Intelligent Transportation System Field Demonstration

Integration of Variable Speed Limit Control and Travel Time Estimation for a Recurrently Congested Highway

Gang-Len Chang, Sung Yoon Park, and Jawad Paracha

Contending with recurrent congestion on commuting corridors has long been a challenging and pressing issue for responsible highway agencies. However, effective strategies to mitigate the congestion level and the accompanying safety issues on those highway segments remain to be developed. In response to such needs, this study presents an innovative system that integrates variable speed control and travel time information for alleviating day-to-day recurrent congestion on a highway corridor. The system presented in this study includes a set of algorithms for setting variable speeds for different highway segments based on traffic conditions detected from roadway sensors and a well-calibrated license-plate-recognition system for displaying the estimated travel time. Field experiments of the proposed system on MD-100 for 8 weeks showed that with proper speed control in real time, the congested highway segment can achieve a higher throughput, a stable traffic condition, and a shorter travel time.

Variable speed limit (VSL) control is an advanced traffic management strategy that has received increasing interest in the transportation community since the advent of intelligent transportation systems in the 1980s. A complete VSL system typically consists of a set of traffic sensors to collect flow and speed data, several properly located variable message signs (VMSs) for message display, a reliable control algorithm to compute the optimal speed limit for all control locations, and a real-time database as well as communication systems to convey information among all principal modules.

The core VSL logic is to adjust dynamically the set of speed limits properly located along a target roadway segment to smooth the speed transition between the upstream free-flow and downstream congested traffic states, thereby preventing formation of an excessive queue due to the shockwave impacts. It is a common belief that proper implementation of a VSL coupled with reliable traffic information messages can facilitate traffic flows to utilize the available capacity of the bottleneck segment and thus result in an increased average traffic speed and throughput during the most congested period. With its dynamic adjustment capability, VSL control can improve traffic safety on some hazardous highway segments that often experience poor weather conditions and justify the reduction in speed to prevent potential accidents.

VSLs can also be an effective strategy to control traffic flows in a highway work zone to improve traffic safety over the capacity-reduced segment with a set of gradually reduced speed limits. According to the purpose of control, one can divide most recent studies on VSL operations into two categories: improving work-zone safety and enhancing efficiency on recurrently congested roadways. In the first category, the Michigan Department of Transportation (*1*), Lin et al. (*2*), Kwon and Brannan (*3*), and Kang and Chang (*4*) analyzed VSL control in a work-zone area. Their studies reported that VSL control can reduce speed variance for safety and increase throughput as well as traffic-flow speeds. A study on the I-495 Capital Beltway (*5*) revealed that VSLs can delay the onset of congestion and help produce more rapid recovery from congestion.

Another category of VSL applications is on highway segments experiencing recurrent congestion or inclement weather conditions. The focus of such applications, mostly deployed in Europe, was to improve roadway safety or increase its operational efficiency. Hegyi and Schutter (*6*) and Bertini and Bogenberger (*7*) showed that VSLs can increase traffic-flow efficiency on recurrently congested highways. Ulfarsson and Shankar (*8*) and Abdel-Aty (*9*) revealed that VSLs can improve traffic safety.

For improving both operation and safety performance, Steel and McGregor (*10*) reported some critical issues associated with the effectiveness of VSL applications in nonwork zones. Jonkers and Klunder (*11*) and Buddemeyer and Young (*12*) focused VSL applications on informing drivers of inclement weather conditions and posted the new speed limit for control of traffic flows. Bertini and Boice (*13*) and Anund and Ahlström (*14*) in contending with recurrent highway congestion investigated the effectiveness of integrated VSLs and travel information on improving safety and operation efficiency. In contrast, research on applying VSLs to minimize volume-induced recurrent congestion remains in its infancy in the United States, regardless of theoretical developments or field investigation, even though there are many successful deployments in Europe (*15, 16*).

In view of deteriorating commuting traffic conditions in most major metropolitan areas and diminishing resources for infrastructure renovation, exploring the potential of nonconstruction strategies such as VSL control to mitigate recurrent highway congestion has emerged as a priority task for the traffic management community.

This paper reports the field experiment results with a proposed advisory VSL system, focusing on the resulting average speed and

G.-L. Chang and S. Y. Park, Department of Civil Engineering, University of Maryland, College Park, MD 20742. J. Paracha, Maryland State Highway Administration, Baltimore, MD 21202. Current affiliation: FHWA, U.S. Department of Transportation, 1200 New Jersey Avenue, SE, Washington, DC, 20590. Corresponding author: S. Y. Park, alza102@gmail.com.

Transportation Research Record: Journal of the Transportation Research Board, No. 2243, Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 55–66.
DOI: 10.3141/2243-07

total throughput over the bottleneck location and the speed transition from free-flow to congested traffic conditions.

This paper is organized as follows: a field VSL demonstration plan is illustrated in the next section. The VSL control algorithm is discussed in the third section, followed by a detailed description of the field demonstration plan in the fourth section. Experimental results are summarized in the fifth section, and research findings and recommendations for future studies are presented in the last section.

FIELD VSL DEMONSTRATION PLAN

On the basis of findings from a literature review and the authors' previous research results, this study used the following criteria to select a recurrently congested roadway segment for field evaluation of VSL control:

- Some significant variation in geometric features (e.g., weaving or lane drop) that may cause the traffic flow to change speed or to raise some safety concerns,
- Significant fluctuation in traffic-flow speed such as evolving from free-flow to stop-and-go congestion conditions during peak hours,
- Traffic volume surge during the peak period causing upstream entry flows to reduce speed dramatically, and
- Significant numbers of incidents per year.

The research team selected the segment MD-100 West from MD-713 to Coca-Cola Drive to experiment with VSL-related control strategies, because in 2008 alone it experienced a total of 39 accidents. Also, during the evening peak period this segment has a high exiting volume from Arundel Mill Boulevard and causes the traffic-flow speed to decline significantly.

MD-100 is a two-lane (in each direction) highway with speed limit of 55 mph. On average weekdays, the evening peak period usually starts at 5 p.m., and the speed usually drops quickly from 60 to 20 mph (e.g., in 5 min) after the onset of congestion. Over Coca-Cola Drive, the speed typically increases and can reach 30 to 40 mph. Figure 1 illustrates the target MD-100 segment selected for VSL control and its spatial distribution of traffic-flow speeds during the peak period.

As evident in the speed profile data, traffic flows generally started at 60 mph from the location intersecting with MD-170 and gradually decreased to about 50 mph after reaching MD-713 during peak hours. Speed dropped sharply to 20 to 25 mph after ramp flows from I-295 were encountered and continued at the same stop-and-go speed until passing Coca-Cola Drive. The dramatic speed drop over a distance of about 2 mi offers the ideal traffic condition for VSL control. It also is desirable to have the estimated travel time from MD-170 to US-1 so that drivers can ease their concerns about downstream traffic conditions. The free-flow travel time from MD-170 to US-1 is about 180 s. However, travel time goes up to 600 s during congestion.

In brief, according to the selection criteria and field survey results, this study selected the MD-100 segment between MD-170 and Coca-Cola Drive where the speed decreases from 60 to 25 mph to experiment with VSL control. During the demonstration period, the system concurrently displayed an estimated travel time from MD-170 to US-1.

VSL CONTROL ALGORITHM

For exploratory purpose, this study applies the VSL algorithm developed by Lin et al. (*2*). Their VSL-1 control algorithm is designed to perform the following tasks:

- Reduce speed of approaching traffic so as to smooth the transition between the free-flow and congested-flow states and
- Take into account the responses of drivers in dynamically setting the appropriate control speed for each transition location.

The proposed VSL control algorithm consists of two modules. As shown in Figure 2, the first module (Module 1) functions to compute the initial speed of each VSL location, and the second module (Module 2) is responsible for updating the displayed speed for each VMS

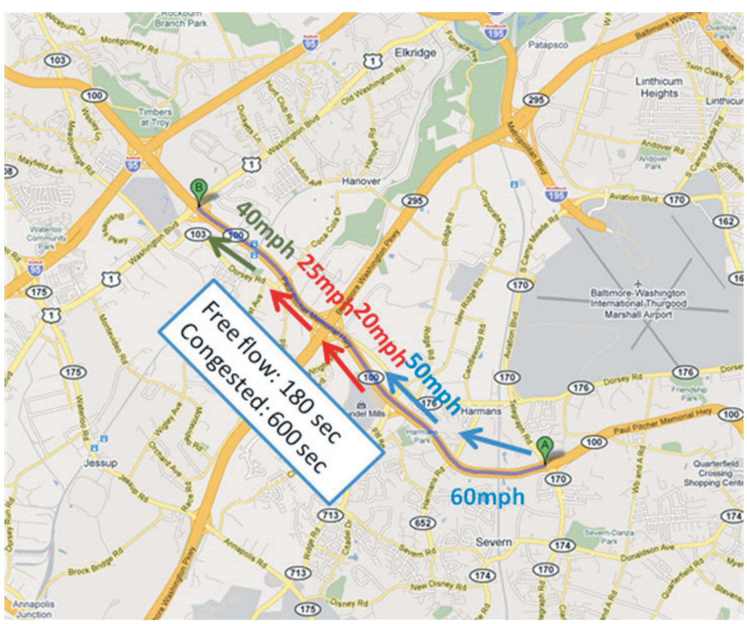


FIGURE 1 Spatial distribution of traffic-flow speeds over VSL control segment.

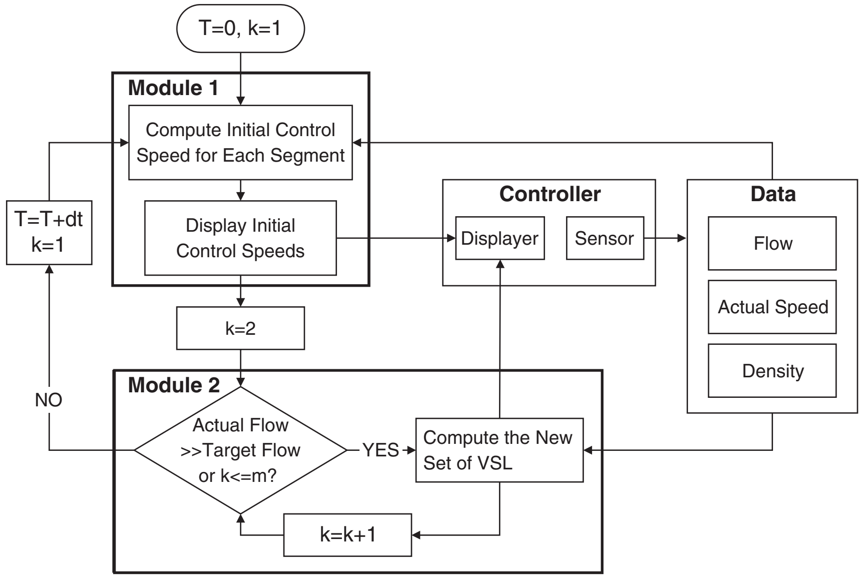


FIGURE 2 Flowchart for VLS control algorithm [T = time, dt = time increment for operation, k = module indicator (1 = Module 1, 2 = Module 2), and m = indicator that system does not trap into Module 2 (value is 2)].

based on the estimated difference between the detected flow and the target control speeds.

- Module 1. To minimize potential queue formation due to downstream congestion, the upstream segment within the potential maximum queue length and its impact range should be divided into a number of subsegments with each being monitored by a set of sensors, VMSs, and VSL signs. The control target for Module 1 is that the traffic-flow rate over the first segment should be approximately equal to the flow rate entering the control area as shown in Figure 3.
- Module 2. Since drivers typically do not follow the displayed control speeds, Module 2 is designed to compute the differences between the detected flow and the target control speeds and to update the displayed speeds accordingly. A detailed discussion of the VSL control algorithm is available elsewhere (*2*).

DESIGN OF VSL SYSTEM DEMONSTRATION

The entire VSL operating system for field demonstration includes hardware deployment, communication setup, software, and an online database for real-time monitoring and management. Figure 4*a* illustrates all principal system components and their interrelationships. The key functions associated with each component are summarized below:

- Traffic sensors. Four high-definition radar sensors from Wavetronix (http://www.wavetronix.com) to measured speed, occupancy, and flow rate by lane at 30-s intervals;
- License-plate-recognition (LPR) system. One pair of an LPR system for travel time measurement;
- VMS. Two sets of VMSs for informing drivers;
- Real-time data conversion and transmission module. A specially designed program to collect all real-time information such as a time stamp of each observed license plate, site identification, traffic volume, average speed of time interval, and transfer of information between the central database and the wireless network; and
- Real-time database module. A customized database that functions to receive data from traffic sensors and LPR units and forward the required information for the travel time and VSL modules to generate estimated travel time and advisory control speeds.

Figure 4*b* illustrates the operational flows between the control system, roadside units, and the web display module. The traffic-flow data detected by the roadside sensors and the LPR system (*17*) will

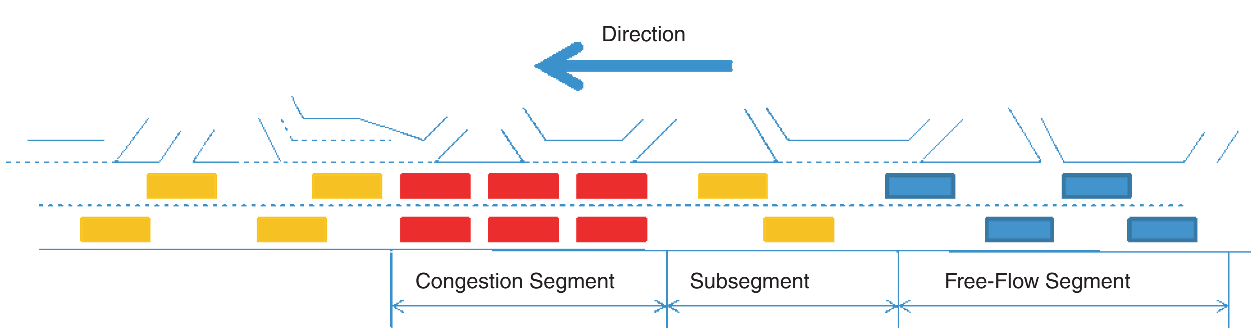


FIGURE 3 Control area for VSL applications.

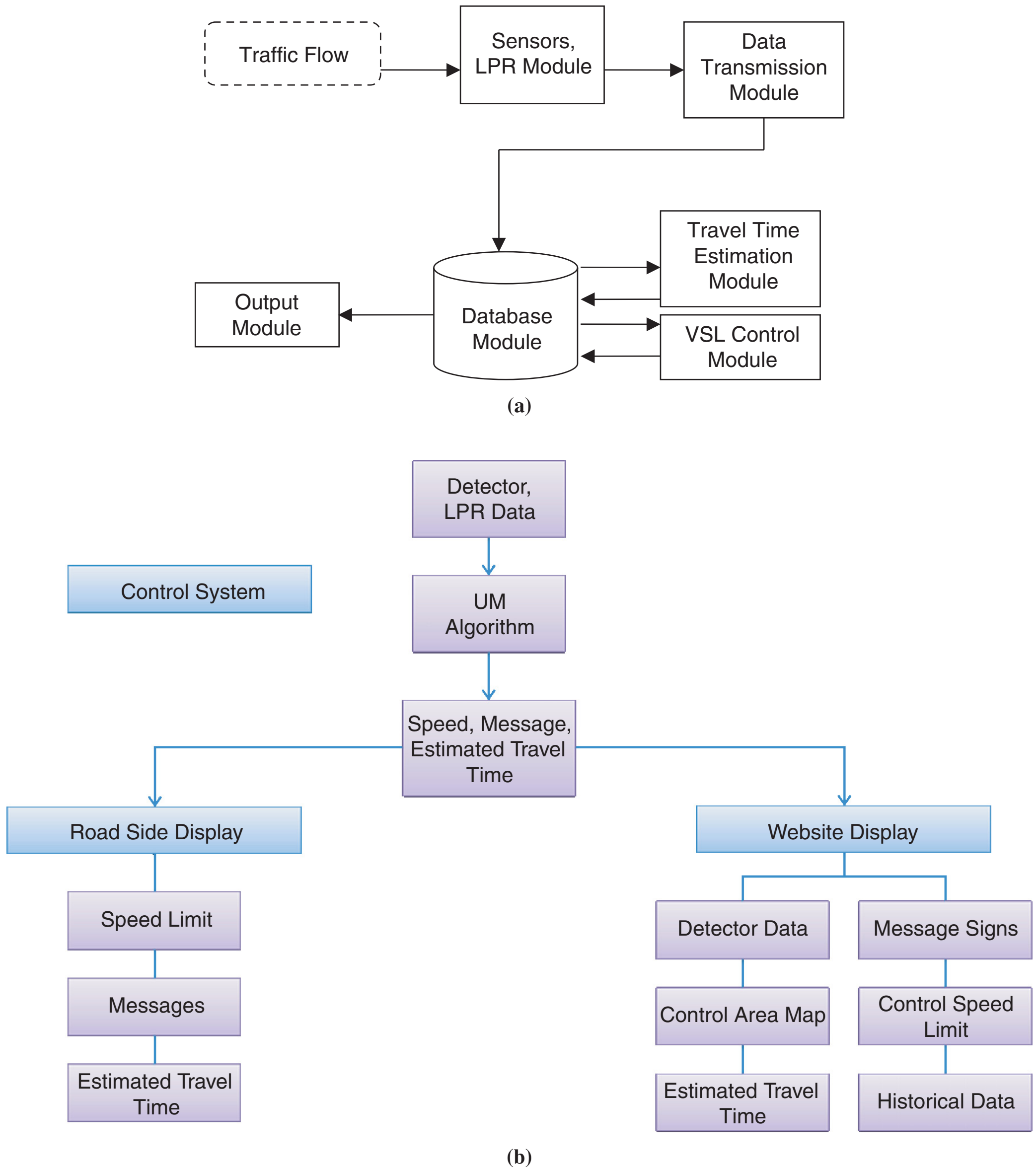


FIGURE 4 (*a*) Principal modules of proposed VSL system and their interrelationships and (*b*) operational flowchart between key components [UM = University of Maryland; UM algorithm includes travel time estimation module (*17*) and VSL control module (*2*)].

trigger the VSL algorithm module to calculate estimated travel times and advisory speed limits. Such information will then be displayed in real time on the roadside VMS and a customized website and will be updated at 1-min intervals.

On the basis of spatial distribution of traffic-flow speeds from MD-170 to Coca-Cola Drive, the segment of MD-100 from MD-713 to Coca-Cola Drive was selected as the target control segment, because the traffic-flow speed exhibits a substantial drop from an average of 50 to 25 mph on this segment due to traffic volumes coming from two ramps (see Figure 5). To capture traffic-flow and speed evolution, Detector 4 was placed on MD-713 to detect the upstream traffic condition and Detector 3 was used to measure the incoming high traffic volume from its ramp during peak hours.

Detector 2, located between two ramps from I-295 to MD-100, functions to detect the starting point of the speed drop in traffic flow. This detector also serves to monitor the speed transition between Detector 1 and Detector 3 locations. The roadside component contains two speed advisory signs: one was deployed next to Detector 4 where drivers began to change from their free-flow to constrained traffic conditions, and the second was placed around Detector 2 to respond to the observed stop-and-go recurrent congestion.

To alert drivers about the speed advisory control plan, the roadside component also includes two VMSs, placed about 1 mi apart, preceding the speed advisory sign, to inform travelers of the downstream traffic conditions and the travel time to US-1.

The entire experimental plan consists of four control periods: no control, display of estimated travel time, VSL control only, and both the VSL control and display of estimated travel time. With these four operational plans, it was possible to observe the response of drivers to the incremental level of control or information availability and their

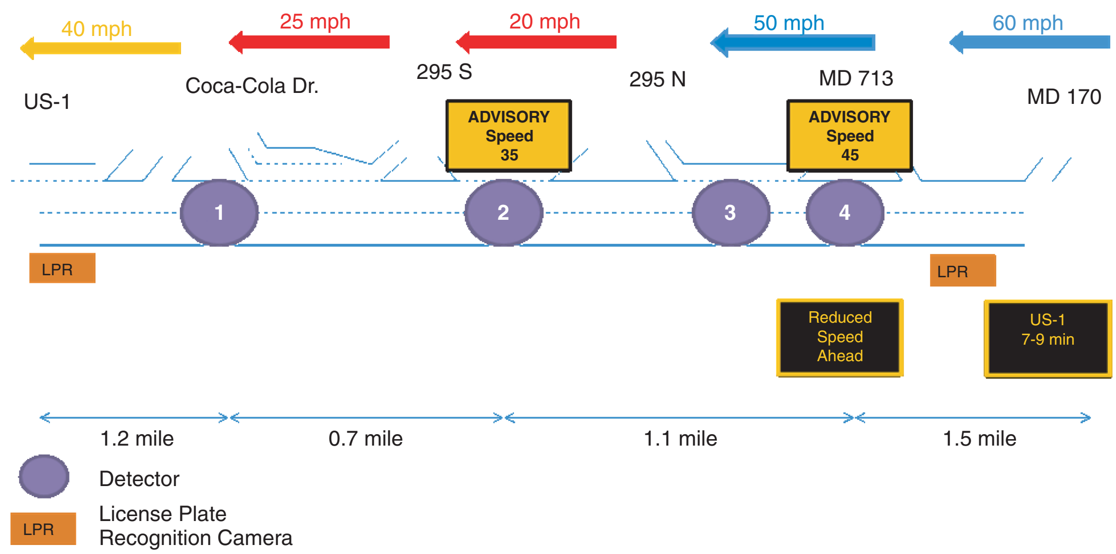


FIGURE 5 Roadside system configuration.

collective impacts on traffic conditions with respect to speed, throughput, and travel time. Key research activities conducted during each experimental period are summarized in Table 1.

ANALYSIS OF EXPERIMENTAL RESULTS

In view of the potential day-to-day traffic fluctuation during the experimental period, this study adopted the following analysis procedures to ensure the reliability of the concluding findings:

Step 1. Evaluate the stability of traffic conditions before and during the field experimental periods, including the speed and volume entering the target segment experiencing recurrent congestion by time of day.

Step 2. Identify the spatial and temporal impacts of different control strategies on the target roadway segment, including the average travel time and speed by time of day over the target congested roadway segment.

Step 3. Compare the average measures of effectiveness (MOEs) under different control strategies on the target roadway segment over their respective deployment period, including average throughput, travel time over different control periods, and on different days.

Stability Evaluation

Figure 6*a* shows the time-varying traffic volume aggregated at 5-min intervals from Sensor 4 over 4 days before system deployment. Figure 6*b* displays the speed evolution from Sensor 1 (end point of the bottleneck) for the same 4 days. As MD-100 is one of the primary commuting corridors, the traffic patterns exhibited in both figures appear quite stable from day to day.

Figure 6*c* compares traffic volumes per 5-min interval over time during the experimental period. The overall traffic pattern exhibits the same level of stability regardless of the implemented control strategies. Figure 6*d* shows the speed evolution patterns under three control strategies, confirming that the overall traffic demand and traffic conditions are quite stable before and during the experimental periods. The peak-hour traffic speeds under the no-control scenario, as expected, are lower than those under different control strategies. Thus, one can conduct a detailed performance analysis and attribute any variation in MOE to the deployed control measures.

Spatial and Temporal Impacts

The main purpose of VSLs is to smooth the speed transition from the free-flow condition to the traffic state that truly utilizes the available capacity of the recurrently congested segment, rather than experiencing a drastic speed drop and forming a stop-and-go bottleneck. The purpose of estimated travel time displayed by VMSs is to encourage drivers to comply with the suggested speed change, intending to convince them that their cooperation will improve the overall traffic condition on the congested segment and they will not incur excessive delay.

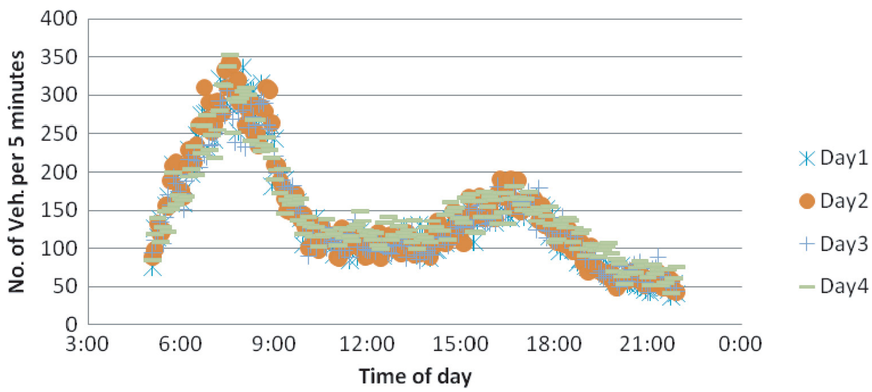
Figure 7 shows traffic-flow speed along MD-100 starting from its intersection with MD-170 to the end point of the intersection with Coca-Cola Drive. As evidenced by the graphic shape, drivers under the no-control or travel time display scenario experienced a speed drop from 60 to around 20 mph when reaching the location receiving the I-295 traffic flow. Such a sharp speed reduction over a distance of less than 2 mi forms a stop-and-go bottleneck and often incurs accidents. On contrast, under the control strategies of VSL and VSL and travel time, traffic flow can maintain an average speed between 40 and 35 mph over the most congested segment. Although all implemented control strategies are advisory rather than mandatory in nature, their effectiveness in reducing speed variance is impressive. A further investigation of the time-varying travel time over the entire segment during the evening peak period confirms the effectiveness of those experimental control strategies.

For instance, the average travel time under the control of VSL and travel time display, as shown in Figure 8, was significantly shorter than that under the no-control condition during the most congested interval from 5 to 5:30 p.m. The travel time differences between the no-control and the three control scenarios, as expected, diminish when traffic conditions on the target roadway are less congested, such as between 6 and 6:30 p.m. The general trend from the graphic

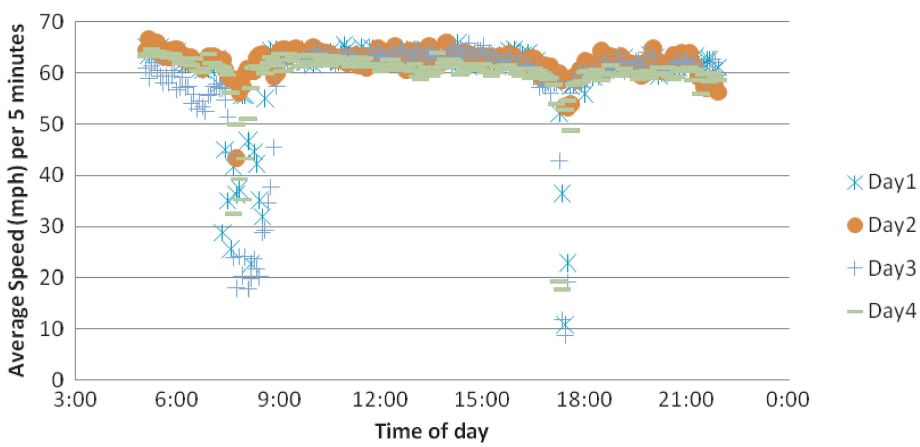
TABLE 1 Demonstration Period and Research Activities

Demonstration Period	Duration[a]	Activities	Note
No-control scenario	Nov. 11, 2009–Nov. 30, 2009	Deploy two LPR trailers, four sensor trailers, two VMS, two VSL at each preselected location. Calibrate LPR system, sensor data, VMS and VSL. Collect background traffic such as traffic volumes, speeds, and travel times. Test the main functions of each system component. Experiment with the interactions between principal components and the operations of the entire system.	No roadside display
Display estimated travel time	Dec. 1, 2009–Dec. 13, 2009	Start the roadside display of estimated travel times from MD-170 or MD-713 to US-1. Test the VSL algorithm with the field data but without the roadside display. Continue the operations of travel time estimation and sensor data update.	Estimated travel time display on VMS
VSL control only	Dec. 14, 2009–Dec. 27, 2009	Filter the data from traffic sensors, and execute the VSL algorithm to produce and display the advisory speed limits. Display the "Reduced Speed Ahead" message on two VMSs when the VSL module is activated. Continue the system operations, including the VSL computation, travel time estimation, and sensor data update.	Advisory speed limit display with "Reduced Speed Ahead" message on VMS
VSL control and estimated travel time display	Dec. 28, 2009–Jan. 25, 2010	Continue the system operations, including the VSL computation, travel time estimation, and sensor data update. Display the advisory control speeds on the two roadside VSL trailers and the estimated travel time on two VMS with estimated travel time display.	When VSL system is active, VMS shows "Reduced Speed Ahead" and estimated travel time. Otherwise, shows estimated travel time only.

[a]Holidays (Nov. 26, Nov. 27, Dec. 24, Dec. 25, Dec. 31, and Jan. 1) are excluded.



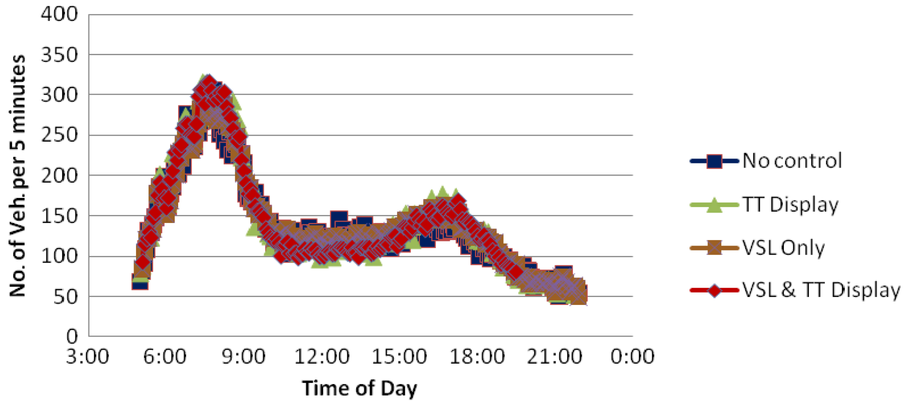
(a)



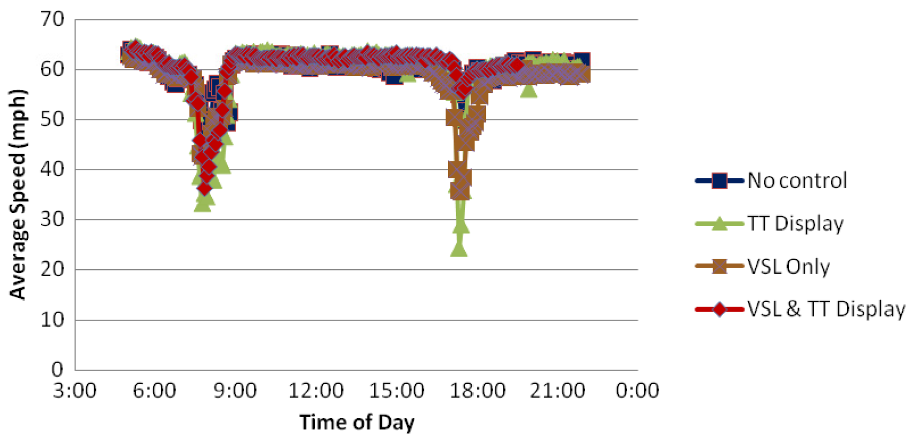
(b)

FIGURE 6 (a) Distribution of average traffic volumes over time before experimental period from Sensor 4 and (b) distribution of average traffic speeds over time before experimental period from Sensor 1.

(continued)



(c)



(d)

FIGURE 6 *(continued)* (*c*) distribution of average traffic volumes during different experimental periods from Sensor 4 and (*d*) distribution of average traffic speeds over time before experimental period from Sensor 1 (TT = travel time).

patterns in Figure 7 also supports the hypothesis that by smoothly decreasing the speed to a proper level over a highway segment of recurrent congestion, drivers need not experience stop-and-go conditions and are likely to have shorter travel times.

Figure 9 presents the average speed collected by Sensor 4 at the most congested location from 4 to 6 p.m. under different control strategies. As shown in the evolution patterns, the most congested interval varies among those four experimental scenarios, where the lowest average speed experienced by drivers was 28.7 mph under the no-control scenario but increased to 33.1 mph under the control of VSL and travel time display. The lowest average speed was around 30 mph if VSL and travel time display were implemented independently. These empirical results appear to support the hypothesis that using variable speed control can prevent sudden speed drops at recurrent congestion locations and thereby reduce the stop-and-go delay. The smooth transition between free flow and congested flow can also minimize potential rear-end collisions due to a small speed variance between vehicles.

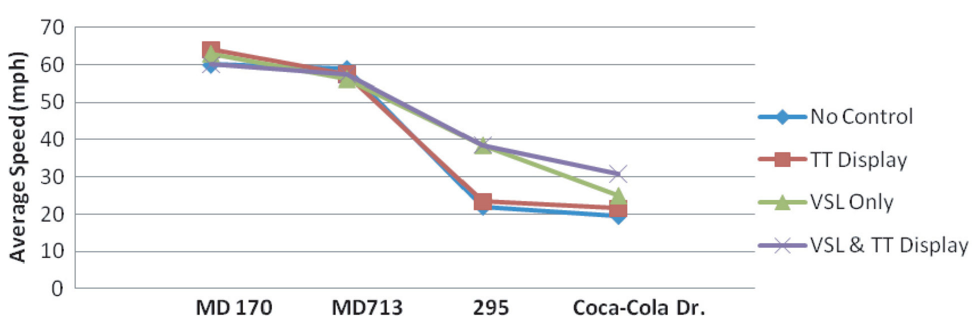


FIGURE 7 Spatial distribution of average traffic-flow speed under different controls.

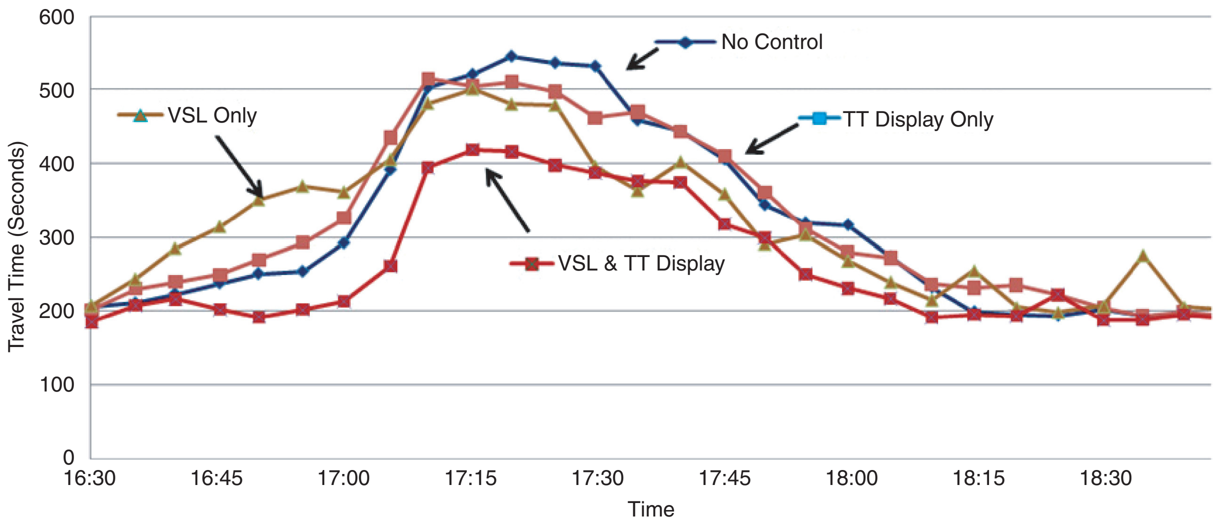


FIGURE 8 Distribution of average travel times (measured by LPR system) under different control strategies.

Comparison of MOEs

In addition to the average speed measured with radar detectors, this study also selected the total throughput and average travel time over a target interval as the MOEs. In theory, a mandatory VSL and travel display control, if properly implemented, should result in an increase in the average flow speed and throughput over the target roadway segment. Since all control strategies deployed at the demonstration site were advisory only, it is critical to have an in-depth analysis of their impacts on traffic conditions.

Figure 10 presents the comparison results of average travel time under different control scenarios over selected peak-hour intervals. Those travel times were measured directly with the deployed LPR system rather than estimated from detector data. As shown in the comparison charts, the average travel time during the most congested half hour under the no-control scenario was about 539 s, significantly longer than the average of 400 s under the VSL and travel time display environment. The average travel times over the same period under travel time display only and VSL control alone were 503 and 484 s, respectively.

A similar trend exists in the average travel time comparison over the most congested 1 and 1.5 h. For example, drivers under the no-control scenario experienced an average travel time of 469 s during the peak period of 1 h but took only 345 s during the same period with VSL and travel time display control. Considering the 3-mi distance of the target roadway segment that typically takes commuters less than 180 s during the off-peak period, one can view the reduction of about 25% in travel time during the peak hour as quite impressive.

Figure 11 illustrates the total throughput under different control scenarios over the peak period of 30 min and 1 h. The comparison results clearly indicate that all three control strategies, if properly implemented, can significantly increase the total throughput over the target recurrent congestion segment. For instance, the total throughput during the most congested half hour increased from 1,883 to 1,974 vehicles under the travel time display scenario and to around 2,040 vehicles with the VSL and travel time display control environment. A further comparison of the total throughput over the peak period of 1 h reveals that the target roadway segment that has recurrent congestion can accommodate 230 (3,713 vs. 3,980 or 3,841) more vehicles under the VSL or VSL and travel time display environment, indicating the unquestionable effectiveness of those deployed control strategies.

Control of the VSL and travel time display yields a slightly smaller total throughput than the VSL alone in Figure 11 because the display of travel time over the target segment has further smoothed the traffic during the peak period and lowered the congestion level. Hence, vehicles during the most congested period were able to travel at slightly higher speeds and in less condensed platoon conditions. This scenario is evidenced in the pattern shown in Figure 7 and the speed evolution data in Table 2.

Figure 12 presents the total throughput comparison on different weekdays. As evidenced in the revealed patterns, the effectiveness of VSL or VSL and travel time display controls with respect to the total throughput is quite consistent on different days of the week.

The third MOE selected for performance evaluation is the average speed evolution during the peak hour under the four traffic control environments. As shown in Table 2, the average speed during the first 15 min of the most congested hour does not appear to benefit from the control strategies that were implemented. However, drivers appeared to be able to respond progressively to the control strategies and to improve their travel speeds significantly after about 30 min. For example, the average speed during the peak hour increased from the no-control scenario of 22.4 mph to 37.4 mph under VSL and travel time display control. However, it is noticeable that implementing a VSL or travel time display alone does not appear to have significant impacts on the average traffic-flow speed. A plausible explanation for this phenomenon is that drivers are willing to comply with the advisory speed produced by the VSL system if they are informed of the resulting travel time over the downstream roadway segment. The higher the compliance rate is, the more the effectiveness the VSL control will be.

The experimental results clearly indicate that highway segments experiencing recurrent congestion can benefit significantly from VSL and travel time display control, including travel time reduction and increased travel speed as well as overall throughput during the peak period.

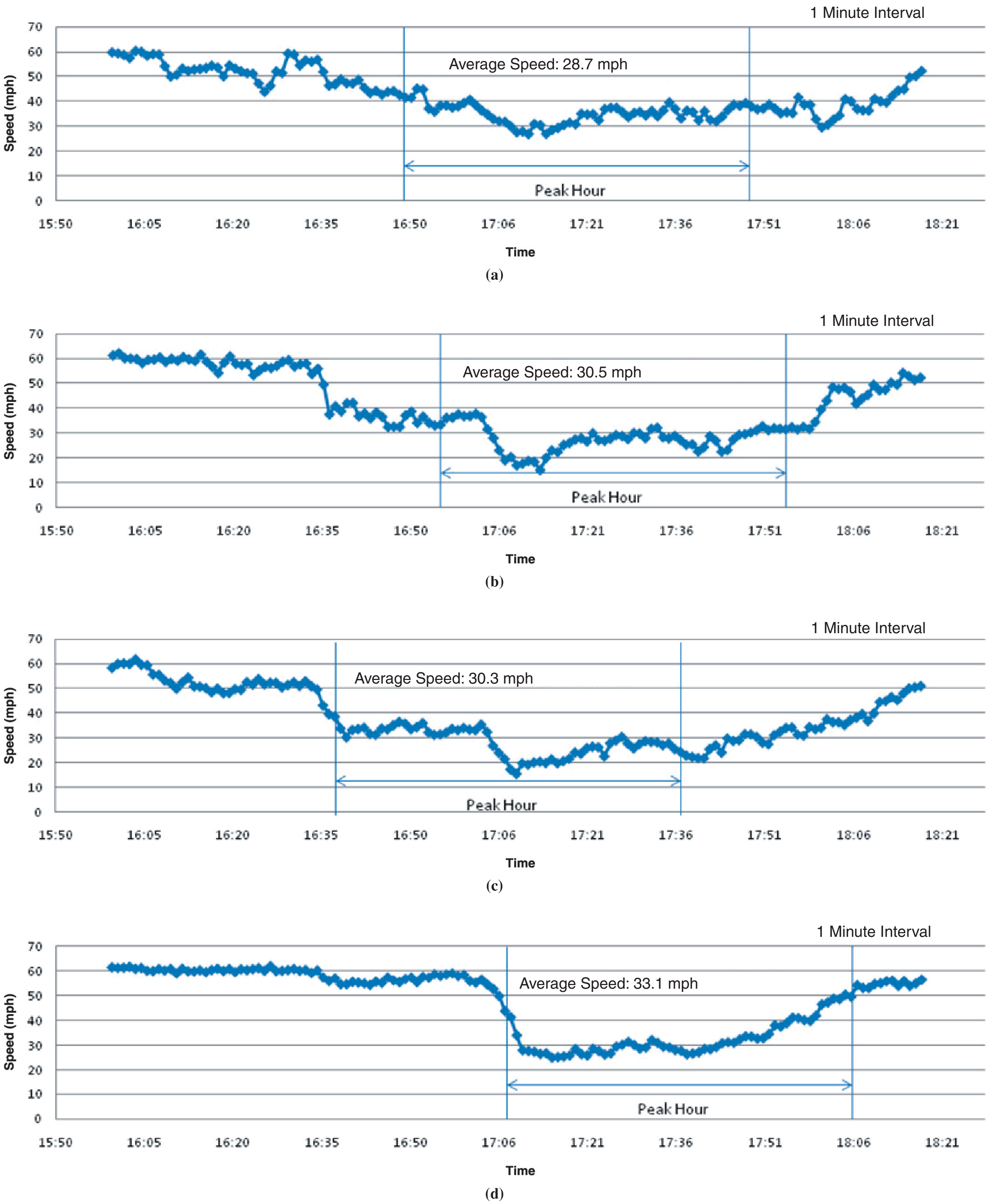
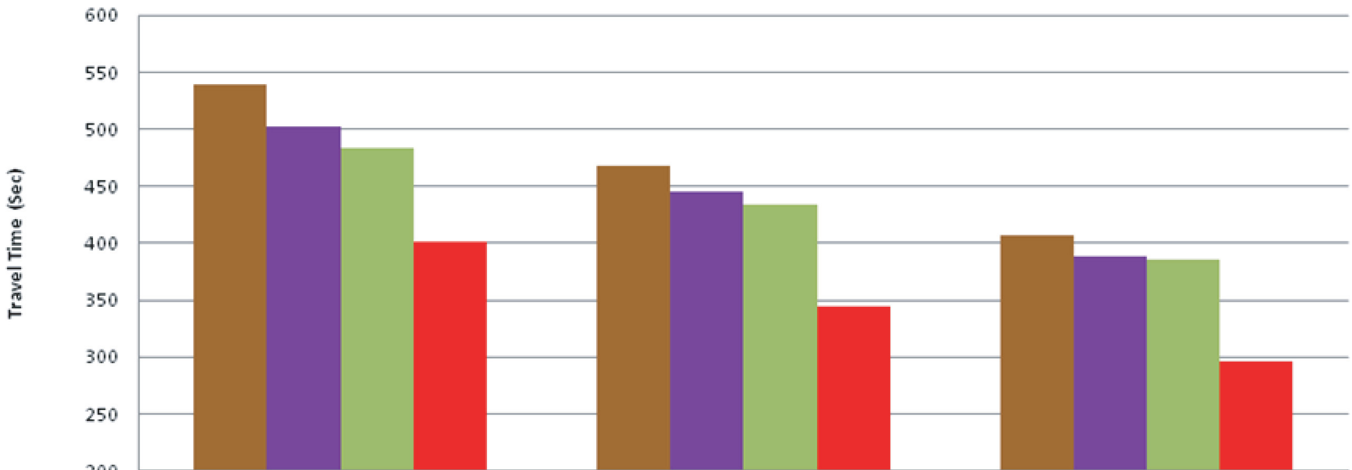


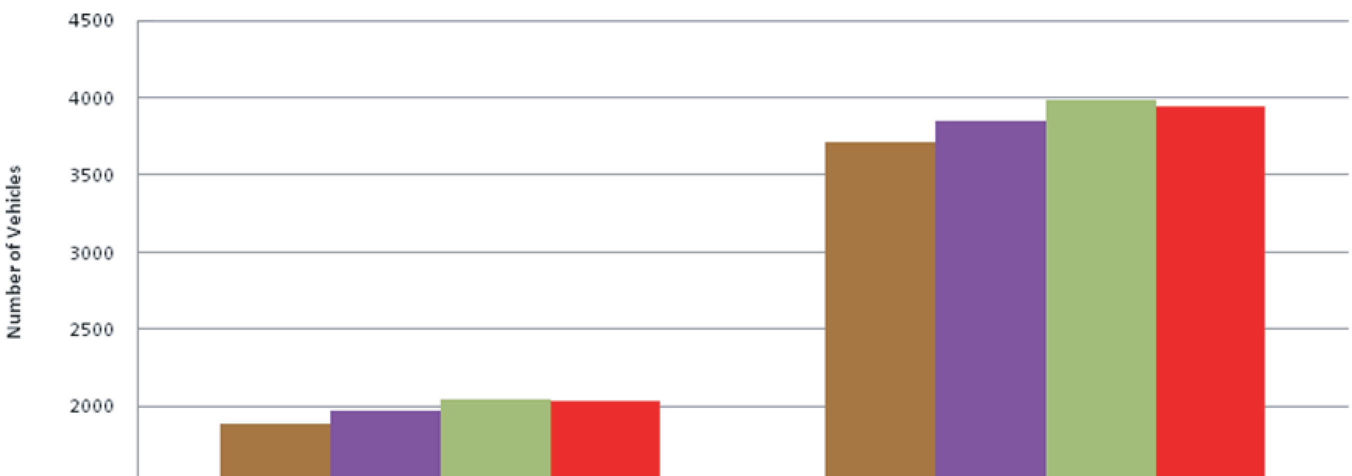
FIGURE 9 Identification of most congested hour under different control strategies: (*a*) no control, (*b*) travel time display only, (*c*) VSL only, and (*d*) VSL and travel time display.



	30 Min *	1 Hour **	1.5 Hour ***
No Control	539	469	407
TT Display	503	445	388
VSL	484	434	385
VSL & TT	401	345	297

*The Peak Period of 30 Minutes **The Peak Period of 1 Hour ***The Peak Period of 1.5 Hour

FIGURE 10 Comparison of average travel times over selected peak periods under different control strategies.



	30 Min *	1 Hour **
No Control	1883	3713
TT Display	1974	3848
VSL	2045	3980
VSL & TT	2036	3941

*The Peak Period of 30 Minutes **The Peak Period of 1 Hour

FIGURE 11 Comparison of total throughput over selected peak periods under different control strategies.

TABLE 2 Evolution of Average Speed During Peak Hour Under Different Controls

Selected Interval	No Control (mph)	Travel Time Display (mph)	VSL (mph)	VSL and Travel Time (mph)
First 5 min	27.8	25.2	24.2	26.6
15 min	19.7	19.6	22.2	20.0
30 min	18.1	19.3	20.8	24.8
1 h	22.4	22.3	23.6	37.4

CONCLUSIONS AND RECOMMENDATION

This paper presents a real-time VSL control system for alleviating recurrent congestion on commuting corridors. The experimental results show that VSL control is a potentially effective control strategy if the spatial distribution of the traffic speed on the highway segment exhibits a dramatic reduction from free-flow speed to a congested or stop-and-go level due to the volume surge over a short distance. The VSL control system, integrated with the travel time information, can smooth the transition between free-flow speed and stop-and-go congested conditions, increase average speed, reduce overall travel time over a recurrently congested roadway segment, and increase total throughput.

As an early field study for exploring the VSL control potential for recurrent highway congestion, the research results have revealed some issues that need to be addressed before comprehensive deployment of the VSL control. Each of those issues is presented below:

- Criteria and guidelines for selecting target roadway segments, which are suited for deploying the VSL control to mitigate their recurrent congestion, including highway geometry features, spatial and temporal distribution of traffic-flow speed, time-varying volume patterns, length of bottleneck segment versus the entire target segment for speed transition, and the theoretically available capacity at the most congested location;
- Guidelines for determining the number of speed advisory points for transition between free-flow and congested speeds;
- Guidelines for determining optimal sensor and VMS locations;
- Developing an effective VSL control algorithm that contains the minimal number of parameters and thus requires minimal effort for field calibration;
- Criteria for activating and deactivating the VSL control for a target roadway segment plagued by recurrent congestion; and

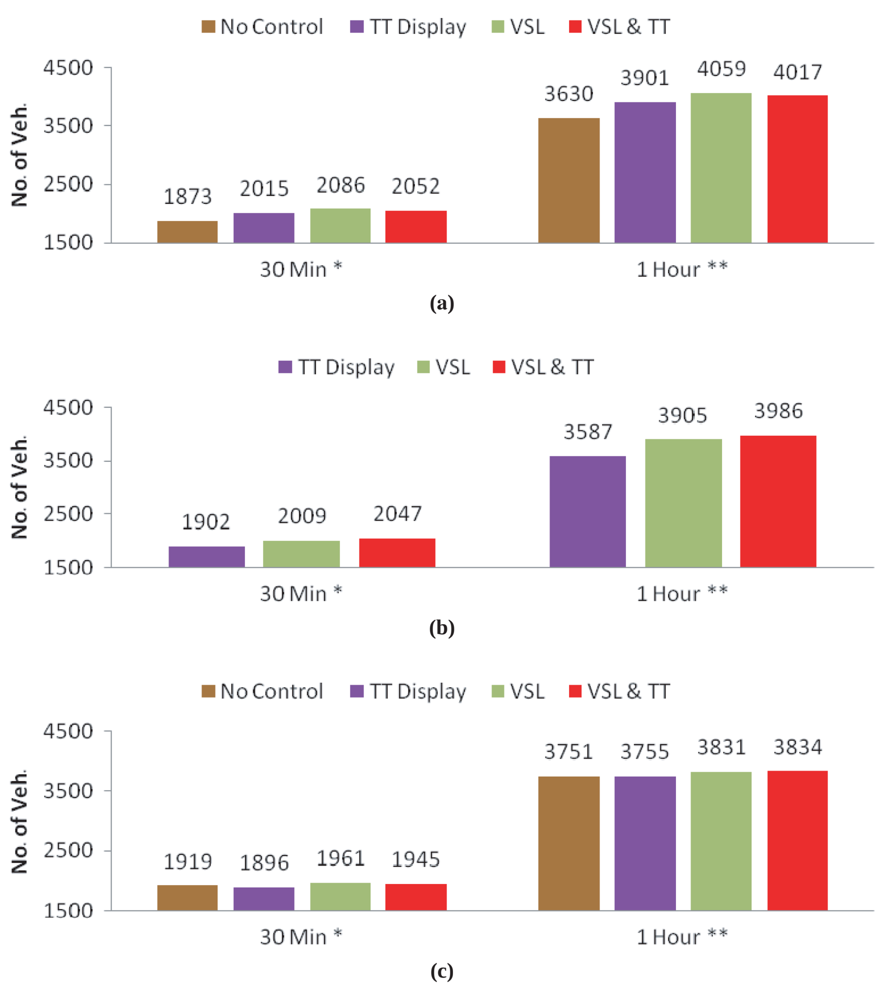


FIGURE 12 Comparison of total throughput on selected weekdays under different control strategies: (*a*) Monday, (*b*) Wednesday, and (*c*) Friday.

- Coordinating various messages with VMSs within the VSL control boundaries so they can complement each other and provide the best advisory information to target drivers rather than confuse them.

In addition to the above issues, highway agencies intending to deploy VSL control should also carefully conduct surveys to understand the preferences and responses of local populations to various messages displayed on VMSs so that the design will be well received by drivers and thereby increase their compliance with the displayed suggestions.

ACKNOWLEDGMENTS

This project was sponsored by the Office of Policy and Research at the Maryland State Highway Administration. The authors extend their appreciation to Michael Paylor, Allison Hardt, Xiang Hua, and Nan Zou for their invaluable assistance during the system demonstration period.

REFERENCES

1. Lyles, R. W., W. C. Taylor, and J. Grossklaus. *Field Test of Variable Speed Limits in Work Zones (in Michigan).* Final Report RC-1467. Michigan Department of Transportation and Michigan State University, Lansing, 2003.
2. Lin, P., K. Kang, and G. L. Chang. Exploring the Effectiveness of Variable Speed Limit Controls on Highway Work-Zone Operations. *Journal of Intelligent Transportation Systems,* Vol. 8, No. 3, 2004, pp. 155–168.
3. Kwon, E., D. Brannan, K. Shouman, C. Isackson, and B. Arseneau. 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, D.C., 2007, pp. 12–18.
4. Kang, K., and G. L. Chang. Development of Integrated Control Algorithm for Dynamic Lane Merge and Variable Speed Limit Controls. Presented at 11th World Conference on Transportation Research, Berkeley, Calif., June 24–28, 2007.
5. Sisiopiku, V. P., A. Sullivan, and G. Fadel. *Implementing Active Traffic Management Strategies in the U.S.* University Transportation Center Report for Alabama, No. 08206, Birmingham, 2009.
6. Hegyi, A., B. De Schutter, and J. Hellendoorn. Optimal Coordination of Variable Speed Limits to Suppress Shock Waves. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1852,* Transportation Research Board of the National Academies, Washington, D.C., 2003, pp. 167–174.
7. Bertini, R., and K. Bogenberger. Impact of Driver Information System on Traffic Dynamics on a German Autobahn: Lessons for U.S. Applications. Presented at 12th World Congress on Intelligent Transport Systems, San Francisco, Calif., Nov. 6–10, 2005.
8. Ulfarsson, G., and V. Shankar. The Effect of Variable Message and Speed Limit Signs on Mean Speeds and Speed Deviations. *International Journal of Vehicle Information and Communication Systems,* Vol. 1, No. 1–2, 2005, pp. 69–87.
9. Abdel-Aty, M. Dynamic Variable Speed Limit Strategies for Real-Time Crash Risk Reduction on Freeways. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2078,* Transportation Research Board of the National Academies, Washington, D.C., 2008, pp. 108–116.
10. Steel, P., and R. McGregor. Application of Variable Speed Limits Along the Trans Canada Highway in Banff National Park. Presented at 2005 Annual Conference of the Transportation Association of Canada, Calgary, Alberta, Sept. 21–25, 2005, Canada.
11. Jonkers, E., and G. Klunder. Development of an Algorithm for Using Dynamic Speed Limits in Relation to the Weather Situation. Presented at 15th World Congress on Intelligent Transport Systems and ITS America's 2008 Annual Meeting, New York, Nov. 16–20, 2008.
12. Buddemeyer, J., R. A. Young, R. J. Cunningham, V. V. Gayah, and L. Hsia. Rural Variable Speed Limit System for Southeast Wyoming. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2189,* Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 37–44.
13. Bertini, R. L., S. Boice, and K. Bogenberger. Dynamics of Variable Speed Limit System Surrounding Bottleneck on German Autobahn. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1978,* Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 149–159.
14. Anund, A., and A. Ahlström. *Evaluation of Local ITS Solutions in Urban Areas.* No. 646. Swedish National Road and Transport Research Institute, Linköping, Sweden, 2009.
15. Bean, S. A Dynamic Variable Speed Limit System. Presented at 9th World Congress on Intelligent Transportation Systems, Chicago, Ill., Oct. 14–17, 2002.
16. Sultan, B., R. Meekums, and J. Ogawa. M42 Active Traffic Management Pilot—Initial Results from Hard Shoulder Running Under 60 mph Speed Limit. Presented at 16th ITS World Congress and Exhibition on Intelligent Transportation Systems and Services, Stockholm, Sweden, Sept. 21–25, 2009.
17. Chang, G., and N. Zou. ITS Applications in Work Zones to Improve Traffic Operations and Performance Measurements. Maryland State Highway Research Report MD-09-SP708B4G. Maryland State Highway Administration, Baltimore, 2008.

The Intelligent Transportation Systems Committee peer-reviewed this paper.