# ITS FIELD DEMONSTRATION: INTERGRATION OF VARIABLE SPEED LIMIT CONTROL AND TRAVEL TIME ESTIMATION FOR A RECURRENTLY CONGESTED HIGHWAY

Gang-Len Chang Department of Civil Engineering The University of Maryland, College Park, MD 20742 <u>gang@umd.edu</u>

Sung Yoon Park Department of Civil Engineering The University of Maryland, College Park, MD 20742 <u>alza102@gmail.com</u>

Jawad Paracha PE, PTOE Maryland State Highway Administration (Note: Mr. Paracha now works for Federal Government) jparacha@hotmail.com

Word count: 4480 + 250\*14 (3500) = 7980

**Abstract.** 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 accompanied 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 the day-to-day congestion at a highway corridor.

The entire 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 licensed-plate-recognition system for displaying the estimated travel time. Our field experiments of the proposed system on MD100 over eight weeks have revealed that with a proper speed control in real time the congested highway segment indeed can achieve a higher throughput, stable traffic condition, and shorter travel time. The display of estimated travel times seem to ease the stress of drivers and to increase their compliance to the suggested speed limits.

### 1. INTRODUCTION

Variable speed limit (VSL) control is one of the advanced traffic management strategies (ATMS) that has received increasing interest in the transportation community since the advent of intelligent transportation systems (ITS) in 1980s. A complete VSL system typically consists of a set of traffic sensors to collect flow and speed data, several properly located VMS 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 between all principal modules.

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

Also VSL can be an effective strategy to control traffic flows in a highway work zone to improve the traffic safety over the capacity-reduced segment with a set of gradually reduced speed limits. Based on the purpose of control, one can divide most recent studies on VSL operations into two categories: improving work-zone safety or enhancing efficiency on recurrently congested roadways. In the first category, Michigan Department of Transportation (MDOT) (1), Lin et al. (2), Kwan et al. (3), and Kang and Chang (4) analyzed VSL control on 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. Also the study on the I-495 Capital Beltway (5) revealed that VSL can indeed 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 either improve roadway safety or increase its operational efficiency. Hegyi and Schutter (6), and Bertini and Bogenberger (7) showed that VSL can improve traffic operation efficiency on recurrently congested highways. Washing state (Ulferasson and Shankar (8)), Abodel-Aty and Mohamed (9) revealed that VSL can improve traffic safety.

For improving both the operation and safety performance, Steel, McGregor, and Robyn (10) reported some critical issues associated with the effectiveness of VSL applications on 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 Ahlstrom (14) in contending with recurrent highway congestion investigated the effectiveness of integrated VSL and travel information on improving safety and operation efficiency. In contrast, the research on applying VSL to minimize the volume-induced recurrent congestion remains at its infancy stage in the United States, regardless of theoretical developments or field investigation even though there are many successful deployments in the Europe. In view of the deteriorating commuting traffic conditions in most major metropolitan areas and the diminishing resources for infrastructure renovation, exploring the potential of nonconstruction strategies such as VSL control to mitigate recurrent highway congestion has emerged as one of the priority tasks for the traffic management community.

This paper reports the field experiment results with our proposed VSL system, focusing on the resulting average speed and the total throughput over the bottleneck location, and the speed transition from the free-flow to congested traffic conditions.

This paper is organized as follows: field VSL demonstration plan is illustrated in Section 2. The VSL control algorithm is discussed in Section 3. Detailed description of the field demonstration plan is presented in Section 4. Experimental results are summarized in Section 5. Research findings and recommendations for future research are concluded in the last section.

### 2. FIELD VSL DEMONSTRATION PLAN

Based on the findings from literature review and our previous research results, this study has employed the following criteria in selecting 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 its speed or incur some safety concerns; or
- Significant fluctuation in traffic flow speed such as evolving from the free-flow to stop-andgo congestion conditions during peak hours; or
- Traffic volume surge during the peak period, and cause the upstream entry flows to dramatically reduce the speed; or
- Significant number of incidents per year.

The research team has selected the segment MD100 West from MD713 to Coca Cola Drive as the target site to experiment various VSL related control strategies, because this segment in 2008 alone experienced a total of 39 accidents. Also during the evening peak period this segment often has a high exiting volume to Arundel Mill Blvd, and causes the traffic to slow down. MD100 is a two-lane (one direction) highway with speed limit of 55 mph. During average weekdays, its evening peak period usually starts from 5 PM, and its speed usually drops quickly from 60 mph to 20 mph (e.g., in 5 minutes) at the onset of congestion. Over the Coca-Cola Dr., its speed typically goes up and can reach up to 30 to 40 mph. Figure 1 illustrates the target MD100 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 the speed of 60 mph from the location intersecting with MD 170, and then gradually reduce to about 50 mph when reached MD713 during the peak hours. Its speed exhibited a sharp drop to 20 to 25 mph after encountering the ramp flows from US295, and continued the same stop-and-go speed until passing Coca Cola Drive. The dramatic speed drop over a distance of around 2 miles offers the ideal traffic condition for VSL control. It also seems desirable to have the estimated travel time from MD 170 to US-1 so that drivers can ease their concerns of the downstream traffic conditions.

In brief, based on the selection criteria and field survey results, this study selected the MD100 segment between MD170 and Coca Cola Drive where the speed reduces from 60 mph to 25 mph to experiment the VSL control. During the demonstration period, the system will concurrently display the estimated travel time from MD170 to US-1.



Figure 1: Spatial distribution of traffic flow speeds over the VSL control segment

# 3. VSL CONTROL ALGORITHM

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

- Reducing approaching traffic speed so as to smooth the transition between the freeflow 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, based on the estimated difference between the detected flow and the target control speeds.



Figure 2 VLS Control Algorithm Flow Chart

<u>Module 1:</u> To minimize the potential queue formation due to the downstream congestion, the upstream segment within the potential maximum queue length and its impact range should be divided into a number of sub-segments 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 approximately be equal to the flow rate entering the control area as shown in Figure 3.



Figure 3: Control Area for VSL applications

<u>Module 2</u>: 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).

### 4. DESIGN OF THE VSL SYSTEM DEMONSTRATION

#### System Framework

The entire VSL operating system for field demonstration includes hardware deployment, communication setup, software, and on-line 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 HD sensors from Wavetronix to measured speed, occupancy, and flow rate by lane at an interval of 30 seconds.
- *LPR (licensed-plate-recognition) system*: one pair of the LPR system for travel time measurement.
- *VMS*: two sets of variable message signs for informing the drivers.
- *Real-Time data conversion/transmission module*: a specially-designed program to collect all real-time information such as timestamp of each observed license plate, site ID, traffic volume, average speed of time interval, and transfer of information between the central database and the wireless network.
- *Real*-Time database module: a customized database that functions to receive data from traffic sensors and LPR units, and then forward the required information for the travel time and VSL modules to generate the predicted travel time and the 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 LPR system will trigger the VSL algorithm module to calculate the estimated travel time and advisory

speed limits. Such information will then be displayed in real time to the roadside VMS and a customized website, and updated at the interval of one minute.



Figure 4-(a) Principal modules of the proposed VSL system and their interrelationships



Figure 4-(b) Operational flowchart between key components

Based on the spatial distribution of traffic flow speeds from MD170 to Coca-Cola Dr. we selected the segment of US100 from MD713 to Coca-Cola Dr. as the target control segment because the traffic flow speed exhibits a substantial drop from an average of 50 mph to 25 mph within this segment due the volumes coming from ramps (see Figure 5). To capture the traffic flow and speed evolution, we placed Detector-4 on MD-713 to detect the upstream traffic condition, and Detector-3 to measure the incoming high traffic volume from its ramp during the peak hours.

Detector-2, located between two ramps from I-295 to MD100, functions to detect the starting point of speed drop in traffic flow. This detector also serves to monitor the speed transition between detector-1 and detector-3 locations. Also, 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 one mile part preceding the Speed Advisory sign, to inform travelers of the downstream traffic conditions and the travel time to US-1.



Figure 5: The roadside system configuration

The entire experimental plan consisted of 4 control periods, which are: No-Control, display of estimated travel time, VSL control only, and both the VSL control and display of the estimated travel time. Through these four operational plans, we were able to observe the response of drivers to the incremental level of control or information availability, and their collective impacts on the traffic condition with respect to speed, throughput, and travel times. All key research activities conducted during each experimental period are summarized below:

Demonstration Period	Duration	Activities	Note
No-Control scenario	Nov 11 2009 ~ Nov 30 2009	Deploy two LPR trailers, four sensor trailers, two VMS, two VSL at each pre-selected 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 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 for estimated travel time from MD-170 or MD-713 to US-1 Test the VSL algorithm with the filed data, but without the roadside display Continue system 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 was activated Continuous the system operation, 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	Continuous the system operation, 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

### Table 1 demonstration period and research activities

# **5 ANALYSIS OF EXPERIMENTAL RESULTS**

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

Step-1: Evaluating 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: Identifying 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: Comparing the average MOEs under different control strategies on the target roadway segment over their respective deployment period, including the 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 an interval of five minutes from sensor-4 over four days prior to the system deployment. Figure 6-(b) displays the speed evolution over time from sensor-1 (the end point of the bottleneck) during the same four prior days. Since US100 is one of the primary commuting corridors, the traffic patterns exhibited in both figures seemquite stable from day to day.

Figure 6-(c) presents the comparison of traffic volumes per 5-minute 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) displays the speed evolution patterns under three different 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 then perform a detailed performance analysis and attribute any MOE variation to the deployed control measures.



Figure 6- (a) Distribution of average traffic volumes over time before the experimental period from sensor-4.



Figure 6- (b) Distribution of average traffic speeds over time before the experimental period from sensor-1.



Figure 6- (c) Distribution of average traffic volumes during different experimental periods from sensor-4.



Figure 6- (d) Distribution of average traffic speeds over time before the experimental period from sensor-1.

# **Spatial and Temporal Impacts**

As stated previously, the main purpose of VSL is to smooth the speed transition from its 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 estimated travel time displayed via VMS is to encourage compliance of drivers

to the suggested speed change, intending to convince them that their cooperation will improve the overall traffic condition on the congested segment and will not incur excessive delay.

Figure 7 displays the traffic flow speed along the US100, starting from its intersection with MD170 to the end point of the intersection with Coca-Cola Drive. As evidenced by the graphical shape, drivers under no-control or TT-display scenario experienced the speed drop from 60 mph to around 20 mph when reaching the location receiving the I-295 traffic flow. Such a sharp speed reduction over a short distance of less than 2 miles inevitably forms a stop-and-go bottleneck and often incurs some accidents. On contrast, under the control strategies of VSL and VSL&TT traffic flow can maintain its average speed between 40 mph to 35 mph over the most congested segment. Although all implemented control strategies are advisory rather than mandatory in nature, their effectiveness on reducing speed variance seems quite impressive. A further investigation of the time-varying travel time over the entire segment during the evening peak-period also confirms the effectiveness of those experimental control strategies.

For instance, the average travel time under the control of VSL & TT display, as shown in Figure 8, was significantly shorter than that under no-control condition during the most congested interval of 5 p.m. to 5: 30 p.m. The travel time differences between no-control and those three control scenarios, as expected, diminish when the traffic conditions on the target roadway is less congested such as between 6 p.m. to 6:30 p.m. Overall, the general trend from those graphic patterns in Figure 7 also supports the hypothesis that by smoothly reducing the speed to a proper level over a highway segment of recurrent congestion, drivers do not need to suffer the stop-and-go condition, and are likely to experience a shorter travel time.



Figure 7 Spatial distribution of average traffic flow speed under different controls



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

Figure 9 presents the average speed collected by sensor-4 over the most congested location from 4 p.m. 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 &TT display. The lowest average speed was around 30 mph if VSL or TT display was implemented independently. These empirical results seem to further support the hypothesis that using variable speed control indeed can prevent the sudden

speed drop at a recurrent congestion location, and thereby reducing the stop-and-go delay. The smooth transition between free flow and congested flow can also minimize potential real-end collisions due to a large speed variance between vehicles.





Figure 9: Identification of the most congested hour under different control strategies

# **Comparison of MOEs**

In addition to the average speed measured with radar detectors, this study has also selected the total throughput and average travel time over a target interval as the MOEs. In theory, a mandatory VSL & TT 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 on the demonstration site were advisory only, it is critical to have an in-depth analysis of their impacts on the traffic conditions.

Figure 10 presents the comparison results of average travel time under different control scenarios over selected peak-hour intervals. Note that those travel times were measured directly with the deployed Licensed-Plate Recognition system rather than estimated from the 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 seconds, significantly longer than the average of 400 seconds under the VSL&TT display environment. The average travel times over the same period under TT-display only and VSL control alone were 503 seconds and 484 seconds, respectively.

A similar trend also exists in the average travel time comparison over the most congested one hour and 1.5 hours. For example, drivers under the no-control scenario experienced the average travel time of 469 seconds during the peak period of one hour, but only took 345 seconds during the same period if with VSL&TT display control. Considering the 3-mile distance of the target roadway segment that typically takes commuters less than 180 seconds during the off-peak period, one shall view the reduction of about 25 percent 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 minutes and one hour. The comparison results clearly indicate that all those 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 1883 to 1974 vehicles under the TT display scenario, and to around 2040 vehicles if with the VSL or VSL&TT display control environment. A further comparison of the total throughput over the peak period of *one hour* reveals that the target

roadway segment that suffers recurrent congestion can accommodate 230 (3713 vs. 3980 or 3841) more vehicles under VSL or VSL&TT display environment, indicating the unquestionable effectiveness of those deployed control strategies.

Note that the control of VSL&TT display yields a slightly less total throughput than the VSL alone in Figure 11 due to the fact that the display of travel time over the target segment has further smoothed the traffic during the peak period and lower the congestion level. Hence, vehicles during the most congested period were able to travel at a slightly higher speed and in less condensed platoon conditions. This is evidenced in the pattern shown in Figure 7 and the speed evolution data in Table 2.

Figure 12 further presents the total throughput comparison on different week days. As evidenced in the revealed patterns, the effectiveness of VSL or VSL&TT display controls with respect to the total throughput is quite consistent among different days of a week.

The third MOE selected for performance evaluation is the average speed evolution during the peak hour under the four different traffic control environments. As shown in Table 2, the average speed during the first 15 minutes of the most congested hour does not seem to benefit from the implemented control strategies. However, drivers appeared to be able to progressively respond to the control strategies and significantly improve their travel speeds after about 30 minutes. 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&TT display control. However, it is noticeable that by implementing VSL or TT-display alone does not seem to have significant impacts on the average traffic flow speed. A plausible explanation for this fact 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 of the VSL control would be.

In brief, the experimental results clearly indicate that highway segment experiencing recurrent congestion indeed can benefit significantly from the VSL&TT display control, including travel time reduction, and an increase in travel speed as well as the overall throughput during the peak period.



\* 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

\* 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







Figure 12 Comparison of total throughput over selected week days under different control strategies

Control selected interval	No control (MPH)	TT Display (MPH)	VSL (MPH)	VSL & TT (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 Hour	22.4	22.3	23.6	37.4

Table 2 Evolution of the average speed during the peak hour under different controls

# **6** CONCLUSIONS AND RECOMMENDATION

This paper has presented a real-time VSL control system for alleviating recurrent congestion on commuting corridors. The experimental results shows that VSL control can be 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, integrating the travel time information, can smooth the transition between the free-flow speed and the stop-and-go congested conditions, increase higher average speed, reduce the overall travel time over all a recurrently congested roadway segment, and increase the total throughput.

As one of the pioneering studies for exploring the VSL control potential for recurrent highway congestion, the research results have revealed some imperative issues that need to be addressed prior to the comprehensive deployment of the VSL control. Each of those issues is briefly presented below:

 Criteria and/or guidelines for selection of target roadway segments which are suited for use the VSL control to mitigate their recurrent congestion, including highway geometry features, spatial and temporal distribution of traffic flow speed, time-varying volume patterns, the 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 the free-flow and congested speeds;
- Guidelines for optimal sensor and VMS locations;
- Developing an effective VSL control algorithm that contains the minimal number of parameters and thus requires the minimal efforts for field calibration;
- Criteria for activating and deactivating the VSL control for a target roadway segment plagued by recurrent congestion; and
- Coordinating various messages via VMS within the VSL control boundaries so that they can complement each other and provide the best advisory picture to the target drivers rather than confusing them.

In addition to the above vital issues, highway agencies intending to deploy VSL control shall also carefully conduct surveys to understand preferences and responses of local populations to various messages displayed via VMS so that the design can be well received by drivers and thereby increasing their compliance to any displayed suggestions.

# ACKNOWLEDGEMENT

The authors would like to extend our appreciation to Michael Paylor from Maryland State Highway Administration and Dr. Zou Nan for their invaluable assists during the entire system demonstration period.

# REFERENCES

- Lyles, R.W., W.C. Taylor, and J. Grossklaus. Field Test of Variable Speed Limits in Work Zones (in Michigan). Michigan State University and Michigan Department of Transportation project, 2003.
- Lin, P., Kang, P., Chang, G. L. Exploring the Effectiveness of Variable Speed Limit Controls on Highway Work-Zone Operations. Intelligent Transportation Systems, 2004. Vol. 8, pp. 155–168.
- 3. Kwon, E. and Brannan, D. Development and Field Evaluation of Variable Advisory Speed Limit System for Work Zones. Transportation Research Record: Journal of the

Transportation Research Board, Washington D.C., 2007. No. 2015, pp. 12-18.

- Kang K. and Chang G. Development of Integrated Control Algorithm for Dynamic Lane Merge and Variable Speed Limit Controls. 11th World Conference on Transport Research 2007.
- Virginia P. S., Andrew S. and Germin F. Implementing Active Traffic Management Strategies in the U.S. University of Alabama at Birmingham report, 2009.
- Hegyi, A and Schutter, B. Optimal Coordination of Variable Speed Limits to Suppress Shock Waves Transportation Research Record. 2003. No. 1852., pp. 167-174.
- Bertini, R. and Bogenberger, K. Impact of Driver Information System on Traffic Dynamics on a German Autobahn: Lessons for U.S. Applications 12th World Congress on Intelligent Transport Systems. 2005.
- Ulfrasson, G. and Shankar, V. The effect of variable message and speed limit signs on mean speeds and speed deviations. International Journal of Vehicle Information and Communication Systems, 2005, Vol. 1, pp. 69-87.
- Abdel-Aty, Mohamed. Dynamic Variable Speed Limit Strategies for Real-Time Crash Risk Reduction on Freeways. Transportation Research Record: Journal of the Transportation Research Board, Washington D.C. 2008, No. 2078, pp. 108-116.
- Steel, P. and McGregor, R. Application of Variable Speed Limits along the Trans Canada Highway in Banff National Park. 2005 Annual Conference of the Transportation Association of Canada, September 2005 in Calgary, Canada.
- 11. Jonkers, E. and Klunder, G. Development of an Algorithm for Using Dynamic Speed Limits in Relation to the Weather Situation. 15th World Congress on Intelligent Transport Systems and ITS America's 2008 Annual Meeting, November 2008 in New York, U.S.
- Buddemeyer, J and Young, R. Rural Variable Speed Limit System for Southeast Wyoming. 89th TRB Annual Meeting, Washington D.C. 2010
- Bertini, R., and Boice, S. Dynamics of Variable Speed Limit System Surrounding Bottleneck on German Autobahn. Transportation Research Record, 2006, No.1978, pp.

149–159.

 Anund, A. and Ahlström, C. Evaluation of local ITS solutions in urban areas. Swedish National Road and Transport Research Institute, 2009. No.646.