Active traffic management (ATM) systems are becoming increasingly important, particularly in urban areas aiming to combat recurrent and nonrecurrent congestion. ATM systems apply proactive strategies to improve safety and mobility, as well as to reduce emissions, noise, and fuel consumption. As one of the key elements in the ATM toolbox, variable speed limit (VSL) systems are being increasingly deployed around the United States. In the past, most VSL systems in Europe have included automated enforcement as part of the system, while systems in the United States have relied on traditional speed enforcement strategies. In the Portland, Oregon, metropolitan area, a new traffic and weather-responsive VSL system has been deployed. It uses variable advisory speeds (VAS), allowing law enforcement to rely on the basic rule for enforcement. Thanks to the availability of high-resolution intelligent transportation systems data, it is possible to conduct post hoc analysis after VSL deployments. This paper focuses on driver compliance with displayed VAS messages. “Compliance” is defined as the difference between the displayed speed and the measured speed of traffic. In addition to analyzing more than 35 days at the Portland site, for comparison purposes, some additional analysis of a VSL site in Munich, Germany, is also included. The analysis of compliance for VSL–VAS deployments is useful for understanding the benefits of these important ATM strategies, assisting with targeting enforcement actions, and better understanding where and when to employ VSL–VAS systems.

The state of Oregon has become an early adopter of intelligent transportation systems and active traffic management (ATM) strategies for improving traffic safety and traffic flow. Specifically on high-traffic freeways surrounding Portland, the Oregon Department of Transportation (DOT) has implemented—among other things—a centralized traffic management center, dynamic ramp metering, incident response, and variable message signs with travel times and traveler information, as well as an online archived data service. Recently, the Oregon DOT has added a variable advisory speed (VAS) limit system on several freeways in the Portland area. The VAS system responds to weather and traffic conditions and displays advisory speeds (black on yellow signs) over each lane at specific gantry locations (1). While some variable speed limit (VSL) systems include regulatory speeds and automated enforcement, an advisory speed limit system was chosen after discussions with the Oregon State Police, who can use the basic speed rule for enforcement in situations in which a driver is not allowed to drive at a speed greater than is reasonable and prudent for conditions.

Oregon Route 217 (OR-217), a 7-mi stretch of freeway, experiences frequent rear-end collisions (approximately 200 per year) and heavy congestion during peak hours extending into the off-peak hours. The Oregon DOT is currently evaluating this application of the VAS system to inform further installations of VAS signs. The Oregon DOT recorded 314 crashes in 2012, roughly a crash rate of about 1.05 crashes per million vehicle miles traveled (2). The state average is 0.88 on non-Interstate urban freeways. Most of these are rear-end crashes, which are linked with stop-and-go traffic. Recent work has documented the preliminary effects of the VAS system on travel time reliability, safety, and other critical performance measures (1).

This paper explores the potential for developing a comprehensive scoring system for tracking the compliance of drivers with displayed VAS signs. Compliance is defined as the difference between the displayed speed and the actual measured speed of traffic.

\[ C = V_d - V_a \]

where

- \( C \) = compliance,
- \( V_d \) = displayed speed, and
- \( V_a \) = actual speed.

This analysis of compliance will assist in gaining a full understanding of the success of the system and includes a corridor perspective depicting when the signs are being used and what the actual traffic conditions are during those times. It is not known if or when enforcement was performed by law enforcement during the study period. To compare the Portland advisory speed limit system with another VSL, a site in Munich, Germany, is also analyzed. The Munich site uses regulatory speed limits and includes an automated enforcement system (although detailed knowledge of when it is activated is not available).

This study is made possible thanks to the availability of archived freeway sensor data to reconstruct the ground truth of actual vehicular
speeds over space and time. In addition, the VAS–VSL system logs have been archived, making it possible to reconstruct the displayed messages. A standardized algorithm compares specific hours or entire days of information to detect driver compliance, variations in driver compliance, and situations in which vehicular compliance is better or worse. This information can be helpful for enforcing speed limits at certain times of day and evaluating system effectiveness, providing useful information for deploying the system on other freeway corridors.

BACKGROUND AND LITERATURE REVIEW

OR-217, located southwest of Portland, Oregon, was converted in the past from a regional arterial to a limited-access freeway corridor with frequent on- and off-ramps. As an alternative to considering a major widening project, the Oregon DOT recently constructed an ATM system on the 7.5-mi freeway to improve congestion and reduce crash frequency. Figure 1 shows schematic drawings detailing the layout of the ATM system components in the northbound and

FIGURE 1 OR-217 detection and VAS system layout.
southbound lanes, with the milepost reading for each detector and VAS gantry as indicated. As shown, there are 14 loop detector and radar sensor stations and seven VAS gantries northbound, and 17 loop detector and radar sensor stations and seven VAS gantries southbound. Also shown is each detector’s influence area, which is the distance measured along the freeway bounded by the midpoints between each detector pair. The corridor runs north–south between US-26 and Interstate 5 and is a common route for commuters traveling between western and southern suburbs and downtown Portland. The corridor is generally two lanes in each direction with auxiliary lanes near western and southern suburbs and downtown Portland. The corridor is also served by a ramp-metering system at the entrance ramps. OR-217 has been well outfitted with loop and radar traffic detectors, as detailed in Figure 1. Free-flow speeds on OR-217 are between 55 and 60 mph. This speed can decrease by 30 mph in peak hours. Peak hour peak flows reach 3,500 vehicles per hour in both directions (3).

The OR-217 VAS system project was aimed at reducing crashes and congestion on the heavily traveled OR-217 (1). Previous work on driver compliance includes a study of driver behaviors linked to a weather-activated VSL system on rural roads in Wyoming, which found that VSL did reduce driver speed variation and that compliance grew worse with larger VSL speed reductions (2). The influence of a VAS or VSL system on traffic flow does not necessarily increase traffic flow but does contribute to fewer lane changes by harmonizing traffic flow across lanes and dampening speeds longitudinally (1, 4). Past research has reported that the system may not increase traffic flow; however, it does increase traffic safety and therefore may decrease congestion resulting from crashes.

The idea of evaluating the quality of traffic information by comparing actual traffic states with sensor data with navigation system congestion warnings already exists, and a quality index of system accuracy was proposed with a ratio of the reported coverage area versus the actual area of traffic congestion and speed information (5). This method relies on the time–space area of the freeway affected compared with the time–space area of the traffic signs and messages along the affected corridor. The analysis of VAS and VSL compliance discussed in this paper builds on the quality metrics developed by Ackaah et al. (5), and the full analysis is contained in Riggins (6).

DATA AND METHODOLOGY

Data for this analysis have been obtained from Portal (www.portal.its.pdx.edu), the online multimodal transportation data archive for the Portland, Oregon, metropolitan region. Freeway dual loop detector and radar detector data are available in each lane at 20-s intervals (count, occupancy, and time–mean speed). The VAS system was deployed on July 22, 2014. The data considered in this paper include data from a period before the system was deployed (static speed limit), data from the initial week of system installation, and a week of data from each month since the VAS system was turned on until March 2015.

The data for this study came from 13 speed detectors located along the 7-mi route of northbound OR-217. The VAS signs generally update themselves every 2 min and store a record in a database table with its location, lane, speed, or warning message. In the early months of system installation, the VAS signs were mostly turned off with sporadic advisory speeds displayed for short durations.

To analyze the ground truth traffic situation compared with the displayed VAS speeds, the database of sensor data was compiled in 1-min segments, combining volume and speeds across lanes of northbound OR-217 per location and per time. Subtracting the speeds of the vehicles traveling with the advisory sign speed yielded compliance graphs. These graphs show the difference in speeds of the vehicles from the VAS signs. Figure 1 shows the arrangement of the VAS signs and the speed detectors (dual loop and radar).

STUDY PARAMETERS

The week of June 15–21, 2014, was used as a basis for driver compliance with previously posted speed limits (a “before” scenario). The detected vehicle speed was compared with a posted 55-mph base speed limit. After system initialization on July 22, 2014, the VAS sign data were compared with measured vehicle speeds to construct compliance speed tables. One week out of each month was analyzed for compliance in July, August, and September of 2014 and January, February, and March of 2015. The dynamically controlled ramp-metering system was set with fixed-time rates and activation periods during October, November, and December 2014, and therefore data from this period were not used for this study. Ramp metering was functioning normally during all other periods (before and after VAS deployment).

RESULTS

The results of the analysis explain the process to evaluate driver compliance with VAS limits. The results are divided into two sections. The first is the analysis of a 7-mi section of northbound OR-217 near Portland, Oregon. The second section is the same analysis of a 20-mi section of the A 99 freeway near Munich, Germany.

VAS Performance of OR-217

The VAS signs are usually deployed at times of system congestion, but often the signs are also “on” during the whole day and on weekends. The details of the algorithm used to determine when to activate the VAS system and what speed to display are described elsewhere (1, 7). The VAS signs are generally spaced every mile with two or three speed detectors following before the next VAS sign. The VAS signs can display “50,” “45,” “40,” “35,” “30,” and “Slow,” in black text with a yellow background. The speeds measured are always displayed for each lane at each gantry. The logs for all VAS messages for each northbound gantry are shown in Figure 2 for Wednesday, March 18, 2015 (stair step function in blue). The speeds measured at the nearest detector station are also shown (time series in red). The sign-off state is represented by “SO.”

As shown in Figure 2, it appears that when speeds are high (e.g., for most of the day at Milepost 0.91), at most gantries the VAS is either off or displays “50 mph.” At other times, at other locations, when speeds drop, it appears that the system also displays appropriate speeds (e.g., Milepost 4.13 during the morning and afternoon peak periods). It is also clear from Figure 2 that there are times and locations at which the actual traffic speed is lower than the displayed VAS speed and also times when the opposite is true. The compliance examination will continue to examine these issues in depth.

During substantial portions of the day, one or several of the VAS signs are either off in non–peak hour times or set to “Slow” in heavy congestion. Figure 2 also shows the percent of time that the VAS system was active by hour of the day for March 18, 2015, at the
bottom of the figure. In the months following the VAS system initialization, the signs were on less than 20% of the time. Also, measured speed fluctuations during overnight and low-flow periods seemed to trigger the system unnecessarily. Beginning in January 2015, after some system calibration, the VAS signs were usually on more than 60% of the time. Drivers tend to drive on average 10 mph above the VAS speed limit and 7 mph faster than the displayed speed during the first few months following VAS installation. On average, during the days tested, 88% of drivers drive over the VAS limit. To systematically assess the VAS system’s status, Figure 3 has been constructed displaying the details from the system for March 18, 2015.

Building on the “slices” in Figure 2, Figure 3, a to c, shows the traffic speeds, displayed advisory speeds, and the difference between the two or the compliance of drivers with the posted speed. Figure 3, a to c, is arranged in a bottom-to-top driving direction. Figure 3a is a time–space plot that builds on the data shown in Figure 2 for each station and shows vehicular speeds measured at 20-s intervals at 13 detector locations along the 7-mi corridors. Vehicles are moving upward in the figure. To produce a ground truth plot, the speeds have been averaged into 1-min segments throughout the day and interpolated longitudinally between detector locations. Speed is denoted by color, with high speeds shown in green and lower speeds in yellow and red. As indicated, during the morning and afternoon peak periods, congestion forms at a known bottleneck near the middle of the corridor.

Next, Figure 3b also builds on the data shown in Figure 2, but applies the VAS messages over space (along the next downstream segment until the next gantry) and time. The VAS plot in Figure 3b uses colors to illustrate the particular speed displayed at a particular gantry over time (green reflects the higher speeds; yellow and red move progressively slower). The speed messages may change as frequently as every 2 min. As shown, when the system is “off” (blank, SO in Figure 2), white space is shown in the figure. When the system reads “slow,” a gray color is used on the figure. For much of the day, the green blocks indicate speeds displayed between 40 and 50 mph. During the peak periods, visually the zones with lower VAS speeds seem to match with the congestion mapped in Figure 3a. Figure 3b indicates that somewhat surprisingly the system was on between midnight and 6 a.m. and after 7 p.m., displaying 50 mph speeds. During the middle of the day, the signs on several gantries in the middle of the corridor were off, while others displayed speeds in the 45- to 50-mph range.
FIGURE 3 OR-217 northbound (NB): (a) vehicle speed, (b) VAS displayed speed, and (c) compliance, March 18, 2015 (MP = milepost).
With a time–space plot for VAS displayed speed and actual and measured vehicular speeds, it is possible to examine the compliance, which is the arithmetic difference between the two. So Figure 3c is a plot of the difference between the VAS sign readings from the measured speed detector readings. In this case, color is used to illustrate the arithmetic differences between measured vehicular speeds (from the nearest detector stations) and the displayed VAS speeds, applied downstream. Green represents times and locations where vehicles were traveling faster than the VAS displays. Visually from the figure it appears that during the off-peak periods (overnight and midday), most of the traffic was traveling faster than the VAS displays. In the figure, the yellow–red colors reflect situations in which vehicles were recorded traveling slower than the displayed speeds on the VAS signs. In most cases this appears to have occurred during the peak periods, where traffic was likely moving more slowly than indicated by the VAS displays.

**Compliance Scoring Parameters**

To further understand the level of compliance with the VAS system, a set of analyses was prepared with data from March 18, 2015, as an example. With the matrix behind the creation of Figure 3c, which contains one “compliance” value for each gantry every 2 min during the day (when the VAS system was on), a histogram was created, shown in Figure 4a. From the histogram, one can observe that the mean compliance value was +9 mph (median was +9 mph) with a standard deviation of 8 mph. This observation says that considering all of the compliance observations (independent of traffic flow at that time and location), the mean value was 8.7 mph above the posted VAS speed. Investigating further, Figure 4a reveals that a total of 7% of the observations were below the posted VAS speed, and 88% were above (3% matched the VAS speed). Also a total of 20% of the observations fell within ±5 mph, while 53% fell within ±10 mph. Clearly on this day, most of the time vehicle speeds were well above the posted VAS speeds.

One weakness in Figure 4a is that all compliance observations are treated equally, independent of traffic flow at each time and location. To incorporate exposure of the VAS system to actual drivers, a volume-weighted approach was taken for the construction of the compliance scores. Clearly, during overnight hours there may be few vehicles contributing to the measured speeds, while during peak periods, vehicular flows will be higher, exposing more drivers to the VAS system. Thus, Figure 4b is constructed with a weighting system that proportionally weights each compliance observation according to observed vehicle counts in that time interval and at that location. As shown in Figure 4b, the histogram is somewhat similar to the view obtained in Figure 4a. Now Figure 4b shows that the mean (and median) compliance value was +11 mph and the standard deviation was 7 mph. Similarly, 88% of the exposed vehicles were traveling above the VAS speed, while 10% were below. A total of 57% of drivers were within ±10 mph of the display, while 15% were within ±5 mph.

Going beyond the one day analyzed here, Table 1 shows a summary of the compliance statistics (using volume-weighted analysis, with percentages above or below the displayed VAS). The table includes the mean, median, standard deviation, and variance of the compliance scores throughout each day and over the entire corridor. Further, the minimum and maximum percent less than the posted speed and percent greater than the posted speed are tabulated. The
percent of vehicles traveling at the VAS speed is shown, followed by
groupings to indicate the percent of vehicles traveling ±5%, ±10%, ±15%, and ±20% below or above the posted speed. Finally the
percent of vehicles traveling more than 20% above the posted speed is listed. Four days are included before the system was activated,
with comparisons made against the posted regulatory speed limit of
55 mph. As shown, 76% of vehicles were traveling faster than the
speed limit, while 22% were traveling slower, likely because of con-
gestion. A total of 90% of vehicles were traveling up to 20% below or
above the speed limit, with only 5% traveling more than 20% faster.

In contrast to the before conditions, a total of 35 days are included
in Table 1 after the system has been deployed, including 23 week-
days and 12 weekend days. As shown, on weekdays, 80% of vehicles
were traveling faster than the speed limit, while 15% were traveling
slower, likely because of congestion. A total of 58% of vehicles
were traveling up to 20% below or above the variable speed limit,
with 37% traveling more than 20% faster. On weekends, 87% of
vehicles were traveling faster than the speed limit, while 5% were
traveling slower, likely as a result of congestion (less congestion
occurs on weekends). A total of 48% of vehicles were traveling up
to 20% below or above the variable speed limit, with 51% traveling
more than 20% faster.

Compliance per VAS Speed

Figure 5 shows a box plot of the speed compliance at each of the
displayed speeds for the volume-weighted observations on March 18,
2015. The figure reveals an interesting and generally increasing
relationship between the displayed speed and the compliance value.
At times when the VAS displays “30” and “35,” the median com-
pliance is slightly less than zero, meaning that vehicles are traveling
at speeds lower than those displayed. Also noticeable is that average
compliance to higher advisory speeds (including “40,” “45,” and
“50”) is on average approximately 10 mph above. Also shown is
the fact that when the VAS system was on, most of the time the sign
was displaying “50.” The relationship between the sign display and
the compliance level is a subject that should be analyzed further.

VAS Performance of Autobahn 99

in Munich

To compare the U.S.-based VAS system with another deployment,
the same compliance analysis procedure has been reproduced for a
33-km (20-mi) section of the A 99 freeway near Munich. The lane
layout and VSL gantry locations are shown in Figure 6, where traffic
is moving from left to right. Figures 7 and 8 show the results of these
analyses for one sample day: Thursday, April 19, 2012.

The German VSL system differs from the Oregon VAS system
in that the German variable speed limits are enforced with gantry-
mounted speed cameras while the Oregon system is advisory. Another
distinguishing factor is the German VSL system turns on only when
activated by traffic congestion or weather. During other times, the
system is off and drivers are allowed to travel as fast as they would
like (no speed limit). For that reason, the VSL graph is centered on
the peak hours in the morning and afternoon when speed harmoni-
zation is necessary because of congestion. The traffic control system
displays no reading during free-flowing traffic. The detected driver
speed for the given day (Thursday) shows several traffic flow break-
downs around 10 a.m. and 7 p.m. Twenty-five VSL signs regulate
speeds on the 20-mi section of the freeway.
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**TABLE 1 Summary of Results for VAS Compliance on OR-217**
FIGURE 5  Box plot of drivers’ compliance grouped per VAS posted speed, March 18, 2015, OR-217 NB.

FIGURE 6  A 99 detection and VAS layout.
FIGURE 7 Results for April 19, 2012: (a) A 99 detected southbound (SB) vehicle speeds (km/h), (b) VSL displayed speeds, and (c) VSL compliance (actual–displayed).
Figure 7 is similar to Figure 3, in that it displays ground truth measured detector speeds (km/h) in Figure 7a; several known bottlenecks are visible. In this case, Figure 7b shows the VSL displayed speeds (which can be either “60,” “80,” “100,” or “120”) in km/h. The figure is blank or white when the system is turned off. Finally, Figure 7c shows the compliance (subtraction) in km/h, where green shows measured speeds above the VSL display, with yellow and red indicating speeds below the VAS display.

Similar to Figure 4b, Figure 8 shows the volume-weighted compliance histogram in regard to the speeds above or below the VSL display. Here the mean is about −0.3 km/h below the VSL (median ±3 km/h above the VSL), with a standard deviation of about 17.4 km/h. The shape of the histogram is substantially different from the one in Figure 4b—this one has two peaks—one below the VSL and one above—while the OR-217 histogram has just one peak above. As shown in the figure, about 58% of the traffic is moving above the VSL while it is active, which is notably less than in the case of OR-217. A total of about 40% of the traffic is moving below the VSL speeds, which is more than in the Oregon case. In Munich, 70% of drivers were within ±10 mph of the display, which is higher than the 57% in this category in Oregon. In Munich, 41% were within ±5 mph, again much higher than the 15% that were in this category in Oregon. With 2 days of data, on average in Munich, 70% of drivers were within ±10 mph of the display, which is higher than the 57% in this category in Oregon.

**Conclusions**

The implementation of a congestion-responsive VAS system has the potential to increase the safety of heavily used infrastructure. Harmonizing drivers’ speeds prevents accidents and eases stop-and-go traffic. Considering the short time that the OR-217 system has been up and running—1 year at the time this paper is being written—the algorithm has had time to be better tuned to be congestion responsive. It remains important to evaluate the results of the VAS system’s influence on traffic to increase the effective potential of the system. Increasing effectiveness means making sure that the ground truth vehicle data are closely reflected within a tight time-space window on VAS sign displays in addition to investigating actual driver response to advisory speeds. The methods presented in this paper for evaluating system effectiveness may provide tools for refining system effectiveness. In this analysis, measurements were considered during congested and uncongested conditions, recognizing that vehicles in congestion may not have the ability to comply with the displayed VAS speed limits. Future research should explicitly account for or exclude these situations. Further investigation into the detection-VAS response-driver compliance loop is needed to maximize the full potential of the VAS system. Future analyses should also attempt to
consider other confounding effects, such as incidents. As shown in the comparison with the A 99 freeway in Munich, compliance rates are higher because of enforcement at each VSL gantry.

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REFERENCES


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