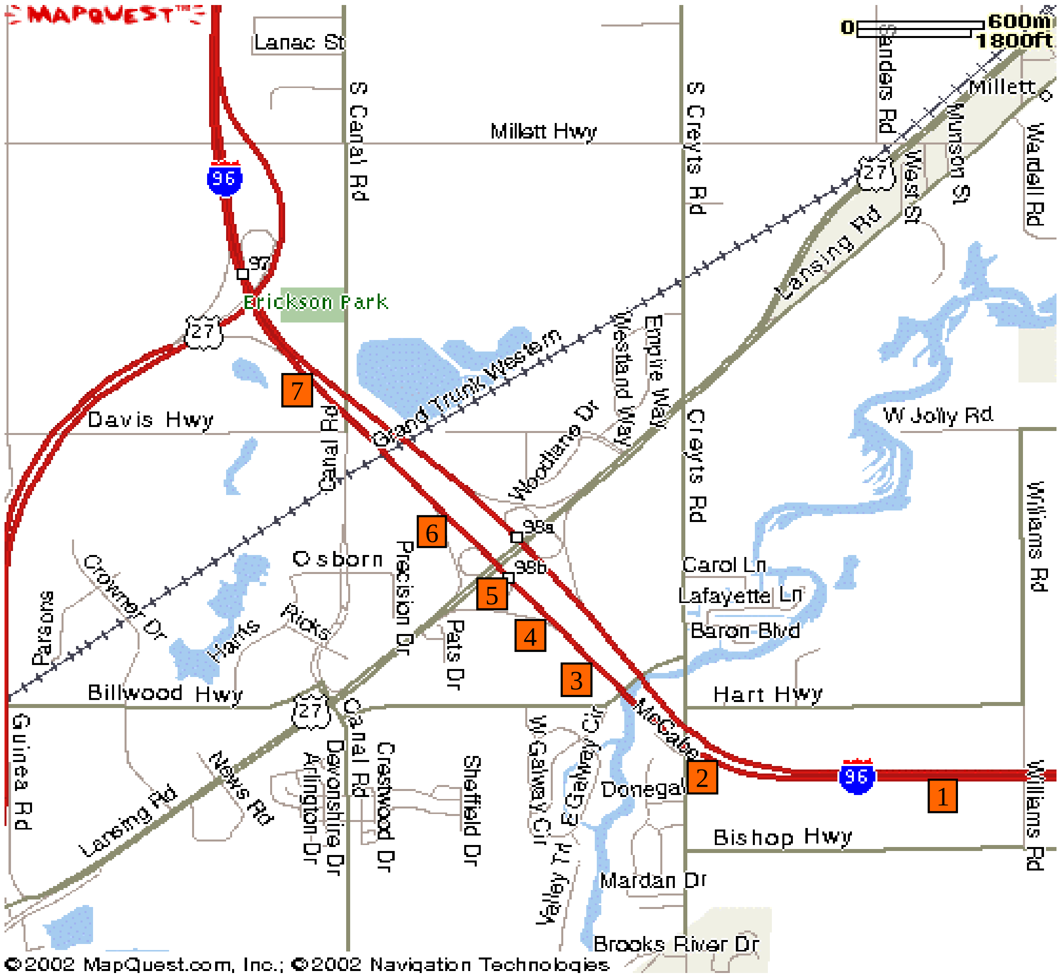
Trailer	6AM - 8PM	8PM – 6AM	VSL based on avg. speed at trailer
1	Based on profile 1.	Based on profile 3.	1
2	Based on profile 1.	Based on profile 3.	1
3	Based on profile 1.	Based on profile 3.	2
4	Based on profile 1.	Based on profile 3.	3
5	Based on profile 1.	Based on profile 3.	4
6	50 mph	Based on profile 3.	5
7	60 mph	Based on profile 4.	6

speed-setting profiles (algorithms)

PROFILE:	1	2	3	4
L.O. THRESHOLD - 0%	50	60	70	70
H.O. THRESHOLD – 70%	40	40	40	60
MID OCCUPANCY				
$v < 40$	40	40	40	60
$40 \leq v < 43$	45	45	45	60
$43 \leq v < 48$	50	50	50	60
$48 \leq v < 53$	50	55	55	60
$53 \leq v < 58$	50	60	60	60
$58 \leq v < 63$	50	60	65	65
$63 \leq v < 68$	50	60	70	70
$v \geq 68$	50	60	70	70

Third Deployment

I-96 EASTBOUND LOCATION MAP



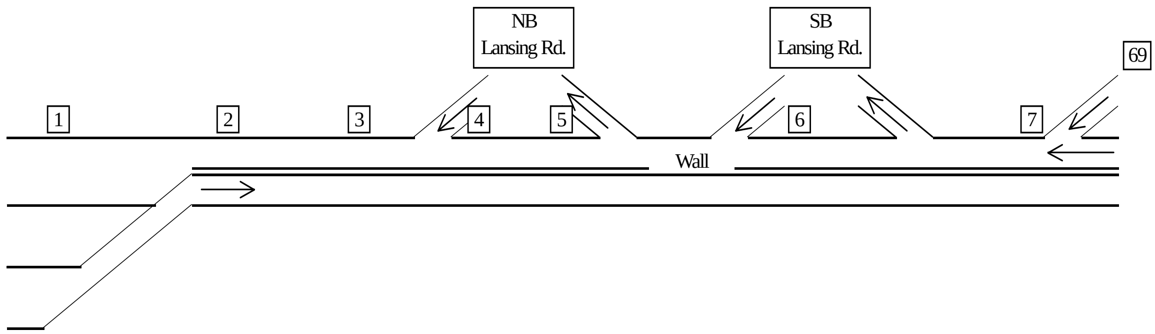
n VSL trailer

relative sign locations

trailer	distance relative to trailer 7 (mile)	distance to the next trailer (mile)
7	0.0	0.6
6	0.6	0.2
5	0.8	0.3
4	1.1	0.1
3	1.2	0.4
2	1.6	0.7
1	2.3	

THIRD DEPLOYMENT

SIGN LOCATIONS



SPEED DISPLAYS

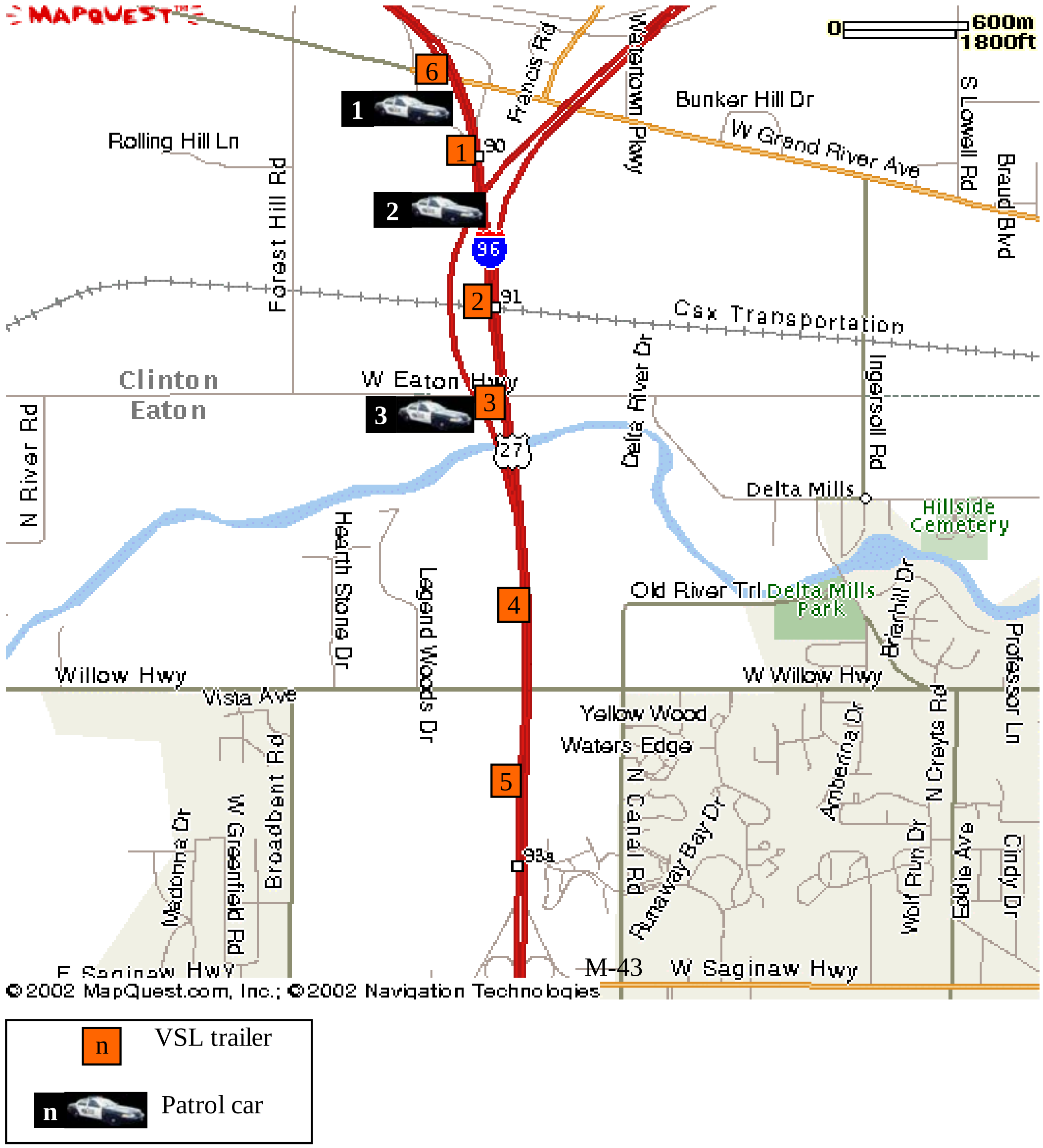
Trailer	Displayed Speed	VSL based on avg. speed at trailer
1	70 mph	N/A
2	Based on profile 3.	1
3	Based on profile 3.	2
4	Based on profile 1.	4
5	Based on profile 2.	N/A*
6	Based on profile 1.	6
7	60 mph	N/A

* Occupancy is based on itself.

SPEED-SETTING PROFILES (ALGORITHMS)

PROFILE:	1	2	3
L.O. THRESHOLD - 0%	50	60	70
H.O. THRESHOLD – 90%	40	40	40
MID OCCUPANCY			
$v < 40$	40	60	40
$40 \le v < 43$	45	60	45
$43 \le v < 48$	50	60	50
$48 \le v < 53$	50	60	55
$53 \le v < 58$	50	60	60
$58 \le v < 63$	50	60	65
$63 \le v < 68$	50	60	70
$v \ge 68$	50	60	70

FOURTH DEPLOYMENT
I-96 WESTBOUND
LOCATION MAP

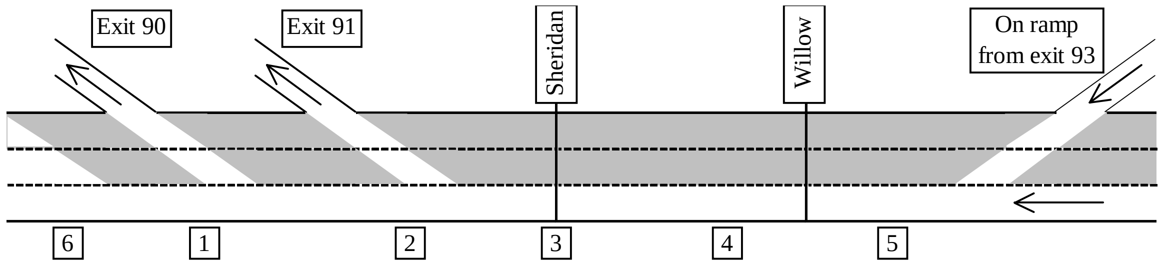


relative sign locations

Trailer	Distance relative to trailer 5 (miles)	Distance to the next trailer (miles)
5	0.00	0.60
4	0.60	0.70
3	1.30	0.40
2	1.70	0.60
1	2.30	0.30
6	2.60	

FOURTH DEPLOYMENT

SIGN LOCATIONS



SPEED DISPLAYS

Trailer	6AM - 10PM	10PM – 6AM	VSL based on avg. speed at trailer
1	Based on profile 1.	Based on profile 2.	1
2	Based on profile 1.	Based on profile 2.	1
3	Based on profile 1.	Based on profile 2.	2
4	Based on profile 1.	Based on profile 2.	3
5	Based on profile 1.	Based on profile 2.	4
6	70 mph (fixed)	70 mph (fixed)	N/A

speed-setting profiles (algorithms)

PROFILE:	1	2
L.O. THRESHOLD - 0%	50	70
H.O. THRESHOLD – 90%	40	40
MID OCCUPANCY		
$v < 40$	40	40
$40 \le v < 43$	45	45
$43 \le v < 48$	50	50
$48 \le v < 53$	50	55
$53 \le v < 58$	50	60
$58 \le v < 63$	50	65
$63 \le v < 68$	50	70
$v \ge 68$	50	70

OTHER CONDITIONS: **The speed difference between a sign and the previous upstream sign can never be less than –10 mph, with the downstream sign being controlling sign.**