OPERATIONAL ANALYSIS OF A FREEWAY VARIABLE SPEED LIMIT SYSTEM - CASE STUDY OF DEPLOYMENT IN MISSOURI

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ABSTRACT

Variable Speed Limit (VSL) systems have been more widely implemented in Europe as compared to the United States. Studies have demonstrated positive safety impacts of such systems; however, there are very few studies that used actual deployment data to investigate the operational benefits of VSL systems. This paper presents the operational impacts of a VSL deployment on Interstate 270 in the state of Missouri in United States. Techniques such as parametric curve fitting, non-parametric methods, and other statistical tests were used to identify the traffic changes between before and after conditions. The effect of VSL on traffic performance was investigated at eight heavily congested locations. The two-dimensional Kolmogorov-Smirnov test results indicated that flow-occupancy diagram changes were statistically significant at seven out of eight locations. The slopes of flow-occupancy plots for over critical occupancies were found to be steeper after VSL. Slight changes in critical occupancy were observed after VSL implementation. However, the changes were inconsistent across locations with some witnessing an increase and others witnessing a decrease. The maximum flow prior to breakdown, the pre-breakdown flow, decreased at four locations and increased at four locations after VSL. The maximum flow after breakdown, the post-breakdown flow, decreased at three locations and increased at five locations after VSL. The average daily duration of congestion decreased at five locations and increased at three locations after VSL. Findings of this study help to develop VSL control algorithms that are more efficient in improving VSL traffic operations benefits.
INTRODUCTION

Variable Speed Limit (VSL) systems have been implemented in the United States in Tennessee, Washington, Delaware and New Jersey; and in European countries such as England, Netherlands, Germany and Greece. The goal of VSL systems is to adjust the speed limit of a roadway based on prevailing road, traffic, and environmental conditions to improve safety and efficiency. In May 2008, the Missouri Department of Transportation (MoDOT) installed 65 VSL signs along 38 miles of Interstate 270 and Interstate 255 in St. Louis to alleviate congestion and to make travel safer to the public. Traffic sensor data was used to determine the speed limits that ranged from 40 mph to 60 mph with 5 mph increments. This is one of the very few (if not the only) VSL deployments in the United States (US) that is specifically aimed at improving freeway conditions in addition to deriving safety benefits. Most of the VSL deployments in the US originated from a safety concern – to warn drivers of weather related hazardous conditions, visibility conditions, etc (1). There have been a few temporary VSL deployments for managing non-recurring congestion (e.g., work zones) but not for recurring congestion.

In this paper, the effects of Interstate 270 VSL system on traffic flow characteristics are investigated. A before and after study is performed to evaluate the effects of VSL on flow and occupancy. Different statistical and curve fitting methods are used to compare the traffic conditions before and after VSL deployment. First, the flow-occupancy plots of before and after data are compared using the two-dimensional Kolmogorov-Smirnov test. Second, standard curve fitting (regression) is used to fit flow-occupancy data for free flow and congested conditions. Additional measures such as the critical occupancies, pre-breakdown and post-breakdown flow as surrogates for capacity are also compared. The research presented in this paper adds to the existing body of VSL literature and makes the following new contributions:

1) The study area is in a different geographical area (US) compared to those reported in the literature (Europe). The use of VSL as an active traffic management tool is relatively new in the US, and this is the first corridor-level implementation of the VSL specifically aimed at improving traffic conditions and resolving congestion. Therefore, the findings of this study could provide guidance on future VSL implementations (performance expectations, data to be archived, etc) in the US.

2) Statistical analysis is performed using the two-dimensional Kolmogorov-Smirnov (KS) test to analyze changes in flow-occupancy and speed-occupancy relationships for before and after conditions. The two-dimensional Kolmogorov-Smirnov has great potential to be used in other before-after traffic studies.

REVIEW OF VSL LITERATURE

Robinson (1) provided a synthesis of VSL systems that have been implemented in the United States and Europe. The implementations in United States were focused on improving safety on the freeway corridors. However, the implementations in Europe focused on improving both safety and traffic operations.

VSL systems were implemented on a few major motorways in England on a pilot basis with the main purpose of improving traffic flow during peak periods. Early evaluations of the system (2) proved that in addition to the operational benefits, there was a reduction in crash frequencies and crash severities due to reduction in speed variance and an overall increase in
speed limit compliance. A study by Borrough (3) found that the England VSL system in conjunction with video enforcement resulted in a 28% reduction in crashes over a one and half year period.

Van den Hoogen and Smulders (4) reported the results of VSL experimentation on a 20 km segment of a freeway in the Netherlands. They found that the VSL system: (i) reduced the variation of speeds within and across lanes indicating improved safety and (ii) improved traffic flow and reduced travel times. Alessandri et al. (5) proved theoretically that VSL could avoid congestion and improve the stability of traffic flow by dynamically updating speeds based on prevailing traffic densities. Breton et al. (6) used a macroscopic simulation model to show that by adopting reduced speed limits during peak periods, the upstream traveling shock wave was suppressed by a downstream traveling low-density wave. Mirshahi et al. (7) reviewed the VSL implementations in European countries including Denmark, Germany, Greece, and Netherlands. In terms of operational benefits they reported that Netherlands’ MCSS speed harmonization project resulted in a 3% to 5% increase in throughput and 16% reduction in collisions.

Hegyi et al. (8) introduced a model predictive approach for optimal coordination of VSL with the objective of suppressing shockwaves. The developed framework was applied to a benchmark network and shown to effectively eliminate shockwaves. In a subsequent study, Hegyi et al. (9) developed a predictive coordinated control method for optimal coordination of VSL and ramp metering. They found the coordination of VSL and ramp metering to improve the network outflow and reduce the total travel time. Hegyi et al. (10) proposed the SPECIALIST algorithm for dynamic speed limit control based on shock wave theory. Results of field experiments of the SPECIALIST algorithm conducted on a 14 km segment of the Dutch A12 freeway are reported in Hegyi and Hoogendoorn (11). They reported that VSL decreased the number of vehicles arriving at a traffic jam, was able to resolve 80% of shockwaves, and on average saved 35 vehicle-hours per one resolved shockwave.

Papageorgiou et al. (12) investigated the effects of VSL on macroscopic traffic characteristics on a European motorway. The main focus of the study was to determine the changes in the shape of flow-occupancy diagram due to the implementation of VSL. They found that VSL decreased the flow-occupancy diagram slope at undercritical occupancies. The critical occupancy, defined as the occupancy at which the traffic flow is equal to capacity, was found to have increased due to VSL. The changes in capacity due to VSL were not consistent, with only some locations witnessing an increase and others not witnessing any increase.

Carlson et al. (13-14) studied the impact of VSL on improving traffic conditions on ring-road A10 in Amsterdam using simulation. It was found that the traffic flow can be substantially improved by implementing a standalone VSL system or the integrated VSL and ramp metering system. In a subsequent study, Carlson et al. (15) designed a simple feedback controller for the proposed VSL and ramp metering control system that takes into account several practical and safety constraints for field implementation.

Heydecker and Addison (16) investigated the relationship between speed and occupancy in freeways and the effect of speed limit control on this relationship. They analyzed data for a site on M25 London Orbital Motorway in England during one day of the week. The Underwood’s exponential form was found to best explain the speed-occupancy relationship. The statistical estimation results showed that different relationships exist for different speed limits.
DESCRIPTION OF CASE STUDY LOCATIONS AND DATA

A before and after study was conducted at eight freeway locations located in heavily congested areas of Interstate 270 (I-270) in St. Louis, Missouri (see Figure 1). There were no consistent active bottlenecks in the study area; the location of the bottlenecks varied from one day to another. Therefore, the eight most frequently congested locations were selected. Occupancy, speed and flow data obtained from microwave detectors deployed on I-270 were used in this research. Each study location represents a single detector station covering all lanes. Detector data was aggregated by the agency into five-minute intervals. Three months of data, from February to April, were processed to identify days without faulty and missing data. A consideration was to use the same period of time before and after VSL deployment for evaluating changes. The data processing resulted in selecting five weekdays from 5:30 am to 9:30 pm during April for before (2008) and after conditions (2009). The chosen days ensured that there were no severe weather events reported in the before or after period. Locations A and B are on the I-270 Eastbound segment and locations C, D, E, F, G and H are located on the I-270 southbound segment. Figure 1 shows the location of VSL signs in the vicinity of study locations.

The study locations varied from one another in terms of geometrics. Seven out of the eight study locations were located within the footprint of an interchange (see Figure 2). Location A was between the exit ramp and entrance ramp of a diamond interchange. Location B was between the second exit ramp and second entrance ramp of a full cloverleaf interchange. Locations C, D and G were similar to location A and were between the exit ramp and entrance ramp of a diamond interchange. Location E was upstream of an entrance ramp of a directional interchange (freeway to freeway interchange). Location F was on a tangent section of the freeway (non-interchange). And, location H was upstream of an entrance ramp of a partial cloverleaf interchange. Study location details, including the distance between study locations and adjacent VSL signs, and descriptive statistics of before and after data, are presented in Table 1.
The main objective of the VSL algorithm implemented by MoDOT is to reduce the speed of vehicles before they reach a congested area (congestion due to a bottleneck, a crash, or a work zone). Figure 3 shows a flowchart of the VSL control algorithm. The study corridor was divided
into zones to make it easier for the MoDOT operators to manage the VSL algorithm alerts (speed limit updates). Each zone consisted of two or three detector stations along the freeway. All detectors in a given zone are averaged every 30 seconds. For each 30 second interval, if the average occupancy of a freeway segment is greater than 7% and flow is greater than 10 vehicles and average speed is less than 55 mph (maximum speed limit is 60 mph) the algorithm recommends a reduction in congested segment speed limit. The recommended speed limit is the congested segment average speed rounded up to the next highest multiple of 5 mph.

\[ \text{Speed, flow, occupancy data (30 second averages)} \]

If
\[ \text{Occupancy} > 7\% \text{ AND flow} > 10 \text{ vehicles AND speed} < 55 \text{ mph} \]

No \[ \text{Set VSL} = 60 \text{ mph} \]

Yes
\[ \text{Set congested segment VSL} = \text{ROUNDUP(speed)} \]

Update upstream VSL signs as shown in Figure 4

FIGURE 3 Variable speed limit control algorithm

The speed limits of the areas upstream of the congested segment are updated in 5 mph increments. Figure 4 shows an example of how the speed limits of upstream segments are updated. After determining the congested segment, the recommended speed limit is posted in the congested segment and the same speed limit is applied on VSL signs within 3 miles upstream of this segment (segment X shown in Figure 4). The speed limits in the upstream segments Y, Z, and so on are updated in increments of 5 mph of the immediately downstream segment until reaching the maximum speed limit of 60 mph. In addition, when there are multiple congested segments any two consecutive VSL signs cannot be different by more than 15 mph (i.e., one VSL cannot display 60 mph when the immediately downstream VSL displays 40 mph). An exception to this rule is during flow recovery. For example, an upstream VSL displays 40 mph while the immediately downstream VSL displays 60 mph.

The traffic management center operators verify the traffic conditions through ATMS cameras closest to the area before posting the speed limits on signs closest to the congested segment first. They then update the speed limits upstream of the congested segment. Once a VSL is changed, it cannot be changed until at least five minutes have elapsed. The variable speed limits were regulatory (enforceable) and the signs were installed in the median or right shoulders of the freeway.
METHODOLOGY

This section presents the different methodologies used to analyze the data from before and after VSL implementation. The first methodology, the two-dimensional Kolmogorov-Smirnov test, was used to examine the statistical significance of changes in the flow-occupancy distributions as a whole. However, the Kolmogorov-Smirnov test does not provide insights on changes within the distribution, (i.e., within any particular occupancy interval). Such trends could be obtained using curve fitting procedures as illustrated by Papageorgiou et al. (12). To do this, the occupancy axis is divided into two regions based on the critical occupancy: undercritical flow and congested flow. Critical occupancies are inferred from flow-occupancy plots because of a noticeable break point. Other field data also exhibited similar break points on the flow-occupancy diagram (17-18). Linear regression is used to find the best fit lines for flow-occupancy diagrams. In order to compare the best fit lines for the before and the after data, hypothesis testing is performed to determine if the slopes of these lines are statistically different.

Two-dimensional Kolmogorov-Smirnov Test

The Kolmogorov-Smirnov test is a nonparametric goodness-of-fit test that is commonly used to test if two samples are from the same population (19). This is done by comparing the cumulative distribution functions (CDFs) of the two samples (20). The application of the Kolmogorov-Smirnov test to one-dimensional data is straightforward. Once the observations and their corresponding frequencies are known, computation of the CDF is trivial. Unfortunately, the same is not the case with two-dimensional data such as flow-occupancy diagrams. Application of Kolmogorov-Smirnov test to a multi-dimensional space requires a probability function which is not dependent of the ordering direction. Obtaining such a probability function in a $d$ dimensional space is challenging considering that CDF can be defined in $(2^d - 1)$ ways (21). A method for performing the two-dimensional Kolmogorov-Smirnov test is further explained. Let $B = \{(x_{b1}, y_{b1}), (x_{b2}, y_{b2}), \ldots, (x_{bn}, y_{bn})\}$ represent the set of before observations (e.g.,$(flow, occupancy)$). Similarly, let $A = \{(x_{a1}, y_{a1}), (x_{a2}, y_{a2}), \ldots, (x_{am}, y_{am})\}$ represent the set of after observations. In these sets, $b$ and $a$ are the indexes for before and after data. Let $F$ and $G$
represent cumulative density functions of the before and after data, respectively. A null
hypothesis is defined as
\[ H_0 : F(x, y) = G(x, y), \quad \forall (x, y) \in \mathbb{R}^2 \] (1)

Peacock (22) introduced a method to obtain the probability function which is not
dependent on the ordering direction. In this method all possible CDFs are developed using all
possible ordering directions; then the maximum difference between CDFs is calculated and
considered as the test statistic. For a point \((x_i, y_i)\), all natural quadrants around the point
\[ [(x_i > x_j, y_i > y_j), \ (x_i < x_j, y_i > y_j), \ (x_i < x_j, y_i < y_j), \ (x_i > x_j, y_i < y_j)] \] are examined and an integrated
probability in each quadrant is calculated. The maximum difference between integrated
probabilities is considered as the test statistic, \(D\). The proposed method involves exhaustive
enumeration and is very computationally demanding (21). Fasano and Franceschini (23)
proposed a new variant of the Peacock method which improves the test speed and also considers
the sample size and correlation of sample points. Instead of using a Kolmogorov-Smirnov table,
the significance level for a two-dimensional Kolmogorov-Smirnov test is calculated as (24):
\[
\text{Probability}(D > \text{observed}) = Q_{KS} \left( \sqrt{ND} \right)
\]
\[
= \frac{\sum_{j=1}^{\infty} (-1)^{j-1} e^{-2j^2}}{1 + \sqrt{1 - r^2} \left(0.25 - 0.75 / \sqrt{N} \right)}
\]
\[
D = \frac{\sqrt{N} D}{1 + \sqrt{1 - r^2} \left(0.25 - 0.75 / \sqrt{N} \right)}
\]
\[
Q_{KS}(\lambda) = 2 \sum_{j=1}^{\infty} (-1)^{j-1} e^{-2j^2} \] or the cumulative Kolmogorov-Smirnov distribution
\[
\lambda = 0, \quad Q_{KS} = 1
\]
\[
\lambda = 1, \quad Q_{KS} = 0
\]
\[ Q_{KS} \] is a monotonic function, thus \(Q_{KS}(0) = 1, \ Q_{KS}(1) = 0\). In two-dimensional Kolmogorov-
Smirnov, it is assumed that both datasets have the same coefficient of correlation.

**Statistical Test for Comparing Slopes of Fitted Regression Lines**

In order to compare two fitted plots, statistical tests are performed to identify if slope of fitted
lines are statistically different. Let \(m\) be the number of before observations and \(n\) the number of
after observations. Let \(B = \{(x_{b,1}, y_{b,1}), (x_{b,2}, y_{b,2}), \ldots, (x_{b,m}, y_{b,m})\}\) represent the set of before
observations and \(A = \{(x_{a,1}, y_{a,1}), (x_{a,2}, y_{a,2}), \ldots, (x_{a,n}, y_{a,n})\}\) represent the set of after observations. In
these sets, \(b\) and \(a\) are the indexes for before and after data. A dummy variable \(Z\) is defined
where \(Z = 0\) represents before data and \(Z = 1\) represents after data. A single multiple regression
model is fitted to the combined data.
\[
Y = \beta_0 + \beta_1 X + \beta_2 Z + \beta_3 XZ + \varepsilon
\]
\[
Y = \{(y_{b,1}, \ldots, y_{b,m}, y_{a,1}, \ldots, y_{a,n})\}
\]
\[
X = \{(x_{b,1}, \ldots, x_{b,m}, x_{a,1}, \ldots, x_{a,n})\}
\]
In this equation $\beta_0$, $\beta_1$, $\beta_2$, and $\beta_3$ are regression coefficients, $X$ is the set of independent variables from before and after data, $\epsilon$ is the error term, and $Y$ is the set of dependent variables from before and after data. Based on value of $Z$, the above model can be written as

$$Z = 0 \quad Y_a = \beta_0 + \beta_1 X + \epsilon$$  \hspace{1cm} \text{for before data}$$

$$Z = 1 \quad Y_a = (\beta_0 + \beta_2) + (\beta_1 + \beta_3) X + \epsilon$$  \hspace{1cm} \text{for after data}$$

(9)

Two hypotheses are defined to compare slope and intercepts of regression lines:

Hypothesis 1, $H_0: \beta_1 = 0$, in which case the slope of both before and after lines are equal. Partial F-test or its equivalent t-test can be used as the test statistic for this hypothesis. Hypothesis 2 is defined as $H_0: \beta_2 = \beta_3 = 0$, in which case the two regression lines coincide with each other (24).

RESULTS OF BEFORE AND AFTER ANALYSIS

This section presents the results of analysis of traffic data before and after the implementation of VSL at the eight locations described previously. The purpose of the analysis was to identify the effect of VSL on maximum observed flow and critical occupancy at the study locations. The flow-occupancy plots for over critical occupancies provide evidence if higher flows can be attained at higher occupancies with VSL. The slope of the best-fit line for over critical occupancies is indicative of how rapidly the flow deteriorates with increase in occupancies, the flatter the slope the better. The effect of VSL on these slopes was also investigated.

Changes in traffic conditions before and after the implementation of VSL were analyzed using two separate methods: the nonparametric two-dimensional Kolmogorov-Smirnov test and the parametric flow-occupancy curve fitting. The results from the Kolmogorov-Smirnov test indicated that the flow-occupancy diagram, with the exception of Location F, changed after the implementation of VSL with $p = 0.00$. The $p$-value for location F was 0.36. The location F is the only study location not in the vicinity of a freeway interchange.

As described previously, the Kolmogorov-Smirnov test only shows if the before and after conditions are statistically different, and curve fitting was used to provide insights on the changes from before to after conditions. The functional form of the best fit curve was varied and the linear form was selected for simplicity and similarity of results with other higher-order forms (quadratic, cubic). A reverse lambda shaped flow-occupancy curve was observed (18) at all eight locations. Two types of capacity values are usually obtained from flow-occupancy plots (26) – 1) pre-queue flow (PQF) which is the maximum flow observed during the undercritical flow conditions, and 2) queue discharge flow (QDF) which is the maximum flow observed during congested flow conditions. Since PQF and QDF terms are only applicable to active bottlenecks, terms “Pre-breakdown flow” and “Post-breakdown flow” are used instead in this paper. Figure 5 shows flow-occupancy fitted plots for all study locations. Critical occupancies are determined using a two-step procedure. First, the scatter plots of flow-occupancy data were observed for any clear change in trends. The initial trend of increase in flow with increase in occupancy was observed. This trend reversed after the critical occupancy was reached. From the data it was evident that this change in trend occurred within the occupancy range of 6% to 11% for all locations. However, the exact critical occupancy value was not easily discernible from the scatter plot. Next, to determine the critical occupancy value, regression lines were fitted for free flow and congested regions for different possible critical occupancy values, and the root mean square error (RMSE) were computed. The critical occupancy value that resulted in the least RMSE was chosen. The pre-breakdown flow and post-breakdown flow values were obtained from best fit-
FIGURE 5  Flow-occupancy plots for locations of study
lines at critical occupancies. Best-fit lines for the congested region were drawn only until the maximum observed occupancy values. Table 2 reports the Pre-breakdown flow, Post-breakdown flow, and before and after critical occupancies.

Statistical tests indicated that the slopes of before and after plots for undercritical occupancies were statistically different for all locations of study with a $p$-value of 0.00. With the exception of location D, the slopes of undercritical occupancies slightly increased from before to after conditions. The $p$-values only indicated that before and after slopes were different and did not provide information on the magnitude of difference in the before and after samples. Cliff’s delta statistical test is an effect size test used for investigating the magnitude of difference between samples (27). The Cliff’s delta statistics were calculated for before and after undercritical flow-occupancy samples. Test statistics were close to 0 for all eight locations of studies indicating very minor differences in the before and after data. In six out of the eight locations, the critical occupancies for before data were greater than 7% and the flow and speed conditions were also met. This meant that the VSL was active for a few undercritical occupancies as well (those greater than 7% but less than critical occupancy). This partly explains why the after-conditions plot for undercritical occupancies is different from the before-conditions plot. For over critical occupancies, the slopes of before and after plots were statistically different for locations A, B, D, F and G with $p$-values of 0.05, 0.00, 0.01, 0.00, and 0.00 respectively. The slopes of before and after plots for locations C, E, and H were not statistically different. And, the slopes of flow-occupancy plots for over critical occupancies were steeper after VSL for all locations. The steeper slopes indicate that the flow deteriorated more rapidly with increases in occupancies during VSL use.

The critical occupancy slightly increased at locations A, C, D and F; and slightly decreased at locations B, E, G and H. However, the change in critical occupancy was less than 1.25%.

The results for pre-breakdown and post-breakdown flows are shown in Table 2. Pre-breakdown flow and post-break down flow at locations B and E decreased after VSL. At location G pre-breakdown flow decreased but the post-breakdown flow increased after implementation of VSL. At location A pre-breakdown flow decreased but the post-breakdown flow remained approximately the same. At location H pre-breakdown flow increased but the post-breakdown flow decreased after implementation of VSL. Both pre-breakdown and post-breakdown flows increased at locations C, D, and F with the increases in pre-breakdown flow being higher than the increases in post-breakdown flow. The most desirable case was location D, where pre-breakdown flow increased by 9% and post-breakdown flow increased by 6%.

<p>| TABLE 2 Pre-breakdown flow, post-breakdown flow, and critical occupancies at study locations |
|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|</p>
<table>
<thead>
<tr>
<th>Location</th>
<th>Pre-breakdown Flow (veh/h/ln) Before</th>
<th>After</th>
<th>Change</th>
<th>Post-breakdown Flow (veh/h/ln) Before</th>
<th>After</th>
<th>Change</th>
<th>Critical Occupancy (%)</th>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1478</td>
<td>1435</td>
<td>-43 (-3%)</td>
<td>1124</td>
<td>1128</td>
<td>3 (0%)</td>
<td>7.75</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>2115</td>
<td>1983</td>
<td>-131 (-7%)</td>
<td>1742</td>
<td>1704</td>
<td>-37 (-2%)</td>
<td>9.75</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>2114</td>
<td>2329</td>
<td>215 (+9%)</td>
<td>1783</td>
<td>1794</td>
<td>11 (+1%)</td>
<td>10</td>
<td>10.5</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>2034</td>
<td>2232</td>
<td>198 (+9%)</td>
<td>1715</td>
<td>1830</td>
<td>115 (+6%)</td>
<td>6.5</td>
<td>7.75</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>1881</td>
<td>1775</td>
<td>-107 (-6%)</td>
<td>1657</td>
<td>1636</td>
<td>-21 (-1%)</td>
<td>9</td>
<td>8.25</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>1634</td>
<td>1724</td>
<td>90 (+5%)</td>
<td>1487</td>
<td>1552</td>
<td>65 (+4%)</td>
<td>6.25</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>2084</td>
<td>2043</td>
<td>-41 (-2%)</td>
<td>1747</td>
<td>1809</td>
<td>62 (+3%)</td>
<td>9.75</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>1988</td>
<td>1995</td>
<td>7 (0%)</td>
<td>1763</td>
<td>1741</td>
<td>-22 (-1%)</td>
<td>7.5</td>
<td>7.25</td>
<td></td>
</tr>
</tbody>
</table>
Previous studies were limited in findings about traffic congestion reduction from field implementations of VSL. The VSL algorithm reported in this paper, as developed and implemented by Missouri DOT, was different from those reported in the literature. The algorithm was based on flow, speed, and occupancy thresholds for determining congested segment and upstream segment speed limits. In this study, the change in maximum observed flow was not consistent across all locations, which is similar to the finding of Papageorgiou et al. (12). However, the increases in critical occupancy due to VSL reported by Papageorgiou et al. (12) were not found in this study. The critical occupancies decreased at five locations and increased in the other three locations. The maximum observed increase in critical occupancy after VSL was 1.25%, and the maximum decrease was 0.75%.

Figure 6 displays the flow-occupancy curves based on the displayed speed limit. A fit is created only if there are 15 or more observations available for that speed limit. Fifteen observations correspond to 75 minutes of data.

The flow-occupancy plot for over critical occupancies with VSL would have shifted upwards from the no-VSL conditions if VSL were effective in improving traffic conditions. This shift was clearly observed at location D, but the opposite shift was observed at three locations (A, B, H). At locations C, E, F, and G, the best-fit plots of ‘No VSL’ and VSL speed limits intersected and therefore the shift was not consistent across the whole occupancy range.

Under VSL it is expected that the best-fit lines for a speed limit would be above the best-fit line of a lower speed limit. This trend is evident at location A where the 55 mph fit is above the 50 mph fit. Similarly at location B the 50 mph fit is above the 45 mph fit. The trend at location E was counterintuitive with the 40 mph fit being above the 45 mph fit. The trend at locations F and G were not consistent. For example, at location F the 50 mph fit is above both 45 mph and 40 mph but the 40 mph fit is above the 45 mph fit. Locations C, D, and H had only one speed limit best-fit line (since there were fewer than 15 observations for other speed limits) and therefore such trend analysis was not possible.

The counterintuitive trends at locations E, F and G were further investigated. Due to space constraints only location E is presented as an example. Figure 7 shows time-series plots of traffic speed and displayed speed limits for three weekday evening peak periods at Location E after VSL implementation. These plots are shown to illustrate instances when a higher speed limit was displayed for lower traffic speeds. On day 1 at 3:00 pm speed limit was lowered from 60 mph to 55 mph. The next available speed limit record shows that speed limit was reduced to 45 mph for a period of 20 minutes. The speed limit then dropped to 40 mph for the next 95 minutes. During this period traffic speed was consistently less than 40 mph including a 45-minute period when it was less than 20 mph.

On day 2, a speed limit of 45 mph was displayed for the whole congested period although the speeds dropped to 20 mph in many instances. The congested period lasted more than 2 hours and in that period for almost 2 hours traffic speed was less than 30 mph while speed limit was 45 mph. Congestion started around 3:00 pm at day 3. Speed limit was set to 45 mph for 90 minutes although the traffic speeds reached values below 20 mph. At 4:30 pm speed limit was changed to 40 mph when the traffic speed has dropped to 15 mph.

Thus there were instances where different speed limits were displayed for the same traffic speeds on different days. Such instances affected the best-fit lines for VSL speed limits at locations E, F, and G. For example, it was possible that the data for 45 mph consisted of more slow traffic observations (e.g., less than 30 mph) than the data for 40 mph and therefore the best-fit for 45 mph was below the 40 mph fit.
FIGURE 6  Flow-occupancy plots based on displayed speed limits
Another way of evaluating the flow-occupancy data is to quantify the number of congested observations (occupancies greater than critical occupancy) and to differentiate between before and after VSL implementation. Figure 8 shows the changes in the duration of congestion (daily) due to VSL. For each location, the dataset was normalized to obtain the same total (free flow and congested) sample size for before and after conditions. Figure 8 shows the number of congested observations increased at three locations A (+45 min), E (+30 min), F (+5 min), and decreased at five locations, locations B (-19 min), C (-71 min), D (-87 min), G (-2 min), and H (-17 min) after the VSL implementation. Thus the desirable decrease in daily congestion duration was observed at five of the eight locations. Although not investigated in this study the congestion duration reductions could have a positive impact on travel times, travel time reliability, and safety (e.g., reduction in secondary incidents).

In summary, the same inconsistent results appeared for congested flow durations as in the pre-breakdown and post-breakdown flows, shift in flow-occupancy plots and shift in best-fit speed limit lines. The Missouri DOT conducted an independent evaluation of the VSL system and found that the operational benefits obtained from the system were marginal and inconsistent (28). As a result, the regulatory VSL system was recently converted to an advisory system making it non-enforceable. In future research, additional data can be collected for the same locations during the same time of the year and the results compared with those obtained in the current study. The differences in advisory and regulatory VSL can then be documented.
CONCLUSIONS

This paper presented the results of an evaluation of VSL deployment on Interstate 270 in Missouri. This paper built upon previous VSL research and duplicated the use of piecewise parametric curve fitting as employed by others. In addition, techniques such as non-parametric methods and statistical tests were used to identify the traffic changes between before and after conditions. One traditional performance measure for various traffic flow applications is the capacity value. However, for applications such as VSL, the effect of traffic control affects a wide range of traffic conditions than just capacity. Traffic flow relationships such as flow-occupancy are useful for describing the range of traffic conditions that drivers experience on roadways. Therefore one significant contribution of this study is the application of two-dimensional statistical tests to traffic flow relationships. The Fasano and Franceschini implementation of the Pearson’s two-dimensional Kolmogorov-Smirnov test is an efficient method to test the goodness-of-fit for traffic flow relationships. This method was applied to study changes in traffic flow relationships due to the implementation of VSL.

The two-dimensional Kolmogorov-Smirnov test results indicated that flow-occupancy diagrams changed after implementation of VSL at seven out of eight locations. The slopes of flow-occupancy plots for over critical occupancies were found to be steeper after VSL. Slight changes in critical occupancy were observed after VSL implementation. However, the changes were inconsistent across locations with some witnessing an increase and others witnessing a decrease. The maximum flow prior to breakdown, pre-breakdown flow, decreased at four locations and increased at four locations after VSL. The maximum flow after breakdown, post-breakdown flow, decreased at three locations and increased at five locations after VSL. Location D witnessed the maximum observed increases in pre-breakdown flow and post-breakdown flow of 9% and 6%, respectively. The average daily duration of congestion decreased at five locations and increased at three locations after VSL.

Based on the findings of this paper, transportation agencies should be aware that depending on the implemented algorithm, VSL may not result in significant increases in maximum observed flows. The chosen VSL algorithm and the threshold values may not result in
efficiency improvements if that is the only motivation of the agency. The implemented algorithm does not consider individual lane speed and calculates the average speed over all lanes across a zone (two or three adjacent sensors). Assuming that congestion starts at one lane and then affects adjacent lanes, aggregating the speed and occupancy could possibly delay identification of congestion and thus negatively affect the performance. Unfortunately, the researchers could not make changes to the algorithm and were limited to evaluating the implemented algorithm as is. Safety evaluation of VSL was not within the scope of this paper. In the future, the impact of VSL on reducing primary and secondary incidents can be conducted to obtain safety benefits. Analysis of before-after crash data will also provide insights into the types of crashes that may be reduced due to VSL deployment.

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REFERENCES


