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Work Zone Variable Speed Limit Systems: Effectiveness and System Design Issues

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Variable speed limit (VSL) systems have been used in a number of countries, particularly in Europe, as a method to improve flow and increase safety. VSLs use detectors to collect data on current traffic and/or weather conditions. Posted speed limits are then dynamically updated to reflect the conditions that motorists are actually experiencing. Presenting drivers with speed limits that are appropriate for current conditions may reduce speed variance, a concept sometimes called speed harmonization. If properly designed, VSL systems have been shown to reduce crash occurrence and can also reduce system travel time through increased uniformity in traffic speeds.

High-volume urban work zones tend to be prone to congestion and safety problems, and VSLs may be one way to ameliorate these issues. VSLs were recently installed at a high-volume, congested urban work zone located on I-495 (the Capital Beltway, hereinafter the Beltway) between the Springfield Interchange in Springfield, Virginia, and the Virginia-Maryland state line on the Woodrow Wilson Memorial Bridge. VSL signs were activated in late July 2008, but initial evaluations of the system showed inconclusive effects. Changing site conditions made a direct before-and-after evaluation of the system deployed in the field problematic, and some problems with the control algorithm were also noted.

Given the difficulties in evaluating the system deployed in the field, a calibrated simulation of the site was constructed to assess the effects of the VSL system on traffic operations and safety surrogate measures. The simulation platform also provided an opportunity to examine a number of system configurations to assess how changes in system design and driver behavior might affect a variety of measures. The results indicated that the VSL could create substantial improvements in traffic operations provided the demand did not exceed capacity by too large a margin. The location of the VSL signs played an important role in operational performance.

The study recommends that the Virginia Department of Transportation continue to pursue this technology but carefully scrutinize algorithm design and VSL sign placement. Further, a cost/benefit analysis indicated that VSLs may be most appropriate for long-term applications.

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ABSTRACT

Variable speed limit (VSL) systems have been used in a number of countries, particularly in Europe, as a method to improve flow and increase safety. VSLs use detectors to collect data on current traffic and/or weather conditions. Posted speed limits are then dynamically updated to reflect the conditions that motorists are actually experiencing. Presenting drivers with speed limits that are appropriate for current conditions may reduce speed variance, a concept sometimes called speed harmonization. If properly designed, VSL systems have been shown to reduce crash occurrence and can also reduce system travel time through increased uniformity in traffic speeds.

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INTRODUCTION

As congestion continues to increase in urban areas, states are increasingly searching for innovative approaches to maximize existing roadway capacity. One major source of congestion is highway work zones. Studies (Chin et al., 2002; Cambridge Systematics, Inc., with Texas Transportation Institute, 2005) have estimated that between 10% and 17% of all congestion and delay experienced by drivers was caused by work zones. Work zones are also often associated with an increased risk for crashes. One synthesis found that crash rates can increase 7% to 119% when work zone crashes are compared to the pre-construction conditions (Ha and Nemeth, 1995). Further, a study of Virginia work zone crash data indicated that many rear-end crashes are correlated with high speed variance and speed differentials (Garber and Zhao, 2002). High speed variance has also been strongly correlated with crash rates (Committee for Guidance on Setting and Enforcing Speed Limits, 1998; Garber and Gadirau, 1988).

One potential method that can be used to mitigate operational and safety concerns in work zones is the use of variable speed limits (VSLs). VSLs set speed limits based on current road and traffic conditions, possibly resulting in higher credibility of speed limits, greater levels of compliance, and less variation in speeds. If drivers are presented with speed limits appropriate for the current conditions, the likelihood that drivers will select similar speeds—concept sometimes called speed harmonization—will increase (Committee for Guidance on Setting and Enforcing Speed Limits, 1998).

VSL systems have been successfully implemented in many areas around the world, particularly in Europe (Mirshahi et al., 2007; Robinson, 2000). Most VSL systems operate by first obtaining data from sensors. These data normally consist of general traffic characteristics, but in some cases, other information such as road surface condition and weather conditions is also collected. The data are then input into an automated algorithm, or control logic, to determine if a reduction or increase in the speed limit at certain locations would improve driving conditions. A typical method of speed alteration in a bottleneck management scenario has been to decrease upstream speed limits approaching a queue while increasing downstream limits past the bottleneck. This should decrease incoming speeds to reduce conflicts at the end of the queue while increasing flow exiting a congested area to alleviate a bottleneck more quickly.

In July 2008, a VSL system was installed along a segment of heavily traveled urban interstate in Northern Virginia that will undergo several years of continuous construction. This was the first deployment of a traffic-responsive VSL system in Virginia. The site was located between the I-95/I-495/I-395 Springfield Interchange and the Woodrow Wilson Memorial Bridge, known as the Woodrow Wilson Bridge (WWB), between Virginia and Maryland. The VSL system was installed to address capacity reductions that would occur during overnight periods, resulting in considerable congestion. Previous VSL deployments in other locations often yielded improvements in flow, so it was hoped that travel conditions would be improved by deploying the VSL at this site. There is little guidance on how these systems should be configured. Likewise, there is little information available on how a VSL system might operate on an extremely congested urban freeway.

PURPOSE AND SCOPE

The purpose of this project was to evaluate the potential of VSL systems to improve safety and mobility in work zones on heavily traveled urban freeways. The scope of the project was limited to the VSL system deployed in July 2008 on the WWB described previously, the associated work zone site, and immediately adjacent freeways.

Existing data on the VSL system’s deployment, operation, and effect on operations and safety were reviewed to determine lessons learned from the field deployment. This was augmented by visits to the site to observe the set up and operations of the system. The actual work zone site was then modeled using a microscopic computer simulation to help assess the role of key system parameters in dictating the overall operational effectiveness of the VSL system.

The specific objectives of the project were:

- Review the WWB VSL field implementation to determine lessons learned on the deployment and operation of the system. The effect of the system on traffic operations and safety were also reviewed. Site visits and existing project documentation were used to address this objective.

- Assess the effectiveness of VSLs over a range of system designs, driver characteristics, and roadway network characteristics using a simulation test bed. This part of the evaluation focused on the operational effects of VSL since the impact of the VSL on crashes could not be directly assessed with simulation.

- Develop recommendations for improvements to the design and operation of future VSL systems to ensure they are as effective as possible.

METHODS

The objectives of the study were achieved by performing four major tasks:

1. *Conduct a review the literature.* Field tests and simulation studies were reviewed to gather information on VSL system and algorithm design as well as measures of effectiveness (MOEs) applicable to VSLs.

2. *Review the WWB VSL system.* Trips to the WWB VSL site were made to examine how the system was deployed and responded to changing traffic conditions. Available project data were also reviewed to determine any lessons learned during the deployment and initial operation of the WWB VSL system.

3. *Develop and calibrate a microscopic simulation of the WWB VSL system*. A simulation network was developed based on the WWB VSL site. The results of the literature review and the review of the WWB VSL system were used to develop an experimental plan to investigate the impact of important system design parameters and driver behavior characteristics on overall system performance. The network was then calibrated based on travel time data collected in the field.

4. *Analyze the results of the simulation.* The results of the simulations were analyzed to determine the impact of different factors and their interactions on traffic operations and safety surrogate measures. The results of this analysis were used to develop recommendations for future VSL deployments.

Literature Review

The VDOT Research Library, the University of Virginia library, and relevant online databases were searched to identify information related to VSLs. In particular, information on VSL system design and overall VSL performance was examined. Field deployments and simulation studies related to VSLs were reviewed.

Review of the WWB VSL System

Field visits to the WWB VSL system were made to gather information about the actual operation of the system. From this, observations were recorded pertaining to traffic conditions, sign visibility, and enforcement strategies. Documentation of system performance and operational issues was synthesized and combined with field observations to assess the VSL system as deployed in the field.

Development and Calibration of a Microscopic Simulation

Simulation Development

The microscopic traffic simulation model VISSIM was used to investigate the performance of VSLs. VISSIM has an add-on module called the Vehicle Actuated Programming interface that allows the user to develop code that dictates driver behavior. This interface was used to develop control algorithms that could simulate a variety of VSL configurations and was the key reason this software was selected for this project. VSL sign locations and detectors and their impact on driver behavior could also be simulated using this tool.

A VISSIM model of the Beltway site was developed by tracing the roadway network over a background aerial photograph. The VISSIM network extended beyond the actual limits of the VSL zones to create a realistic simulation where vehicles would enter the network at normal travel speeds. This also provided ample room to model queuing, ensuring that all measures were captured accurately. On- and off-ramps were modeled from the freeway to their intersection with surface streets so that queuing on the ramps would be captured as well. Figure 1 shows the overall network constructed in VISSIM, extending from beyond the Springfield Interchange and into Maryland.

Volume data on the Beltway between the Springfield Interchange and the Washington, D.C. / Virginia line were gathered from the Virginia Department of Transportation's (VDOT) Traffic Monitoring System (TMS) for the northbound and southbound directions of I-95/I-495. Next, ramp volumes (for on- and off-ramps) were estimated. Since volume data for the ramps were not so readily available as the main line volume data, estimates were based on the counts of ramp volumes for this section of the Beltway made by Mazzenga and Demetsky (2009). These values were subsequently inflated using daily and seasonal factors derived from a continuous count station located in this section of the Beltway.

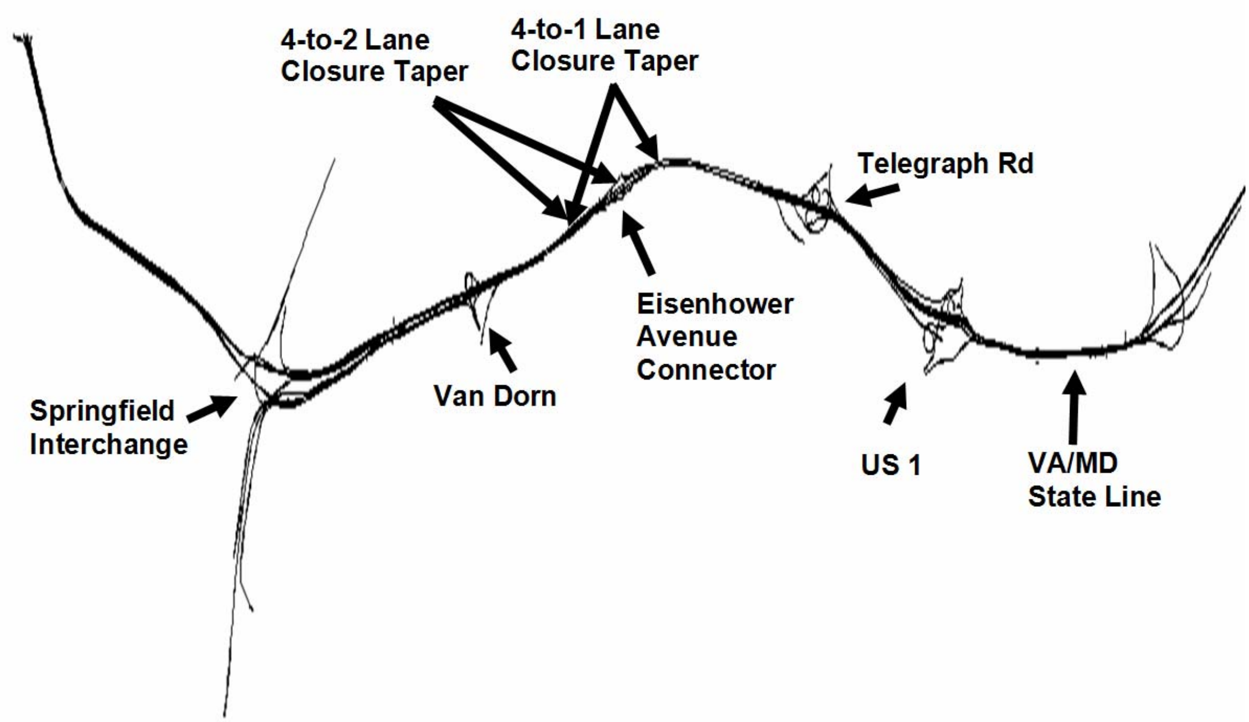

Figure 1. VISSIM Network of I-95/I-495. Not to scale: Vertical scale exaggerated for presentation.

After the base simulation network was developed, an experimental plan was created based on the findings from the review of the field deployment and the literature review. Key factors that may influence the performance of the system were identified, and then they were evaluated in a factorial design so that main effects and factor interactions could be identified. The specific experimental design tested is discussed later.

Vehicle detectors and VSL sign locations were placed in the simulation at the same locations as in the real-world field test. These locations were determined by the consultant operating the WWB VSL system and were strictly adhered to for the simulation of all VSL alternatives. As such, exact sign locations may not have been optimal for a specific work zone configuration but were used to allow for consistency between the field and simulation environments.

Several MOEs were evaluated using the simulation. Travel time, speed, queue length, stops, and lane change information were collected throughout the simulation. Travel time and mean speed served as operational measures, and the standard deviation of speed, mean queue length, and mean number of lane changes per 5 min served as surrogate measures for safety.

Travel Time Data Collection and Simulation Calibration

Travel time data were collected at the site during work zone lane closures to calibrate the model. Floating car runs using global positioning system (GPS) units were performed to generate time-space trajectories of the probe vehicles. The GPS location data were converted into speed data, which could also be used to reveal the location within each run where speeds dropped because of the work zone. These data were used to calibrate the VISSIM model to ensure that the model accurately portrayed real-world traffic conditions.

The boundaries of the travel time sections were determined for both directions. The distance of the travel time section exceeded the actual VSL limits in both directions so that all travel conditions encompassing the entire area could be reviewed, if necessary. It also allowed the transition from uncongested flow to queued traffic to be captured.

Data collection trips were made between June and September 2008. They were typically conducted over two consecutive weekday nights (usually Tuesday and Wednesday) between the hours of 9 P.M. and 2 A.M. The duration of data collection was usually around 4 hours per night. “Before” data collection trips took place June 10 through 12, June 17 through 19, and July 14 through 16, 2008. The “after” trips were not conducted until nearly 1 month later after the VSL system was activated so that initial technical issues could be resolved and drivers could become acclimated to the system. As a result, the after trips were performed August 12 through 14, August 20 through 21, and September 22 through 24, 2008. Prior to the scheduling of each data collection trip, VDOT lane closure schedules were consulted. Each data collection trip was scheduled on days where at least one lane was scheduled to be closed overnight for work activities. The researchers sought out these cases since they wanted to capture information during congested conditions. Two floating cars were used for this data collection, with staggered start times of approximately 10 min. Lane closure locations, disabled vehicles, and police vehicles alongside the road were logged by the probe vehicles. In addition, general notes of traffic conditions and anything that could possibly have had some effect on traffic conditions were recorded. Afterward, the data from each run in each direction were individually downloaded and placed into Microsoft Excel files for analysis.

Calibration of the model was possible through a comparison of travel time data. Travel times collected from the simulation were compared to travel times found by driving within the actual work zone. Driving behaviors were modified until all simulated travel times fell within 10% of the real-world travel times.

Simulation Data Analysis

VISSIM was programmed to produce unique output files for each run performed for every simulation scenario. The MOE output files for this project included raw speed data, queue length, vehicle stops, and lane change data. Data were summarized in 5-min aggregation intervals.

First, high level trends were examined graphically. Changes in speed, queue length, stops, and lane changes over the course of the simulation were plotted across different factors to determine which variables appeared to be creating differences in system performance. Second, the actual influence of each factor compared to the others was analyzed using SPSS statistical software. Testing was performed through a univariate general linear model that tested each MOE independently against the fixed levels of each factor used in this project. The differences among the factors were determined at an $\alpha = 0.05$ significance level. This analysis indicated the significance of both individual factors and interactions between factors. The primary emphasis of the analysis was on examining changes in operations. VSLs are also likely to create safety improvements, but these improvements are difficult to quantify directly using simulation. Some safety surrogate measures (such as lane changes and standard deviation of speed) were examined, but directly correlating those measures to changes in crashes is difficult.

RESULTS

Literature Review

Several field evaluations of VSLs on European freeways have shown that they can produce significant safety and mobility benefits. Crashes fell from 10% to 30% after VSLs were installed on freeways in Germany (Mirshahi et al., 2007; Robinson, 2000), the United Kingdom (Mirshahi et al., 2007; Robinson, 2000), and The Netherlands (Mirshahi et al., 2007). In addition, results from Finland showed a decrease in mean speed and speed variability when a VSL was installed because of poor weather conditions (Rama, 1999). Data from The Netherlands showed that throughput may be able to increase 3% to 5% because of the speed harmonization benefits of VSLs (Mirshahi et al., 2007). These systems were often used in conjunction with automated speed enforcement, which may have influenced the effectiveness of these deployments.

Several simulation-based evaluations of freeway VSLs have also been conducted, although only one focused on work zone operations. One study of a freeway VSL system investigated the impact of using different time intervals between speed limit changes (Lee et al., 2004). A 2-min interval was found to be detrimental to safety, whereas 5- and 10-min intervals were found to reduce crash potential. Another simulation based on a segment of I-4 in Orlando, Florida, showed that changing speed limits by 10- or 15-mph increments produced negative safety impacts versus changing them in 5-mph increments (Abdel-Aty and Dhindsa, 2007). An evaluation of Northern Virginia roads found that there were benefits to using VSLs on freeways, although benefits were minimal under heavy congestion (Mazzenga and Demetsky, 2009). The one simulation-based study of work zone VSLs focused on the development of new control algorithms rather than implementation guidance for sites (Park and Yadlapati, 2002). That study examined the ability of different logics to facilitate improved merging at lane closures and improve a variety of safety surrogate measures.

There are relatively few examples of field deployments of work zone VSLs. In some cases, work zone VSL systems were not traffic responsive at all, changing based only on time of day or some other fixed logic. For example, one study examined a VSL system that changed the posted speed limit based solely on the time of day (McMurtry et al., 2009). Another study of I-494 in Minnesota evaluated a traffic-responsive advisory VSL system composed of two signs (Kwon et al., 2007). That evaluation found that the VSLs created a 7% improvement in throughput during 1 hour of the day, although changes during other hours were not significant. Another study evaluated a traffic-responsive work zone VSL system on I-96 near Lansing, Michigan (Lyles et al., 2004). As a result of the VSL implementation, average travel speeds increased by about 1 to 3 mph when the VSLs were in operation, but no noticeable change in speed variance was found (Lyles et al., 2004). The researchers thought that certain operating restrictions imposed by the Michigan Department of Transportation, such as a 50 mph speed limit restriction near ramps and congestion preceding the VSL, likely reduced the beneficial effects of the system (Lyles et al., 2004). In contrast to European deployments, this project relied on traditional enforcement by police who were notified by pager of speed limit changes.

Table 1 summarizes the major findings from the literature review. Although the literature review provides some insight into the potential effectiveness of VSL systems, there has been little investigation into a number of system design and driver behavior parameters. The impact of certain network variables, such as driver compliance with posted speed limits, has not been thoroughly investigated along a network based on an actual segment of highway. Likewise, the combined impact of multiple variables has not been assessed. In addition, certain MOEs, including queue length, vehicle stops, and lane changes, have not received a great deal of study.

WWB VSL Assessment

As previously discussed, the WWB VSL project was deployed to ameliorate potential congestion and safety problems as a result of the Telegraph Road interchange reconstruction project on the Beltway. This project was part of the larger WWB replacement project. Between three and six travel lanes were available in each direction through the work zone, with four lanes usually available in the work zone activity area. The work zone was approximately 5.2 mi long

Table 1. Summary of Reviewed Field Tests and Simulations of VSLs

Type of Test	Location	Major Findings
Field	Germany, Autobahn 5	30% reduction in injury crashes[a]
	United Kingdom, M25	10%-15% reduction in crashes.[b]
	The Netherlands	16% reduction in crashes and 3%-5% increase in system throughput[a]
	Near Munich, Germany, Autobahn 9	Slow flow sustained during times of congestion; similar German VSL sections have seen 20%-30% reduction in crash rates[b]; concept of speed-flow-density algorithm uncovered here[c]
	Finland, Highway E18	Mean speed and speed variability decreased; projected crash rate decrease of 8%-25%[d]
	Utah, I-80 work zone	VSLs changed by time of day; some reduction in speed variance at entrance to activity area[e]
	Minnesota I-494 work zone	Throughput increased 7% during 1 hour of day; no change in another hour; compliance with speed limits 20%-60%[f]
	Michigan, I-96 work zone	Speeds slightly higher than if no VSLs present, resulting in minimal decrease in travel time[g]; several restrictions imposed on system may have minimized potential benefits
Simulation	Hypothetical freeway	Short (2-min) intervals were detrimental for safety; 5- and 10-min intervals potentially reduced crashes.[h]
	Orlando, I-4 segment	Best results involved 5-mph increment change by decreasing upstream limits while increasing downstream limits or just simply increasing downstream limits[i]
	I-64 in Covington, Virginia work zone evaluation	The two logics concerned with reducing mean speeds produced safer conditions[j]
	Northern Virginia	VSLs alleviated dangerous drops in speed and reduced queue length but were less effective under heavy congestion[k]

[a] Mirshahi, M., Obenberger, J., Fuhs, C.A., Howard, E., Krammes, R.A., Kuhn, B.T., Mayhew, R.M., Moore, M.A., Sahebjam, K., Stone, C.J., and Yung, J.L. *Active Traffic Management: The Next Step in Congestion Management.* FHWA-PL-07-012. Federal Highway Administration, Washington, DC, 2007.

[b] Robinson, M. Examples of Variable Speed Limit Applications. Presented at the Speed Management Workshop, 79th Annual Meeting of the Transportation Research Board, Washington, DC, January 9, 2000.

[c] Bertini, R.L., Boice, S., and Bogenberger, K. Dynamics of a Variable Speed Limit System Surrounding a Bottleneck on a German Autobahn. In *Transportation Research Record: Journal of the Transportation Research Board,* No. 1978. Transportation Research Board of the National Academies, Washington, DC, 2006, pp. 149-159.

[d] Yrjö, P-S, and Jukka , L. (1995) as cited in Research and Innovative Technology Administration. In Finland, road weather information posted on dynamic message signs was well perceived and remembered by surveyed drivers; 90 percent deemed variable speed limit signs useful. http://www.itsbenefits.its.dot.gov/its/benecost.nsf/print/1e3bc12fd49b30f98525733a006d5f1b. Accessed January 16, 2008.

[e] McMurtry, T., Saito, M., Riffken, M., and Heath, S. Variable Speed Limit Signs: Effects on Speed and Speed Variation in Work Zones. *TRB 88th Annual Meeting Compendium of Papers on CD-ROM.* Transportation Research Board of the National Academies, Washington, DC, 2009.

[f] Kwon, E., Brannan, D., Shouman, K., Isackson, C., and Arseneau, B. Development and Field Evaluation of Variable Advisory Speed Limit System for Work Zones. In *Transportation Research Record: Journal of the Transportation Research Board,* No. 2015. Transportation Research Board of the National Academies, Washington, DC, 2007, pp. 12-18.

[g] Lyles, R.W., Taylor, W.C., Lavansiri, D., and Grossklaus, J. A Field Test and Evaluation of Variable Speed Limits in Work Zones. *TRB 86th Annual Meeting Compendium of Papers on CD-ROM*. Transportation Research Board of the National Academies, Washington, DC, 2004.

[h] Lee, C., Hellinga, B., and Saccomanno, F. Assessing Safety Benefits of Variable Speed Limits. In *Transportation Research Record: Journal of the Transportation Research Board,* No. 1897. Transportation Research Board of the National Academies, Washington, DC, 2004, pp. 183-190.

[i] Abdel-Aty, M., and Dhindsa, A. Coordinated Use of Variable Speed Limits and Ramp Metering for Improving Safety on Congested Freeways. *TRB 86th Annual Meeting Compendium of Papers on CD-ROM*. Transportation Research Board of the National Academies, Washington, DC, 2007.

[j] Park, B., and Yadlapati, S. *Development and Testing of Variable Speed Limit Logics at Work Zones Using Simulation.* University of Virginia, Charlottesville, 2002.

[k] Mazzenga, N.J., and Demetsky, M.J. *Investigation of Solutions to Recurring Congestion on Freeways*. VTRC 09-R10. Virginia Transportation Research Council, Charlottesville, 2009.

in the northbound direction (the Outer Loop) and 4.9 mi long in the southbound direction (the Inner Loop) and extended between the Springfield Interchange and the WWB into Maryland. There were five interchanges within this area. This section of road had an annual average daily traffic (AADT) in 2008 of approximately 154,000 and has significant recurring congestion during peak hours. A unique feature of the site is that the WWB is a drawbridge that occasionally opens during overnight hours.

During construction, lane closures were planned for overnight hours to minimize traffic disruptions. One or two lanes were typically closed, and the length of the activity area following the lane closures was usually around one-half mile. Even with nighttime lane closures, significant queuing was still expected given the high traffic volumes. The general contractor for the WWB project and VDOT agreed to test VSLs as an innovative congestion management tool given the high traffic volumes at the site and the complexity of the work zone.

VSL System Configuration and Operation

The VSL system was activated on July 28, 2008, along both the Inner Loop and the Outer Loop, although the limits of the system were not the same in each direction. The Outer Loop's VSL system began just east of the Springfield Interchange and ended between the Telegraph Road and U.S. 1 interchanges. The Inner Loop's VSL system began with a sign located around the midpoint of the WWB and was in effect until just west of the Eisenhower Avenue Connector Interchange. In total, seven VSL signs were installed on the Outer Loop and five were installed on the Inner Loop. The total cost of the system to VDOT was $3.2 million for 2 years, including hardware, software, training, and operational support.

Prior to the installation of the VSLs, a static 55 mph speed limit was posted at the site. The VSL system installed was regulatory, not advisory, but was operated in only a traffic responsive mode when lanes were closed. The VSL system had an allowable maximum speed limit of 50 mph, and the minimum speed limit that could be posted was 35 mph. When lanes were not closed, the maximum speed limits were displayed in a static mode. Following VSL activation, speed limits were displayed using the signs shown in Figure 2. Flashing beacons were present on the signs to alert drivers when the VSLs were active.

Once the VSLs had been activated, static informational signs were used to inform motorists of the upcoming VSL zone and the length of the zone. Figure 3 shows an example of this signing. In addition, several variable message signs leading up to the VSL zone displayed expected travel times through the work zone. If significant lane closures were planned, the variable message signs would sometimes suggest that motorists take an alternate route so as to avoid congestion.

The control logic used to determine the posted speed limit was a key feature of the system. A detailed description of the control logic is provided later in this report; it is briefly summarized here. Upon initial activation, all VSL signs were set to display their maximum allowable speed limit. Next, data from microwave sensors co-located with the VSL signs were used to determine the cumulative volume and cumulative occupancy at each site during an analysis interval.

Figure 2. VSL Signs Posted in Work Zone

Figure 3. Sign Alerting Drivers to Beginning of VSL Zone

The work zone was divided into “zones” in each direction, and all speed limits displayed on the VSLs within a single zone were the same. The Outer Loop had three zones, and the Inner Loop two. Thus, no more than two or three different speed limits would be displayed in one direction in a work zone. The cumulative volume and occupancy at each site were compared to threshold values defined by the VSL vendor. The average threshold values within a zone were then used to define a desired speed limit.

The control logic ensured that downstream zone speed limits were not higher than those upstream. If they were computed to be higher, they were reduced so that they were equal to the upstream speed. Finally, speeds were presented to the WWB control center, where recommended speed limits were manually approved before new speeds were posted to each zone. The control center would also alert enforcement agencies of the new speed limit.

Although VDOT had statutory authority to implement the VSL system, it had no legal authority to implement automated speed enforcement. Since traditional police enforcement was used, speed limits were retained for a minimum of 20 min to allow sufficient time for officers to be notified of changes and enforce new limits. Although noticeable enforcement was occasionally present during the first 4 months of the system’s operation, only 21 speed citations were issued during that period (Woodrow Wilson Bridge Project, 2009).

Field Observations and Preliminary System Performance

The research team conducted several trips to the site after VSL activation to examine the VSL system. Work zones are inherently dynamic, which can pose challenges to the deployment of intelligent transportation systems. Changes in construction activities and the desire to keep the VSL equipment out of the way of work activities may have also impacted the effectiveness of the system. Some of the potential barriers observed during deployment included:

- *Although the VSL sign locations did not vary, lane closure locations did.* As a result, VSL signs were often not ideally located to influence travel conditions leading up to a lane closure. Although it would have been costly to relocate signs continually, the lack of consistency between sign locations and work zone configuration likely limited the system’s effectiveness.

- *The VSL system was not activated consistently during night lane closures.* During several trips to the site, lane closures, queuing, and congestion were present but the VSLs were not active. A lack of consistency in activating the system could have negatively impacted driver expectancy.

- *The fact that signs were exclusively placed on the right side of the road may have made it difficult for motorists in the median lanes to see the signs, especially during times of congestion.* Some of the signs were also placed in locations where other roadside signing obscured the view of the VSL signs.

- *Since the VSL system was activated only for certain night closures, the vast majority of motorists traveling through the work zone did not see the VSLs operating* *dynamically.* This may have reduced the impact of the VSL signs since many regular commuters may not have been expecting the speed limits to change on their normal routes.

- *There was little space available within the work zone for law enforcement officials to pull over vehicles.* Concrete Jersey barriers were often present, so no shoulder was available for enforcement on long stretches of the work zone. This difficulty in enforcement could have also acted to reduce the impact of VSLs.

A preliminary evaluation of the Beltway VSL system was written in early 2009 (Woodrow Wilson Bridge Project, 2009). Unfortunately, a variety of factors made it impossible to conduct a thorough empirical analysis of the performance of the system. First, significant variation in the lane closure locations, demand volumes, and work activity made it difficult to perform before-and-after comparisons under similar conditions. Construction activities changed enough that there was never a clear one-to-one match between lane closures before and after the VSL was activated. Second, the VSL system was activated on a relatively inconsistent basis, with only eight major activations between August and November 2008. These activations sometimes coincided with events such as drawbridge lifts, which further limited the ability to relate traffic conditions to VSL operation. Inherent issues with the algorithm design and response were also noted. In some cases, the algorithm appeared to be somewhat reactive, with a delayed response to the onset of congestion. It also sometimes failed to recover back to the maximum speed limit, even when conditions warranted posting a higher limit.

Some positive results were reported. A slight reduction in average vehicle speeds upon VSL activation occurred, although this was often temporary as vehicles soon returned to typical non-compliance rates (Woodrow Wilson Bridge Project, 2009). Throughout the work zone, speed limit compliance remained poor overall, as the mean travel speed continued to be about 5 to 10 mph above the posted speed limit.

All of these factors led to an inconclusive result during the initial VSL deployment. No large changes in speed or queue length were observable, but this was possibly due to the limited data available after the VSL was activated. Since the initial evaluation of the system, the VSL control logic has been changed by the vendor to respond better to changing traffic conditions. The exact nature of the changes has not been made publicly available by the vendor and has not been formally assessed. There was also concern that the limited activations of the VSL system have created a situation where many drivers do not recognize that the system is, in fact, dynamic. The hours of operation of the VSL system were also expanded such that it was being operated in a traffic responsive mode during peak congested periods. This was done to help emphasize that the speed limits do change based on conditions. It was hoped that these changes would help improve motorist response to the system by increasing the robustness of the control algorithm and driver familiarity with the system. The VSL system was removed from service in February 2010 following the completion of major construction activities at the Telegraph Road Interchange. A final evaluation of the system by the project general contractor is pending.

Simulation Development and Calibration

The results of the literature review and the field deployment both pointed toward the need to perform further investigations into how VSL systems should be designed and deployed. The literature review found several positive results, but they were not manifested in the WWB field deployment. As a result, there was a need to assess whether modifications to the WWB VSL system could result in improved performance.

A VISSIM simulation was developed to investigate the impact of various system design and driver behavior characteristics on overall VSL effectiveness. This task consisted of three major activities. First, the baseline driver compliance with existing speed limits needed to be established. Second, the experimental design for the simulation was finalized based on the results of the literature review and field deployment. Third, the model was calibrated so that it replicated observed field conditions.

Baseline Speed Distribution Data

It was necessary to define the baseline speed distribution of traffic prior to the implementation of the VSL system. This provided an indication of the level of compliance with existing 55 mph static speed limit signing and served as a lower bound on expected compliance with the VSLs. Speed data were gathered from count stations within the work zone activity area during the period prior to installation of the VSL system. Figure 4 shows the cumulative probability distribution of speeds during the period when static 55 mph speed limit signs were posted. Although posted speed limits throughout the work zone were set at 55 mph, the majority of motorists drove in excess of that speed during free-flow conditions. As Figure 4 indicates, only about 20% of motorists actually drove at or below the posted speed limit during free flow periods. The speed distribution shown in Figure 4 represented the baseline expected level of speed compliance at the site.

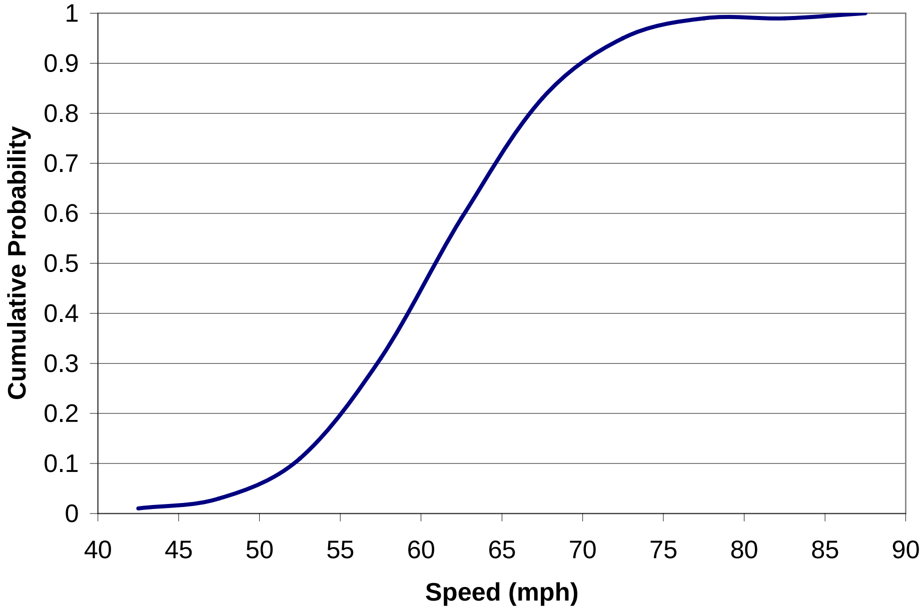

Figure 4. WWB Work Zone Speed Distribution

Experimental Design

An experimental design for the simulation was developed based on the results of the field deployment and the literature review. As a result of those tasks, the following factors that may influence the performance of the system were selected for evaluation:

- lane closure configuration
- VSL speed control algorithm
- speed limit compliance rate
- time between speed limit updates.

Each of these factors is discussed here in greater detail.

In developing the experimental design, it was decided that several factors would not be explicitly evaluated. First, the location of VSL signs in the simulation was the same as in the field. This provided consistency between the simulation and the field results. Second, speed limits could change by no more than 5 mph between adjacent signs. This was selected based on the findings by Abdel-Aty and Dhindsa (2007) that a 5 mph speed change interval performed the best.

Lane Closure Configuration

Two lane closure scenarios were tested based on work zone configurations seen at the site: a four-to-one lane closure and a four-to-two lane closure. The lane closures were simulated on the Outer Loop of the Beltway around the Eisenhower Avenue Connecter Interchange, as shown in Figure 1. A four-to-one lane closure was observed at this specific location, so there was a calibration data set available for this location.

Each lane closure scenario was modeled with different input volumes. Since the four-to-one scenario comprised a much more dramatic capacity loss, it was modeled using a later start time than the four-to-two lane closure. This was done since such a severe capacity loss would create significant delays and queuing if implemented early at night, conditions that VDOT would be unlikely to support. Table 2 details the input volumes at the Springfield Interchange for each lane closure scenario, but it should be noted that additional traffic would enter and leave the network at intermediate interchanges.

Table 2. Hourly Input Volumes at Springfield Interchange for Each Lane Closure Scenario

Start Hour	One Open Lane Network Volumes	Two Open Lanes Network Volumes
7 P.M.	N/A	2936
8 P.M.	N/A	2553
9 P.M.	N/A	2236
10 P.M.	1686	1686
11 P.M.	1030	1030
12 A.M.	616	616
1 A.M.	382	382
2 A.M.	N/A	560

These volumes consisted of an average of 35% heavy trucks. Although this may seem high, VDOT traffic data for this site show that truck percentages during overnight hours were much higher than during the day. Many truckers through the area stage their trips to avoid congested peak hour travel in the Washington, D.C., area and so that they arrive at northeast destinations outside morning peak hours.

Since VISSIM simulations start with an empty roadway network, a lower traffic volume was applied for 1 hour before the volumes shown in Table 2 were simulated. This allowed traffic to travel throughout the simulation so that vehicles would not be encountering an empty network during the first hour of the model.

Work zone lane closures were simulated by removing lanes that were closed because of construction. Proper taper length was provided for each lane dropped using the distances specified in the *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD) (FHWA, 2007). VSL signs were simulated at the same locations as in the field deployment. As such, the exact sign locations may not have been optimal for the specific lane closure simulated, but they were chosen to allow for consistency between the field and simulation environments.

VSL Control Algorithms

The logic used to change the speed limit on a VSL sign was expected to play a role in the overall operational and safety effects of the system. As a result, three alternative speed control strategies were evaluated:

1. A base case where static 55 mph speed limits were displayed.
2. A VSL case where the speed limits were changed in a manner based on what was actually deployed at the WWB site.
3. A VSL case where speed limits were changed using a control logic similar to that used on the German Autobahn.

For the base case, a desired speed distribution identical to that shown in Figure 4 was used. The VSLs were simulated in VISSIM using the Vehicle Actuated Programming (VAP) feature, which allows for traffic behavior rules to respond to current traffic conditions. The VAP code developed for this project essentially changes the desired speed distribution of traffic at each sign location based on the speed limit recommendation produced by the control algorithm. The control logics for the two VSL cases are discussed in more detail here.

Field-Tested Control Logic. One of the VSL control logics tested in this project included a slight modification from that actually used in the field. The logic used in the field appeared to have a flaw that would inhibit recovery to reasonable free-flow speeds by making it unnecessarily difficult for the VSL zones to return to their maximum allowable posted speed limit. The existing logic did not allow for speeds to increase as one progressed through the VSL area and essentially required all VSL zones to drop to their lowest levels before recovery could begin. For example, if the VSL Zone 1 (the final zone) speed needed to increase, it would have to wait for Zones 2 and 3 to increase to posted speeds above that for Zone 1. This delay in recovery time prohibited vehicles from efficiently clearing the merge area, particularly for zones that appeared after a merge area. Several simulations of this original version of the logic revealed very poor results, such as free-flow travels speeds of just below 40 mph where base free-flow speeds were in excess of 55 mph. Therefore the field-tested code was modified in the simulations to allow for more efficient recovery by allowing downstream speed limits to be higher than upstream limits.

Upon initial activation, all VSL signs were set to display their maximum allowable speed limit. Next, each detector recorded an occupancy rate and cumulative volume and cumulative occupancy at each sign location. A threshold value was then determined for each detector in each zone. The threshold values had been predetermined by the WWB VSL vendor and were as shown in Table 3 (Ali, 2008):

The threshold values for all detectors in a zone were then summed and divided by the number of detectors to obtain an average threshold value in the zone. This average threshold value was then applied to calculate a value called the segment level (Ali, 2008). Equation 1 shows the segment level calculation, and Table 4 shows the posted speed limits that correspond to the segment levels. Zone 1 represents the activity area, with subsequent zones moving further away from the work zone activity area into the advance warning area.

$$seglev = 1 + \frac{thresavg - 1}{queuelevel - 1} \times (speedlevels - 1) \qquad \text{[Eq. 1]}$$

where

seglev = the “segment level” used to determine speed set to VSL signs
thresavg = the average of the thresholds from all detector locations in a zone
speedlevels = the number of possible speed limit values that a zone allows, shown in Table 4
queuelevels = 3, for this project (normal, slowing, or stopped).

Table 3. Field Code Thresholds and Parameters[a]

Threshold Value	Parameters
1 (normal)	Occupancy < 8% or Volume < 1400 vehicles per hour (vph)
2 (slowing)	8% ≤ Occupancy ≤ 15% or 1400 vph ≤ Volume ≤ 1600 vph
3 (stopped)	Occupancy > 15% or Volume > 1600 vph

[a] Source: Ali, S.U. *Field Implementation of Variable Speed Limits on the Capital Beltway (I-95/I-495) for the Woodrow Wilson Bridge Project*. George Mason University, Fairfax, VA, 2008.

Table 4. Possible Posted Speed Limits by Zone and Segment Level[a]

	Outer Loop			**Inner Loop**	
	Zone 1 (Activity Area)	**Zone 2**	**Zone 3**	**Zone 1 (Activity Area)**	**Zone 2**
No. of Possible Speed Limits	4	5	3	4	3
Segment Level =1	50	55	55	50	50
Segment Level =2	45	50	50	45	45
Segment Level =3	40	45	45	40	40
Segment Level =4	35	40	N/A	35	N/A
Segment Level =5	N/A	35	N/A	N/A	N/A

[a] Source: Ali, S.U. *Field Implementation of Variable Speed Limits on the Capital Beltway (I-95/I-495) for the Woodrow Wilson Bridge Project*. George Mason University, Fairfax, VA, 2008.

Speed-Flow-Density VSL Control Logic. A second control logic based on a method used on the German Autobahn was also tested (Bertini et al., 2006). This control logic differed from the one tested in the field in several ways. First, the VSL system was not divided into large zones that had to display the same speed limit. Speed limits were allowed to vary on a sign-by-sign basis, and there was no longer a requirement to maintain the same speed limit in a larger zone. Second, speed limits were set based on speed-flow-density relationships developed from several well-known traffic stream models.

As with the preceding code, all VSL signs were set to display 55 mph during the first cycle in the simulation's warm-up phase. Each detector gathered speed and flow data during each speed update cycle. The cumulative flow and space mean speed at the end of each speed update cycle were then used to determine the traffic density during that period. The next step was to determine the worst (highest) density at each VSL sign location. Since there was a detector in each lane at each sign location, the worst density represents only one lane but was used to represent the entire location.

Once the worst density has been determined for each location, the desired posted speed for that location can be determined based on downstream density. This was done to allow vehicles to prepare for upcoming conditions. Desired speeds for each VSL sign were derived from pre-determined density ranges that are appropriate for each speed based on the Greenshields and Greenberg traffic stream models. The Greenshields model is shown in Equation 2, and the Greenberg model is shown in Equation 3. These two models were evaluated to find appropriate density ranges that corresponded to five ranges of speed. Two jam densities within the typically accepted range for this parameter, 185 vehicles per mile (vpm) and 220 vpm, were evaluated (May, 1990). A free flow speed of 65 mph was used since the field data collection speeds were at approximately this level.

$$\bar{u}_s = u_f - \frac{u_f}{k_j} k \qquad \text{[Eq. 2]}$$

where

u_s = space mean speed
k = density (vpm)
u_f = free flow speed
k_j = jam density.

$$\overline{u_s} = c \ln \frac{k_j}{k} \qquad \text{[Eq. 3]}$$

where

u_s = space mean speed
c = speed at maximum flow (set at 32.5 mph)
k_j = jam density
k = density (vpm).

Density values corresponding to each speed limit were computed for both traffic stream equations and then averaged. The densities and corresponding speed limits are listed in Table 5.

With each location's desired speed having been determined, the code is then checked to make sure there was no drop in speed limits between zones greater than 5 mph. Starting at the final VSL sign location in the system (the last to be encountered by motorists before leaving the VSL area), desired speeds were checked against the next upstream desired speed. If the next desired speed was greater than a 5-mph drop, it was adjusted so that the speed drop between the two signs was 5 mph. This process proceeds upstream until the first VSL sign has been reached, subject to a maximum speed limit of 55 mph being posted. After this has been completed, the code cleared density, volume, and speed values to reset the algorithm for the next cycle.

Table 5. Speed-Flow-Density Speed Limit Thresholds

Density	Speed Range	Speed Limit Posted
0 to 34.2 veh/mi/lane	Greater than 52.5 mph	55 mph
34.2 to 45 veh/mi/lane	47.5 to 52.5 mph	50 mph
45 to 56.4 veh/mi/lane	42.5 to 47.5 mph	45 mph
56.4 to 68.5 veh/mi/lane	37.5 to 42.5 mph	40 mph
Greater than 68.5 veh/mi/lane	Below 37.5 mph	35 mph

Speed Limit Compliance

The level of driver compliance with VSLs was analyzed to determine its impact on overall system effectiveness. As noted earlier, compliance with static speed limit signs at this location was poor, so it could not be assumed that high levels of compliance would be achieved with the VSLs. *Driver compliance* was defined as the percentage of vehicles that travel at or below the posted speed limit. In this project, speed limit compliance levels of 20% and 50% were evaluated. The 20% level represented the actual speed limit compliance along the corridor with static signs, and the 50% level was tested to determine if higher levels of compliance would result in substantial benefits. Higher levels of compliance may be possible if drivers recognize the dynamic nature of the VSL, increased enforcement is present, or public information campaigns successfully modify driver behavior. When a compliance level is set in the simulation, the compliant vehicles have a desired speed of exactly the posted speed and the non-compliant vehicles follow a shifted speed distribution based on what was observed in the field.

Speed Limit Change Intervals

Time intervals between speed limit changes of 5, 10, and 20 min were tested. The 5- and 10-min intervals were derived from Lee et al.'s (2004) freeway simulation findings from the literature review. The 20-min interval was taken from the actual interval used in the WWB VSL field tests. This factor was investigated to determine if a more traffic responsive system could create greater operational effects versus what was actually deployed in the field.

Summary of VSL Factors

In the end, 24 VSL scenarios were run in a full factorial design. These factors are summarized in Table 6. In addition to these factors, both lane closure scenarios were tested using a simulated static 55 mph speed limit so that a relevant baseline could be established.

Each scenario tested was simulated 20 times using unique random number seeds. All simulations were run until all congestion on the network was eliminated and traffic had returned to free flow conditions.

Table 6. VSL Factors Tested in Simulation

Factors	Levels
Lane Closure Scenarios	4 open lanes to 1 open lane 4 open lanes to 2 open lanes
Control Logic	Algorithm developed by VSL operator Speed-flow-density algorithm
Driver Speed Limit Compliance	20% 50%
Time Between Speed Limit Changes	5 min 10 min 20 min

Simulation Validation

Data collection trips before VSL activation were conducted June 10 through 12, June 17 through 19, and July 14 through 17, 2008. Lane closures, traffic conditions and compositions, weather, and bridge lift tests were unique every night of these before-VSL activation trips. Data from the June 11, 2008, trip were used to calibrate the VISSIM simulation. This night's data were chosen because this was the only night of pre-VSL data that did not feature unusual factors that would impact the travel time runs (i.e., poor weather, unusual lane closures, drawbridge lifts, etc.). This night involved a four-to-one lane closure at the site, and travel times were generally stable through the work zone. A total of 10 floating car travel time runs were performed on that night.

Driver behavior characteristics in VISSIM were modified to calibrate the base model to observed travel times at the site. When the VISSIM model was initially compared to field observations, it was noted that actual merging behavior at the site was much more aggressive than was seen in the simulation. As a result, car following model parameters were altered to increase driver aggressiveness in gap acceptance. After this calibration was performed, there was a good match between the simulated travel times and the actual travel times recorded in the field. Table 7 shows the comparison between the simulated travel times and those collected in the field. The mean absolute error was 5.65% and the average error was 0.43%, indicating a good representation of field conditions and no appreciable bias in the model.

Table 7. Comparison of Calibrated Simulation Travel Times and Field Measured Travel Times

Time	Simulated Travel Time (sec)	Field Travel Time (sec)	Error (%)	Absolute Error (%)
9:03 P.M.	454	481	-5.61%	5.61%
9:10 P.M.	446	551	-19.06%	19.06%
9:49 P.M.	447	447	0%	0%
11:00 P.M.	435	412	5.58%	5.58%
11:00 P.M.	435	417	4.32%	4.32%
11:38 P.M.	422	399	5.76%	5.76%
11:48 P.M.	427	409	4.22%	4.22%
12:04 A.M.	425	404	5.20%	5.20%
12:30 A.M.	418	397	5.29%	5.29%
12:46 A.M.	418	424	-1.42%	1.42%
Average Error			0.43%	5.65%

Initial Trend Analysis of Simulation Data

An initial trend analysis was performed to provide a broad overview of the impact the VSLs had as compared to the base case with static speed limits. Differences between each VSL system configuration were also examined. This was done to provide a high-level indication as to whether VSLs provide any clear improvements compared to the base case before a more in-depth statistical analysis was performed to determine significance among variables. For this analysis, average trends in each MOE across the 20 simulation replications of each variable/network combination are presented. Trends are discussed separately for the four-to-one lane closure and four-to-two lane closure networks since findings for those two cases differed substantially.

Four-to-One Lane Closure

Mean Speed

Figure 5 shows the trends in average speed across the network for the four-to-one lane closure. The results show that the average speed of the base case and the two VSL control algorithms were essentially identical for the simulation, especially during congestion. The only major differences were observed at the end of the simulation period when the base case rebounded to a higher level than either VSL alternative. This was due to the high level of noncompliance observed in the base case, resulting in many travel speeds in excess of the posted speed limit. For the VSL cases, even a 20% compliance rate was enough to slow the entire traffic stream traveling through the work zone during free flow conditions. It appears that demand so far exceeded capacity at this site that the VSL did not offer any operational improvement in this case.

Speed Standard Deviation

Figure 6 shows the aggregate standard deviation of speed through the work zone for the base case and the two VSL control options. Standard deviation of speed is often viewed as a surrogate measure of safety, since several studies have shown that wide variability in speeds is tied to an increased likelihood of crashes (Committee for Guidance on Setting and Enforcing

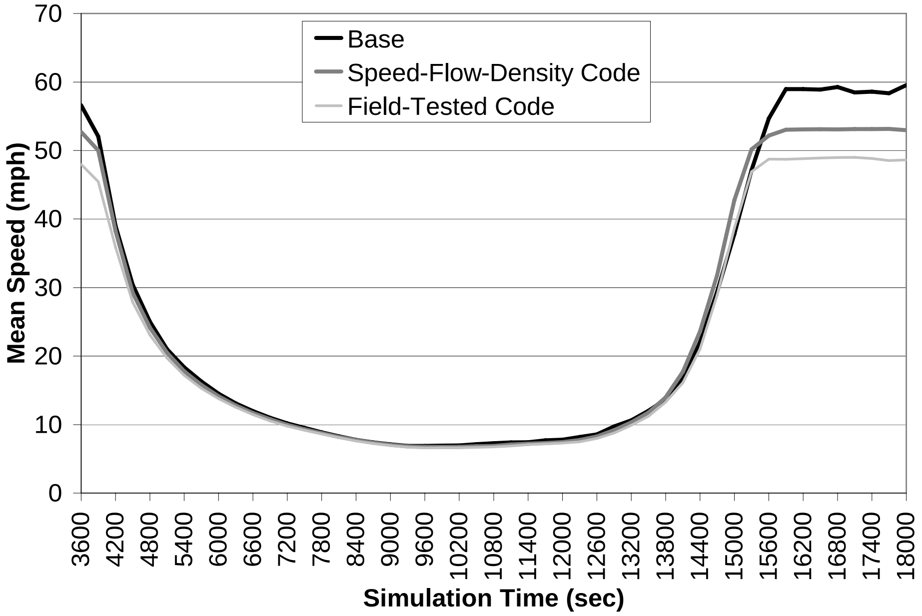

Figure 5. Average Network Speeds, Four-to-One Lane Closure Network

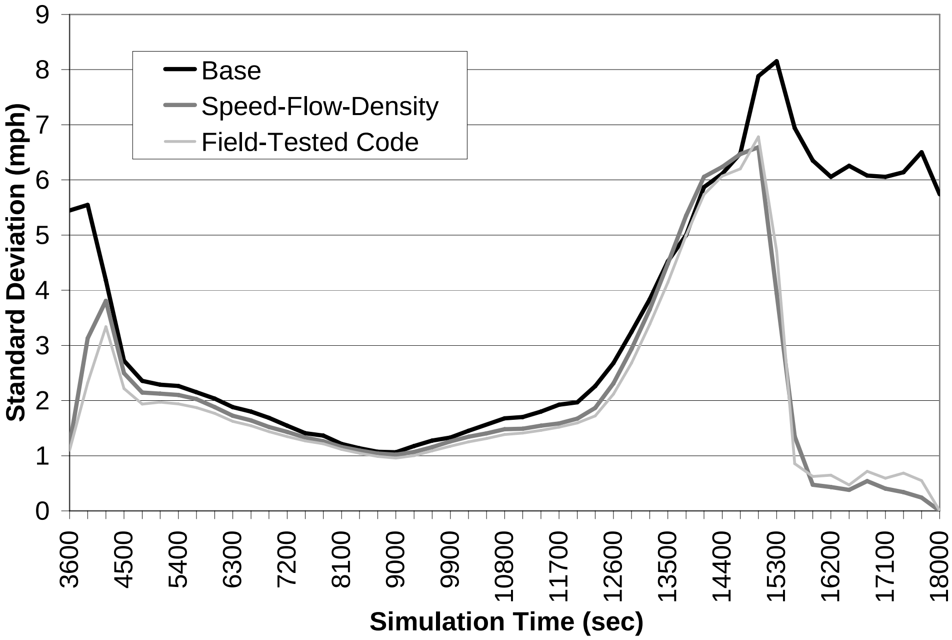

Figure 6. Speed Standard Deviations, Four-to-One Lane Closure Network

Speed Limits, 1998). In this case, standard deviations were low during congested flow for all scenarios since there was little variability in the traffic stream. Standard deviations spiked as congestion dissipated in all cases, with the standard deviations for VSLs then returning to a level lower than for the base case during free flow conditions. These data show that the VSLs offer little benefit during congested conditions but could potentially reduce speed variability (and thereby improve safety) during free flow conditions.

Queues and Stops

Trends in queue length and number of stops were similar, as shown in Figures 7 and 8. For both of these measures, the VSL cases and the base case showed nearly identical trends for most of the simulation. The VSL cases caused the queue to dissipate completely approximately 10 min earlier than for the base case, but the maximum queue length was nearly identical. Figure 8 shows that the number of stops was essentially the same for all cases evaluated.

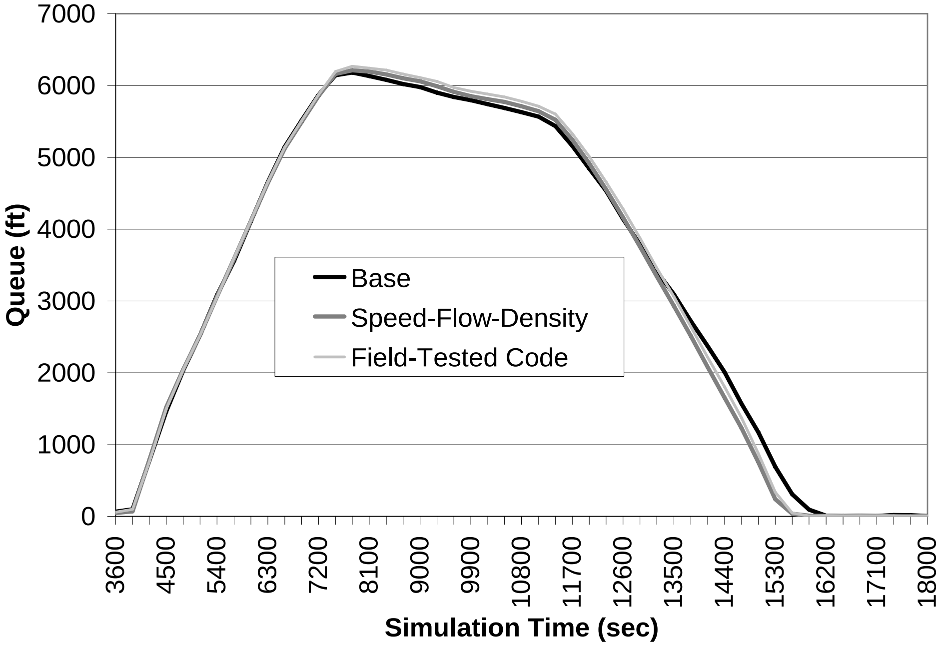

Figure 7. Queue Lengths, Four-to-One Lane Closure Network

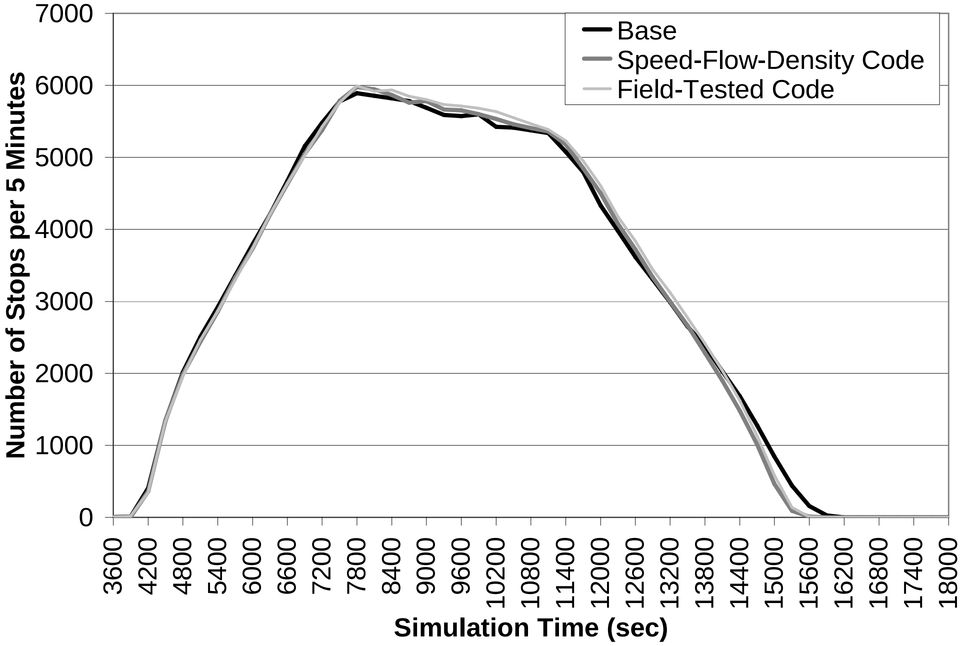

Figure 8. Number of Stops per 5 Minutes, Four-to-One Lane Closure Network

Lane Changes

Figure 9 shows the trends in the number of lane changes among the different control strategies. The number of lane changes was the only measure for which there were obvious differences between the VSL cases and the base case. Both VSL control algorithms showed substantially fewer lane changes than the base case, especially as the queue was continuing to grow. The gap between the VSLs and the base case narrowed as the queue began to dissipate, but the VSL alternatives still had fewer lane changes than the base case. The large gap between the VSL cases and the base case is likely due to improved speed harmonization approaching the end of queue, resulting in less lane changing. Lane changes can also be viewed as a surrogate safety measure, so a reduction in this measure could be construed as an improvement in safety. Each lane change would require judgment on the part of the driver during the gap acceptance process. The means that each lane change would represent an instance where there may be an opportunity to make an error in judgment that could result in a crash.

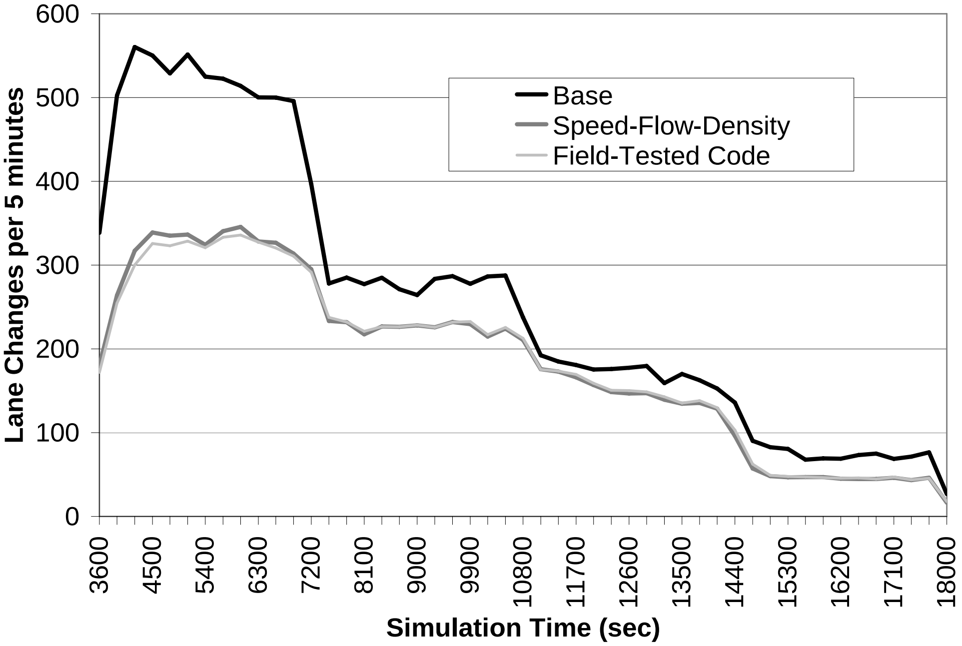

Figure 9. Number of Lane Changes per 5 Minutes, Four-to-One Lane Closure Network

Four-to-Two Lane Closure

Although the four-to-one lane closure scenario often showed little difference in performance between the VSL cases and the base case, differences in performance were much more pronounced with the four-to-two lane closure scenario. Each MOE is discussed here.

Mean Speeds

Figure 10 shows the average network speed for the base case and the two VSL control algorithms. The VSL results are further broken down by the percentage of vehicles in compliance with the posted VSL speeds for each control logic. Figure 10 shows that all VSL cases were able to maintain a higher speed than the base case during congestion, with the base case recovering to a higher speed only during free flow conditions. This is again due to the very high levels of non-compliance with the static speed limits. It should also be noted that the VSL cases sometimes recovered back to free flow more than 1 hour earlier than the base case. In this case, the speed harmonization benefits of the VSLs appear to be creating smoother flow through the work zone, resulting in more rapid recovery.

Figure 10 also shows interesting trends in VSL operation. First, the speed-flow-density code based on the German Autobahn logic generally recovered more rapidly and to higher speeds than the field-tested code. This could be partially attributable to the ability to post speed limits individually on each VSL sign in the speed-flow-density logic. A rather unexpected finding was that traffic recovered faster in both algorithms when a 20% compliance rate instead of a 50% compliance rate was used. The researchers investigated this result, and it appears that this finding is actually more strongly related to the location of the VSL signs relative to the lane closure than to the compliance rate itself.

At a work zone lane closure, speeds typically increase once vehicles pass the capacity reduction at the lane drop. In the VSL simulations, the VSL signs were located at the same locations as the field, which meant that the signs were located about 1 mi past the work zone lane closure. When a high degree of compliance with the VSLs was assumed, this meant that vehicles were forced to travel for about 1 mi at a speed much lower than the vehicles could realistically travel. As a result, high compliance rates made speeds lower. A lower compliance rate allowed the vehicles to accelerate to a higher speed based on the lower density of traffic. This suggests that the VSL sign location was the main driver of this finding. It appears that VSL signs should be located shortly after a lane drop so that vehicles can accelerate to a higher speed.

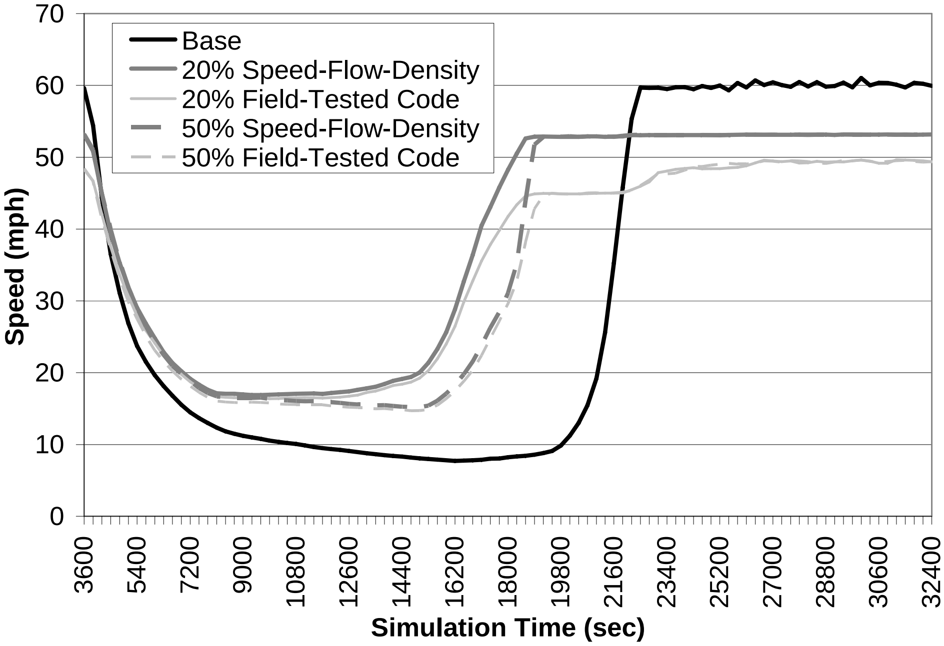

Figure 10. Average Network Speeds, Four-to-Two Lane Closure Network

Speed Standard Deviation

Figure 11 shows the trends in standard deviation of speed between the base case and the two VSL control algorithms. Once again, the different levels of compliance are separated for the VSL cases. In this case, the VSLs actually have a higher standard deviation of speed during congested flow. Since the VSLs are able to maintain a higher average travel speed, as shown in Figure 10, they have the ability to exhibit more variability in speed. Since the base case had extremely low travel speeds, averaging less than 10 mph during congestion, it had little variability. The base case did exhibit higher variability during free flow conditions, again indicating the speed harmonization benefits of the VSLs.

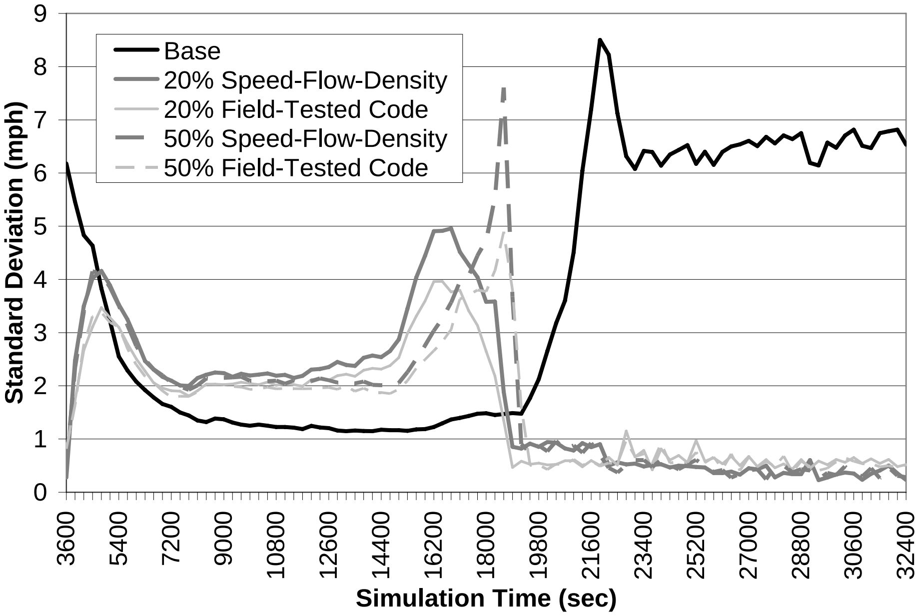

Figure 11. Speed Standard Deviation, Four-to-Two Lane Closure Network

Queues and Stops

Figures 12 and 13 show the trends in queues and stops for the four-to-two lane closure case. There were no discernable trends between the two control algorithms for these measures, but there were different trends between the two compliance levels tested with the VSL cases. Figure 12 shows that the maximum queue length for the VSL cases was less than half of that seen in the base case. The 20% compliance rate also had a shorter maximum queue length than the 50% compliance case, which is likely tied to lower throughput through the work zone lane closure. Similar trends can be seen in Figure 13 for the number of stops. Both VSL levels of compliance clear the queue at approximately the same time, and the queue completely dissipates about 1 hour earlier than the base case.

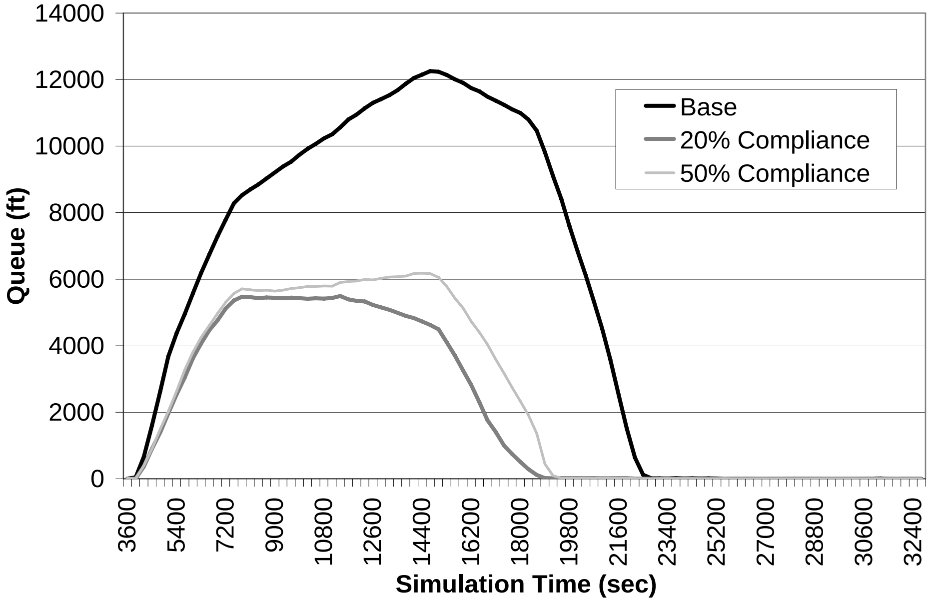

Figure 12. Queue Length, Four-to-Two Lane Closure Network

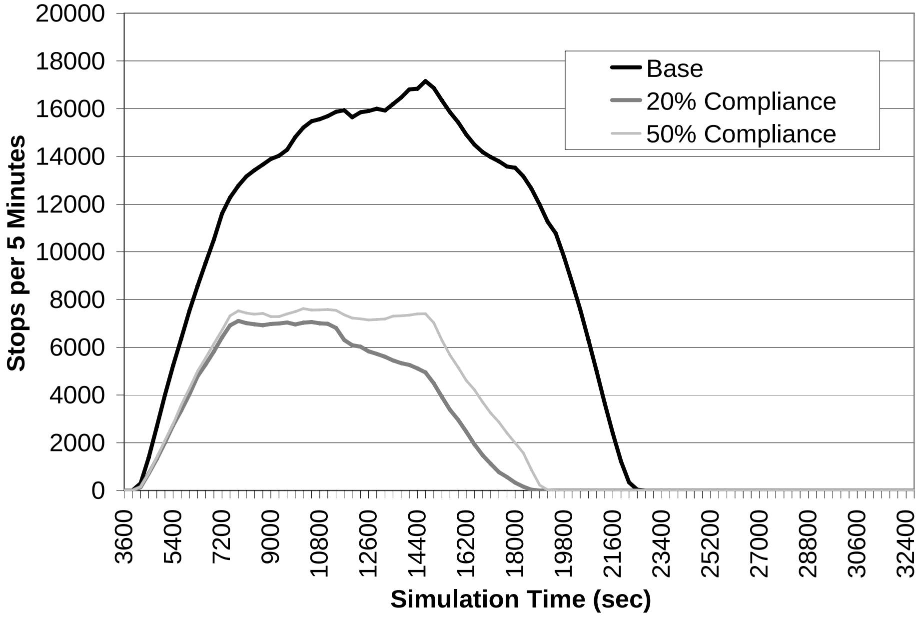

Figure 13. Number of Stops per 5 Minutes, Four-to-Two Lane Closure Network

Lane Changes

Figure 14 shows the difference in number of lane changes per 5 min between the base case and the two VSL control logics. Once again, the two VSL cases show substantially fewer lane changes than the base case. This indicates that safety may improve with the VSL alternatives since there would be fewer potential conflicts between vehicles.

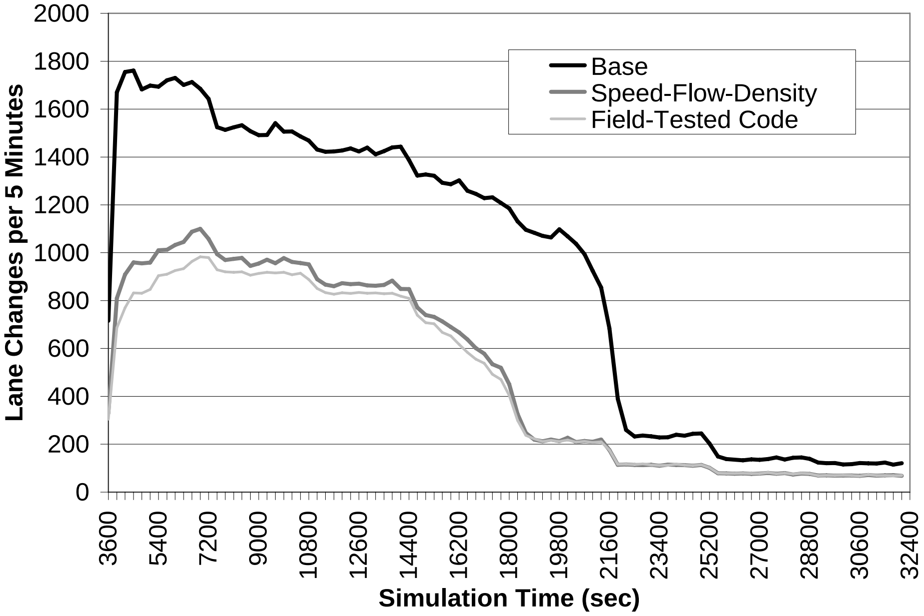

Figure 14. Number of Lane Changes per 5 Minutes, Four-to-Two Lane Closure Network

Statistical Analysis of Data

Although the preceding analysis found some broad trends in the data, it did not assess the statistical significance of factors or interactions between factors. The statistical software SPSS was used to analyze the data using a general linear model (GLM). The GLM analysis allowed for all factors to be analyzed together and for separating the effects of factors and interactions between multiple factors. The four-to-one and four-to-two lane closure networks were again analyzed separately given the obvious differences in operations between the two networks.

Four-to-One Lane Closure

Few factors were found to exert statistically significant influences on any of the MOEs analyzed for the four-to-one lane closure. This is probably not surprising given the broad trends in the data shown earlier.

Queue and Vehicle Stops Analysis

Table A-1 in the Appendix shows the results of the GLM analysis on queue length for the four-to-one lane closure. None of the main effects or interactions was found to exert a statistically significant difference on queue length. Thus, the base case and all VSL configurations produced results that were not significantly different from one another. This confirms the findings of the earlier trend analysis.

Table A-2 shows the results of the GLM analysis of stops. Once again, none of the main effects or factor interactions exerts a statistically significant influence on the number of stops. This validates the findings of the initial trend analysis of the four-to-one lane closure case.

Mean Speed Analysis

Table 8 shows the results of the GLM analysis of the mean speed on the network. Unlike the analysis of queue length and vehicle stops, the analysis of the mean speed along the network did reveal statistically significant differences between the base case and the two VSL control algorithms tested. None of the other factors was found to exert a statistically significant influence on mean speed.

Table 9 summarizes the mean speeds and confidence intervals for the base case, VSL field-tested algorithm, and VSL speed-flow-density algorithm. Table 9 shows that the field-tested algorithm produces a mean speed that was lower than that of both the base case and the speed-flow-density algorithm by a statistically significant margin. The results for the speed-flow-density algorithm and the base case are not significantly different. The cause of this lower speed for the field-tested algorithm appears to be related to the lower ultimate recovery speed at the end of the simulation. Thus, it appears that the VSL does not offer any travel time improvements over a static speed limit on the four-to-one lane closure network. The capacity reduction was so great in this case that the speed harmonization benefits of the VSL did not offer any opportunity to delay the onset of congestion.

Table 8. Overall Network Speed Between-Subjects Effects, Four-to-One Lane Closure Network

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	9086.340	12	757.195	2.361	0.005
Intercept	5044307.947	1	5044307.947	15727.499	0.000
Algorithm	6077.571	1	6077.571	18.949	0.000
SpeedLimitChange	122.656	2	61.328	0.191	0.826
Compliance	8.427	1	8.427	0.026	0.871
Algorithm × SpeedLimitChange	208.487	2	104.244	0.325	0.723
Algorithm × Compliance	110.574	1	110.574	0.345	0.557
SpeedLimitChange × Compliance	24.676	2	12.338	0.038	0.962
Algorithm × SpeedLimitChange × Compliance	60.329	2	30.164	0.094	0.910
Error	3998562.420	12467	320.732		
Total	9964105.970	12480			
Corrected Total	4007648.760	12479			

Table 9. Effect of Control Algorithm on Mean Overall Network Speed, Four-to-One Lane Closure Network

Control Algorithm	Mean Speed (mph)	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Base	23.389	0.578	22.256	24.522
Field-tested	20.992	0.236	20.529	21.454
Speed-flow-density	22.445	0.236	21.982	22.907

Lane Changes

Table 10 shows the results of the GLM analysis of the number of lane changes on the four-to-one lane closure network. Surprisingly, the analysis showed that none of the main effects or interactions was significant, even though the initial trend analysis showed some notable

Table 10. Number of Lane Changes per 5 Minutes Between-Subjects Effects, Four-to-One Lane Closure Network

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	5.247E+06	12	437244.207	37.430	0.000
Intercept	4.244E+08	1	4.244E+08	36330.631	0.000
Algorithm	2904.050	1	2904.050	0.249	0.618
SpeedLimitChange	1260.890	2	630.445	0.054	0.947
Compliance	2041.884	1	2041.884	0.175	0.676
Algorithm × SpeedLimitChange	3339.772	2	1669.886	0.143	0.867
Algorithm × Compliance	.584	1	.584	0.000	0.994
SpeedLimitChange × Compliance	1450.693	2	725.346	0.062	0.940
Algorithm × SpeedLimitChange × Compliance	59.099	2	29.550	0.003	0.997
Error	1.456E+08	12467	11681.588		
Total	6.168E+08	12480			
Corrected Total	1.509E+08	12479			

differences between the base case and the two VSL cases in Figure 9. As a result, additional analysis was performed to verify the GLM results.

The influence of control algorithm was assessed to determine whether it was, in fact, a significant factor. The results in Table 11 show that the base case did in fact have a statistically significant higher number of lane changes than either VSL scenario, but there was no significant difference between the two VSL control algorithms. Detailed investigations of other factors and interactions did not show any significant differences in any factor except for the control algorithm.

Table 11. Effect of Control Algorithm on Mean Number of Lane Changes per 5 Minutes, Four-to-One Lane Closure Network

Control Algorithm	Mean Number of Lane Changes per 5 min	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Base	264.182	10.857	242.903	285.461
Field-tested	186.813	4.432	178.126	195.500
Speed-flow-density	187.817	4.432	179.130	196.505

Four-to-Two Lane Closure

Queues and Stops

First queue length and stops were analyzed for the four-to-two lane closure. Tables A-3 and A-4 in the Appendix provide the results of the GLM analysis for queue length and stops, respectively. The queue length and stop results are highly correlated since longer queue lengths will naturally result in more instances where a driver must come to a complete stop. Tables A-3 and A-4 both show that the speed compliance variable was a significant factor in determining the queue length and number of stops. As noted earlier, it appears that this factor is, in fact, a surrogate measure for the influence of sign location.

Table 12 shows the relationship between control algorithm, compliance level, and queue length. The data indicate that both VSL control algorithms reduce queue lengths by a statistically significant margin over the base case. The lower levels of compliance are also associated with shorter queue lengths for the two VSL algorithms. Again, this is indicative of the influence of sign spacing more than the actual speed compliance. The two VSL control algorithms were not significantly different when compliance levels were held constant.

Table 13 shows the average number of stops per 5 min for each control strategy and compliance level combination. Trends are again similar to those seen with queue length. The two VSL strategies substantially reduce the mean queue length, although the two control strategies are not significantly different when similar compliance levels are compared. The trends related to compliance were the same for stops and queue length.

Table 12. Effect of Control Algorithm and Speed Limit Compliance on Queue Length, Four-to-Two Lane Closure Network

Control Algorithm	Compliance (%)	Mean Queue Length (ft)	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
Base	20	5428.459	60.471	5309.934	5546.985
Field-tested	20	1959.588	34.913	1891.157	2028.019
	50	2399.471	34.913	2331.041	2467.902
Speed-flow-density	20	1972.978	34.913	1904.548	2041.409
	50	2382.336	34.913	2313.905	2450.766

Table 13. Effect of Speed Limit Compliance on Number of Stops per 5 Minutes, Four-to-Two Lane Closure Network

Control Algorithm	Compliance (%)	Mean Number of Stops per 5 Minutes	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
Base	20	7364.712	80.513	7206.902	7522.522
Field-tested	20	2256.477	46.484	2165.365	2347.589
	50	2829.476	46.484	2738.364	2920.587
Speed-flow-density	20	2269.370	46.484	2178.259	2360.482
	50	2797.942	46.484	2706.831	2889.054

Mean Speed Analysis

Table 14 summarizes the results of the GLM analysis of mean speed. The analysis indicated that both the control algorithm and the compliance level were significant factors. This is consistent with the initial trend analysis and the data shown in Figure 10.

Table 15 summarizes the mean speed by control algorithm. All three control strategies were significantly different from one another. The base case had a statistically significant lower speed than all other alternatives, and the speed-flow-density algorithm had the highest mean speed.

Table 16 summarizes the mean speed disaggregated by control algorithm and compliance level. Once again, the base case produced mean speeds that were the lowest by a statistically significant amount. The speed-flow-density control algorithm produced the highest average speeds over the course of the simulation. The compliance level was once again found to be a

Table 14. Overall Network Speed Between-Subjects Effects, Four-to-Two Lane Closure Network

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	125021.021	12	10418.418	38.742	0.000
Intercept	2.599E+07	1	2.599E+07	96642.040	0.000
Algorithm	60044.972	1	60044.972	223.285	0.000
SpeedLimitChange	45.228	2	22.614	0.084	0.919
Compliance	20407.698	1	20407.698	75.889	0.000
Algorithm × SpeedLimitChange	636.083	2	318.041	1.183	0.306
Algorithm × Compliance	118.702	1	118.702	0.441	0.506
SpeedLimitChange × Compliance	314.429	2	157.215	.585	.557
Algorithm × SpeedLimitChange × Compliance	65.368	2	32.684	.122	.886
Error	6.779E+06	25207	268.916		
Total	3.932E+07	25220			
Corrected Total	6.904E+06	25219			

Table 15. Effect of Control Algorithm on Overall Network Mean Speed, Four-to-Two Lane Closure Network

Control Algorithm	Mean Speed (mph)	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Base	31.311	0.384	30.558	32.063
Field-tested	34.627	0.157	34.320	34.934
Speed-flow-density	37.839	0.157	37.532	38.146

Table 16. Effect of Control Algorithm and Speed Limit Compliance on Overall Network Mean Speed, Four-to-Two Lane Closure Network

Control Algorithm	Compliance (%)	Mean Speed (mph)	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
Base	20	31.311	0.372	30.581	32.041
Field-tested	20	35.492	0.215	35.071	35.913
	50	33.762	0.215	33.341	34.184
Speed-flow-density	20	38.847	0.215	38.425	39.268
	50	36.831	0.215	36.410	37.253

significant factor in mean speeds, with lower compliance with VSLs being associated with higher speeds. This is again an artifact of the locations of the signs rather than truly being indicative of the true impacts of compliance level.

Lane Changes

Table 17 summarizes the results of the GLM analysis of lane changes on the four-to-two lane network. In this case, both the control algorithm and compliance level were found to be significant factors in determining the number of lane changes per 5 min at the site.

Table 18 summarizes the trends in the number of lane changes by the control algorithm tested. The base case was found to have significantly more lane changes than both VSL alternatives, whereas the field-tested algorithm was found to have the fewest by a statistically significant margin.

Table 17. Lane Changes per 5 Minutes Between-Subjects Effects, Four-to-Two Lane Closure Network

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	3.691E+08	12	3.076E+07	188.306	0.000
Intercept	6.662E+09	1	6.662E+09	40784.682	0.000
Algorithm	5.582E+06	1	5.582E+06	34.177	0.000
SpeedLimitChange	14994.687	2	7497.344	0.046	0.955
Compliance	2.539E+06	1	2.539E+06	15.546	0.000
Algorithm × SpeedLimitChange	23712.149	2	11856.074	0.073	0.930
Algorithm × Compliance	209.608	1	209.608	0.001	0.971
SpeedLimitChange × Compliance	26549.812	2	13274.906	0.081	0.922
Algorithm × SpeedLimitChange × Compliance	5602.790	2	2801.395	0.017	0.983
Error	4.117E+09	25207	163334.339		
Total	1.105E+10	25220			
Corrected Total	4.486E+09	25219			

Table 18. Effect of Control Algorithm on Mean Number of Lane Changes per 5 Minutes, Four-to-Two Lane Closure Network

Control Algorithm	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Base	924.415	7.637	909.446	939.384
Field-tested	460.011	3.118	453.900	466.122
Speed-flow-density	490.982	3.118	484.871	497.093

Table 19 summarizes the analysis of the interaction of algorithm and compliance. When trends in lane changes are analyzed by compliance level, differences in VSL algorithm performance are seen depending on the compliance level. The 20% compliance level is associated with significantly fewer lane changes per 5 min than the 50% compliance level, regardless of the control algorithm. The lower numbers of lane changes with the 20% compliance level are likely attributable to the lower levels of congestion seen in those cases. If there is less congestion, drivers likely will not seek to change lanes as frequently to improve their travel time. Again, the reduction in lane changes is probably not the result of the lower compliance level itself but instead is probably related to the impact of the sign locations noted earlier.

Table 19. Effect of Control Algorithm and Speed Limit Compliance on Number of Lane Changes per 5 Minutes, Four-to-Two Lane Closure Network

Control Algorithm	Compliance (%)	Mean Number of Lane Changes per 5 Min	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
Base	20	924.415	7.637	909.446	939.384
Field-tested	20	449.473	4.409	440.831	458.115
	50	470.550	4.409	461.908	479.192
Speed-flow-density	20	480.633	4.409	471.991	489.275
	50	501.330	4.409	492.688	509.973

CONCLUSIONS

Effectiveness of VSL in the Field

The initial results from the field deployment of the WWB VSL system were inconclusive. The limited application of the system, as well as issues with the responsiveness of the control algorithm, created difficulties in evaluating the system using field data and likely reduced the ability of the system to impact driver behavior. Some conclusions could be drawn from this initial test, however:

- *The work zone environment presents fundamental challenges to the placement of VSL signs that are not seen in permanent freeway applications*. The needs of changing construction activities can make it difficult to place the VSL signs at locations that are highly visible to drivers. This problem is exacerbated during very congested conditions, especially if signs are posted on only one side of the road.

- *If an agency is going to install VSLs, they should be activated on a consistent basis to ensure that maximum benefits are obtained. The WWB VSL system was not consistently operated in a traffic-responsive mode, even when work zone lane closures were present.* This could have worked against the effectiveness of the system. It is possible that motorists did not perceive the VSLs to be dynamic since the signs did not change the vast majority of the time. This could have caused the signs to blend into the background visual noise of the work zone.

- *VSL control algorithms should be constructed so that they can facilitate response from congestion. The initial VSL algorithm appeared to operate in a reactive mode and sometimes did not effectively alleviate congestion once it formed.* The control algorithm has subsequently been modified by the vendor, but no results on its effectiveness are available.

Effects of System Design, Driver Behavior, and Network Characteristics on VSL Effectiveness Based on the Simulation Study

The simulation study provided an opportunity to evaluate the impact of a number of combinations of system designs, driver behaviors, and roadway networks in a controlled environment. Some of the conclusions from the simulation test include:

- *VSLs offer no substantial benefits when capacity is dramatically reduced, increasing congestion rapidly.* This suggests that VSLs should not be used when demand far exceeds available capacity. In these cases, congestion is so severe that the speed harmonization benefits of VSLs would not merit their installation.

- *Locating VSL signs to facilitate outflow past the work zone lane closure is very important.* If no VSL is positioned shortly after the final lane closure, travel times may needlessly increase if drivers continue to comply with the reduced speed limit.

- *The VSL control logic can have a significant impact on operations and safety surrogate measures.* The speed-flow-density VSL algorithm performed better than the field-tested code a majority of the time, likely because it allowed for unique speeds to be posted to every sign instead of using larger aggregate zones.

- *VSLs can have a benefit even at relatively low driver compliance levels.* Both compliance levels tested in the simulation produced positive benefits provided sufficient capacity was available. Significant reductions in queue length and lane changes were possible, and mean travel speed could increase. The speed harmonization benefits of VSLs can have significant benefits in terms of delaying the onset of congestion with driver compliance levels as low as 20%.

- *The 20-min update interval used at the site did not compromise the effectiveness of the system.* There was no statistically significant differences in performance at speed update intervals of 5, 10, and 20 min.

- *The VSL system generally produces positive effects on safety surrogate measures.* Lane changes were reduced for both networks studied, and the number of stops was reduced for the four-to-two lane closure network. These reductions are likely to translate into fewer crashes, but there is no way to predict directly the level of safety improvement at the site.

- *The simulation results show that a well-configured VSL system can provide safety and mobility benefits in a congested, urban work zone provided demand is not too far above capacity.*

- *Although the focus of this research was on a work zone application, many of the simulation findings should be transferable to a broader application of VSLs in a bottleneck management scenario.*

RECOMMENDATIONS

1. *Because a well-configured VSL system can provide operational benefits and improvements in safety surrogate measures provided that demand does not exceed capacity by too large a margin, VDOT's Operations & Security Division (OSD) and regional operational staff should consider deployment of a permanent VSL system at a site where congestion is not as severe as was modeled in this project. A volume-to-capacity threshold where VSLs would provide an operational benefit was not defined in this research since site-specific characteristics, such as ramp geometry and spacing, will likely have a significant effect on operations. Prior to deploying future VSL systems, it is suggested that specific site simulations be performed to determine likely operational impacts.*

2. *In future VSL deployments, VDOT regional operations staff should ensure that the VSL signs are located in such a way that they facilitate driver understanding and smooth operations.*

Signs should be placed so that they are not at risk of being obstructed and are not generally difficult to see under normal circumstances. The field visits showed that VSL signs on high-volume roads should be placed on both sides of the road or on overhead sign structures to decrease the likelihood of a motorist missing a posted speed attributable to an obstructed sign. Further, the simulation results indicated that speed limits should also be posted past a bottleneck to "pull" vehicles through the capacity reduction. Given that work zone operations and traffic control can change rapidly, this suggests that VSL signs should be portable so that they can be moved to appropriate locations as construction activities change. In permanent applications, VSL signs should be placed just past any bottlenecks that are constraining flow.

3. *In future VSL deployments, VDOT regional operations staff should ensure that the VSL system is operated consistently.* A concept of operations for future VSL systems should be developed and followed to ensure consistent application of systems. In the field test, the VSL system was not operated in a consistent manner initially, which may have had an impact on its effectiveness.

4. *In future VSL deployments, VDOT's OSD and regional operations staff should ensure that the VSL control algorithm is (1) designed to facilitate rapid response to changing traffic conditions and (2) based on sound traffic flow theory principles.* The simulation results show that algorithm design can make a significant difference in performance. Likewise, it appears that allowing speed limits to be set sign by sign rather than by zone can improve operations. It is important the VDOT staff have a clear working knowledge of how the system works, even if this requires signing non-disclosure agreements.

5. *VDOT regional operations and OSD staff should carefully consider operational and safety tradeoffs prior to installing VSL systems on roads where demand far exceeds capacity.* VSLs do not appear to provide significant operational benefits where there is a sudden, severe onset of congestion. Indications from this study, as well as several other studies, suggest that VSLs offer no substantial operational benefit in these cases. The VSLs do, however, appear to offer operational benefits when demand is at or just above the capacity of the road. This implies that the primary operational benefits would be obtained during the shoulders of the peak hours. The simulation results show a reduction in the standard deviation of speed with VSLs during the onset of congestion, so the VSLs could offer some safety benefit by alerting drivers approaching the end of the queue to the slow or stopped traffic ahead. Prior to investing in a VSL installation, VDOT staff should assess whether potential safety benefits could justify installation even if operational benefits are minimal.

SUGGESTION FOR FURTHER RESEARCH

Although some VSL benefits are apparent during congested work zone operations, it is unclear whether safety benefits are significant during uncongested operations. Translating safety surrogates such as stops and lane changes into actual crashes reduced is often problematic.

Further research on sign placement and the direct safety benefits of work zone VSLs would address these issues.

COSTS AND BENEFITS ASSESSMENT

The benefits of the VSL system could be realized in terms of user delay savings and crash reductions. Since the simulation models do not directly assess crash reductions and U.S. data on the direct crash reduction benefits of VSLs are limited, benefits were assessed through estimated improvements in operations only. This may mean that the benefits assessment of the VSL system is conservative, but there is not a quantitative basis for making an assessment of the safety benefits of the system.

Benefits were computed by examining differences in travel time between the base case with static speed limits and the best performing VSL alternative. The value of travel time was assumed to be $15.47 per hour for passenger cars and $102.12 per hour for trucks, which are the values used in the Texas Transportation Institute's *2009 Urban Mobility Report* (Schrank and Lomax, 2009). This is an average value of time and is not region-specific to the Washington, D.C., metropolitan area. In the case of the four-to-one lane closure, none of the VSL alternatives evaluated produced an increase in network speeds. As a result, no positive operational benefits could be quantified. In the case of the four-to-two lane closure, the best VSL configuration resulted in a mean savings of 267.04 vehicle-hours of delay during the course of the simulation. This translates into a $12,229.76 user delay savings per day that the lane closure was present with the traffic volumes simulated.

Given this daily delay savings, it is possible to determine the number of days that a VSL system would need to be operational to recoup the costs of deploying the system based purely on operational improvements. A $3.2 million system cost was assumed, which was the same as that for the system deployed in the field. Using that system cost, it would take 262 days of operation to recover the costs of deploying the system in user delay savings. This indicates that VSL systems would be most appropriate for long-term deployments, not for short-term temporary deployments. As mentioned previously, this does not account for any safety improvements generated by the system. Further, this estimate of benefits applies purely to the location modeled in this research. Other locations may have characteristics more appropriate for the application of VSLs and therefore see higher benefits.

If a VSL system is intended to be portable and temporary, at least a portion of the system costs could be recoverable over a longer time horizon across multiple sites. Additional costs to transport, calibrate, and install the system at a new site would be incurred, but costs to train staff on the equipment and some hardware costs would not be incurred again. Given that VDOT used a lump-sum lease arrangement for the WWB VSL system, these separate costs cannot be defined for an analysis across multiple sites. This would also serve to improve the benefit-cost ratio of the system, however.

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APPENDIX

SELECTED STATISTICAL TABLES

Table A-1. Queue Length Between-Subjects Effects, Four-to-One Lane Closure Network

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.433E+07	12	1.194E+06	0.209	0.998
Intercept	1.165E+11	1	1.165E+11	20423.671	0.000
Algorithm	7.743E+06	1	7.743E+06	1.358	0.244
SpeedLimitChange	106124.018	2	53062.009	0.009	0.991
Compliance	321100.035	1	321100.035	0.056	0.812
Algorithm × SpeedLimitChange	622580.153	2	311290.077	0.055	0.947
Algorithm × Compliance	2.473E+06	1	2.473E+06	0.434	0.510
SpeedLimitChange × Compliance	873100.410	2	436550.205	0.077	0.926
Algorithm × SpeedLimitChange × Compliance	2.147E+06	2	1.073E+06	0.188	0.828
Error	7.111E+10	12467	5.704E+06		
Total	2.110E+11	12480			
Corrected Total	7.112E+10	12479			

Table A-2. Number of Stops per 5 Minutes Between-Subjects Effects, Four-to-One Lane Closure Network

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.136E+07	12	946384.779	0.182	0.999
Intercept	9.976E+10	1	9.976E+10	19141.051	0.000
Algorithm	5.589E+06	1	5.589E+06	1.072	0.300
SpeedLimitChange	186633.793	2	93316.896	0.018	0.982
Compliance	458363.503	1	458363.503	0.088	0.767
Algorithm × SpeedLimitChange	455020.841	2	227510.420	0.044	0.957
Algorithm × Compliance	1.746E+06	1	1.746E+06	0.335	0.563
SpeedLimitChange × Compliance	826466.444	2	413233.222	0.079	0.924
Algorithm × SpeedLimitChange × Compliance	2.084E+06	2	1.042E+06	0.200	0.819
Error	6.498E+10	12467	5.212E+06		
Total	1.849E+11	12480			
Corrected Total	6.499E+10	12479			

Table A-3. Queue Length Between-Subjects Effects, Four-to-Two Lane Closure Network

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.999E+10	12	1.666E+09	214.075	0.000
Intercept	1.679E+11	1	1.679E+11	21570.977	0.000
Algorithm	20404.726	1	20404.726	0.003	0.959
SpeedLimitChange	3.101E+06	2	1.551E+06	0.199	0.819
Compliance	1.049E+09	1	1.049E+09	134.847	0.000
Algorithm × SpeedLimitChange	7.839E+06	2	3.919E+06	0.504	0.604
Algorithm × Compliance	1.356E+06	1	1.356E+06	0.174	0.676
SpeedLimitChange × Compliance	1.283E+07	2	6.416E+06	0.825	0.438
Algorithm × SpeedLimitChange × Compliance	2.832E+06	2	1.416E+06	0.182	0.834
Error	1.962E+11	25207	7.782E+06		
Total	3.649E+11	25220			
Corrected Total	2.161E+11	25219			

Table A-4. Number of Stops per 5 Minutes Between-Subjects Effects, Four-to-Two Lane Closure Network

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	4.354E+10	12	3.628E+09	288.496	0.000
Intercept	2.570E+11	1	2.570E+11	20432.913	0.000
Algorithm	505531.712	1	505531.712	0.040	0.841
SpeedLimitChange	4.561E+06	2	2.281E+06	0.181	0.834
Compliance	1.766E+09	1	1.766E+09	140.396	0.000
Algorithm × SpeedLimitChange	1.821E+07	2	9.107E+06	0.724	0.485
Algorithm × Compliance	2.872E+06	1	2.872E+06	0.228	0.633
SpeedLimitChange × Compliance	2.492E+07	2	1.246E+07	0.991	0.371
Algorithm × SpeedLimitChange × Compliance	5.615E+06	2	2.808E+06	0.223	0.800
Error	3.170E+11	25207	1.258E+07		
Total	5.740E+11	25220			
Corrected Total	3.605E+11	25219			