Review of Variable Speed Limits and Advisories
Theory, Algorithms, and Practice

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Previous studies on variable speed limits (VSLs) were reviewed. These studies were classified as three types: simulations for algorithm development and evaluations, VSL implementation and field testing, and a combination of VSLs with ramp metering. The review considered strategies and algorithms, targeted traffic improvements (safety, throughput, etc.), applicable traffic conditions, performance evaluations, and simulation or test results and their implications. Most practices in Europe indicated that the use of VSLs was effective in both traffic safety and flow improvement, although the former was more significant. Practices in the United States indicated that safety improvement was significant but the impact on traffic flow was controversial. Practices are summarized, and some new viewpoints and future research directions are presented.

Variable speed limits (VSLs) have been used in the United Kingdom since the 1960s for safety purposes. In the past decade, some VSL algorithms were developed through simulation for improvement of both safety and mobility. VSLs have been widely practiced in Europe in the past 5 years, especially in Germany, the Netherlands, France, and Sweden. In recent years, several states in the United States have field-tested some simple VSL algorithms, beginning with Washington State in 2009. The main objective of using VSLs in the United States was to improve safety and traffic flow, primarily safety. VSLs could be enforced or advisory, locally applied or along a freeway corridor, or at work zones or other types of recurrent bottlenecks. VSLs displayed on roadside variable message signs (VMSs) have emerged as a widespread traffic control measure on motorways in many countries and have led to substantial traffic safety benefits.

Some work in this aspect has also been reviewed.

This paper reviews VSL development in the following aspects: (a) simulation for algorithm development and evaluation, which is the usual way of algorithm development before field tests; (b) main practices and their evaluations; and (c) combination of VSLs with coordinated ramp metering (CRM) in a larger framework for active traffic management, which is more than VSLs alone. This paper has not exhausted all the literature in VSL algorithm development and practice. However, the authors have reviewed the most relevant literature and tried to collect useful information on lessons learned and experience gained. The paper does not give comments immediately after the cited reference. Instead, comments are presented in the section on looking into the future. Most practices have also been summarized with respect to some important features. Viewpoints and possible research pointing toward field implementation are suggested. These contributions are the main contributions of this paper.

The paper is organized as follows. The simulation approach with VSL development and performance evaluations are reviewed. The use of VSLs and variable speed advisories (VSAs) around the world is discussed. The theory and practice of the combined VSL and ramp metering approach is discussed. Research and practice directions in this field are recommended, and concluding remarks are presented.

SIMULATIONS FOR ALGORITHM DEVELOPMENT AND EVALUATION

Algorithm development and evaluation with simulation before field testing is always a good practice because field testing could be costly and could produce unexpected and negative results to public traffic if it is not done properly. Chen et al. used VGrid, a VIVI-based networked computer system developed from simulation for real-time operation purposes (1). It was intended to achieve information broadcasting, safety alert, traffic parameter estimation, or VSL information. The approach tried to maximize throughput and reduce latency without an optimization process. Instead, each vehicle calculates the speed limit by itself. There is a problem here: no coordination occurs unless all the vehicles calculate with the same algorithm and with the same set of data. If the use of the same algorithm and data set cannot be achieved, each vehicle may have a different speed limit value. Different values cannot help to reduce speed variance and shock waves.

Work by Lin et al. presents two VSL algorithms, combined with ramp metering, for traffic improvement (2). It is believed that VSLs not only can improve safety and emissions, but also can improve traffic performance by increasing throughput and reducing delay, primarily for work zones. Two control algorithms were presented. VSL-1 was for reducing time delay by minimizing the queue upstream of the work zone, and VSL-2 was for reducing total time spent by maximizing throughput over the entire work zone area. Simulation results showed that VSL-1 may even outperform VSL-2 in speed variance reduction. Alessandri et al. designed VSLs using the second-order METANET model (3). The model assumed that the on-ramp and off-ol ramp flows were stochastic variables with known probability density function in an optimal control approach. An extended Kalman filter was used for traffic state estimation. Then a VSL strategy was designed by minimizing an objective function. Several objective functions were proposed, including total travel time and throughput.
In the work of Juan et al., freeway congestion was classified in two types: (a) demand driven, as a result of the increase of traffic volume; and (b) supply driven, due to the road geometric condition, weather, or traffic incident or accident (4). Simulation was conducted in view of the cause of congestion and several factors that led to the instability of freeway traffic flow, including

- Small time headway,
- Large speed variance, and
- Frequent disturbances.

Many scenarios of VSLs were simulated. The results indicated that the VSL benefits were obvious when the traffic volume was equal to or greater than 2,800 vehicles per hour (vph) (double lane). It was suggested that VSLs needed to be combined with ramp metering to control the traffic when the traffic volume was higher than 2,800 vph for a two-lane freeway.

Hegyi et al. suggested using VSLs to suppress shock waves at the end of queues in freeway traffic (5). Hegyi et al. further identified two functions of VSLs: speed homogenization and prevention of traffic breakdown (6). Prevention of traffic breakdown avoided high density, which achieved density distribution control through VSLs. As an example, a VSL strategy was used to suppress shock waves while considering the whole traffic network as a system.

Wang et al. used an empirical approach to investigate the effectiveness of reducing congestion at a recurrent bottleneck and improving driver safety by using feedback to the driver with advisory VMSs on an 18-km highway stretch (7). The feedback includes (a) speed limit (piecewise constant in 12-km/h increments) and (b) warning information (attention, congestion, and slippery). The VSL strategy was based on the traffic situation upstream and downstream of the bottleneck. Data analysis showed that driver response to the speed limit and messages on the VMSs was reasonable. Speed was regulated to some extent, and safety was improved by a reduction in the frequency of incidents or accidents of 20% to 30%; this improvement was more significant than the mobility improvements.

A simple real-time merging traffic control concept was proposed for efficient toll plaza management in cases where the total flow exiting from the toll booths exceeded the capacity of the downstream highway, bridge, or tunnel; without efficient toll plaza management, this flow would lead to congestion and reduced efficiency because of a drop in capacity (8). The merging control strategy for toll plazas was similar to the mainline ALINEA ramp-metering algorithm, which is different from VSLs because VSLs do not completely stop the vehicles. Ramp metering with traffic signals decoupled the platoons into individual vehicles, while VSLs were intended to keep the platoons intact. Because the vehicles are completely stopped, lane dispatch flow is usually limited to 900 vph, whereas VSLs could achieve much higher lane flow.

For reducing shock waves or damping shock waves faster, Breton et al. incorporated several techniques, such as coordination, adaptive control, model-based predictive control, and minimized travel time (9). The work assumed that dynamic origin-destination information was available, although this assumption was impractical. It also incorporated the fundamental diagram into the model. As a consequence of damping the shock wave more quickly, the model claimed to have reduced the total travel time. Because of measurement delay and the effect of hysteresis, it was necessary to predict the traffic and uncertainty over the network. The following two approaches were adopted for VSLs:

- Homogenization (to reduce speed variance) through the use of a reference speed close to the critical speed corresponding to the maximum flow (10) and
- Prevention of traffic breakdown (to avoid or delay high density at the bottleneck and its immediate upstream), achieved with upstream speed control, thus assuming critical density at the capacity flow.

This work used an online optimization approach to adapt to traffic condition changes. The objective was to determine the preferred reference speed trajectory. A second-order model was adopted in this work. Simulations showed some positive potential.

Waller et al. reviewed VSLs and hard shoulder use practices up to the year 2009 (11). They investigated the effect of VSLs and hard shoulder use on traffic improvement and safety with a microscopic simulation. They concluded that VSLs can improve safety but not throughput. Yang et al. proposed VSL algorithms based on traffic prediction to relieve traffic at a recurrent bottleneck (12). The proposed model uses embedded traffic flow relations to predict the evolution of congestion patterns over the projected time horizon and computes the optimal speed limit. The results of a calibrated VISSIM simulation showed some positive improvement of the model over the status quo, as measured in travel time reduction and the number of vehicle stop times (stop-and-go traffic).

The Wyoming Department of Transportation implemented a VSL system in 2009 for traffic safety improvement. The system uses a manual protocol to determine appropriate speed limits to be posted on roadside VSL signs. The posted speed is initiated by either highway patrol or maintenance personnel who request a change on the basis of visual perception of road conditions. To support an automatic VSL operation, Sabawat and Young proposed a methodology for the determination of VSLs according to real-time traffic speeds and weather variables (13). Simulation results indicated that there could be a significant increase in speed compliance and reduced speed variations with this strategy over the manual protocol.

Habtemichael and de Picado Santos studied the combination of different compliance rates and congestion levels and found that the safety and operational benefits varied with these two factors (14). Yang et al. found that the accuracy of the predicted traffic state may significantly affect the performance of VSLs (e.g., VSLs with bad prediction may deteriorate traffic flow) (12). Islam et al. focused on the VSL update frequency and safety constraints to improve VSL performance (15). Li and Ranjitkar examined the combination of ramp metering and VSLs and found that both strategies could lead to improvement, but the improvement would be best with a combination of the two strategies (16). Li and Ranjitkar (16) adopted the flow-based VSL algorithm for M25 in England, but the VSL algorithms in other work (14, 17) were not fully introduced. The algorithm adopted by Yang et al. (12) and by Islam et al. (15) is implicit because the VSLs were generated with an optimization function.

Talebpour and Mahmassani developed a speed harmonization approach that assumed early detection of shock waves and traffic breakdowns through vehicle-to-vehicle communication (18). The advantage of vehicle-to-vehicle communication is that vehicles upstream gain information about the traffic situation downstream; the availability of information reduces time delays in the feedback loop. A microscopic simulation was used to evaluate the impact of the speed harmonization on traffic characteristics and improvements in safety. The speed harmonization approach included two parts: (a) shock wave detection using a wavelet transform algorithm (basically, pattern recognition in a nonstationary situation) and (b) VSL determination based on the traffic situation. Simulation results showed significant improvements in traffic flow and safety. The work also found through fundamental diagram analysis the optimal location and time for the VSL transition according to traffic phases. Work by Dong and Mahmassani proposed a simulation
to create a traffic breakdown scenario that is a macroscopic traffic characteristic; in the simulation, driver behavior was changed at the microscopic level (19). The results could help researchers understand how traffic breakdown at the macroscopic level is caused by microscopic vehicle following and stochastic characteristics of differences in driver behavior.

**VSL PRACTICES AND EVALUATIONS**

The use of VSLs on the motorways M25 and M4 in England is well known (20, 21). The objectives were to improve traffic throughput (reduced delay), safety, and emissions. VSLs are activated, modified, and deactivated when flow or speed measurements cross preset thresholds between 35 mph and 65 mph. Evaluation showed positive results in many aspects, including reduction in incidents, increased flow, less lane changing, reduced breakdown times, improved throughput, decreased injury accidents by 10% and property damage—only accidents by 30%, overall decreased emissions between 2% and 8%, improved lane use and headway distribution, reduced driver stress, increased driver acceptance (two-thirds of drivers would like VSLs to be extended to other motorways), and higher critical occupancy values in the fundamental diagram (20, 21).

Preliminary VSL strategies were used in Germany and the Netherlands to improve traffic flow (22–24). Bertini et al. used an empirical approach to investigate the effectiveness of the German approach in reducing congestion at a recurrent bottleneck and to improve driver safety by using feedback to the driver with advisory VMSs at certain locations along a stretch of highway (18 km long) (22). The feedback included (a) speed limit (piecewise constant with 12 km/h increment) and stop and end time and location and (b) warning information (attention, congestion, slippery road). The suggested speed was based on the traffic situation upstream and downstream of the bottleneck. Data analysis showed that driver responses to the speed limits and messages on the VMSs were reasonable, speed was regulated to some extent, and the improvements in safety were more significant than those in traffic throughput (up to 20% to 30%).

The Dutch experiment intended to smooth or homogenize the traffic flow along a stretch of highway by using VSLs with enforcement when volume approached capacity, and volume was kept constant along a section of the freeway (24). Two speed limits were used: 70 km/h and 90 km/h; the speed limits were updated every 1 min. Traffic volume and average speed were measured in each section. Tests were conducted on multiple stretches totaling 200 km. Analysis showed that speed control was effective to some extent in reducing speed and speed variation and the number of shock waves, especially when vehicles maintained smaller driving headways. However, there was no significantly positive effect on capacity (24).

Besides, the overall performance of the freeway was not significantly enhanced. This result may suggest combining the variable speed and its messages on the VMSs were reasonable, speed was regulated to some extent, and the improvements in safety were more significant than those in traffic throughput (up to 20% to 30%).

Several traffic management and driver information data sources along an 18-km (11.2-mi) section of Autobahn 9 near Munich, Germany, have been used to analyze traffic dynamics and driver behavior before, during, and after bottleneck activation (22). The main focus was on the effect on driver behavior and traffic (bottleneck formation) of VSLs displayed on overhead gantries. VSLs and traffic information did cause drivers to slow down, a result that delayed bottleneck activation; traffic density increased, but the traffic was still moving at 35 to 40 km/h. The algorithms for the VSLs were based on the fundamental relationships of speed, flow, and density between detector stations. Transformed curves of cumulative count and time-averaged velocity versus time were used to diagnose bottleneck activation. However, the shock wave back-propagation speed when VSLs were on was still 18 km/h.

In France, use of VSLs started in 2007 on the A7/E15 motorways south of Lyon (25). As of 2011, VSLs were used on overhead gantries on several highways, covering 650 km. The main objectives are for traffic throughput and safety improvement. The VSL algorithms used included a maximum VSL of 110 km/h. The VSL control is triggered when the total flow exceeds 3,000 vph. Truck access is banned for some areas in peak hours. Observed results include increased lane utilization, improved safety, and positive impact on lane flow distribution. The evaluation on the A13 motorway with a similar VSL strategy showed more positive results (26): average speed increased by 4% to 10%; the number of bottlenecks (jams) was reduced by 50%; average travel time was reduced by 30 s; lane capacity was unchanged; level of service was improved; crashes were reduced by 17%; time gaps were unchanged; and the compliance rate was still low.

Hoogendoorn et al. systematically evaluated performance of enforced VSLs on the A20 highway near Rotterdam, Netherlands, with several types of before-and-after data, including driver behavior change, traffic mobility and safety improvement, emissions, and noise reduction (27). The comparison approach used was reasonably objective because data affected by external factors such as bad weather, special events, incidents or accidents, and road work were eliminated. The previously applied fixed-VSL strategy significantly reduced the flow of the overall system, worsened traffic congestion, and changed driver behavior in changing lanes and merging. Therefore, a dynamic speed limit was used; VSLs were between 80 km/h and 100 km/h and were changed according to the traffic situation. Evaluation results showed (a) a driver response delay, which was different for increases and decreases in VSLs; (b) response difference between lanes; (c) higher compliance with higher VSLs; (d) less of an effect on central lanes than on other lanes; (e) improvement in mobility of about 4%, with a decrease of 7% to 18% in queue duration; and (f) no observed improvement in emissions.

Weikl et al. systematically analyzed the effect of VSLs on German Autobahn A99 (16.3 km) near Munich with loop detector data (28). The control means were enforced VSLs and traveler information about weather, incidents, and traffic congestion downstream. The VSL algorithms were based on the fundamental relationship between speed, density, and flow, but the objective of the algorithm was not stated clearly. Traffic aspects analyzed included speed, spatial–temporal extent of the queue (congestion), flow changes caused by identified bottlenecks, distribution of flow across lanes, percentage of trucks per lane, and flow homogeneity between lanes. Bottlenecks were first identified with oblique accumulated flow. The lane flow distribution was much better balanced when VSLs were in operation. Associated with smaller differences in lane flow, the incident rate was expected to be lower. However, the impacts of VSLs on bottleneck capacity varied in the field tests. The capacity drop when congestion happened with VSLs on was slightly larger than with VSLs off (from 4% to 3%, respectively). Several factors may affect the capacity observed. First, the bottleneck location was changed as a result of the VSLs; therefore, two bottlenecks were compared. Second, drivers did not know where VSLs were enforced and likely assumed that VSLs were enforced downstream of the bottleneck. Third, traffic conditions were different when VSLs were on versus when they were off. The former condition was dominated by wide jams (characterized by low speeds with small variations), whereas the latter was dominated by stop-and-go traffic (characterized by
large variations in speed). Fourth, the driver compliance rate was unknown. With these factors, the VSL performance on capacity is not very solid either.

VSLs and enforced VSLs could generate different driver compliance rates. The focus of the work done by Nissan was to examine the impacts of VSSAs and VSLs by analyzing the driver compliance effect using microscopic simulation with a case study on the E4 motorway in Stockholm, Sweden (17). Simulation results showed that the effect of VSSAs increases as the compliance rate increases. Simulations indicated that higher compliance rates resulted in delayed onset of the congestion and associated speed breakdowns and higher overall speeds. Simulations also showed that, with a compliance rate of 25% or less, the VSLs have almost no effect on traffic. Two generations of weather-related VSLs have also been evaluated (29).

Several empirical studies have been conducted in the United States since the 1960s in several states with varying levels of development, primarily for safety improvement and secondary for traffic flow improvement (30). The outcomes were diverse; there were some positive results, but most were negative. The most impressive positive outcome was the work conducted in New Jersey, which was similar to the approach in Germany, but with the speed enforced instead of advised. Some experiments on individual vehicle speed advisory and enforcement were also successfully conducted for trucks traveling downhill (30).

On April 27, 2009, the Washington State Department of Transportation began operation of VSLs on westbound I-90 between I-5 and I-405 as part of the I-90 two-way transit project, aimed to relieve congestion and increase throughput and to reduce rear-end collisions. Later, the VSL strategy was further developed into an active traffic management system. At the beginning, the VSL algorithm was ad hoc and the VSL signs were controlled by engineers. Recently, automatic algorithms have been implemented. An extensive study has been conducted for the performance of the system with VSLs (31). Researchers have observed some interesting traffic speed thresholds at which traffic flow may change significantly.

DeGaspari et al. focused on travel time reliability through analysis of 5-min data over 19 detector stations on I-5 in Washington State, where the VSLs were enforced (32). Two reliability indices, the planning time index and buffer index, have been used. The results showed significant improvements in travel time reliability in most cases except during the morning peak between 6:00 and 8:00 a.m. The results also found a 5% to 10% flow drop, which may be a result of the impact of VSLs on driver route choice. However, traffic throughput may have been sacrificed.

VSLs have been deployed on Interstate 270 in Missouri. The performance has been evaluated recently (33). The effect of VSLs on traffic performance was investigated at eight heavily congested locations. Traffic sensor data were used to determine speed limits, ranging from 40 to 60 mph, in 5-mph increments, to reduce vehicle speed before vehicles reached a congested area (congestion from a bottleneck, crash, or work zone). The before and after field data indicated that differences in the changes in two-dimensional flow—occupancy and speed diagrams (two forms of the fundamental diagram) were statistically significant at seven of eight locations. The slopes of the flow—occupancy plots for over critical occupancies were found to be steeper after VSLs. Slight changes in critical occupancy were observed. The changes in maximum flows before and after traffic breakdown were inconsistent; they increased in some locations but decreased in other locations.

Papageorgiou used data analysis to evaluate VSL strategies (34). The paper summarizes available information on the VSL impact on fundamental diagram—aggregate traffic flow behavior as follows:

- Decrease the slope of the flow—occupancy diagram at under critical conditions,
- Shift the critical occupancy to higher values, and
- Enable higher flows at the same occupancy values in overcritical conditions.

The authors concluded that there was no clear evidence of improved traffic flow efficiency in operational VSL systems for the implemented VSL strategies.

Chang et al. focused on the evaluation of a field test (35). The speed drop was significant in the evening peak around 5:00 p.m., dropping from 60 mph to 20 mph in 5 min. The algorithm used can be described as reducing approaching traffic speed to smooth the transition between the free-flow and congested-flow states and taking into account the responses of drivers in dynamically setting the appropriate control speed for each transition location. Test results showed that the proposed VSA strategy was effective at this location in the following aspects: higher average speed and throughput, shorter travel time, and smoothing the transition between the free-flow speed and stop-and-go traffic.

Hegyi et al. developed an algorithm to remove or reduce moving jams (shock waves) at recurrent or nonrecurrent bottlenecks using the second-order METANET model with model predictive control (6). The basic idea is to reduce the feeding flow into the moving bottleneck and coordinate the traffic flow along a corridor. This idea can be explained in detail with space—time trajectories (36). The algorithm is further refined as the SPECIALIST, which was tested in the field, with results presented elsewhere (36). This approach is basically a feed-forward (open-loop) approach. The implementation requires the detection of shock wave fronts for both congestion and discharge waves, which requires high-density road sensors or significant market penetration of vehicle-to-infrastructure communication. Field experiments showed some effectiveness of the algorithm. However, care needs to be taken in that if the VSLs are too restrictive, they will cause new shock waves and bottlenecks upstream.

VSLs and VSAs were implemented at a recurrent bottleneck at a work zone on I-494 in Minneapolis—Saint Paul, Minnesota, and tested for a 3-week period in 2006 (37). The algorithm adopted a two-stage speed reduction scheme by reducing the traffic flow into the end of the queue upstream of the bottleneck. Two VSL displays were used: one in the work zone and one upstream. Field test data showed a 25% to 35% reduction in speed variation in the morning peak and a 7% increase in total throughput in the evening peak. The driver compliance rate had a 20% to 60% statistical correlation with VSLs in the morning peak.

The Minnesota Department of Transportation also tested VSLs on I-35W in the MnBYPASS section of Minneapolis—Saint Paul (38). The algorithm used detection of traffic downstream to determine VSL display 1.5 mi upstream. It gradually reduced the speed of the incoming traffic to the end of the queue at the bottleneck. The VSL values depended on current speed upstream (measured), speed near the end of the queue (measured), travel distance, constant deceleration, and so forth. The upper bound of VSL is 5 mph less than the fixed roadside speed limit. The VSL display update rate is 30 s. Evaluation of the effectiveness is not yet available.

**COMBINED VSLs AND CRM**

Papageorgiou reported on the use of a second-order model for combined VSLs and CRM control design (39). Abdel-Aty and Dhindsa (40) considered the combined effect of VSLs and CRM in reduc-
looking the risk of crashes and improving operational parameters such as speeds and travel times on congested freeways. Microsimulation showed some positive effect. Caligaris et al. adopted the METANET model adapted to different vehicle classes for combined VSLs and CRM design with model predictive control (41). Alessandri et al. used a second-order model for optimal VSLs and ramp metering plus an extended Kalman filter for state estimation (42). Optimization was done with an empirical mean cost function according to the Monte Carlo method. Papamichail et al. considered combined VSLs and CRM with an optimal control approach (43). They claimed an algorithm feasible for large-scale systems and showed by simulation that traffic flow significantly improved with combined VSLs and CRM versus using each strategy alone.

Other work designed coordinated VSLs and CRM by using model predictive control with the METANET model (44–46). It is believed that ramp metering was useful only when the traffic demand was not too high. The results showed (a) mainline traffic harmonization if there was no demand from the on-ramp, (b) delayed traffic breakdown with large demand from the on-ramp, and (c) increased effective range of ramp metering. The explanation was based on the fundamental diagram. Mainline traffic flow control using combined VSLs and CRM was investigated by Carlson et al. (47, 48). An extended METANET model was used for tightly coupled VSLs and CRM control design for freeway network traffic. A nonlinear optimization process was necessary at each time step. Simulation modeling with field data was used to show the effectiveness of the algorithm proposed.

Lu et al. (49, 50) and Su et al. (51) developed another combined VSL and CRM approach for freeway corridor traffic control. The main idea was that freeway corridor traffic flow was limited by bottleneck flow; if the section upstream of a bottleneck was congested, the bottleneck flow would drop well below its capacity. Therefore, a logical approach to maximize recurrent bottleneck flow was to create a discharge section immediately upstream of the bottleneck. This work proposed a control strategy for combining VSL and CRM design to achieve this objective when the bottleneck could be represented as a lane (or virtual lane) reduction, although VSLs and CRM can be implemented individually. The CRM was designed by an optimal control approach with a linearized model. The objective function was the difference between scaled total travel time (vehicle hours traveled) and the total travel distance (equivalent to vehicle miles traveled). The control problem was further simplified as a finite time horizon model predictive control. It used efficient linear programming at each time step. The algorithm took into account the following factors:

- Demand variation at each on-ramp,
- Demand and capacity of the upstream links,
- On-ramp storage capacity (queue length limit), and
- On-ramp capacity flow.

LOOKING INTO THE FUTURE

This section briefly summarizes some lessons learned and experience gained from the previous work that could benefit future research, in particular how VSL and VSA research and practice should be conducted:

1. Most safety-oriented VSL and VSA approaches used an ad hoc algorithm that was unlikely to improve traffic flow. For throughput, the objective needs to be quantified and scientifically incorporated into the algorithm and implementation.

2. VSL strategies and algorithms for traffic flow improvements need extensive development. They need to take into account traffic demands, sensor locations, traffic speed estimation, ramp metering, feedback to the driver, public outreach, and so forth.

3. VSL and VSA algorithms for freeway corridors need traffic predictions. Because VSLs and VSAs will affect the traffic stream, which is speed dependent, and the link travel time depends on traffic behavior, a proper dynamic model is necessary for traffic prediction. The model needs to include speed dynamics, either flow-speed or density-speed dynamics. Although traffic density is difficult to measure directly, vehicle-to-infrastructure information could be fused with road sensor data for real-time density estimation (52).

4. Speed harmonization is a special case of VSLs and VSAs. It intends to control traffic streams to a speed corresponding to a static traffic state between free flow and saturated. However, practical traffic may change rapidly as a result of a variety of factors, including high peak hour demands, flow into off-ramps, and, most important, driver behavior. An ad hoc speed harmonization approach is unlikely to improve throughput significantly, as found by the Washington State Department of Transportation.

5. The strategies for shock wave reduction, speed harmonization, and bottleneck flow maximization must be targeted for certain types of road geometry and traffic situations and activated properly. Care needs to be taken not to reduce flow unnecessarily, which could possibly activate traffic congestion earlier or cause congestion or shock waves upstream.

6. Practices in the United States indicated that safety improvement was significant, but impact on traffic flow was somehow controversial. This result was partially due to immaturity of the VSA and VSL algorithms and partially due to institutional issues, such as enforcement.

7. The oblique accumulated flow approach used by Weikl et al. could possibly be used in analyzing aggregated traffic data for performance evaluation (28). This parameter is complementary to root mean square error or relative root mean square error, popularly used for simulation model calibration.

8. The VSL thresholds related to traffic flow drop observed by Hammond are interesting and could be used as a reference in field testing (31). It is necessary to find the reasons for traffic changes near those thresholds.

9. In the long run, VSLs need to be combined with CRM because the latter controls the demand from the on-ramp and the former controls driver behavior. They are complementary in function. Their combined effect would be more significant than the effect of just one of them.

10. If there are no institutional issues, VSLs should be enforced for effectiveness. However, VSAs may still have positive effects if the posted information can persuade drivers that following the posted VSA will lead to better safety and flow; such persuasion will require adequate outreach to the public. In peak hours, traffic density is rather high in general. If 15% to 20% of drivers follow the posted speed, others have to follow.

11. With gradual market penetration of vehicle-to-vehicle and vehicle-to-infrastructure communication and vehicle automation technologies (53), VSLs and VSAs designed on the roadside could be passed to vehicles for driver speed advisory or used as the set speed for vehicle control if the vehicle has Cooperative Adaptive Cruise Control capability. This direction is the most favorable direction because differences in the driver behavior will be gradually reduced and eventually eliminated.

Table 1 briefly summarizes major VSL practices around the world and in the United States.
<table>
<thead>
<tr>
<th>VSL System Location</th>
<th>Regulation</th>
<th>Feedback</th>
<th>Objectives</th>
<th>Control Means and Algorithm</th>
<th>Evaluation Results</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD-100, Maryland</td>
<td>Advisory</td>
<td>Roadside signs</td>
<td>Reduce recurrent congestion and improve safety</td>
<td>Reduce approaching traffic speed to smooth transition between free-flow and congested-flow states; take into account responses of drivers in dynamically setting appropriate control speed for each transition location.</td>
<td>Effective at recurrent bottlenecks in following aspects: higher average speed and throughput, shorter travel time, and smoother transition between free-flow speed and stop-and-go traffic.</td>
<td>2, 35</td>
</tr>
<tr>
<td>I-270/I-255 Corridor, Missouri</td>
<td>Advisory</td>
<td>Roadside signs: 65 VSL signs along 35 mi</td>
<td>Corridor-level VSL: to improve both traffic mobility and safety</td>
<td>Traffic sensor data were used to determine speed limits that ranged from 40 to 60 mph with 5-mph increments; to reduce the vehicle speed before reaching congested area (congestion caused by bottleneck, crash, or work zone).</td>
<td>Higher average speed and occupancy, limited mobility performance at some segments; noticeable reduction in crashes; satisfactory congestion relief, compliance rate, and sign visibility.</td>
<td>33</td>
</tr>
<tr>
<td>I-80, Wyoming</td>
<td>Advisory and regulatory</td>
<td>Overhead signs</td>
<td>Warn of adverse weather conditions; reduce speed variation</td>
<td>Standard posted speed limit is 120 km/h (75 mph); VSL: 50 km/h (32 mph), 70 km/h (43 mph), 90 km/h (56 mph) determined by average speed and volumes across all lanes at 1-min intervals. VSL for incident is 50 km/h.</td>
<td>No constant results have been achieved.</td>
<td>13</td>
</tr>
<tr>
<td>I-35W, Minneapolis–Saint Paul, Minnesota</td>
<td>Advisory</td>
<td>Overhead signs; lane-wise display; all lanes same speed; every 1.5 mi</td>
<td>Prevent propagation of shock waves</td>
<td>Detection of traffic downstream to determine VSL display 1.5 mi upstream; gradually reducing speed of incoming traffic to bottleneck; using constant deceleration rate to determine VSL in end of queue; update every rate 30 s; display 60 mph in snow; all lanes use same VSL although display is lane by lane; VSL used together with lane management and dynamic shoulder use.</td>
<td>Lower deceleration rate, reduced travel time with higher volume; other evaluation results are not available yet.</td>
<td>38, 39</td>
</tr>
<tr>
<td>I-4, Florida</td>
<td>Regulatory</td>
<td>Roadside signs</td>
<td>Improve traffic flow; reduce rear-end and lane-change crash risks</td>
<td>Florida Department of Transportation conducted an engineering and traffic investigation that identified reasonable and safe speed under different weather and traffic conditions (e.g., some sections in congested period have VSL at 20 to 30 mph); lowering upstream speed limits by 5 mph and raising downstream speed limits by 5 mph.</td>
<td>Not available</td>
<td>54</td>
</tr>
<tr>
<td>I-5, I-90, Washington State</td>
<td>Regulatory</td>
<td>Overhead signs</td>
<td>Warn of adverse weather conditions; reduce congestion; improve traffic flow</td>
<td>In first period: ad hoc or set VSL value based on operator’s observation from video; automatic algorithm was implemented later. It uses traffic speeds upstream of gantry. If speed is below given threshold, system automatically adjusts posted speed in 5-mph increments. Lower bound of VSL is 35 mph. Manual VSL set can override VSL determined by sensor estimation.</td>
<td>Reduced average speed; reduced flow; maximum throughput speeds found to be (optimal flow speed) thresholds: 70% to 85% of posted speed (about 42 to 51 mph); travel time reliability increased.</td>
<td>32, 33</td>
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<tr>
<td>Location</td>
<td>VSL System</td>
<td>Control Means and Algorithm Evaluation Results</td>
<td>Reference</td>
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<tr>
<td>A7/E15 south of Lyon, France; spread to more than 650 km in 2011</td>
<td>Regulatory</td>
<td>Overhead gantries</td>
<td>Improve mobility, safety, and driving comfort; VSL with maximum speed of 110 km/h; triggered when total flow exceeded 3,000 vph; ban truck access in peak hours.</td>
<td>25, 26</td>
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<tr>
<td>M25, M4, UK</td>
<td>Regulatory</td>
<td>Overhead gantries</td>
<td>Improve safety, congestion, and environment; change fundamental diagram; VSL is activated, modified, or deactivated when flow or speed measurements, or both, cross preset thresholds between 35 and 65 mph; in bad weather, different thresholds will be used; thresholds are based on traffic flow or speed measurement.</td>
<td>20, 21</td>
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<tr>
<td>A99 (16.3 km), Munich, Germany</td>
<td>Regulatory</td>
<td>Overhead gantries</td>
<td>Improve bottleneck flow and safety; VSL and travelers’ information; algorithms are based on fundamental relationships of speed, flow, and density between detector stations.</td>
<td>22</td>
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<tr>
<td>A20 (4.2 km), Rotterdam, Netherlands</td>
<td>Strictly enforced</td>
<td>Overhead gantries</td>
<td>Improve traffic operations without deteriorating local air quality; Dynamax: dynamic speed limit strategy; speed limit is increased from 80 km/h to 100 km/h as soon as congestion appears to set in and during the night; original fixed speed limit 80 km/h; key idea of measure is to counterbalance negative effects of strictly enforced dynamic speed limits; incident speed limit is 80 km/h; manual set VSL has highest priority.</td>
<td>27</td>
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<tr>
<td>E4, E22 motorways, Stockholm, Sweden</td>
<td>Advisory</td>
<td>VMS, overhead gantry</td>
<td>Improve safety, reduce shock wave, improve throughput; Speed signaling triggered by automatic incident detection alarms for downstream queues; 70, 60, 50, 30 km/h or lane closure.</td>
<td>18, 29</td>
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Note: NOx = oxides of nitrogen; PM10 = particulate matter up to 10 µm in size.
CONCLUDING REMARKS

It is well known that VSLs and VSAs, including speed harmonization, can significantly improve freeway traffic safety if the compliance rate is high enough. However, the impact on traffic throughput is still controversial. Although some improvements have been reported, the improvements may not be significant and are not generally recognized because of several factors. There are three main factors: (a) the traffic system is highly stochastic and sensor measurements are limited, which makes it difficult to detect the current traffic and predict the traffic in the near future; (b) there are large variations in driver behavior; and (c) VSL and VSA strategies are immature (most practices still use simple ad hoc approaches). Therefore, research and practice in this area still have a long way to go.

REFERENCES


The Intelligent Transportation Systems Committee peer-reviewed this paper.