Evaluation of Variable Speed Limits on I-270/I-255 in St. Louis

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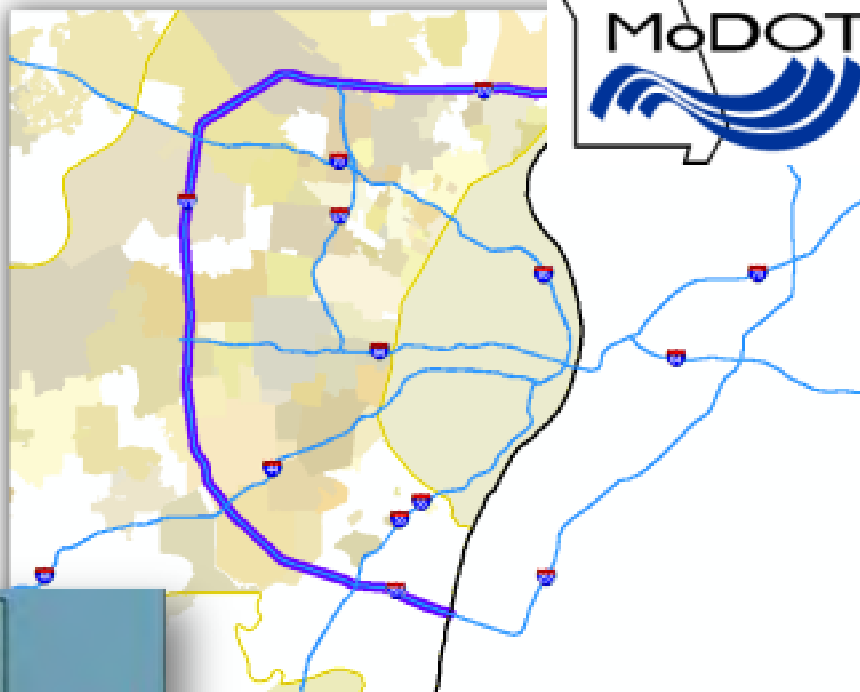

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Evaluation of Variable Speed Limits on I-270/I-255 in St. Louis

Prepared for
Missouri Department of Transportation
Organizational Results

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16. Abstract In May of 2008, MoDOT installed a "Variable Speed Limit" (VSL) system along the I-270/I-255 corridor in St. Louis. This project evaluated the VSL system and its potential impacts and benefits to the transportation users. The technical system evaluation focused on three areas - mobility, safety, and public and police perceptions. The VSL is not performing as desired in terms of improvements to overall mobility along the corridor, but is providing limited benefits to some segments. Noticeable benefits have been seen with respect to reduction in the number of crashes during the evaluation period. The driving public and law enforcement are widely dissatisfied with the VSL system based on their perceptions of benefits to congestion relief, compliance with posted speed limits, and overall visibility of the current sign configuration.		
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EXECUTIVE SUMMARY

Missouri Department of Transportation (MoDOT) installed signs with changeable speed limits in May of 2008. These “Variable Speed Limit” (VSL) signs were installed on the Missouri side of the I-270/I-255 loop around St. Louis. During rush hours and traffic incidents, an automated system with manual overrides, set speed limits in various increments between a low of 40 mph and a high of 60 mph. Speeds were limited in the areas of congestion to encourage consistent speeds within lanes (closing speeds) and speeds between lanes (passing speeds). Speeds were limited upstream of congestion to meter traffic and to reduce closing speed of incoming traffic. The objective of VSL was to improve traffic flow in order to prevent traffic flow breakdown, reduce congestion and delay, and improve safety.

This project evaluated the VSL system performance and its potential benefits to users and MoDOT. The performance evaluation determined the effects of the VSL system on congestion and delay. Changes in travel time, travel time reliability, and capacity were also investigated. Changes in the severity and number of crashes were studied as well. Stakeholder perception data, defined as perceptions of the general driving public and law enforcement agencies, was used to frame the technical results from the perspective of customer satisfaction.

Mobility

The VSL system mobility evaluation used two forms of analysis to best understand the VSL system. Uncontrolled data analysis evaluated data reflecting conditions faced by drivers during weekdays of interest (Tuesdays, Wednesdays and Thursdays) irrespective of any incidents or weather conditions. This analysis examined the VSL effectiveness under real-world conditions. Controlled analysis looked only at days without incidents or weather conditions to better understand VSL operations under comparable pre- and post-VSL traffic flow conditions. That analysis provides guidance in refinement of the system. The uncontrolled and controlled analyses were carried out for four selected segments during peak periods on I-270.

Segment 1 is I-270 southbound approaching Manchester Road. Segment 2 is I-270 northbound approaching I-44. Uncontrolled analysis indicated a 10% higher average volume in post-VSL conditions compared to pre-VSL conditions, indicating benefits in terms of higher traffic volume. When higher volume was observed during post-VSL conditions, congestion did not worsen. Controlled analysis indicated reduction in traffic congestion, indicating VSL system benefits for segment 1. For those segments compared for pre- and post-VSL conditions, when volume was similar, congestion was reduced. The data observed indicates the potential for further refinement of the VSL system and with drivers’ compliance of the posted speed limit, the benefits of the system can be much higher.

Segments 3 is I-270 eastbound and Segment 4 is I-270 westbound both approaching I-170. From both uncontrolled and controlled analysis, the VSL system was found to be effective in reducing duration of peak periods and improving average speeds. Though these improvements were marginal, further improvement can be made in order to increase the benefits of the system.

Additional results and recommendations from the controlled analysis include:

1. Improved operational efficiency of the system with refinement in initiation of the variable speed limits specific to each location's anticipated flow rate,
2. Use of optimal number of detectors versus fixed number of detectors in zones defined by the VSL system.
3. Lack of driver compliance with posted limits resulted in congestion downstream.
4. Several detectors on the segments evaluated were not functional. For improved system performance, the faulty detectors should be fixed.

Safety

Effects of the VSL system on safety were evaluated based on crash numbers and crash rates (number of crashes over traffic volume). Assessment included annual and hourly crashes for highways in general and specific segments, which required determining traffic volumes. To verify the results, two different analysis methods, Naïve and Empirical Bayesian (EB) were used. EB is commonly used for crash prediction and analysis.

The level of crash reduction varied slightly between the two different statistical methods; however, the results consistently indicated the VSL system has contributed to crash reduction. The predicted level of crash reduction ranged from 4.5-8% with a standard deviation of 3-4%. Crashes are down, and based on crash rates, I-270 is the safest major roadway in St. Louis region as shown in Figure 1.

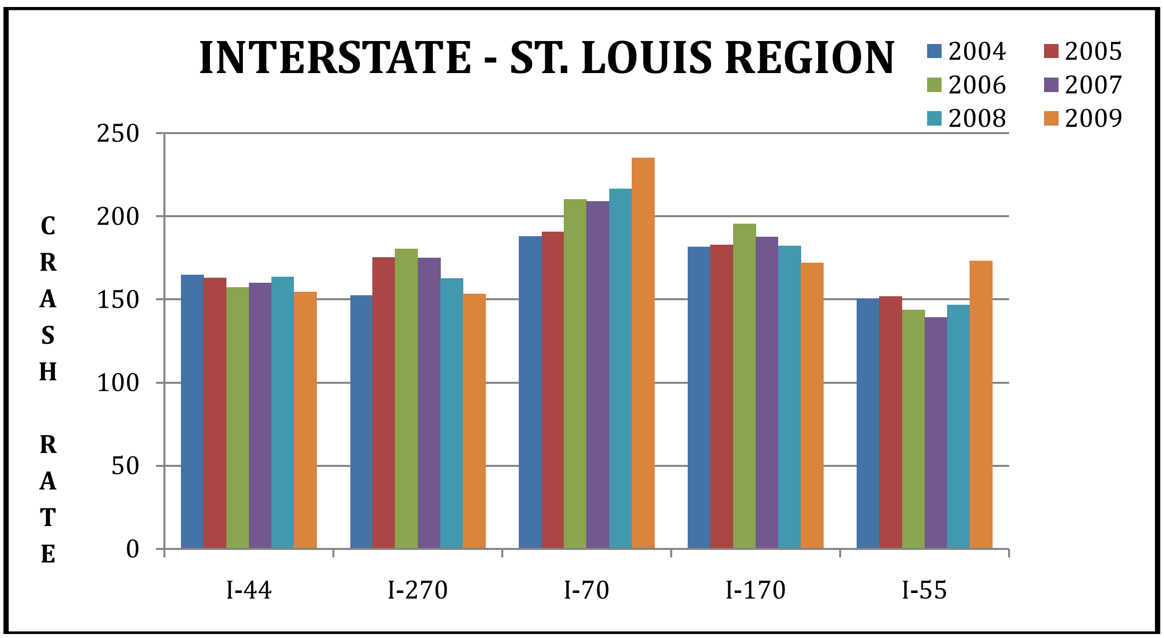


Figure 1. St. Louis Area Highway Crash Rates

Initial crash results are promising; however, they need to be validated over the next few years to ensure that long-term benefits are sustainable. Crash reductions resulting from the VSL system might be attributed to two major factors:

1. More homogenous traffic speed (i.e., smaller speed variance) reduces the chance of rear-end or passing type of crashes (represents 66% of the crashes reported on I-270),
2. Slowing of the traffic speed (metering traffic flow) upstream of crashes or other incidents might improve drivers' awareness and attention; this may reduce potential crashes and secondary crashes.

Public and Law Enforcement Opinions

Respondent input was obtained via an online survey for the general public made available through a link at the MoDOT VSL homepage. In addition, a paper survey was distributed to 15 law enforcement units with responsibility for patrolling the I-270/I-255 corridor around St. Louis. Online survey responses totaled 1030 and law enforcement responses totaled 355 as shown in Figure 2. Survey results show that both the general public and law enforcement

- Are overwhelmingly aware of the VSL project
- Have a high level of dissatisfaction with the system
- Have serious reservations regarding its effectiveness.

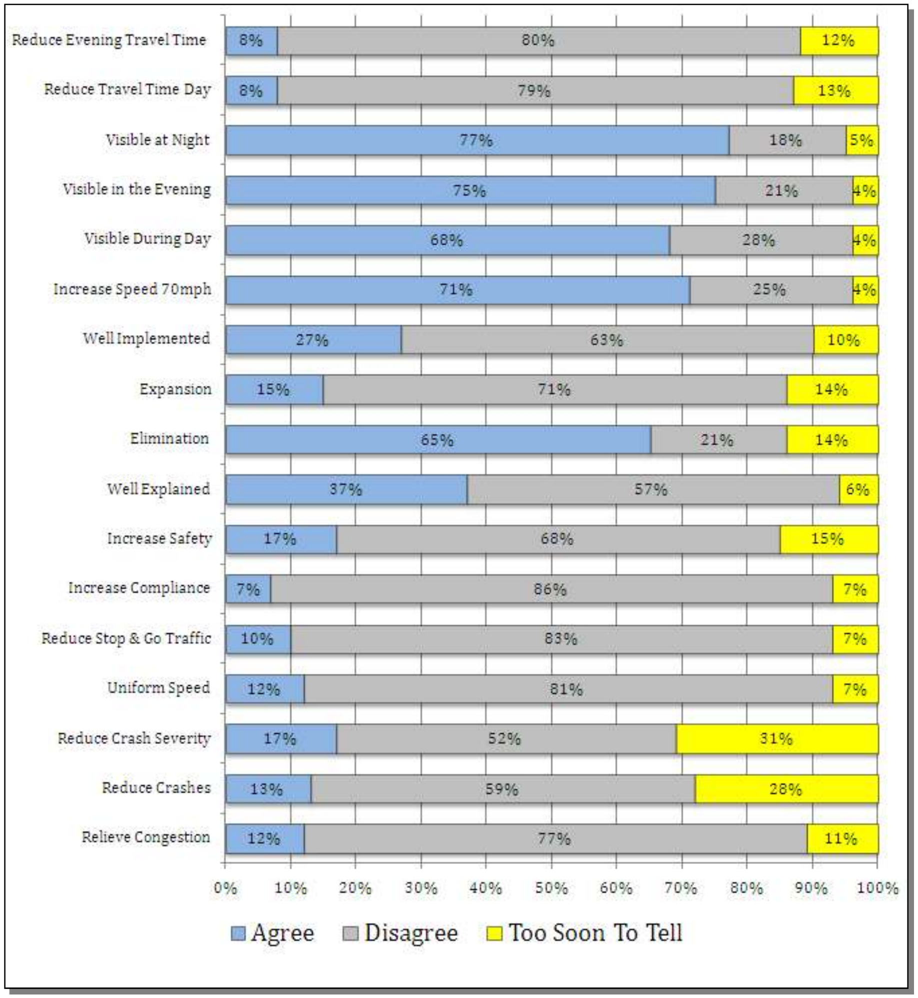
Conclusions and Recommendations

The VSL system did not perform as desired in terms of improvements to overall mobility along the corridor, but provided limited benefits to segments evaluated using select criteria. Noticeable benefits were observed with respect to reduction in the number of crashes during the study period. This reduction is below safety improvements seen with VSL implementations in Europe, but at a statistically significant level. The driving public and law enforcement are widely dissatisfied with the VSL system based on their perceptions of benefits to congestion relief, compliance with posted speed limits, and overall visibility of the current sign. However, perceptions indicated that stakeholders are unsure whether the VSL was useful in the reduction of the number or severity of crashes. This provides an opportunity for greater explanation and engagement of the public and law enforcement by MoDOT.

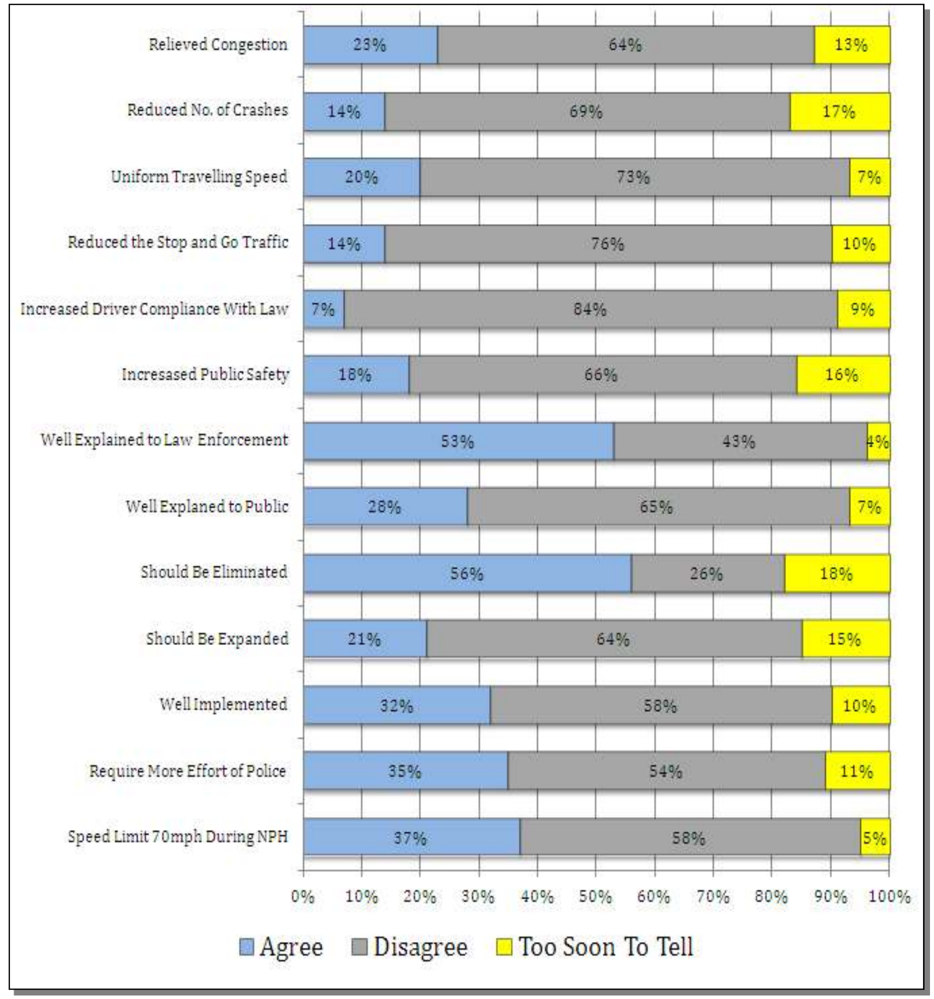
Based on the study results, we recommend the following:

1. Refine VSL system operation to increase the benefits by:
   a. Improving public understanding through more educational efforts.
   b. Improving operation by modifying current settings and evaluating the results to find the optimal settings.
   c. Identify and evaluate ways to improve the system beyond changes in settings.
   d. Collaborate with law enforcement to find positive ways to encourage respect for speed limits.
2. Conduct a cost-benefit study to determine if benefits (and expected benefits from improvements) are worth continued operation, expansion, or contraction of the VSL system.
3. Conduct a study to determine the conditions where VSL is effective and thus a candidate to improve other roadways in Missouri.

Online Survey Response Year 1 and 2 Combined



Law Enforcement Assessment Year 1 and 2 Combined



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1.0 METHODOLOGY

The VSL system was investigated across three elements (mobility, safety, and stakeholder perceptions). Mobility was measured using two different methods. Uncontrolled analysis examined conditions faced by commuters during peak hours irrespective of weather or incident during the heaviest travel days (Tuesday through Thursday). Controlled analysis examined both pre- and post-VSL operations during comparable conditions, without inclement weather or incidents. Additionally, actual field GPS travel time runs were conducted and compared against VSL system's data input. Safety was examined using two statistical techniques, Naive and Empirical Bayesian. Stakeholder perceptions, considered the general public and law enforcement officers for this study, were measured using survey questionnaires for each group. The public provided responses through an online survey. Law enforcement responded through two paper surveys. The detailed methodology used in the project is provided in the appendix.

2.0 RESULTS AND FINDINGS

MOBILITY

Introduction

The mobility report summarizes the findings from the evaluation of four selected segments on I-270/I-255 during peak periods. Table M1 lists and Figure M1 presents the selected segments. The evaluation presents the effects of VSL system on change in traffic volume, occupancy, average speed, travel time, travel time reliability, delay, queue measurements, and user cost. The posted speed limit on I-270 is 60 mph, and varies between 40 mph (lowest) and 60 mph (highest) based on the zones established by MoDOT to operate the system and are presented in Table M1 for the four segments. The data collected from the detectors in the listed zones were used in initiating the VSL signs. The researchers defined the segments very similar to the zones defined by MoDOT.

Table M1. Segments Evaluated

Segments	Zone	Direction	On I-270 Between	Peak Period
1	C	SB	I-64 and Route 100	3:00 - 7:00 PM
2	B	NB	Route 30 and I-44	5:30 - 9:30 AM
3	E	EB	Route 370 and I-170	3:00 - 7:00 PM
4	F	WB	Route 367 and I-170	6:00 - 10:00 AM

The main objective of the VSL system is to reduce congestion, delay and thereby user cost. The VSL system prevents congestion by metering traffic flow in near real time. Traffic metering is regulating traffic flow upstream of bottlenecks (congested segments) to prevent traffic from breaking down. Traffic flow can be prevented from reaching the point of breakdown by slowing vehicles down in order to reduce the flow of traffic from reaching its capacity. Once traffic flow reaches its capacity value, break down in traffic flow is expected.

For evaluation of the VSL system, uncontrolled and controlled analyses were carried out by comparing peak period data for pre- and post-VSL conditions. Uncontrolled analysis consisted of a couple of months of aggregate data with weekdays analyzed with the heaviest traffic volume i.e., Tuesdays, Wednesdays and Thursdays irrespective of any incidents, events or weather conditions. The uncontrolled analysis was carried out to determine the effects of the VSL system implementation. Controlled analysis consisted of several days of data with similar volumes, clear weather conditions and no incidents. Controlled analysis was carried out to suggest improvements to the system.

Figure M1. Segments evaluated on I-270

The VSL system evaluation was mainly based on measures commonly used in transportation engineering and science. These measures are traffic volume, occupancy, average speed, travel time, travel time based reliability indices, and queue measurements.

- Traffic volume presents the count of vehicles passing a point on the highway. Traffic volume can also be expressed in terms of flow.
- The maximum observed traffic flow was used to identify highway capacity.
- Occupancy is the time a short section of highway is occupied. Higher occupancy indicates a highway section occupied for longer periods of time indicating that the

vehicle speeds were lower and traffic density was higher keeping the detector occupied. When higher occupancy is observed over time, it indicates congested state of traffic. When occupancy is low it indicates lower traffic volume, higher vehicle speeds and lower value of traffic density indicating uncongested state of traffic.

- Critical occupancy is defined as the occupancy at which highest flow (volume) is observed.
- Travel times were calculated based on distance between detectors, average speed and traffic volumes retrieved from these detectors.
- If there is a reduction in travel time reliability indices for post-VSL conditions when compared with pre-VSL conditions then it indicates less variability i.e., improved reliability and more consistency between travel time for the peak period (worst condition) and travel time based on the posted speed limit. Travel time reliability was evaluated using three indices
    - Travel Time Index (TTI). TTI is a dimensionless quantity that compares travel times during the peak period to travel times based on the posted speed limit (PSL).
    - Buffer Time Index (BTI) also called Buffer Index (BI), expresses the additional time needed to arrive on-time for 95% of the trips.
    - Planning Time Index (PTI). PTI represents the total travel time that should be planned with an adequate buffer time i.e., it includes BTI. Thus, the PTI compares peak hour travel time (worst case) to travel time based on the posted speed limit.

Further, Total Delay, Percent of Congested Travel, duration (in time), extent (in length) and intensity (average speeds) of traffic congestion were used as measures to quantify traffic congestion.

- Total Delay (in minutes) for a roadway segment is determined as the sum of time lost due to congestion.
- The Percent of Congested Travel is an extension of the congested travel measure. It also measures the extent of congestion and is computed as the ratio of delay (minutes) to the total travel time (minutes). More detailed discussion on calculating these measures can be found under Methodology and the detailed results are presented in the appendices.

VSL system evaluation was carried out using archived traffic data (volume, speed and occupancy) for each lane using pre- and post-VSL initiation. Pre-VSL data was only available because MoDOT had previously installed a new data collection system. Since the system was new, it had some start-up problems. Thus, some data were missing.

Aggregate data for every 1- and 5-minutes were used in the analysis. Traffic data from pre- and post-VSL conditions were compared to evaluate the system and observe any changes in the state of traffic. To study the effect of volume, volume over time (profiles) were plotted for different dates and lanes and the differences were recorded. The changes in traffic volume were studied to discern its effect on average speed, travel time, congestion measures, etc. Traffic volume (or flow) versus occupancy were plotted for analysis of critical occupancy.

Mean and standard deviation of speeds were also calculated for each lane. Additionally, differences in speeds across lanes were analyzed statistically. The mean speeds were averaged for peak periods and compared for pre- and post-VSL conditions along the highway. Average volumes were also plotted with the mean speeds to compare them along the highway. Highway capacity between pre- and post-VSL conditions was also compared. VSL system meters traffic and prevents traffic flow from reaching capacity. At capacity, traffic flow breaks down and traffic flow is reduced appreciably causing traffic congestion.

From the controlled analysis, initiation and recovery of variable posted speed limits were evaluated. This was carried out to recommend any improvements required to refine the system. During this analysis, driver compliance with the posted speed limit during the peak period was determined. Drivers driving at posted speed limit plus 5-mph were considered complying with the speed limit. The percent of drivers that complied with the posted speed limit were calculated. The average speeds, occupancy and traffic count corresponding to the peak period were analyzed. Average speeds indicating congested conditions were not included in compliance calculations, as this indicated congested state of traffic and average speeds were lower as a result of congestion instead of complying with the posted speed limit.

Cost analysis was conducted for both uncontrolled and controlled analysis to quantify the benefits of the VSL system for the peak periods. For cost analysis, travel time savings were calculated for cars and trucks. The median value of travel time associated with user cost was used in the analysis. For heavy vehicles, the median value was $43.88/hour/vehicle and for passenger cars it was $22.36/hour/vehicle. From the MoDOT Annual Average Daily Traffic Count Maps data, the proportion of heavy vehicles in traffic was found to be 11.45%. A single multiplication factor of travel time savings for cost estimation was found to be $24.82/hour/vehicle [(0.1145*$43.88) + (0.8855*$22.36)]. This value was used for both pre- and post-VSL time period to produce directly comparable costs, presuming no economic changes other than congestion. The cost savings is a function of the length of the segment, average speed, traffic volume and number of lanes.

The VSL system operation of using traffic data from detectors (placed approximately 1 mile apart), then assessing detectors as a group in a zone together to determine the posted speed limit is important in terms of evaluating mobility. To evaluate if traffic data from multiple detectors grouped reflect actual travel times, travel times on I-270 were collected with a GPS device over a two-week period. The runs were then evaluated against the traffic data collected from segments that contained 2 to 4 detectors on the roadway.

Results

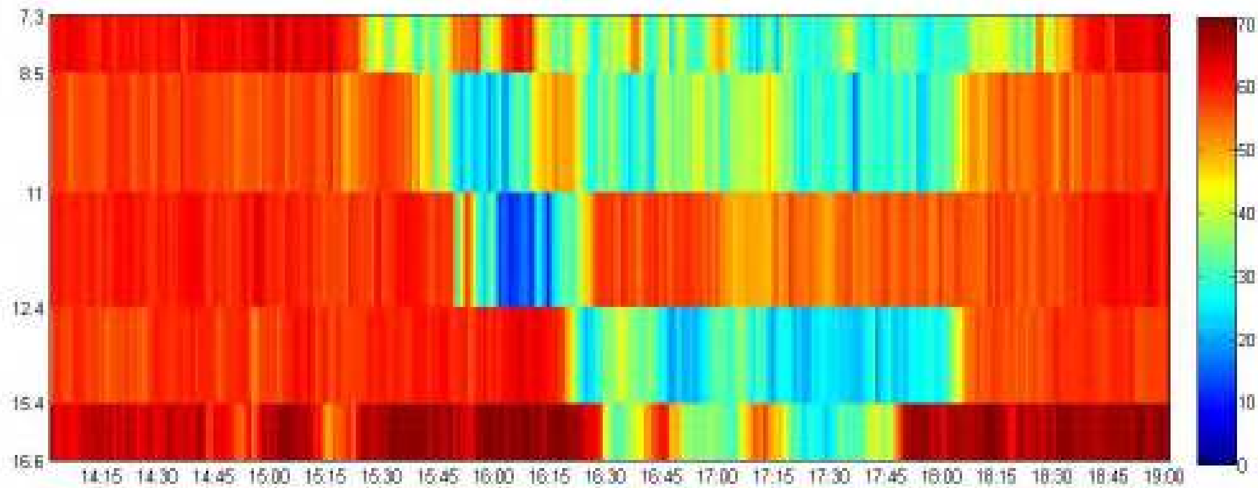
Segment 1

Segment 1 is I-270 southbound approaching Route 100 interchange, and congestion can be observed during the evening peak period. The uncontrolled data analysis conducted for 72 days of data found higher traffic flow by an average of 10% for post-VSL conditions. Average speeds improved by 2 mph. No reduction in peak periods was observed. The average travel time increased by 3.1% and the travel time reliability indices TTI, BTI, and PTI increased 0.25, 11.5, and 1.7%, respectively, which meant the VSL system was neither beneficial in decreasing the travel time nor improving the travel time reliability for this segment. Comparison of critical occupancy and highway capacity indicated no significant change for post-VSL conditions. Therefore, as a result of higher volume other benefits were not observed.

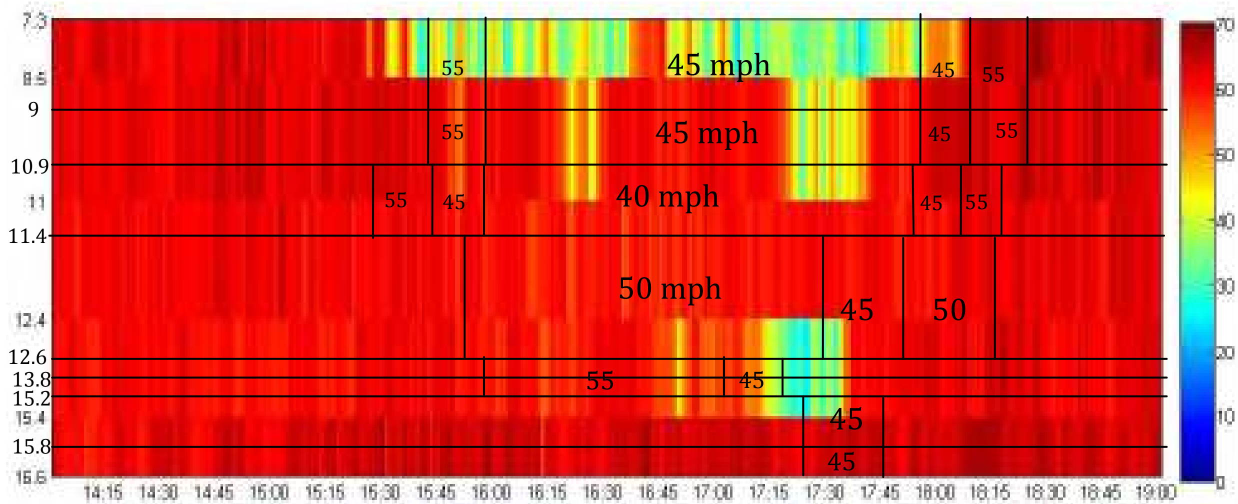
For the controlled analysis, ten days of data for peak periods were analyzed during which pre- and post-VSL volume were similar and traffic conditions were comparable. It was found that peak periods reduced by 30 minutes, average speeds improved by 7.5 mph, and variation in average speeds reduced by 2.3 mph. during post-VSL conditions. Comparison of percent critical occupancy for pre- and post-VSL conditions did not indicate major change; however, average occupancy reduced by 3%. Highway capacity comparison indicated a 100 vph increase during post-VSL conditions. It was also observed that when traffic volume exceeds a certain value, it was not possible to further meter traffic. Further research should investigate this finding to determine the limiting volume.

From controlled analysis, average driver compliance found using five days of data during peak periods at three measurement locations along the segment (detectors 8D, 11D, and 12D at log miles 8.5, 11.0, and 12.4, respectively) were 64, 58 and 40% and the highest average compliance rate of five days was observed for lane 3 with 69%. Travel time reduced by 23.7% in post-VSL conditions and TTI, BTI, and PTI decreased by 24.3, 22.4, and 31.4%, respectively, indicating the VSL system was beneficial in decreasing the travel time and improving the travel time reliability.

Further controlled analysis indicated travel delay decreased by 2.4 minutes and percentage of congested travel decreased by 16% determined using data from five detectors along the segment for post-VSL conditions. Congestion duration, extent and intensity also reduced for post-VSL conditions which can be observed from Figure M2. The time-space plots, presented in Figure M2 compares pre- and post-VSL conditions for the 4th Thursday in October. For additional days analyzed, the reader is referred to the appendix. The results present the average speed at 1-minute time intervals along the highway detectors over time. Mile markers (logmiles) for detectors are presented on the y-axis. The interval indicates the distance between two adjacent detectors and the average speed (mph) indicates the mean speed at the previous detector while travelling downstream (logmiles decreased downstream). The legend (extreme right) indicates the different colors which represent different values of speed on the segment. As a result, the x-axis indicates the queue duration (time) and y-axis indicates the extent (length) of the queue. The queue intensity can be qualitatively observed by the difference in the shades of color. The darker blue shade indicates higher intensity of congestion (lowest speeds). Also, the posted variable speed limits along the highway are also indicated. It should be noted that the posted speed limit on the highway is 60 mph, and it varies between 40 and 60 mph.



a) Pre-VSL data (25th Oct 07)



b) Post-VSL data (23rd Oct 08)

Figure M2. Time space plot for Segment 1

From Figure M2 the duration, extent and intensity of congestion can be quantified. During post-VSL, the duration of congestion reduced appreciably upstream of detector at logmile 8.5. For detectors between logmile 11 and 8.5, the duration of congested state of traffic was reduced approximately from 110 minutes (pre-VSL, 16:00-17:50) to 25 minutes (post–VSL, 17:30-17:55). Similarly, for logmiles from 8.5 to 7.3, the duration reduced by 45 minutes (pre-VSL, 15:40-18:40) and (post-VSL, 15:45-18:00) which indicates improvement in the state of traffic.

In terms of the queue extent (length), it decreased from 9.3 miles (logmile 16.6 to 7.3) for pre-VSL to 3.3 miles (logmile 11 to 7.3) for post-VSL conditions. For pre-VSL conditions, Figure M2 (a) clearly indicates the propagation of congestion upstream as average speeds are lower, starting from detector at logmile 7.3 to 16.6 over time. The pre-VSL conditions indicate that congestion started around 15:30 between logmiles 8.5 to 7.3 and propagated upstream to logmile 11 by 15:50, and further to logmile 12.4 by 16:05. This trend continued upstream and reached logmile 15.4 around 16:20 and further to logmile 16.6 by 16:30. In contrast, for post-VSL conditions it was found that the extent of congestion was considerably shorter. Lower speeds were observed at 15:45 between logmiles 8.5 and 7.3 but congestion did not propagate upstream till 16:15, and the recovery was quick. Lower speeds were observed second time (still higher compared to pre-VSL conditions) between 17:30 to 17:55. No congestion was observed between logmiles 11 and 12.4, however between logmiles 15.4 and 12.4, congestion was observed for 25 minutes. No congestion was observed upstream of logmile 15.4. Comparing the two plots significant reduction in congestion was observed for post-VSL conditions.

In terms of intensity of congestion, the pre-VSL condition also indicated lower values of speed compared to post-VSL conditions. The post-VSL plot shows fewer yellow and blue patches. Additionally, no dark blue patches can be observed. Hence, congestion intensity reduced considerably in post-VSL conditions.

For post-VSL, Figure M2 shows that extent and intensity of congestion reduced, but in case the initiation of variable speeds were delayed (Figure S2.13.1-2 in the appendix), it was observed that recovery took much longer once the segment got congested. This indicates that the VSL system logic can be modified for the system to initiate in near real time with step wise (gradual) decrease and recovery of posted VSL to reduce congestion. It was also observed that when the system was initiated at the same time as average observed speeds reduced, the speeds recovered promptly. The timely logic of initiating the VSL system, therefore, will improve traffic flow and reduce congestion.

For this segment, the detector at logmile 11 was found to be critical since the VSL initiation and posted speeds followed average speeds of this detector very closely. Since the initiation was based on average of traffic data for zones as indicated in Table M1, delay in initiation of VSL signs were also observed on this segment. Hence, initiation based on an individual detector upstream will prevent such lags.

The average cost savings for this segment as a result of reduced delay due to post-VSL conditions were calculated for the five days analyzed. The results of average cost savings represent 250 work days during the peak periods. The difference in travel delay during pre- and post-VSL conditions for this segment was 2.4 minutes. The delay computed (in person minutes) equaled 2,787 person-minutes for 8.1 miles of the highway for pre- and post-VSL conditions. The delay calculated was based on data obtained from detectors at mile-markers 16.4 to 8.5. The annual average cost saving as a result was estimated to be $288,185 (for details please refer to Table S1.16.8, page 158 in the appendix) and $35,578/mile of travel. The per mile calculation was to compare the four segments with respect to one measure of effectiveness. The results indicate benefits of the VSL system installation for segment 1.

Summary of Results for Segment 1

From the analysis of results, it can be inferred that the VSL system was found to be beneficial at this segment when the traffic volumes can be metered upstream of congested sections such as near Olive Boulevard (logmile 8D). In general, traffic flow was higher and VSL system either had little effect on other variables when average volume was higher by 10% or prevented congestion when average volume was similar to pre-VSL conditions. In particular cases, where traffic volumes were the same, congestion reduced significantly. If VSL compliance and settings were effective on all working days, annual average cost saving would be nearly $300,000 per year at this location.

<u>Segment 2</u>

Segment 2 is I-270 northbound approaching the I-44 interchange, and congested conditions are observed during the morning peak period. The data analyzed for uncontrolled analysis found traffic flow higher by an average of 9% for post-VSL conditions. Average speed was lower by 4 mph but travel times were higher by 13.6%, and percent of congested travel was higher by 9.7%. The travel time reliability indices TTI, BTI, and PTI on average were higher by 17, 20, and 17.7%, respectively, which indicated the travel times during post-VSL conditions were less reliable than pre-VSL conditions. In addition, travel delay increased slightly and peak period remained unchanged. The VSL system, therefore, did not indicate benefits for particular measures of performance as a result of higher volume compared to pre-VSL conditions.

Controlled analysis was conducted using 10 days of data. The VSL system initiation was observed to have a lag time of 15 minutes on average. Similarly, VSL speed recovery i.e., from 45 to 60 mph was observed to be delayed by 40 minutes on average. This lag in changing the speed limit may be attributed to use of fewer detector data for this segment as post-VSL data for detector logmile 1.8, 2.4, 4.7 and 7.3 were not available. During these lag times, traffic broke down and congested conditions were observed from detectors at logmile 3.6 and 5.7. In addition, the posted speed limit was dropped from 60 to 45 mph, but was not further reduced to 40 mph. The reasons behind this are not clear. From the detector data observed, it was felt that further reducing the posted variable speed limit to 40 mph may improve the system efficiency. As a result of insufficient detector data, a critical detector such as one in segment 1 could not be identified.

For controlled analysis, average speed for post-VSL conditions increased by 1.23 mph and speed variability decreased by 0.6 mph. Peak periods reduced by 20 minutes. For post-VSL conditions, significant changes were not observed for critical occupancy and highway capacity when compared to pre-VSL conditions. Mixed results were observed for congestion measures; average travel time increased by 11.7% but travel time reliability indices TTI, BTI, and PTI decreased by 0.4, 13.1, and 3%, respectively for post-VSL conditions, which indicate the VSL system improved travel time reliability. Average driver compliance rates examined during peak period at different detectors were 69, 68, and 92% and maximum average of five day compliance rate was observed for lane 2 (lane closest to the median lane) at 80%. Queue measurements could not be carried out for this segment due to detector data issues as mentioned above. Delay increased by 12.39 person-minutes. The segment 2 length was 2.1 miles. This delay was also caused by an increase in volume of 4%. Due to increase in delay for post-VSL conditions, this resulted in no cost savings for segment 2.

On the days selected for controlled analysis, the VSL system initiation logic was found to lower speeds from 60 mph to 45 mph, and when the average speeds fell below 20 mph, the minimum posted speed was 45 mph. Further lowering of the posted speed limits to 40 mph will provide additional benefits to the system. Additionally, the lowering and recovering of speeds should be gradual over time and space from 5 to 10 mph rather than lowering and raising speeds by 15 mph. The gradual reduction is suggested to minimize the formation of shock waves in traffic, a phenomenon that commonly exists in traffic flow.

Summary of Results for Segment 2

VSL system was found to be ineffective on segment 2 because of several possible reasons. The main ones are: first, for the initiation of the VSL system, a critical detector could not be located for this segment. Second, the speed limits were lowered to a minimum of 45 mph but the average speeds reduced to below 20 mph as observed during controlled analysis. A more in-depth analysis of the segment should be performed to propose improvements to the VSL initiation logic and to allow system improvements over this segment.

<u>Segment 3</u>

Segment 3 is I-270 eastbound, approaching the I-170 interchange and is mainly congested during the morning peak period. Uncontrolled analysis indicated higher traffic flow by 3%, higher average speeds by 5 mph, reduction in average occupancy by 10% and average peak period reduction of 15 minutes for post-VSL conditions. Travel time reduced by 5.6% and the travel time reliability indices TTI, BTI, and PTI decreased by 8.6, 14.8, and 10.1%, respectively, which means the VSL system was beneficial as the travel time decreased and the travel time reliability improved for this segment. Travel delay decreased by 0.27 minutes and percent of congested travel reduced by 5.3%. Critical occupancy and highway capacity remained unchanged for both conditions. Overall, these results indicate appreciable improvement in traffic conditions for post-VSL conditions.

Controlled analysis carried out for 10 days indicated improvement in post-VSL average speed of 10 mph, higher variation of 2 mph than the pre-VSL average speeds, and peak period reduction by 45 minutes. Average occupancy indicated a reduction of 15% but critical occupancy remained unchanged. For post-VSL conditions, during the peak periods the average speed reduced gradually and the peak period reduced noticeably. Travel time reduced by 27.4% on average and the travel time reliability indices TTI, BTI, and PTI decreased appreciably by 34.3, 50, and 37.4%, respectively, which means the VSL system was beneficial in decreasing the travel time and improving the travel time reliability for this segment. Average driver compliance rates during peak period at detector logmile 21.4 and 25.1 were 46 and 84%, respectively, and the highest average of five days compliance rate was observed for lane 3 with 71%. Results for Travel delay and percentage of congested travel indicated decrease in delay by 2.0 minutes and congested travel conditions by 29% after VSL system installation. The queue duration, extent and intensity on the segment could not be calculated due to insufficient detector data.

From the controlled analysis, it was found that timely activation of the VSL system reduced the congestion and average speed improved, but when the initiation was delayed, recovery took longer and the segment got congested.

The average cost savings resulted from decrease in delay of 48.1 person-minutes for 3.7 miles of segment length due to post-VSL conditions. This delay was based on four days of data. The average cost savings was applied to 250 working days with peak periods. The annual average cost saving at this segment was estimated to be $4,975 (for details please refer to Table S3.16.6, page 216 in the appendix) and $1,345/mile.

Summary of Results for Segment 3

In summary, the results of data analysis indicated that the VSL system was beneficial for this segment. Comparison of average volume for post-VSL conditions indicated a 3% increase and the measures of performance indicated system benefits for this segment. Segment 3, therefore, indicated benefits in spite of increase in traffic volume.

<u>Segment 4</u>

Segment 4 is I-270 westbound, approaching the I-170 interchange during the evening peak period. Uncontrolled analysis indicated that volume observed was 1% lower in post VSL conditions. Average speeds were observed to be higher by 5 mph and peak periods reduced by 30 minutes. From the flow-occupancy analysis, significant changes were not observed in critical occupancy and highway capacity for pre- and post-VSL comparison. Congestion measures calculated for this segment indicated reduction in average travel time by 19.1%, and the travel time reliability indices TTI and PTI decreased by 10.5 and 7.2%, respectively, but BTI increased 4.1%, which means the VSL system was beneficial in decreasing the travel time and improving the travel time reliability for this segment. Travel delay reduced by 0.41 minutes and percent of congested travel by 9%. The uncontrolled analysis indicated that the VSL system was beneficial for segment 4.

The controlled data analysis was carried out for 10 days. The analysis indicated 10 mph improvement in average speed, 10% in occupancy and 45 minutes reduction in peak periods. Speed variability reduced by 1.2 mph. No change in critical occupancy was observed, however, highest volume observed was lower by 100 vph. The average travel time decreased by 13.4% and the travel time reliability indices TTI, BTI, and PTI decreased 18.4, 12.5, and 16.9%, respectively, which means the VSL system was beneficial in decreasing the travel time and improving the travel time reliability for this segment. Average driver compliance rates during peak period at detectors logmile 28.6, 30.3, and

31.6 were 70, 65, and 82%, respectively, and lane 3 with average of five days compliance rate 92% had the highest compliance rate. Travel delay indicated a decrease of 0.14 minutes along with a decrease of 12% in percent of congested travel. Delay decreased by 13.4 people-minutes for segment length of 3 miles. The queue duration, extent and intensity could not be carried out for this segment due to insufficient detector data. The annual average cost savings at this segment was estimated to be $1386 (for details please to Table S4.16.6, page 242 in the appendix) and $462/mile.

Summary of Results for Segment 4

VSL system was found to be beneficial for this segment. Average speeds improved, peak periods decreased and travel time reduced. The congestion measures also indicated improvements along the segment. Volume comparison indicated 1% reduction for uncontrolled analysis.

Roadway Segment VSL Operation

Traffic flow conditions when free flow to minor traffic congestion existed, the actual field GPS travel runs and detector traffic data produced similar results for travel times and average speeds. When traffic congestion started to form, the field GPS travel runs indicated a greater reduction in average speeds and an increase in travel times than the detectors' traffic data. These factors are explained by the fact that field GPS travel runs produce more data collection points on the roadway segment than the detectors spaced approximately one mile or more apart. The field GPS travel runs are a better representation of traffic conditions along the roadway segment and detect sooner the formation of traffic congestion.

Overall Summary of Results for all Segments

Summary of results is presented in Tables M2 and M3 by segments and types of analysis. Uncontrolled analysis of segments 1 and 2 indicated a 10% higher average volume in post-VSL conditions, which indicated VSL system benefits in terms of traffic volume for the segment examined. Controlled analysis indicated VSL system benefits and reduction in traffic congestion. From these results, it can be concluded that for segments 1 and 2, the VSL system benefits in terms of accommodating higher volume. Analysis of segments 3 and 4 indicated that the VSL system was effective in reducing peak periods and improving average speeds. Though the improvements were marginal, there is room for further improvement in order to increase the benefits of the system. An important finding from this project is that a delay in initiation of the VSLs caused recovery from congestion to require longer time. However, the initiation procedure improved over time and it is recommended to use individual/optimal number of detector data for system initiation instead of varying speed limits as a result of average results from detectors in a zone. Average speeds from detectors in a zone did not provide an accurate estimate of average speed. For the system to be beneficial, it is imperative for it to be well programmed for the specifics of each location's anticipated peak flow.

Table M2. Summary of Results for Uncontrolled Analysis

Segments /Measures	Average Volume Change	Average Occupancy Change	Speed: Average Speed Change	Speed: Peak Period Duration Change	Highway Capacity Change	Congestion Measures: Travel Time Change~	Congestion Measures: Travel Time Reliability Indices Change	Congestion Measures: Travel Delay Change^	Congestion Measures: Percent of Congested Travel Change^
	percent	percent	mph	min	vph	percent	percent	min	percent
Segment 1	10	3	2	0	No change	3.1	0.25 to 11.5	-0.09	-3
Segment 2	9	2	-4	0	No change	13.6	17 to 20.0	0.25	9.7
Segment 3	3	-10	5	-15	No change	-5.6	-8.6 to -14.8	-0.27	-5.3
Segment 4	-1	-15	5	-30	No change	-19.1	-7.2 to -10.5**	-0.41	-9

Table M3. Summary of Results for Controlled Analysis

Segments /Measures	Avg. Vol. Change	Avg. Occup. Change	Speed: Avg. Spd. Change	Speed: Peak Period Change	Speed: Std. Dev. Change	Init. Delay*	Driver Comp.#	Highway Capacity Change	Congestion Measures: Travel Time Change~	Congestion Measures: Travel Time Reliability Indices Change	Congestion Measures: Travel Delay Change^	Congestion Measures: Percent of Congested Travel Change^
	percent	percent	mph	min	mph	min	percent	vph	percent	percent	min	percent
Segment 1	0.60	-4	7	-30	-2.3	15	54	100	-23.7	-22.4 to -31.4	-2.4	-18
Segment 2	4.0	-4	1.23	-20	-0.6	30	76	0	11.7	-0.4 to -13.1	-0.2	-12
Segment 3	1.1	-15	10	-45	2.0	30	65	-200	-27.4	-34.3 to -50.0	-2.0	-29
Segment 4	0.4	-10	10	-45	-1.2	15	72	-100	-13.4	-12.5 to -18.4	-0.14	-12

* Initiation Delay: Difference in time between average speed drop below 60 mph and VSL system initiation

**Just BTI increased 4.1%

Driver compliance

^ Calculations carried out for 8.1 miles of highway from detectors at mile-markers 16.4 to 8.5.

~ Based on delay calculated in person-minutes.

SAFETY

Introduction This section of the report details our findings regarding the changes and/or impacts experienced in public safety that may have resulted from the deployment of the variable speed limit (VSL) system along I-270 and I-255 in St. Louis. This public safety assessment will help us better understand whether or not one of the major objectives for deploying a VSL was achieved – to improve public safety.

Crash rate is a commonly-used performance measurement in safety assessments. Crash rate measures the frequency at which crashes occur and provides an equitable method to compare “before” and “after” conditions. Crash rate were used in this safety assessment to evaluate potential changes in the before VSL and after VSL conditions are as follows:

- Total crashes
- Crash severity
- Crash type
- Peak Hour Crashes

Crash data available for the three years prior to the VSL system deployment were analyzed and compared with crash data since the VSL system was initiated. The crash rates were compared using the statistics extracted from the statewide safety management database contained within the state’s Transportation Management System (TMS).
Before and After Crash Assessment: The collection and validation of data is important in this task. TMS provides detail information on crashes like type, severity, conditions, etc. Crash data was provided for the I-270/I-255 corridor along with crash data from other regional freeway and major arterial corridors to gain a regional perspective to help better identify and assess regional trends. This approach helped better ascertain the potential true safety benefits or impacts from the VSL deployment. Crash data and a more detail discussion on the methodology used are contained within the Appendix section.

Using information from the TMS database, the before-and-after crash analysis was conducted using both simple and advance statistical analysis. Quick comparisons were made using simple statistics such as the Crash Rate (CR) as expressed below:

$$CR = 100{,}000{,}000 \times Crash / ADT \times Length \times Days \qquad (1)$$

where: Crash = Number of crashes for specific section, (are further defined as FAT = Number of fatal crashes, INJ = Number of injury crashes, N = Number of property damage only crashes), Days = Number of days for the study, ADT = Average Daily Traffic, Length = Length of Section and VM = Vehicle Miles.

Statistical crash analysis was done with the Conventional Prediction Naïve method and Empirical Bayesian method. Basically, the Conventional Prediction Naïve method compares two situations (i.e., before-and-after) under the assumption that the predicted number of crashes could be a function of previous crashes. On the other hand, Empirical Bayesian method uses the predicted crash data (rather than the observed crash data) in its comparison. For the prediction of crash data, variables like length of the segment, number of interchanges, truck percentage, number of ramps, ADT, number of lanes, speed, etc. are used to develop regression graphic models to better predict crash data for the "before and after" conditions. ADT was the only variable used in this analysis, since it was determined and used for the crash rate analysis. The detailed methodology used in the project is provided in the appendix.

Crash data was assessed in several different ways ranging from:

- Regional - other Interstates and major roadways,
- Hourly crash occurrence
- Crash severity
- Crash types

The focus to determine the safety impact of the VSL system required the evaluation during periods when the VSL was most likely in operations (peak travel periods). Hourly crash data comparison were conducted in many cases to better reflect safety impacts in the before and after VSL periods.

Many years of before VSL crash and traffic data can be obtained through MoDOT's TMS; however, there is limited after VSL crash and traffic available when this evaluation was conducted. This study focused on the full year before the VSL deployment (2007) and the first full year after the deployment (2009). A recommendation made that a future safety evaluation be made when three or more years of after VSL crash and traffic data is available and compared to findings of this evaluation.

Traffic volumes are needed to develop crash rates. MoDOT's TMS provides Annual Average Daily Traffic (AADT) volumes. The corridor is divided into 28 segments and historical AADT information is available for each segment. Figure S1 shows the total hourly AADT of all segments for 2007 and 2009.

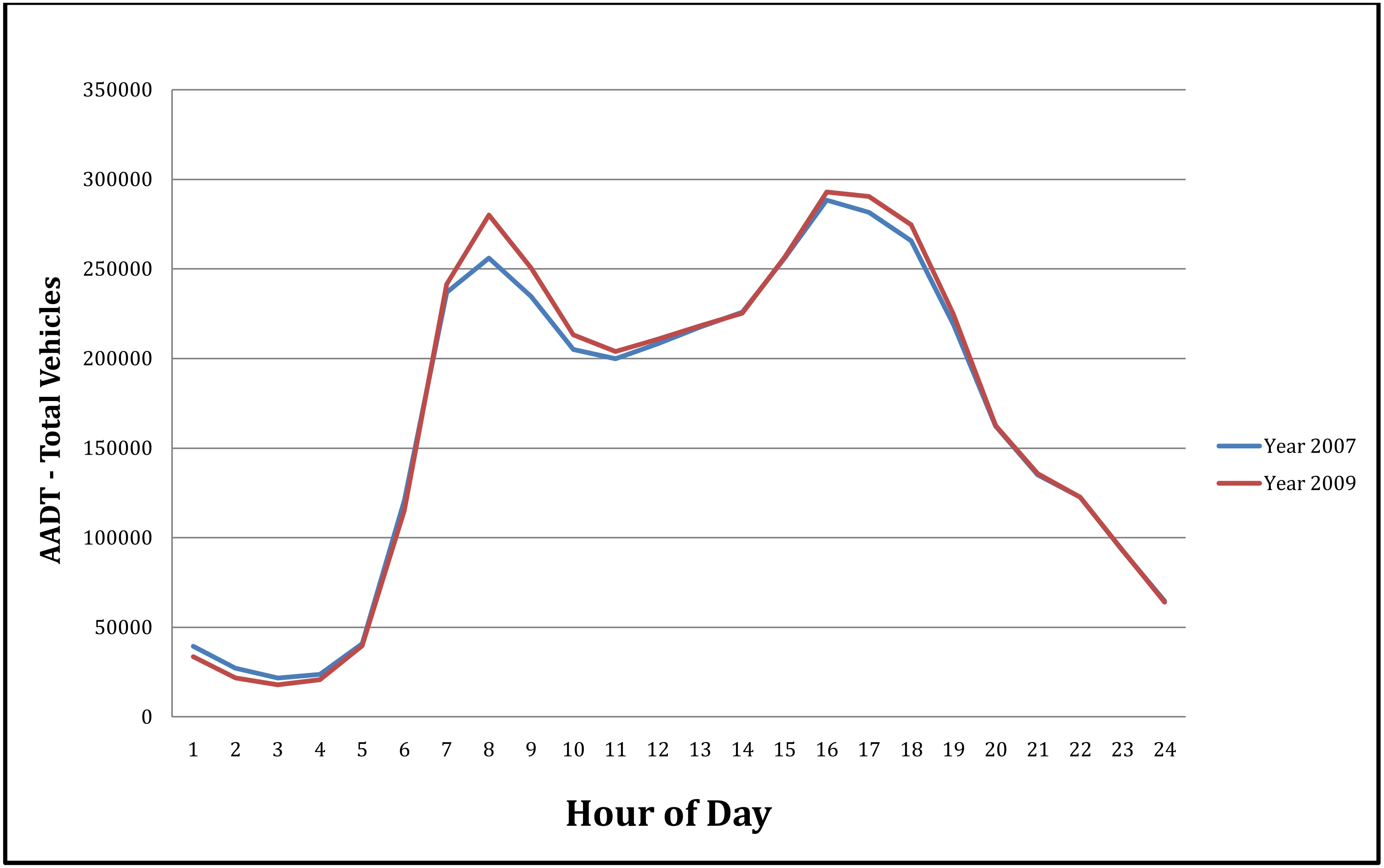
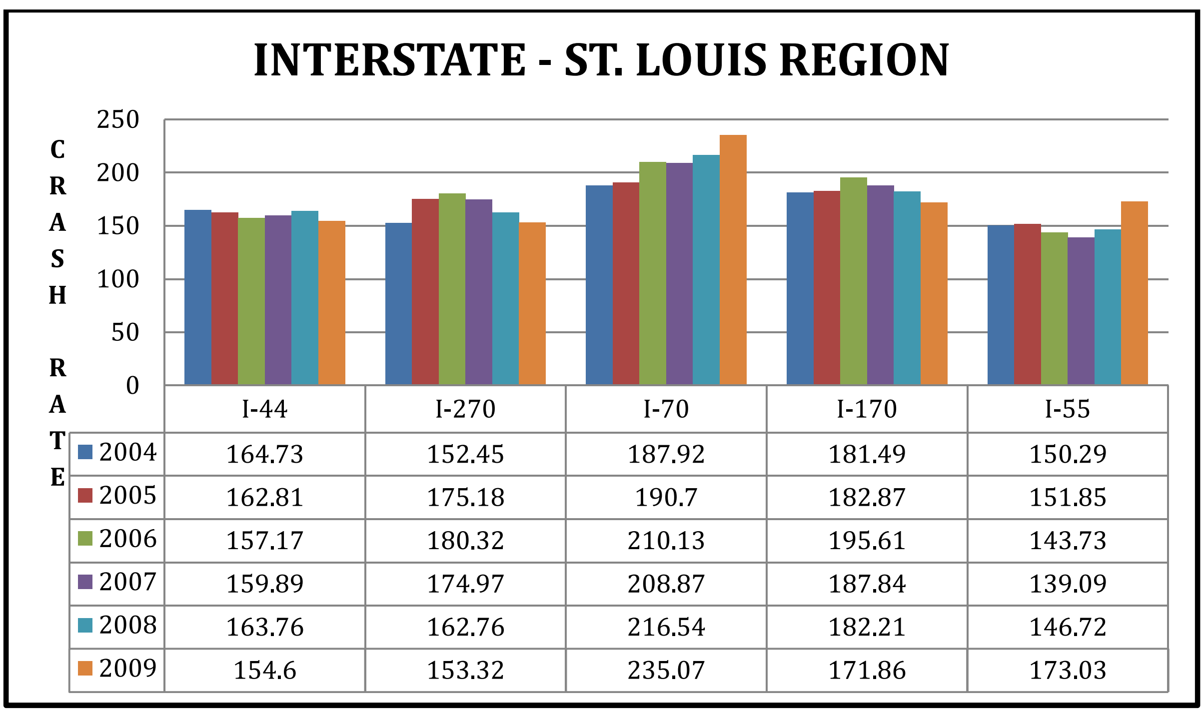


Figure S1. I-270 Hourly Traffic Volumes

Daily traffic has increased slightly along I-270 corridor when comparing 2009, 2008 and 2007. In 2009, I-270 experienced a 1.4% increase in traffic from 2007 to 2009. More details on traffic data are available in the Appendix. Crash rates, calculated using formula (1) shown above, are listed in the following Table S1 and Figure S2.

Table S1. Regional Crash Rates (Total Crashes)

	Route	2004	2005	2006	2007	2008	2009
Interstate Highway	I-44	164.73	162.81	157.17	159.89	163.76	154.60
	I-270	152.45	175.18	180.32	174.97	162.76	153.32
	I-70	187.92	190.70	201.13	208.87	216.54	235.07
	I-170	181.49	182.87	195.61	187.84	182.21	171.86
	I-55	150.29	151.85	143.73	139.09	146.72	173.03
MO Highway	MO366	2627.39	2904.79	2992.78	2996.49	3055.29	3091.91
	MO30	304.27	299.00	294.31	245.90	253.97	257.95
	MO100	529.15	466.08	378.83	397.97	364.97	383.04
	MO115	1299.25	1241.08	1265.67	1340.11	1365.73	1503.50
	MO180	154.23	195.91	182.55	175.39	173.72	208.14
	MO340	281.45	270.49	239.66	223.93	232.50	221.16
US highway and ExpressWay	MO141	764.13	688.04	727.56	722.22	703.61	564.99
	RtD	1557.28	1566.61	1364.90	1347.15	1337.11	1483.61
	US40	165.55	144.67	136.47	156.86	140.70	177.85
	US67	301.07	307.16	282.19	307.28	320.74	287.49
	US61	1243.63	1359.08	1253.10	1082.85	585.35	776.92



	I-44	I-270	I-70	I-170	I-55
2004	164.73	152.45	187.92	181.49	150.29
2005	162.81	175.18	190.7	182.87	151.85
2006	157.17	180.32	210.13	195.61	143.73
2007	159.89	174.97	208.87	187.84	139.09
2008	163.76	162.76	216.54	182.21	146.72
2009	154.6	153.32	235.07	171.86	173.03

Figure S2. Regional Interstate Crash Rate

This table and graph show I-270 had the lowest crash rate in 2009 for all interstates in the St. Louis region. The corridor was also only slightly higher than the lowest crash rate in the six year period evaluated. Only I-270 and I-170 are showing a downward trend in crash rates while other interstate routes' crash rates are trending upward or staying level. There has been a positive trend of improved safety since 2006 along the I-270 corridor. When more "after" VSL crash data is available, it would be appropriate to include additional crash rate information to further evaluate potential trends.

The VSL system operates mostly during the peak traffic periods based on congestion that lowers the average speed along the corridor. Figure S3 shows the hourly distribution of crashes. There was a noticeable reduction in the morning peak period while the afternoon peak period shows a higher spike around 18:00 (6 PM), but total crashes during the afternoon peak period 14:00 to 19:00 (2 PM to 7Pm) were very similar in number of crashes. Hourly crash rates were calculated and displayed in Figure S4 and a similar reduction in the morning peak period with a slight increase in the after peak period.

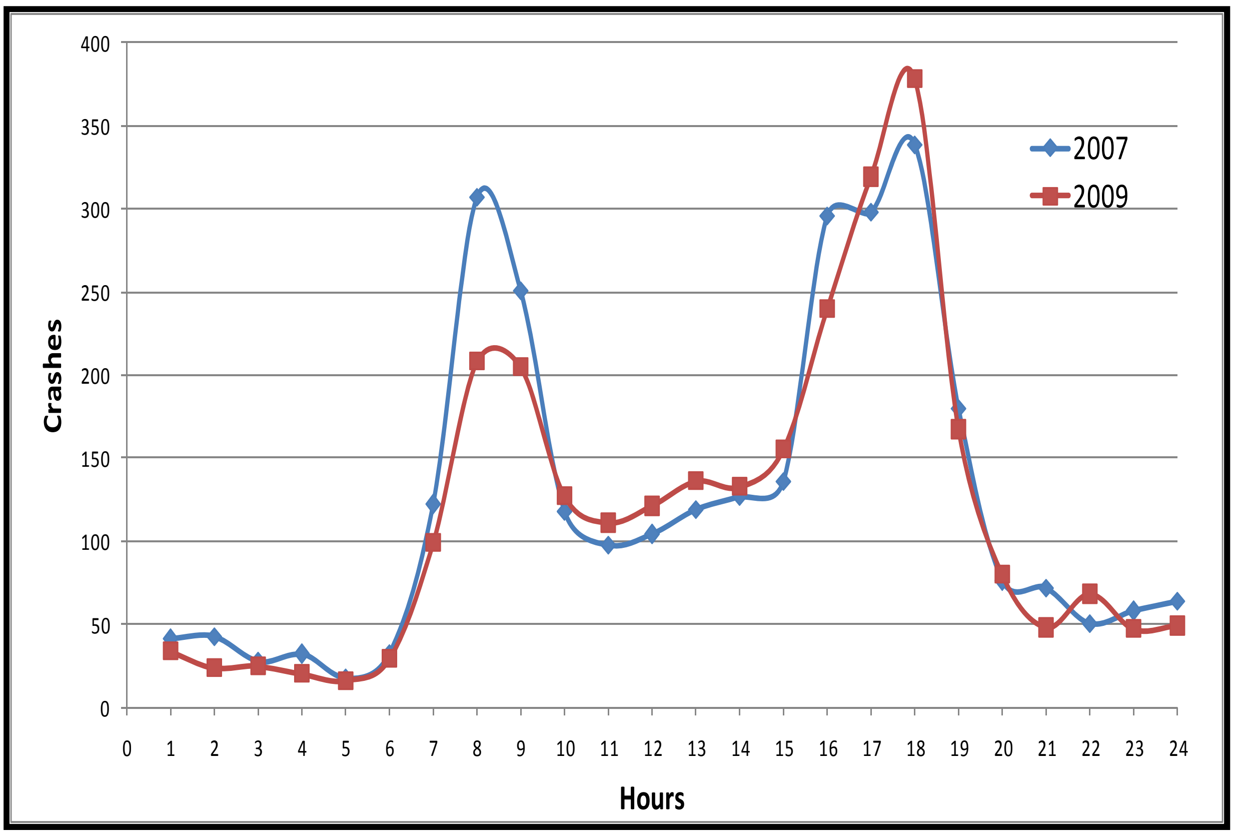


Figure S3. I-270 Hourly Crash Occurrence – 2007 and 2009

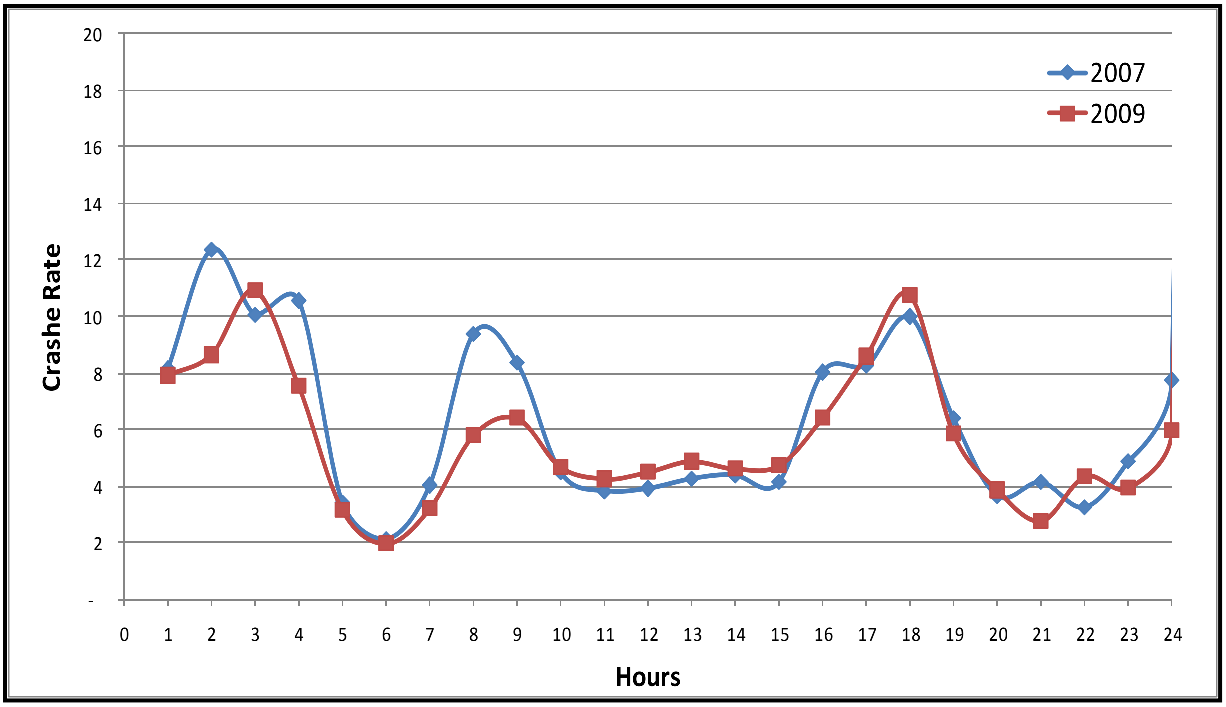


Figure S4. I- 270 Hourly Crash Rates – 2007 and 2009

Crash severity was also assessed and Figures S5 through S7 shows the hourly distribution. These total crash assessments by severity are at the hourly level to help evaluate when the VSL system is deployed.

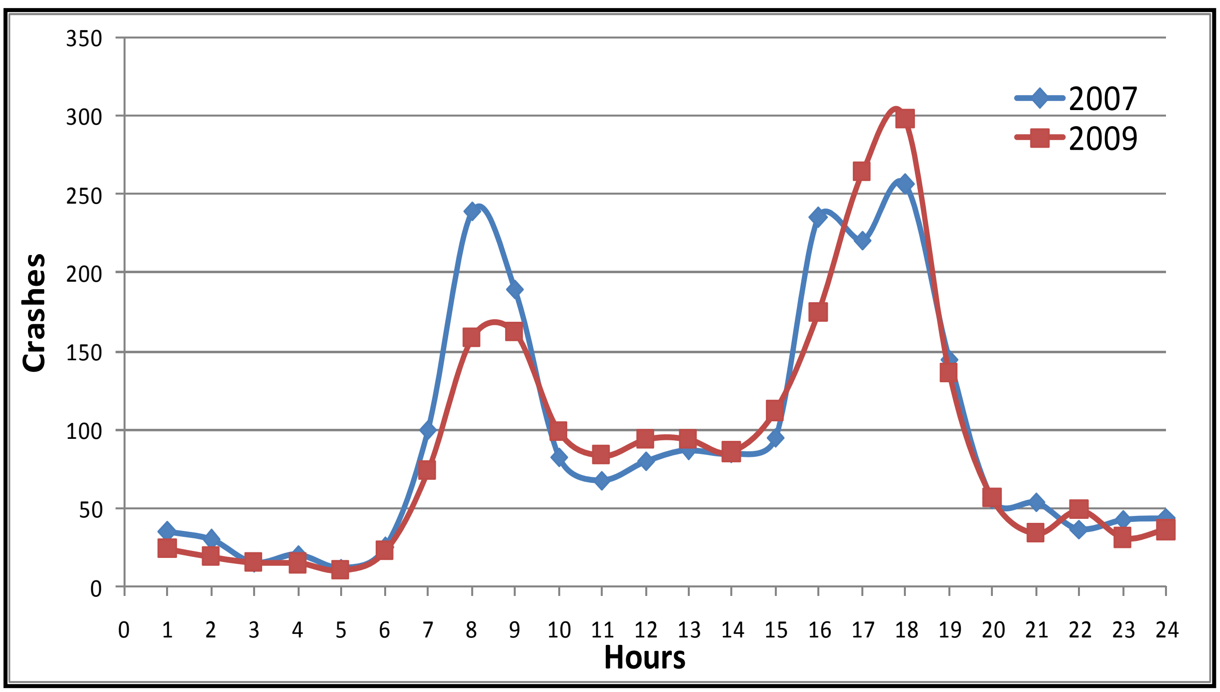


Figure S5. I-270 Hourly Property Damage Only Crashes – 2007 and 2009

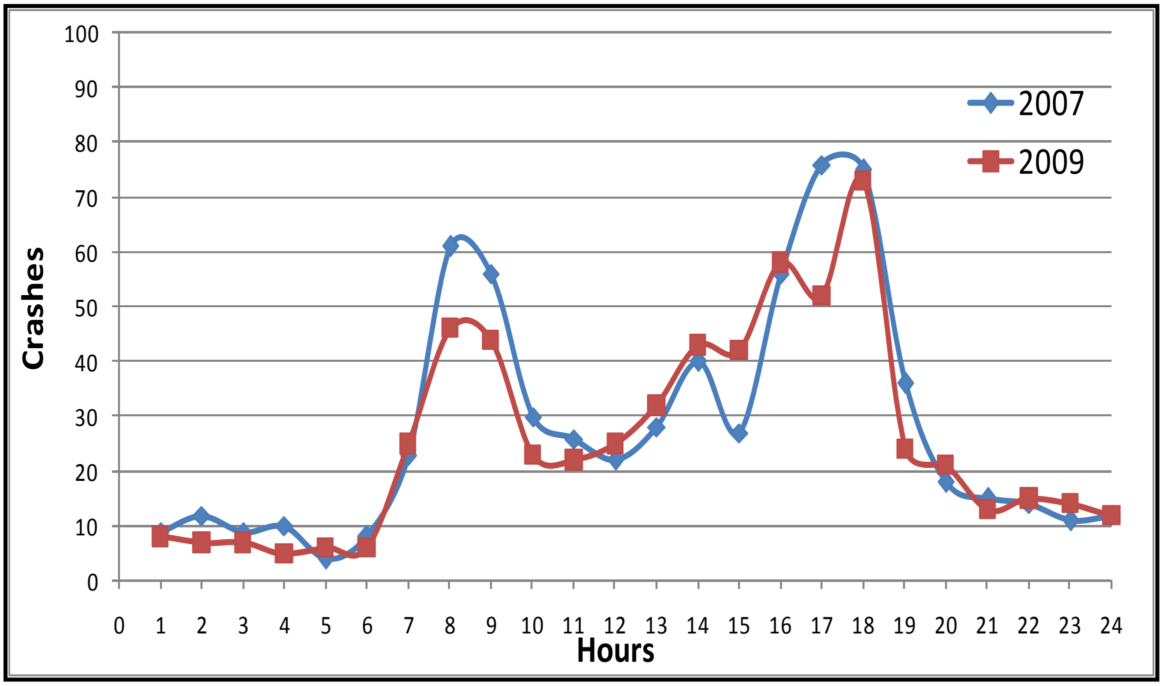


Figure S6. I-270 Hourly Minor Injury Crashes – 2007 and 2009

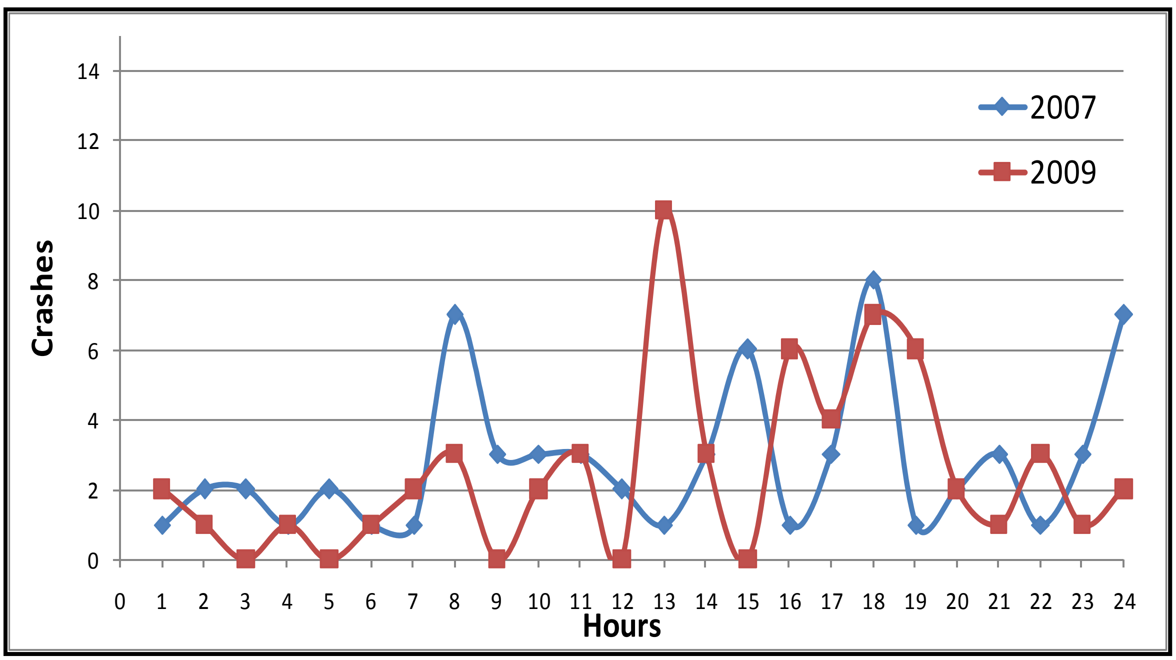


Figure S7. I -270 Disabling Injury Crashes – 2007 and 2009

Property Only and Minor Injury crashes represent approximately 98 % of crashes with Disabling Injury crashes around 2% and Fatal crashes around 0.1%. These explain why the property only and minor show similar characteristics.

Crash type was also assessed and Figures S8 through S10 show the hourly distribution. The crash type assessment was done at the hourly level to help evaluate when the VSL system is deployed. The three major types of crashes make up 86.5% of the crashes that occurred along this corridor. The following is breakdown of the types of crashes by percentage:

- Rear-end crashes – 55.5%
- Out of Control crashes – 18%
- Passing crashes – 12%
- All Other Types – 13.5%

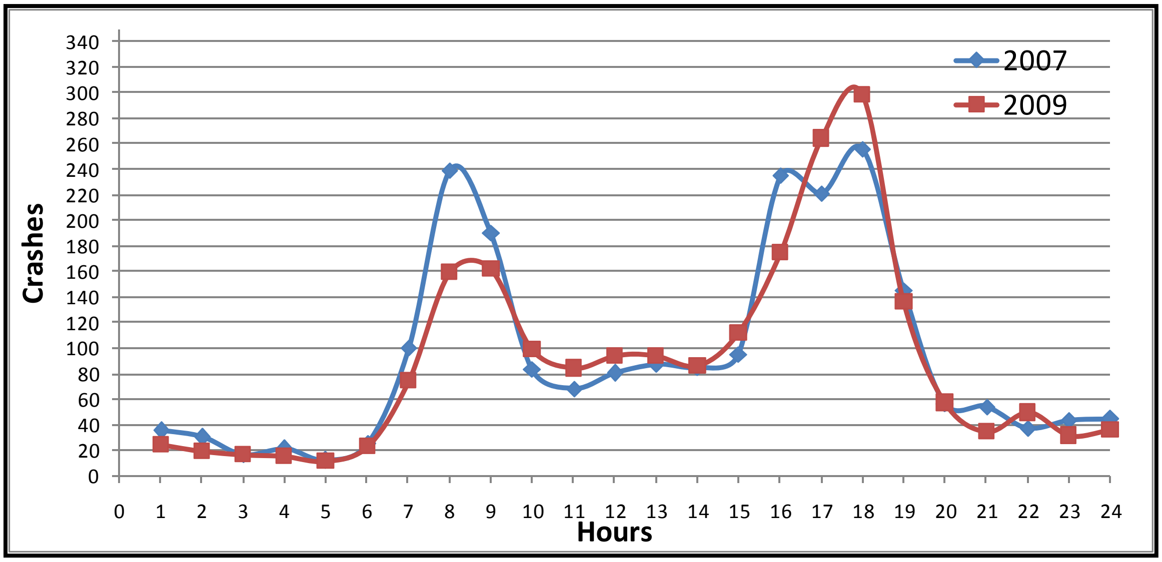


Figure S8. I -270 Hourly Rear-end Crashes – 2007 and 2009

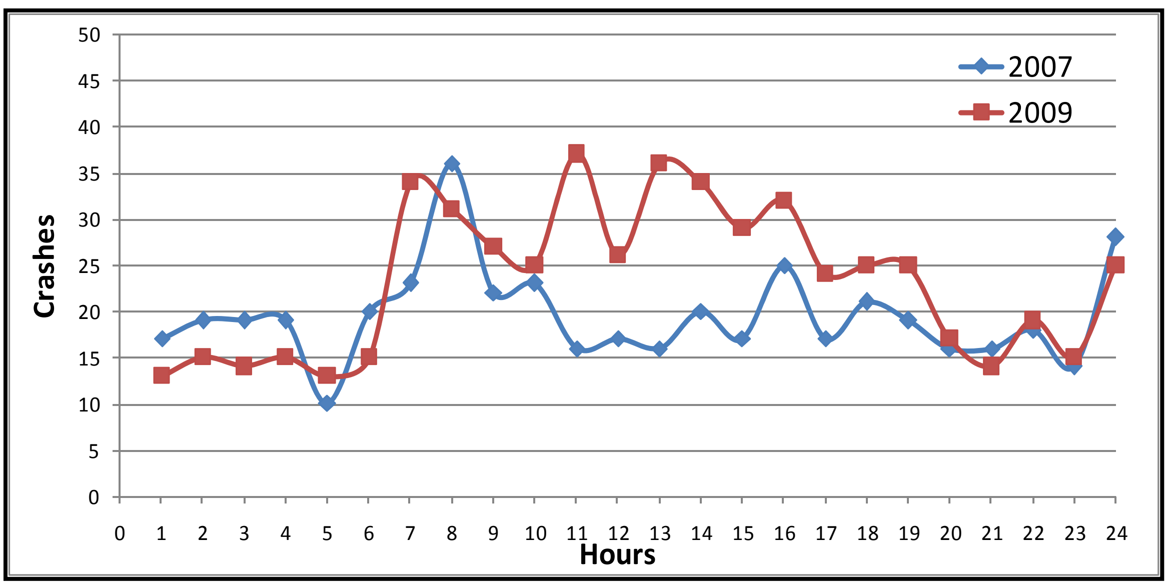


Figure S9. I-270 Hourly Out of Control Crashes – 2007 and 2009

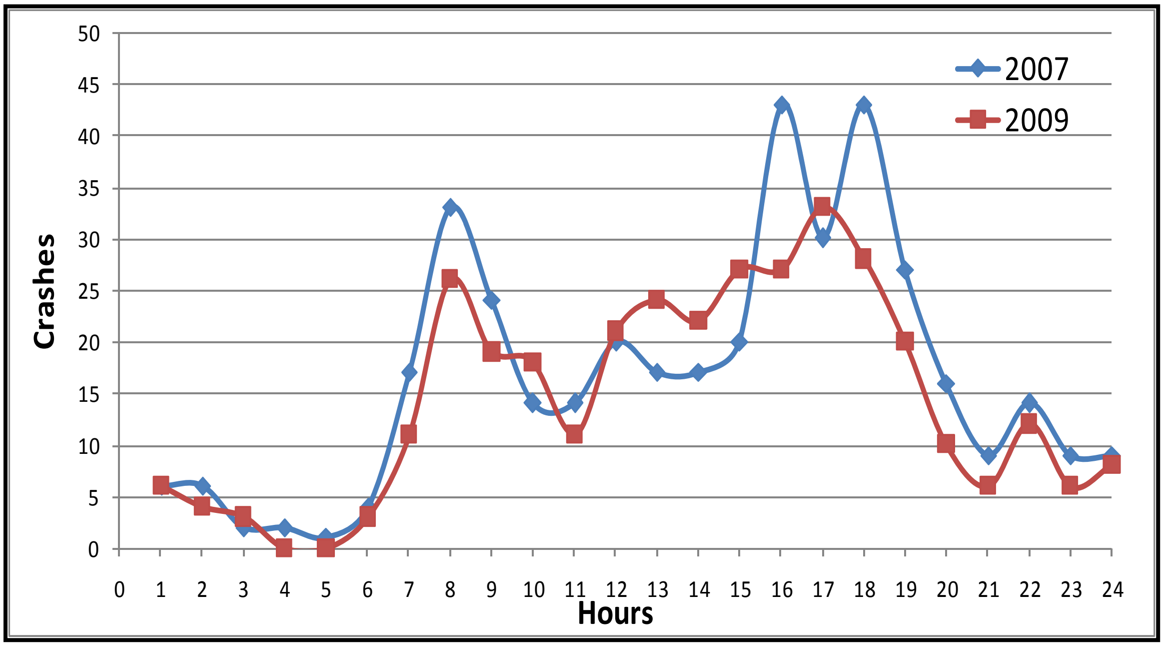


Figure S10. I-270 Hourly Passing Crashes – 2007 and 2009

Rear-end and passing crashes are crash types that might be more associated with traffic congestion where out of control is probably more associated with higher speeds. Out of control crashes increased in 2009 during non-peak periods and could raise the concern that motorists are showing a greater disrespect for the speed limit. If this safety evaluation is updated in the future with additional after VSL crash data, then out of control crash could be further evaluated to better determine potential VSL impacts. Rear-end and passing crashes have very similar trends that have appeared in both total and severity crash assessments.

Crashes and crash rates when compared to the pre-deployment VSL (2007) and post-deployment VSL (2009) period show a reduction. This reduction was somewhat consistent across the various different evaluations. The focus was mostly on the hourly in this report since evaluation was to state whether or not the VSL system is a factor in the reduction of crashes and improved safety. The AM peak shows a definite crash reduction while the PM peak remains about the same.

To further enhance this safety evaluation, two different statistical methods Conventional Prediction – Naïve and Empirical Bayesian (EB) were used. The new Highway Safety Manual encourages the use of these analytical statistical methods to help quantify safety benefits during planning, project development and operation. Table S2 shows segment location information that was used in both evaluations. More detail information on these accepted statistical methods is contained within the Appendix.

Table S2. Segment Locations

Segment Index	Starting Milepost	Ending Milepost	Segment Length	Description
1	0.55	2.15	1.60	IS 55 to MO 21
2	2.15	3.92	1.77	MO 21 to MO 30
3	3.92	6.13	2.21	MO 30 to IS 44
4	6.13	7.63	1.51	IS 44 to BIG BEND BLVD
5	7.63	8.73	1.10	BIG BEND BLVD to DOUGHERTY FERRY RD
6	8.73	10.26	1.53	DOUGHERTY FERRY RD to MO 100
7	10.26	12.70	2.44	MO 100 to IS 64
8	12.70	13.85	1.15	IS 64 to RT AB
9	13.85	14.99	1.15	RT AB to MO 340
10	14.99	16.81	1.82	MO 340 to MO 364-RT D
11	16.81	17.94	1.13	MO 364-RT D to DORSETT RD
12	17.94	20.32	2.38	DORSETT RD to IS 70
13	20.32	21.07	0.76	IS 70 to MO 180
14	21.07	23.14	2.06	MO 180 to MO 370
15	23.14	23.84	0.70	MO 370 to MCDONALD BLVD
16	23.84	25.52	1.68	MCDONALD BLVD to US 67
17	25.52	26.36	0.84	US 67 to IS 170
18	26.36	26.89	0.52	IS 170 to GRAHAM RD
19	26.89	27.86	0.97	GRAHAM RD to RT N
20	27.86	28.37	0.52	RT N to WASHINGTON-ELIZABETH AVE
21	28.37	29.87	1.50	WASHINGTON-ELIZABETH AVE to WEST FLORISSANT AVE
22	29.87	30.57	0.70	WEST FLORISSANT AVE to RT AC
23	30.57	30.92	0.34	RT AC to OLD HALLS FERRY RD
24	30.92	32.09	1.17	OLD HALLS FERRY RD to MO 367
25	32.09	33.07	0.98	MO 367 to BELLEFONTAINE RD
26	33.07	34.05	0.98	BELLEFONTAINE RD to LILAC AVE
27	34.05	35.04	0.99	LILAC AVE to RT H-RIVERVIEW AVE
28	35.04	35.75	0.71	RT H-RIVERVIEW AVE

Table S3 shows excepted crash count (π) versus observed crash (λ) count by segment. The Naive unbiased index of safety effectiveness is 93.5% with standard deviation of 3.3%. The safety effectiveness index defines the predicted reduction (100% - 93.5%) with a variance 0f 3.3%. The Naïve results indicate that after removing the effect of traffic on crashes, the implementation of the VSL system could potentially contribute to a crash reduction of 6.5%.

Table S3. Naïve Approach (Expected (π) vs. Observed (λ))

Segment	Crash Counts	
	π	λ
1	95	127
2	101	70
3	142	126
4	91	62
5	74	39
6	99	91
7	169	146
8	69	29
9	74	88
10	113	133
11	58	54
12	133	161
13	41	33
14	88	44
15	37	61
16	79	94
19	45	45
20	22	23
21	70	35
22	28	29
24	40	55
25	28	34
26	20	27
27	17	7
28	14	23
Total	1748	1636

Table S4 shows excepted crash count (π) versus observed crash (λ) count by segment. The Empirical Bayesian index of safety effectiveness is 91.6% with standard deviation of 3.8%. The safety effectiveness index defines the predicted reduction (100% - 91.6%) with a variance of 3.8%. The Empirical Bayesian results indicate that the implementation of the VSL system could potentially contribute to a crash reduction of 8.4%.

Considering the predicted crash reduction ranged of 4.5% to 8% with a standard deviation range of 3% to 4%, this shows that the VSL deployment has played a role in reducing crashes.

Table S4 Empirical Bayesian Method (Expected (π) vs. Observed (λ))

Segment	Crash Counts	
	π	λ
1	97	127
2	151	70
3	212	126
4	165	62
5	57	39
6	134	91
7	149	146
8	58	29
9	68	88
10	121	133
11	49	54
12	117	161
13	36	33
14	71	44
15	33	61
16	81	94
19	28	45
20	30	23
21	31	35
22	8	29
24	35	55
25	23	34
26	15	27
27	2	7
28	12	23
Total	1748	1636

PUBLIC AND LAW ENFORCEMENT OPINION SURVEY

This section of the report details our findings regarding public, as well as law enforcement, awareness and engagement/satisfaction with the VSL implementation. Respondent input was obtained via an online survey for the general public made available through a link at the MoDOT VSL homepage, as well as a paper survey distributed to the 15 law enforcement units with responsibility for patrolling the I-270/I-255 corridor around St. Louis. Online survey responses totaled 1030; law enforcement responses totaled 355.

Over a thousand people completed the online survey. The survey included a self-reported question to determine whether participants had taken the survey previously. Only first-time responses were analyzed. Because of the online survey format, there is a bias toward respondents with internet access as well as those with higher comfort levels with technology. The survey was available on request in paper form and initial publicity did indicate this option; no respondents requested a paper survey. The general public is overwhelmingly aware of the VSL project, but has a high level of dissatisfaction with the system and has serious reservations regarding its effectiveness. The vast majority also report that it has not increased public safety, reduced stop and go traffic, created a uniform traveling speed, or increased driver compliance with posted speed limits. An overwhelming majority believe that the VSL should be eliminated and that it has not been well explained to the public despite high levels of awareness.

Over three hundred law enforcement officials completed paper surveys. Law enforcement officers also reported negative responses to the VSL. They do not believe that it has reduced the number of crashes, alleviated stop and go traffic, or reduced congestion. Moreover, they overwhelmingly believe that it has been ineffective in increasing driver compliance with posted speed limits. The vast majority report that it should be eliminated and not considered for expansion.

Online Survey Responses

The general public

- is overwhelmingly aware of the VSL project
- has a high level of dissatisfaction with the system
- has serious reservations regarding its effectiveness.

Results are summarized in the figures/charts below. In general, a summary analysis for the combined results from years one and two is presented. Figure P1 shows level of awareness.

Figure P1 showcases responses stating agreement/disagreement with statements from the survey questionnaire. High levels of disagreement indicated that the public does not believe the VSL is succeeding with its goals to reduce crashes or relieve congestion when based solely on those agreeing or disagreeing with survey statements. Respondents do believe that the VSL has a good level of visibility at all times of day/evening. However, they strongly disagree that it has positively impacted their travel times during either the morning or evening commute. The vast majority also believes the VSL has had no impact on safety, stop and go traffic, uniform traveling speed, or driver compliance with posted speed limits. Based only on agreement/disagreement levels an overwhelming majority believes the VSL should be eliminated and it has not been well explained to the public despite high levels of awareness.

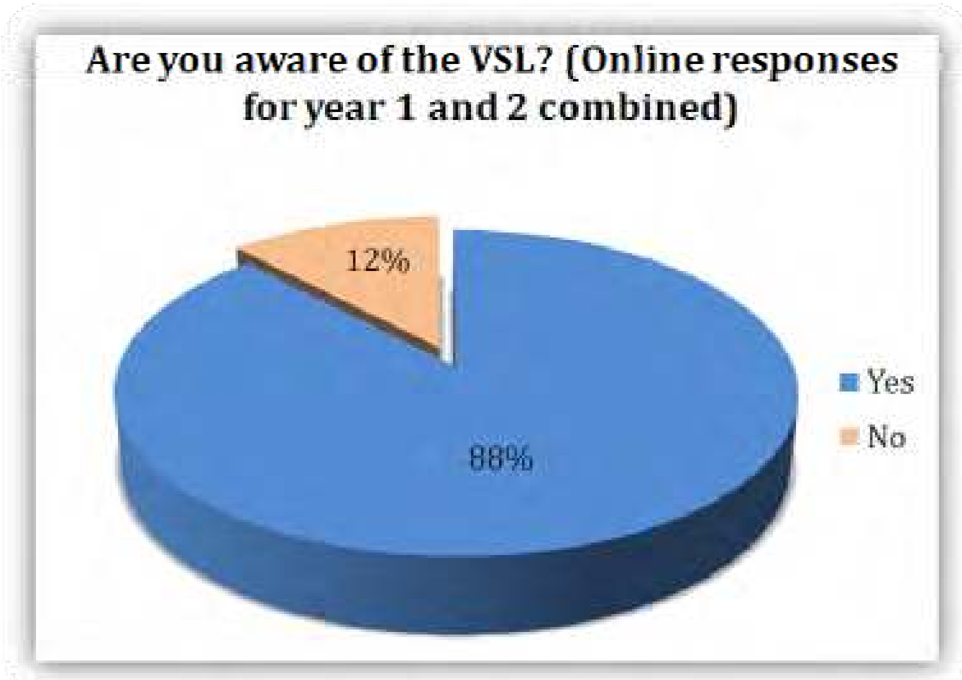


Figure P1. VSL Awareness Years One and Two

Online Responses Year 1 and 2 Combined

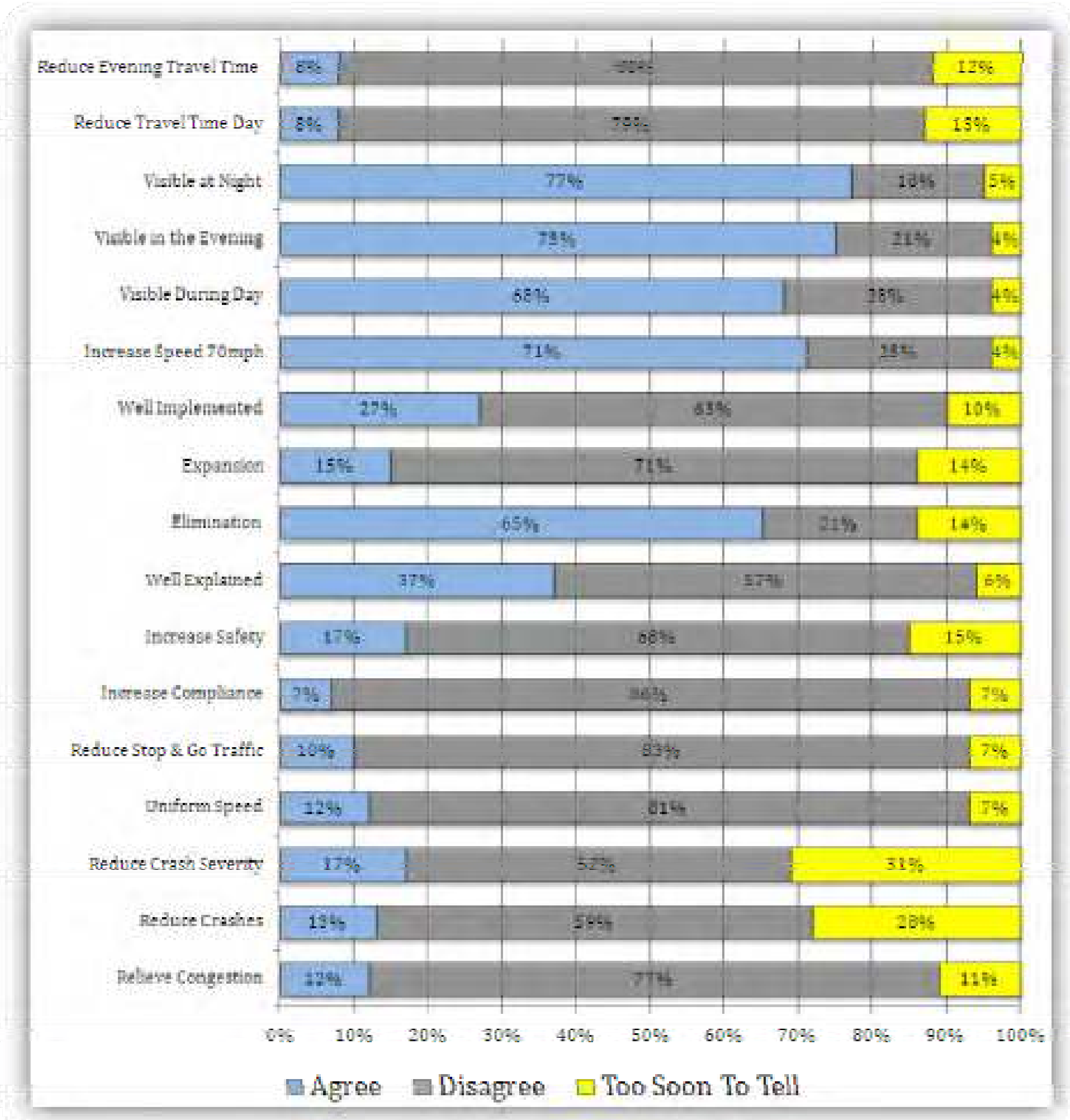


Figure P2. VSL Online Assessment Years One and Two

Basic demographic information for respondents is included below. Figure P3 shows that survey respondents are overwhelmingly male. Figure P3A provides St. Louis demographic data for comparison.

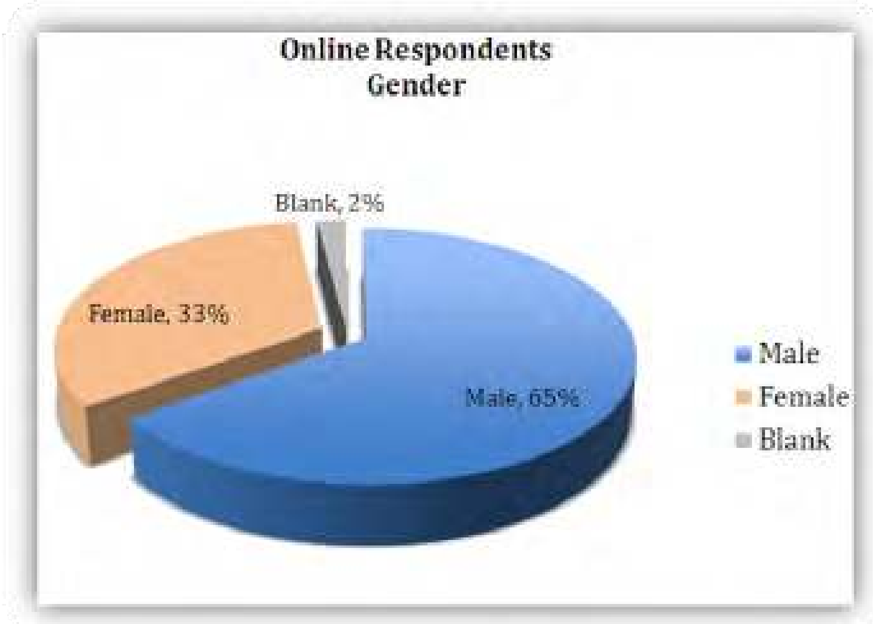


Figure P3. VSL Online Gender Year One

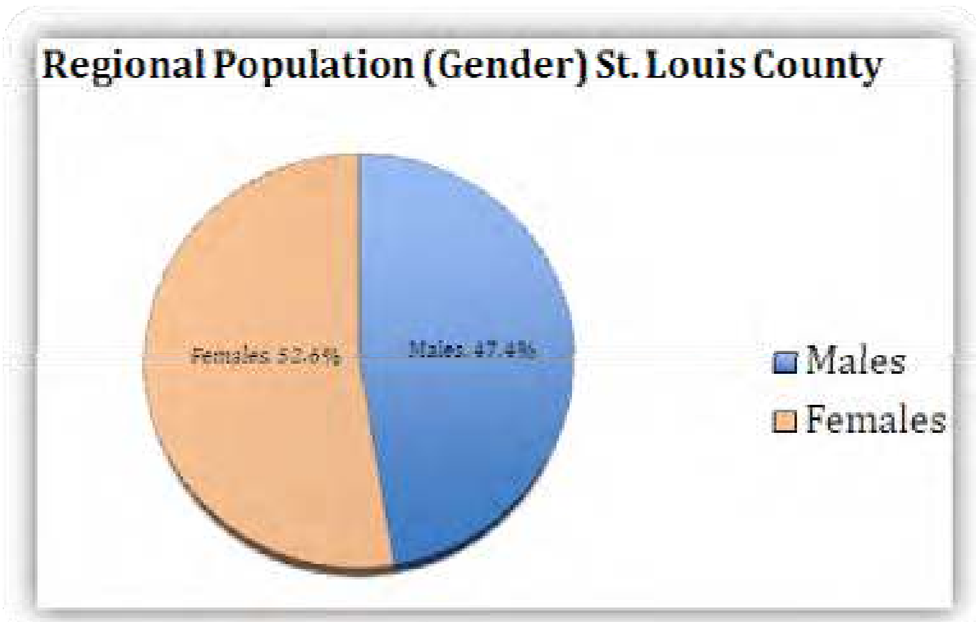


Figure P3A. Regional Demographics of St. Louis (*Ref: www.city-data.com*)

The bulk of respondents fall between the ages of 26 and 65 with a slight majority falling into the age category 41-65 (see Figure P4). Regional demographic data is provided for comparison in Figure P4A.

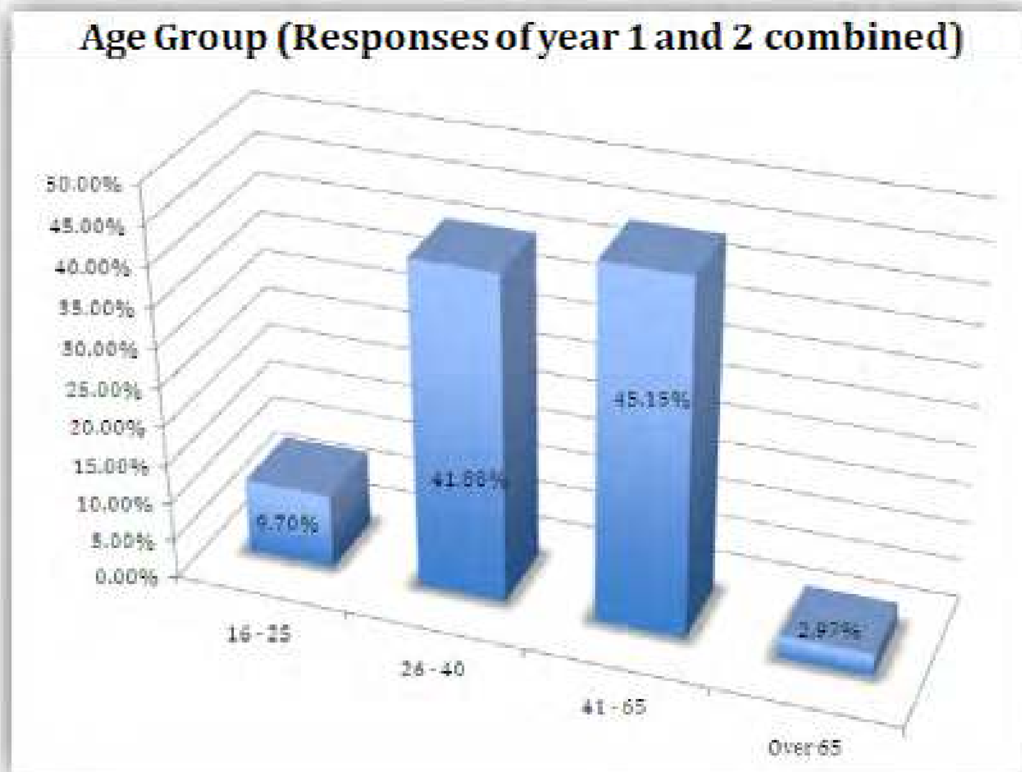


Figure P4. VSL Online Age Statistics Years One and Two

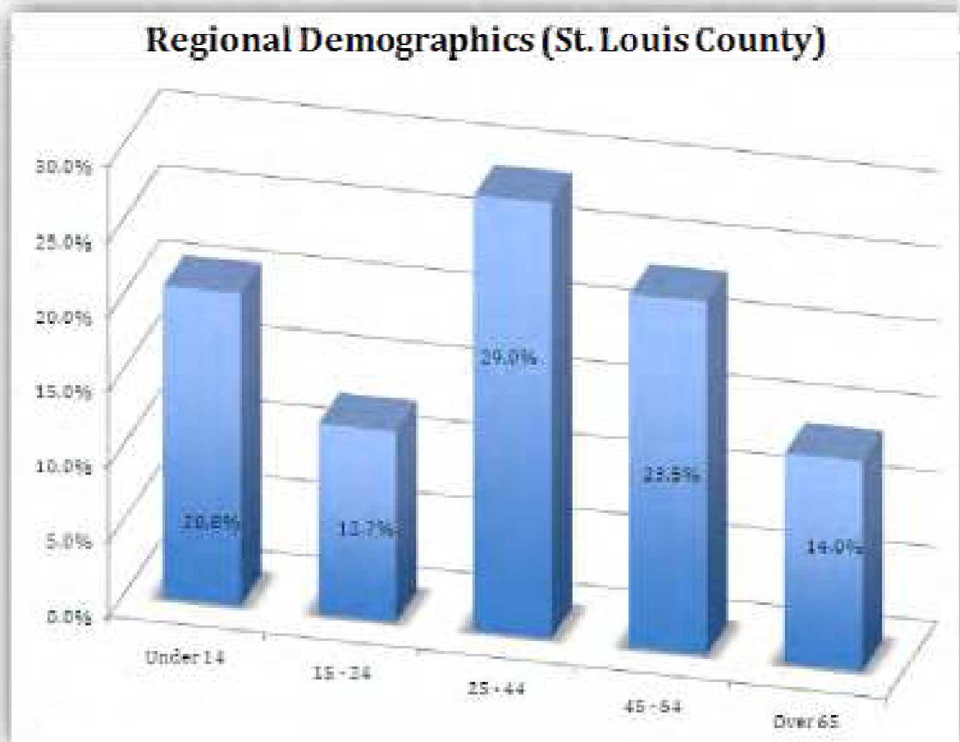


Figure P4A. Regional Demographics of St. Louis (*Ref: www.city-data.com*)

Using I-64 as an approximate midpoint of zip-codes, respondents are biased to home addresses south of I-64 at 54% (Figure P5). A slight majority (52%) of respondents commute to work locales north of I-64 (Figure P6). The two year responses include some Illinois residents as well as Missouri residents who work in Illinois.

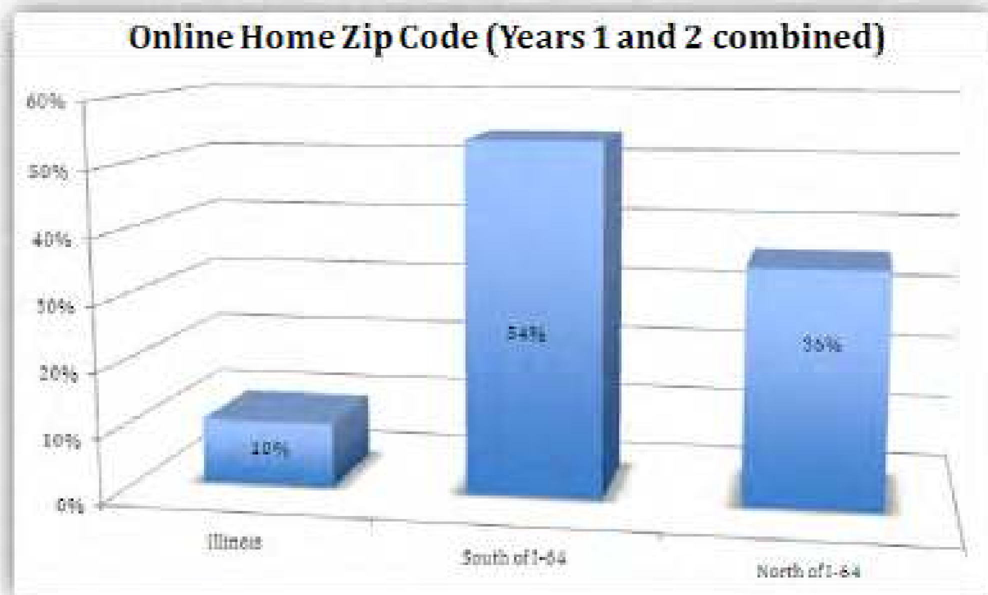


Figure P5. VSL Online Home Zip Code Years One and Two

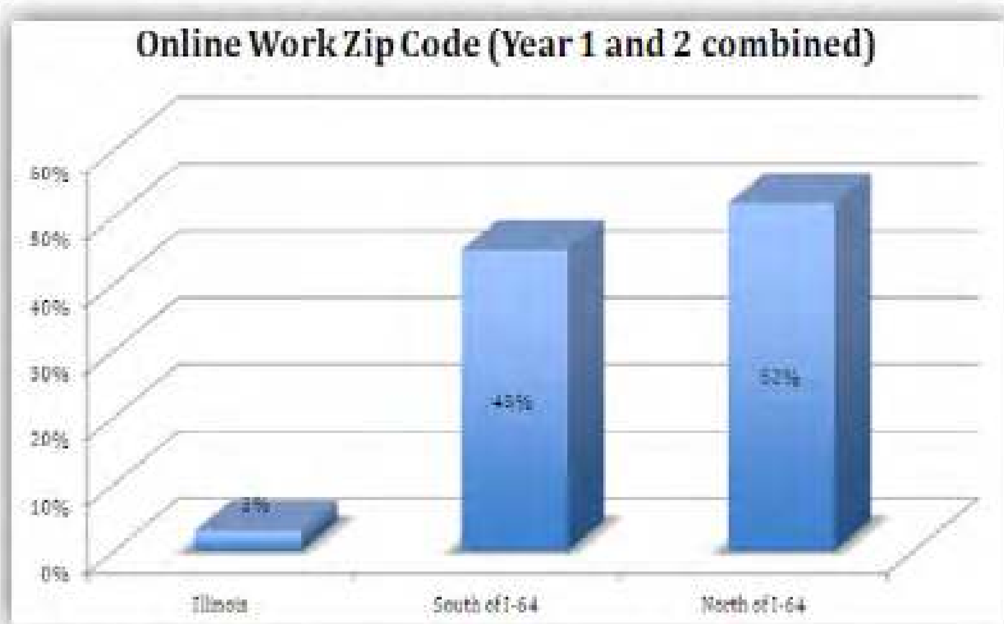


Figure P6. VSL Online Work Zip Codes Years One and Two

The most prevalent income categories fall between $61,000-120,000 ($61-120K) as shown in Figure P7.

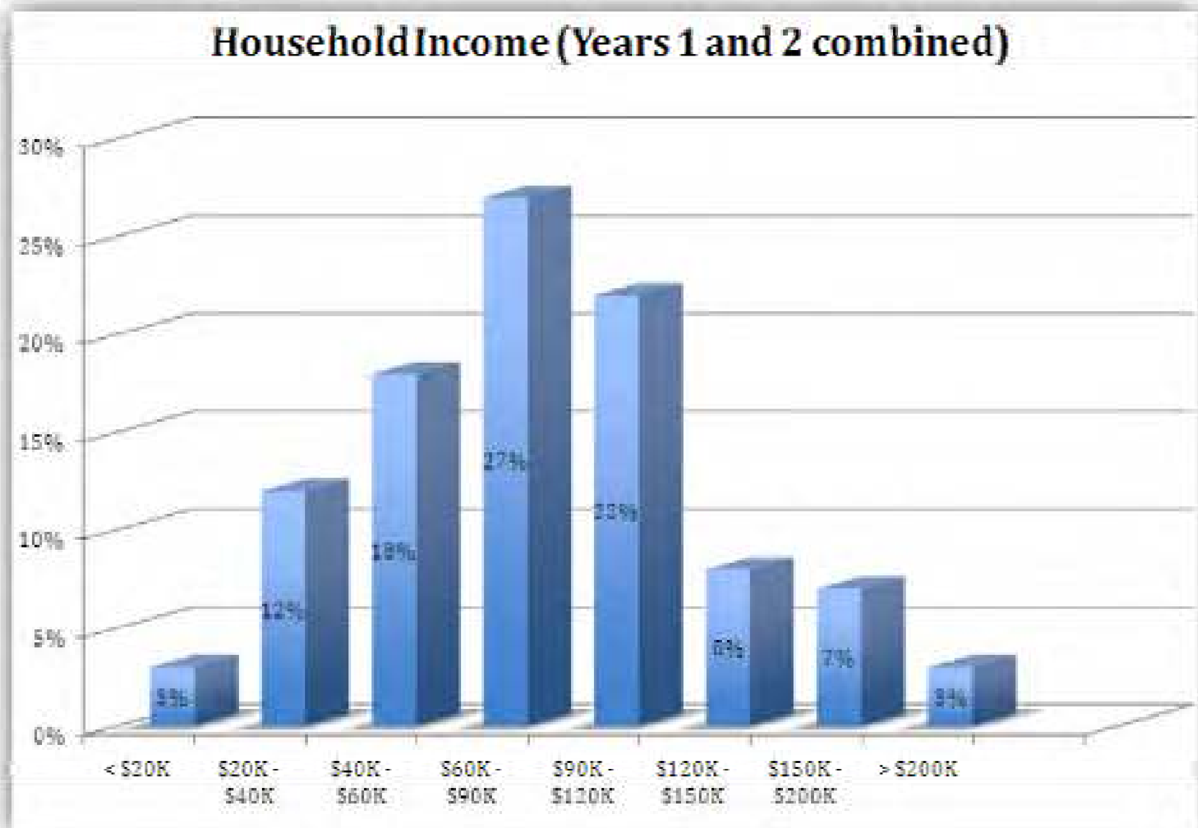


Figure P7. VSL Online Household Income Years One and Two

Although the online survey results indicate an overwhelming majority of white/Caucasian respondents, the survey is considered an acceptable mix of diversity due to representation of minority categories as part of the survey make-up. This is shown in Figure P8. Figure P8A provides regional demographic data for comparison.

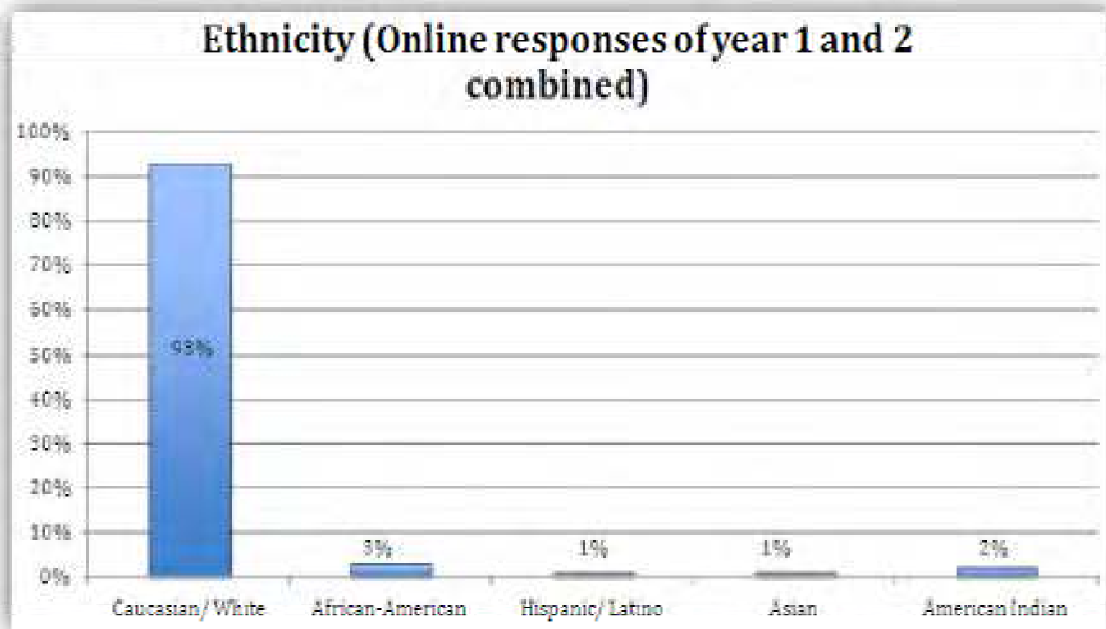


Figure P8. VSL Online Ethnicity Years One and Two

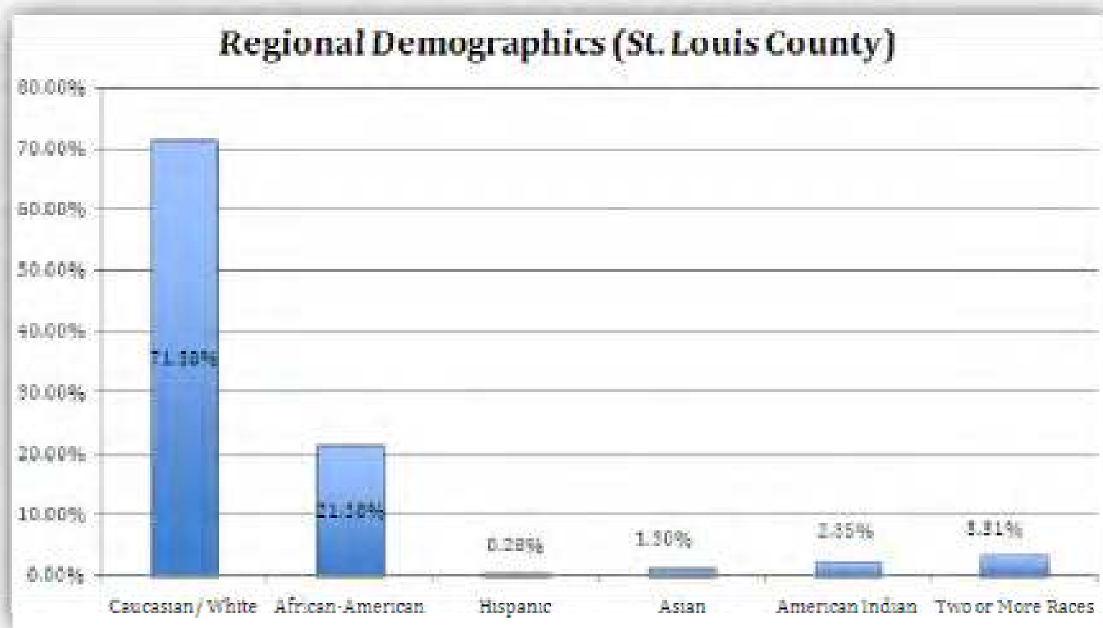


Figure P8A. Regional Demographics of St. Louis (*Ref: www.city-data.com*)

Law Enforcement Survey

The next series of charts indicates the opinions of law enforcement precincts with responsibility for enforcing the laws along the I-270/I-255 corridor. A breakdown of responding units is shown in the Figure P9.

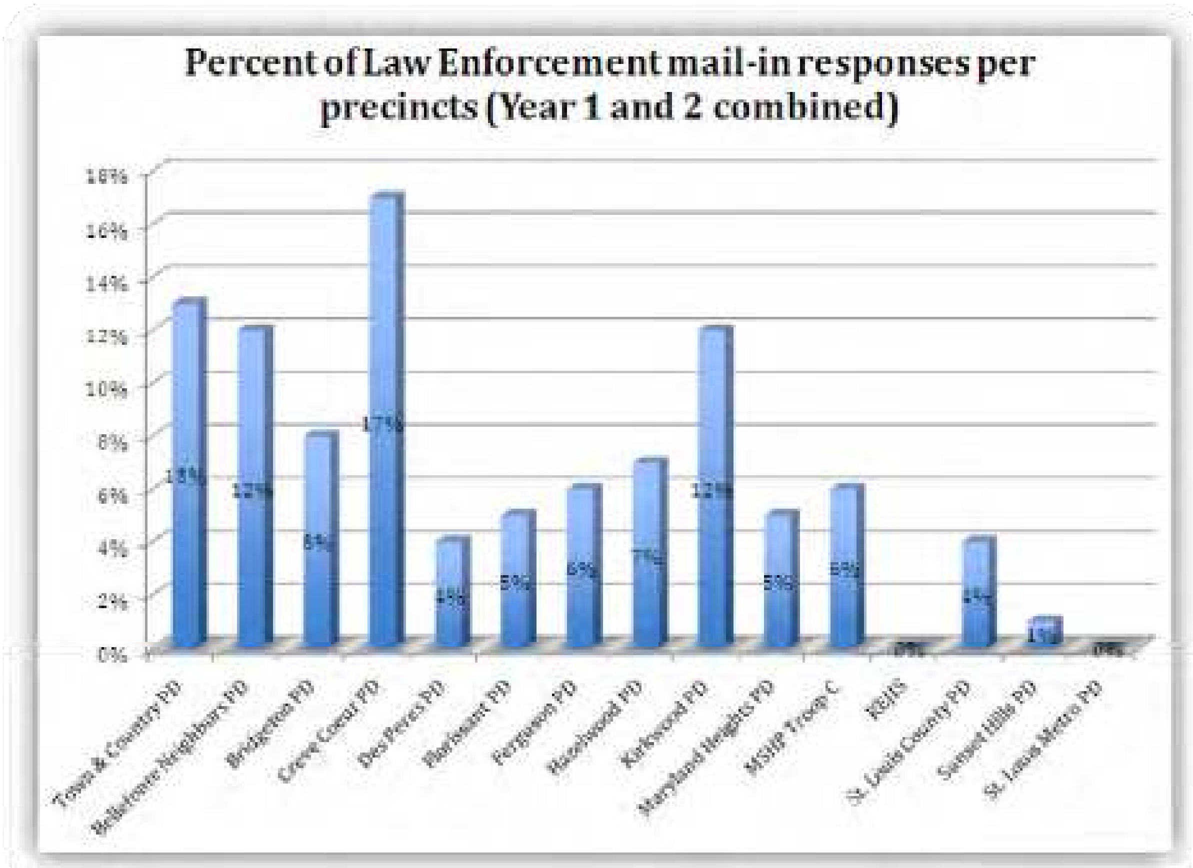


Figure P9. VSL Law Enforcement Survey Years One and Two

Figure P10 indicates law enforcement officers opinions on a comparable set of questions to those asked of the general public. Law enforcement officers gave largely negative responses to the survey questions. They do not report the VSL has reduced the number of crashes, alleviated stop and go traffic, or reduced congestion. Moreover, 93% believe the VSL has been ineffective in increasing driver compliance with posted speed limits. The majority (64%) believes the VSL should be eliminated and not considered for expansion.

Law Enforcement Assessment Year 1 and 2 Combined

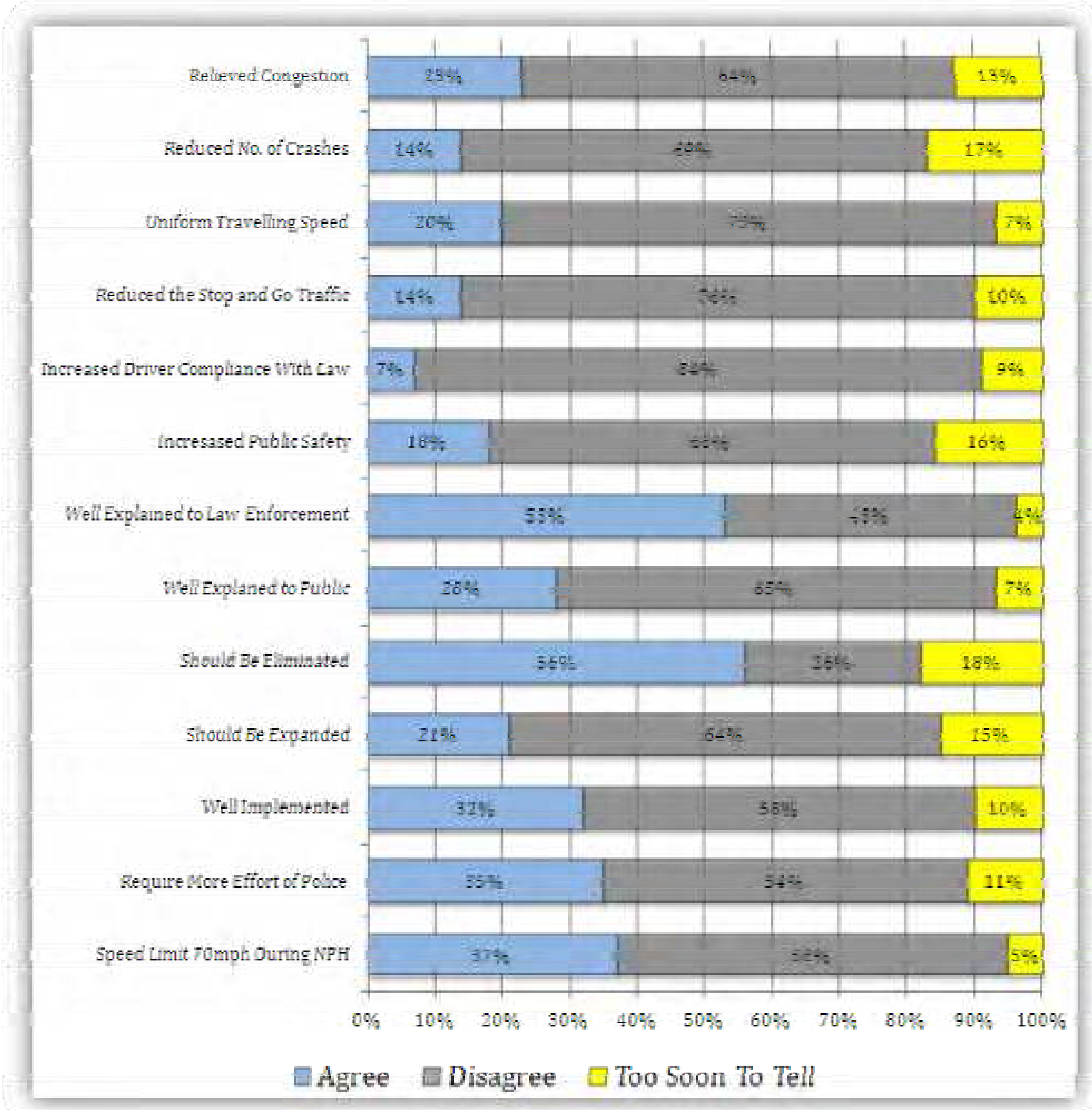


Figure P10. VSL Law Enforcement Assessment Years One and Two

Officers split regarding their feelings of level of effort spent on enforcing. There is a slight negative response to the statement that the VSL requires more effort of police. Another interesting response is found in their evaluation of whether the VSL has been well explained. Although most officers believe that it has been well explained to them, 31% believe that it has been well explained to the public.

Cross-Survey Agreement

The table below shows results on common questions. The similar levels of agreement indicate good reliability of results. Law enforcement and the public disagree widely on only one issue: whether the speed limit should be increased to 70 mph during non-peak hours. The public is strongly in favor; law enforcement is strongly opposed.

Table P1. Cross-Survey Agreement Table

Level of agreement (strongly or slightly)	Online survey response	Law enforcement response	Percent Change
Relieved congestion	13%	26%	-13%
reduced #/severity of crashes	25%	18%	7%
uniform travelling speed	12%	21%	-9%
reduced the stop and go traffic	10%	17%	-7%
increased driver compliance with the law	7%	8%	-1%
increased public safety	19%	23%	-4%
well explained to public	40%	31%	9%
should be eliminated	75%	67%	8%
should be expanded	17%	25%	-8%
well implemented	29%	35%	-6%
speed limit 70mph during NPH	74%	38%	-36%
Number of Responses	1030 responses	356 responses	

Publicly funded transportation management systems such as VSL are heavily dependent on stakeholder acceptance for full success. These systems are forms of sociotechnical systems and can be analyzed using system heuristics and guidelines normally used for projects requiring significant stakeholder participation and "buy-in". Sociotechnical systems are defined as "technical works involving significant social participation, interests, and concerns." (Maier and Rechtin, 2002) Stakeholders function as consumers in this case assigning value to the VSL initiative similar to that found with the introduction of new products. Value is often based more in perception than fact and can negatively bias implementation results (Kleijnen, 2009; Maier and Rechtin, 2002). [Note: as a relevant example, public perceptions of dissatisfaction with ramp-metering in Minnesota led to a deactivation of the system; additional review and public opinions following deactivation determined that the system had been effective. See http://www.dot.state.mn.us/rampmeterstudy/execsumnov2001.PDF]

This simplistic version of change does not describe the level of resistance that many individuals experience with change to familiar products and experiences, especially those including the introduction of innovative technologies (Kleijnen, 2009; Robbins and Coulter, 2005; Woodward and Hendry, 2004). Resistance can stem from many sources including a disparity in what constitutes sufficient awareness of the benefits of the proposed change. Individuals are far more resistant to change when it involves loss of control over longstanding patterns of behavior. The form of the resistance varies according to the systemic culture and can include the passive form: "if you wait it out, it will eventually go away" (Clegg and Walsh, 2004; Woodward and Hendry, 2004). This seems to be the case with respect to public and law enforcement attitudes regarding the VSL.

A comprehensive analysis of change resistance may prove useful in identifying potential areas of disconnect. Such approaches use lessons learned from new product development marketing theory and outline a series of steps that often increase the chances of achieving successful change. Change models of this type give keen insight into motivations for change. The literature suggests that trust is one of the most critical factors in assuring acceptance of change (Long and Spurlock, 2008; Sayles, 1973; Lines, et al, 2005).

Resistance to technological innovation can be mapped to three main consumer reaction types: rejection, postponement and opposition. Briefly, rejection details active resistance driven by consumer attitudes that an innovation will not work. Postponement refers to consumer lags in acceptance based on their desire for an innovation to be more fully tested. Opposition, the strongest form of resistance is typically rooted in objections based on principles or values (Kleijnen, 2009). Linkages of these patterns to the VSL implementation in St. Louis suggest rejection and provide guidance for MoDOT's response.

3.0 RECOMMENDATIONS

MOBILITY

This study evaluated the variable speed limit system deployed on I-255/I-270. The study concludes that the VSL system was beneficial for segments 1, 3 and 4. Segment 2 did not indicate benefits of the system because of considerably higher volume compared to other segments, but room for improvement was identified.

The VSL system initiation to reduce and recover variable speed limits on segment 1 was found to be considerably delayed at detectors 12D and 8D due to zone averages which averaged traffic data for all three detectors (12D, 11D and 8D). Detector 11D was found to be critical for VSL initiation on segment 1. Such critical detectors were not identified for other segments. In addition, for all segments the system should be initiated proactively rather than being reactive. This can be achieved by reducing the lag between the time the average speed falls below the posted speed limit and when the system is initiated and using individual or optimal number of detectors to initiate the VSL signs in the region not the zone averages. Further, the posted variable speed limits should be initiated and recovered gradually on I-270, similar to segment 1.

From the analysis conducted, it is evident that segment 2 requires the most improvement and an in-depth investigation is required to identify the possible reasons for its inefficiency and propose remedies for improvement. For detailed investigation at this segment, data from several detectors is required.

Other recommendations include more efficient means of detector data acquisition, repair and/or replacement of detectors in a timely manner, placement of additional detectors to reduce spacing to around 0.5 mile between detectors especially on congested segments and near interchanges, installation of detectors at on- and off-ramps especially at major interchanges.

To increase public compliance of the system, photo enforcement of speed limits is an option which may be implemented upstream of congested sections near critical detectors to reduce congestion and prevent traffic from breaking down downstream. It should be noted that even a fully functional system may not depict benefits if the public largely does not comply with the posted speed limit.

The VSL activation logic should be developed based on a combination of real-time and archived data. The archived data should be used mainly in case the real-time data is not available. The current logic is based on very simple rules based on three main parameters of traffic flow. A detailed algorithm based on real time data should be developed which takes into account traffic conditions upstream and downstream of congested conditions. The algorithm before implementing the suggested speed limits should be capable of evaluating the future traffic conditions by simulating the segments with near real time traffic data and suggested variable speed limits. Further improvements to the suggested variable speed limits, therefore, can be made from the results of simulation and the modified speed limits then used with the VSL system.

It was observed on I-270 that the dynamic message boards are currently used mainly for the purpose of displaying travel time to different exits. An important usage of the dynamic message signs is to divert drivers to other routes before they reach congested segments of I-270. However, this is not carried out. Effective measures are required to implement diversion of drivers in real time before they reach congested segments. The dynamic message signs when used effectively in tandem with variable posted speed limits will reduce congestion and improve traffic flow.

SAFETY

The safety assessment of the VSL system found that the I-270 corridor has shown a positive trend in crash reduction from the VSL pre-deployment (2007) period to the VSL post-deployment (2009). In 2009, the I-270 corridor had the lowest crash rate of all regional interstate. It showed the following crash reductions between 2007 and 2009:

- Eleven percent less total crashes
- Three percent less rear-end crashes (rear-end crashes represented 55% of all crashes)
- Hourly crash comparison (2007 to 2009) showed a reduction of crashes of almost 80 crashes in the morning peak period with about same number of crashes in the afternoon peak period when the VSL system is most active.
- Two different statistical analysis methods showed crash reduction of 4.5 to 8%. Regional positive highway safety trends and the VSL system deployment were probably contributors.

These factors and other related information found during the safety assessment lead to our initial findings that the VSL system has played a part in safety improvements along the I-270 corridor.

1. Assessing only one year of crash data may not truly show all potential benefits. Safety trends across Missouri and the US are all showing positive trends. Three to five years of after VSL deployment are needed to substantiate initial findings.

2. The project's work plan was developed to analyze the whole corridor as single entity. While investigating the whole corridor, it was found that a roadway segment analysis might be a better analysis method. Roadway segments would be analyzed on individually segment or group segments based on certain criteria. It could be possible to evaluate a certain group of homogenous segments with similar properties like roadway sections with more than 3 lanes in a direction of traffic flow or section with auxiliary lanes between interchanges. This more in-depth analysis would require extensive review of individual crash reports and could not be completed under this study.

3. Crash types and associated causes should be further analyzed with additional years of crash data. Compared to year 2007 and 2009, the read-end crashes decreased by 3% (from 58% to 55%). To statistically validate this observation, each crash type or cause can be analyzed separately. Additional crash data in future years could substantiate the rear-end crash reduction.

4. Secondary crashes should be analyzed with additional data. For this type of analysis, the crash data should be collected with time of crash occurrence, actual responding emergency staff narratives, etc. This effort would have required additional time and resources to complete, but could provide some in-sight into motorist's awareness and reaction to see a reduced speed limit and congestion ahead.

The Safety Performance Function (SPF) that was used in the statistical safety analysis could be extended with multiple variables. In this study, the SPF is simplified using only VMT (AADT), but other explanatory variables can be tested to better fit the crash data. For instance, existence of an interchange, number of lanes, horizontal or vertical curves within the segment can be considered as potential variables.

STAKEHOLDER PERCEPTIONS/PUBLIC AND LAW ENFORCEMENT OPINIONS

Publicly funded transportation management systems such as VSL are heavily dependent on stakeholder acceptance for full success. Stakeholders function as consumers in this case assigning value to the VSL initiative similar to that found with the introduction of new products. [Note: as a relevant example, public perceptions of dissatisfaction with ramp-metering in Minnesota led to a deactivation of the system; additional review and public opinions following deactivation determined that the system had been effective. See http://www.dot.state.mn.us/rampmeterstudy/execsumnov2001.PDF]

MoDOT has significant goodwill accrued through its successful planning, implementation, and management of the I-64 redesign. The VSL implementation publicity and public education efforts took a necessary back-seat to the needs of the I-64 project. Although it is doubtful that failure or perceived failure of the VSL system will erode the significant trust and goodwill established through the I-64 project with respect to highway design projects, negative perceptions of VSL can have negative outcomes on future intelligent system projects (expansion of VSL, ramp metering, etc.). MoDOT can best address this issue through a concerted effort to control the message, whether good or bad, regarding the future of VSL in St. Louis and throughout Missouri.

Our recommendations include:

1. MoDOT should prepare a series of press releases and educational media for better explanations of goals and proper use of the VSL.
2. Findings regarding mobility and safety need to be used in combination with stakeholder responses to clarify findings and address concerns.
3. Talk with law enforcement regarding ways to support enforcement objectives. Mandatory enforcement of VSL speed limits was inconsistent with enforcement policies and objectives for I-270 both in theory and practice. Law enforcement reported that VSL signs in other locales served an advisory, rather than enforcement function; this should be evaluated for the St. Louis VSL system.
4. MoDOT should investigate ways to make the VSL more relevant to the drivers' experience. Respondents reported perceptions that speeds reduced for no apparent reason and that speed limits were higher than congestion made feasible. Better public understanding and more effective match of speed limits with roadway conditions would improve VSL credibility. This should include a review of the use of dynamic message boards in combination of VSL signs based on law enforcement comments.