

Virginia Transportation Research Council

research report

Investigation of Solutions to Recurring Congestion on Freeways

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<p>Abstract:</p> <p>Persistent daily congestion, which has been increasing in recent years, is commonly experienced for several hours or more during the morning and evening on Virginia's urban freeways. Many of these roadways are at or near capacity, which causes severe delays and backups. One solution to reducing recurring congestion is to add capacity by building more lanes; however, this is usually the last resort as it is an expensive and time-consuming approach. Another strategy proposed to combat recurring congestion is to manage the current freeways so that they operate more efficiently. Reducing congestion through better managed freeways has numerous documented benefits, including reducing travel times, smoothing the traffic flow, increasing average fuel economy, shortening the rush hour period and reducing vehicle queuing.</p> <p>The highway operational strategies implemented to reduce recurring congestion have shown promising results abroad where there is an extensive use of active traffic management systems. To prove the effectiveness of a better managed freeway in mitigating recurring congestion, this study tested the effectiveness of an active traffic management system on a simulated model of I-66 and I-95 in Northern Virginia. Hard shoulders, variable speed limits, and ramp metering are several active traffic management systems simulated in this study. The simulation model was based on the geometric characteristics, ramp volumes, vehicle flows, and speeds of actual recorded conditions. Compared with the simulated control conditions, the results of the study indicated improvements in average fuel economy, travel delay, delay of the onset of congestion, and reduction of queues. The two active traffic management systems, i.e., variable speed limits and hard shoulders, showed the highest potential for reducing recurring congestion and should be considered as potential countermeasures in congested corridors.</p> <p>Although the capital costs of implementing these strategies would be high, the return on investment in the first year of operations is estimated at \$500,000, with the potential to grow to as much as \$8 million annually in subsequent years.</p>				

FINAL REPORT

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ABSTRACT

Persistent daily congestion, which has been increasing in recent years, is commonly experienced for several hours or more during the morning and evening on Virginia's urban freeways. Many of these roadways are at or near capacity, which causes severe delays and backups. One solution to reducing recurring congestion is to add capacity by building more lanes; however, this is usually the last resort as it is an expensive and time-consuming approach. Another strategy proposed to combat recurring congestion is to manage the current freeways so that they operate more efficiently. Reducing congestion through better managed freeways has numerous documented benefits, including reducing travel times, smoothing the traffic flow, increasing average fuel economy, shortening the rush hour period and reducing vehicle queuing.

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INTRODUCTION

Highway congestion accounts for billions of gallons of wasted fuel, vehicle hours of delay, and dollars in lost productivity each year.¹ This congestion is a direct result of any combination of the following: limited highway capacity, bottlenecks, traffic incidents, construction, and weather. Among all the types of congestion combined, recurring congestion on highways accounts for 40 percent of the total delay in hours, which is more than the delay from construction and traffic incidents combined.² Innovative control devices and new congestion mitigation techniques have been developed to reduce the impact of bottlenecks, smooth the flow of traffic, increase average fuel economy, reduce travel delay, delay the onset of congestion, and improve the overall commute.

Northern Virginia is plagued with 2 of the top 18 worst congested highways in the nation.² I-66 and I-95 heading into and out of the Washington, D.C., area handle roughly 196,000 and 267,000 vehicles per day, respectively, during peak periods.² Bottlenecks on these segments of highway reduce capacity and increase travel times during peak periods. A bottleneck can be anything from a physical feature of the highway, such as an entrance ramp with merging traffic, to a reduction in the number of lanes. A bottleneck subsequently causes drivers to brake, which in turn creates a disturbance in the traffic flow, resulting in vehicle queues. The impact of bottlenecks and the resulting congestion on Northern Virginia can be potentially mitigated by applying operational changes to I-95 and I-66.

PURPOSE AND SCOPE

The purpose of this research was to develop and test the effectiveness of active traffic management strategies for reducing recurring congestion on a simulated model of I-95 and I-66 in Northern Virginia to determine which congestion mitigation techniques would have the highest likelihood of success at reducing recurring congestion.

To make this determination, the simulation models were based on the flow, speed, routing, and geometric characteristics of actual conditions and selected mitigation techniques were tested in these models.

METHODS

Seven tasks were completed to achieve the study objectives:

1. A literature review was conducted.
2. Highway segments were selected for study.
3. Congestion-related performance measures were selected for study.
4. Congestion mitigation techniques were selected for study.
5. Congestion mitigation techniques identified in Task 3 were developed for use in the simulation network model.
6. Congestion mitigation techniques and combinations thereof were tested on each highway study segment.
7. The results of the simulations were analyzed, and recommendations were developed.

Literature Review

A literature review of congestion mitigation practices in the United States and abroad was conducted. Further, the congestion mitigation techniques currently being used on I-95 and I-66 were identified and the extent of their functionality was documented. The main focus of the literature review was on experimental and innovative recurring congestion mitigation practices, such as variable speed limits and advanced ramp metering algorithms. The literature review also included relevant performance measures to quantify the results.

Sources for the literature review included the VDOT Research Library, TRIS, Worldcat, TLcat, University of Virginia engineering databases, and department of transportation websites. Since much innovation in congestion mitigation comes from abroad, a substantial amount of information was obtained from international transportation sources such as ITS International and international departments of transportation.

Site Selection

Specific regions of Northern Virginia were selected for the study. From those regions, freeway segments were chosen using the following criteria:

- availability of roadway data
- quality of detector data
- availability of modeling data
- level of congestion
- recommendations from the Virginia Department of Transportation (VDOT).

Since this study was developed in response to congestion in the Northern Virginia region, I-66 and I-95, which are the two main freeways leading into and out of Washington, D.C., were selected for study. At the time of site selection, I-395, I-495, and I-66 inside the Capital Beltway were not chosen because of the limited availability of detector data. Moreover, a network model available from a previous research effort influenced the geometric scope of the study area. The network model used for this study was adapted from the Northern Virginia VISSIM Network Model, which was developed at the University of Virginia in conjunction with the Smart Travel Laboratory, a joint effort of the University of Virginia's Center for Transportation Studies and VDOT. The specific segments of I-66 included the eastbound and westbound directions between the Route 15 interchange at Exit 40 and the I-495 interchange at Exit 64. The specific segments of I-95 included the northbound and southbound directions between the Russell Road interchange, Exit 148, and the I-495 interchange, Exit 170. The length of the study area for I-66 eastbound and westbound was 20.7 mi and 20.74 mi, respectively. The length of the study area for the I-95 northbound and southbound segments was 24 mi in each direction. Maps of the I-66 and I-95 study segments and interchange layouts are provided in Appendix A. Since the focus of the study was recurring congestion, peak periods during the morning and evening rush hours on I-95 and I-66 were analyzed between 5 A.M. and 8 A.M. and between 3 P.M. and 7 P.M. Figure 1 highlights the selected freeway segments, and Appendix A shows details of the interchange locations and configurations.

An analysis of the high-occupancy vehicle (HOV) lanes for I-95 was not within the scope of this study because they are barrier separated; however, the vehicle flows for their on and off ramps were taken into account. In addition, a specific analysis of the HOV lanes for I-66 was not included in the scope of the study, although the impact of vehicles moving across the general purpose lanes to and from the HOV lane was captured. As is discussed later, the way in which the simulation model operates is that once an HOV vehicle enters the system from an on ramp it will immediately move into the HOV lane and remain there until it is designated to exit when it moves immediately toward its assigned off ramp. With this being the case, there was little noticeable interaction between HOV and non-HOV vehicles with regard to the detector data being recorded. Observations showed that an HOV vehicle may pass two or three detector stations at a spacing of 0.2 mi before moving into the HOV lane, where it would remain until it exited; further, no undesirable or unnatural vehicle backups were witnessed in these locations. When HOV vehicles moved between the mainline lanes and the HOV lane, they were subsequently accounted for using the mainline detectors.

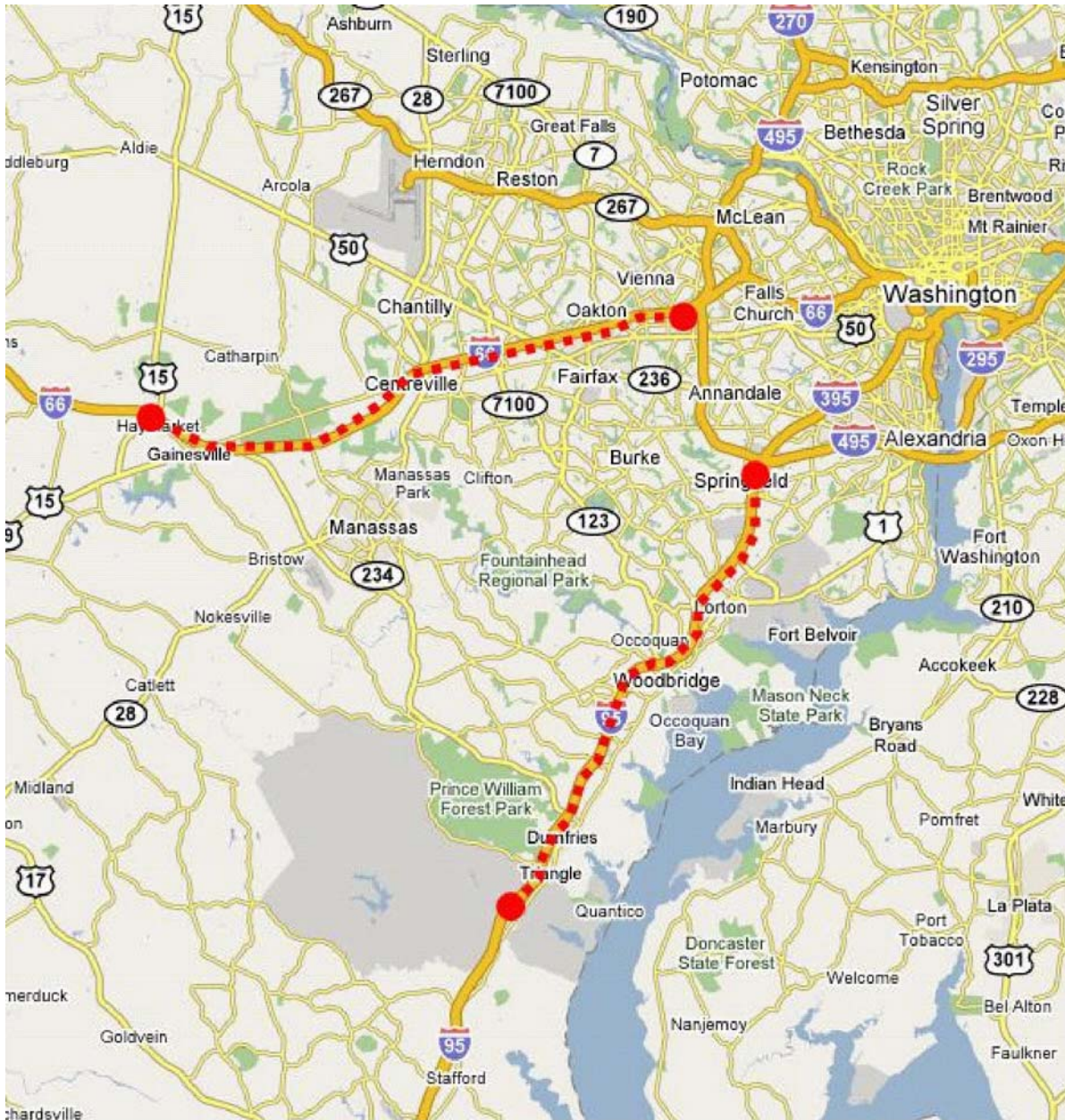


Figure 1. Map Showing Selected Freeway Segments

Selection of Congestion-Related Performance Measures

Because of the study’s emphasis on congestion identification, it was important that the performance measures used properly reflect and quantify congestion. In addition, it was essential that they be easily understood by engineers and the public alike. The performance measures were calculated from the aggregate data recorded during the simulations. These data included 5-min averages of speed, flow, occupancy, vehicle mix, travel time, and vehicle counts.

The performance measures chosen for this study that best demonstrate congested conditions and the later improvements included:

- ramp queue length
- average flow
- average lane occupancy
- average speed
- vehicle miles traveled (VMT)
- travel delay
- average fuel economy in congestion.

Ramp queue length and VMT were chosen as performance measures to indicate whether or not the tested system had an adverse effect on the arterials and the number of vehicles the system was capable of processing.

Selection of Congestion Mitigation Techniques

Appendix B lists the congestion mitigations techniques identified in the literature review. From that list, congestion mitigation techniques were developed to be considered for this study (see Appendix C). Then, several systems were chosen to be tested for their potential effectiveness in reducing recurring congestion based on the following criteria:

1. proven effectiveness in reducing congestion
2. untested combinations of techniques
3. relative ease of implementation
4. minimal required infrastructure modifications
5. ability to interact and complement other congestion management techniques.

Using these criteria, two congestion mitigation techniques were selected for this study: variable speed limits (VSL) and hard shoulders (HS) running.

Development of Simulation Network

In collaboration with other researchers at the University of Virginia, a comprehensive network of the Northern Virginia freeway system was developed. The software package used to develop the model was PTV Vision's VISSIM, a microscopic behavior-based vehicle simulation program. In developing the network, Google's Google Earth application was used in conjunction with VDOT's GIS Integrator to collect geometric characteristics. The Northern Virginia Transportation Operations Center provided operational details for the ramp metering, HOV, and HS systems. Vehicle counts were collected from traffic videos and available data from the Archived Data Management System (ADMS); these counts were then used to determine vehicle origins and destinations. Travel time data collected from a VDOT-sponsored I-66 study and an I-95 global positioning system (GPS) driving study conducted for this project were used to calibrate the model further to verify it against actual driving conditions.¹⁶ The selected congestion mitigation strategies were then incorporated into the simulation model.

Variable Speed Limits

Complex algorithms have been developed for many of the European active traffic management systems using VSL; however, the coding for these systems is not publicly available. With this being the case, the study modified a version of a publicly available VSL code, which is described as follows:¹⁷

1. Identify bottlenecks and choke point locations.
2. Place detectors in areas of congestion, and collect occupancy, speed, and flow data for developing congestion.
3. Plot speed-flow and speed-occupancy curves.
4. Associate corresponding flow and occupancy with optimal speeds.
5. Develop coding using the optimal speed, flow, and occupancy from Step 4.
6. Input speed decision points and detectors at bottleneck locations.

The actual layout of the VSL system included a combination of detectors and speed decision points, with an emphasis on the interchange locations. Figure 2 is an example of the downstream and upstream VSL system layout for a typical bottleneck location.

The system updated the speeds every 5 min using averaged flow and occupancy data. For all VSL stations upstream of bottlenecks, detectors were placed 1 mi downstream of the speed decision point and the detectors themselves were placed just upstream of the bottleneck. The reason for placing the detectors immediately upstream of the bottleneck was to identify as close to the time as possible when the bottleneck was activated so that mitigation techniques might be implemented. This was done to allow sufficient time and distance for vehicles to reduce their speed in case of any downstream congestion. For all VSL stations downstream of bottlenecks, there was just a ½-mi separation between the speed decision point and the detectors. This distance is shorter because if there is no downstream congestion, it is important for vehicles to return to normal operating speeds.

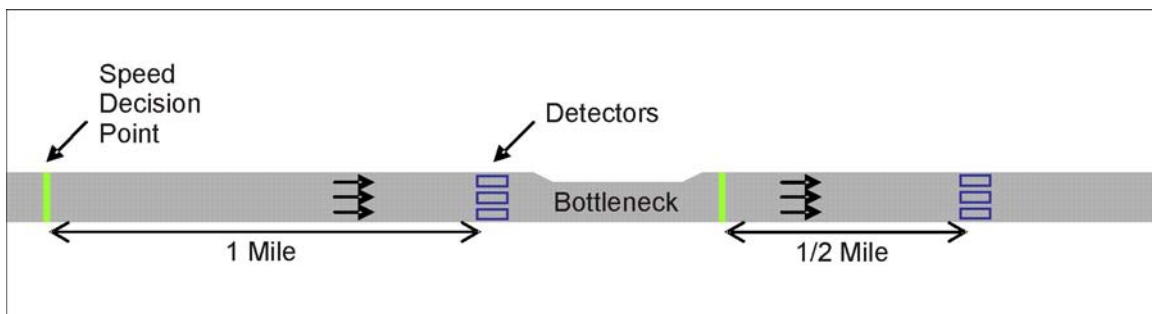


Figure 2. Typical Layout for Variable Speed Limit (VSL) System

Hard Shoulders

Although HS are currently used as part-time travel lanes on portions of I-66, this does not occur on I-95. A careful review of VDOT’s Digital Photo-Log, aerial photography, and a video driving survey by the research team showed that the I-95 northbound and southbound directions have adequate shoulder space for vehicles to travel during congested times. The HS system evaluated in this study for I-95 extended the entire length of the study area from the Russell Road interchange, Exit 148, to the Springfield Interchange, Exit 170. Although the study period extended a full 3 hr, the northbound and southbound shoulders are open to travel for only 2.5 hr beginning 30 min after the start of each simulation. It should be noted that no attempt was made to determine the design adequacy of the shoulder pavement. Confirmation of adequate pavement structural characteristics would be required before considering implementation of HS use on any roadway.

Simulation Testing

A total of 24 testing scenarios were developed for I-95 northbound and southbound and I-66 eastbound and westbound in the study area. Each scenario was run five times to test the variation among the different runs at a resolution of 10 steps per simulation second, which means that every vehicle’s position was calculated 10 times per second. A random seed was also used so that each simulation was different; the random seed rate increase was set at 1. Once the five runs were completed, a random run was pulled from one of the five simulations to be used for data analysis. A statistical analysis of the travel times for all simulation runs for each of the 24 tested scenarios verified that any one of the five simulation runs was representative of the mean of all five runs. The results of the statistical analysis are provided in Table 1.

Table 1. Results of Statistical Analysis

Technique	Correlation Factor	One-Way ANOVA
<i>I-66 Eastbound</i>		
Control	0.997	0.879
VSL	0.998	0.471
<i>I-66 Westbound</i>		
Control	0.991	0.610
VSL	0.997	0.381
<i>I-95 Northbound</i>		
Control	0.991	0.371
VSL	0.997	0.438
HS	0.950	0.860
HS + VSL	0.998	0.648
<i>I-95 Southbound</i>		
Control	0.995	0.680
VSL	0.995	0.865
HS	0.984	0.380
HS + VSL	0.997	0.739

ANOVA = analysis of variance, VSL = variable speed limits, HS = hard shoulders.

First, a Pearson correlation analysis of the travel times was conducted, which indicated that the travel times all belonged to the same population. Next, a one-way analysis of variance (ANOVA) was conducted on the travel times to show that the dataset from each individual run was representative of the mean. For the ANOVA, a 99 percent confidence interval was used. The lowest correlation factor reported among the five runs for each of the scenarios is shown in Table 1 along with the p -value from the one-way ANOVA. The closer the correlation factor is to 1 represents how that dataset falls within the entire population. The final results of the statistical analysis indicated that any of the five simulation runs is representative of the mean of all five simulation runs for every tested scenario. For this study, a 3-hr simulation took an average of 20 to 30 min to run on a Pentium 4, 3.2 GHz, desktop computer with 500 MB of RAM.

Simulation Analysis

The simulation data were collected from detectors and then input into Microsoft Excel for data analysis. The collected data were compiled into 5-min averages of speed, occupancy, and total vehicle counts. Using the vehicle counts and the interval time, the hourly flow was calculated. Travel times and vehicle counts were obtained from the travel time records. With these aggregate data, charts and tables were developed to facilitate data analysis of the following:

- ramp queue length
- spatial flow plot
- spatial occupancy plot
- spatial speed plot
- VMT
- travel delay savings
- average fuel economy.

Many of the tables and charts reflect the improvement over control conditions. It should be noted that it takes approximately 15 to 20 min for the network to become fully populated with vehicles at the beginning of each simulation run. To ensure that the network was at full operating capacity, a 30-min warm-up period was taken into account for the data analysis. Little weight was given to results recorded during the first 30 min. The spatial plots developed using the speed, occupancy, and flow data assisted with identifying bottlenecks, shockwaves, queue lengths, and delays. Figure 3 is an example of an occupancy spatial plot used in the data analysis.

The following steps summarize the process used for the analysis:

1. Identify shockwaves on spatial plots as compared to control conditions.
2. Cross check the shockwave location and length for each subsequent congestion mitigation scenario.
3. Identify the extent to which congestion is reduced visually on the plots.

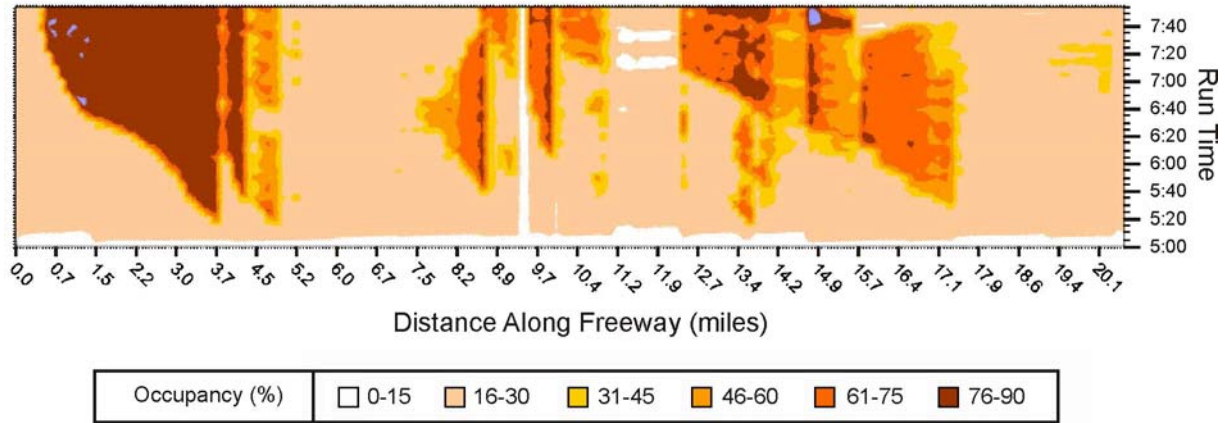


Figure 3. I-66 Eastbound Control Condition Spatial Occupancy Plot

4. Identify improvements in VMT to confirm that the mitigation technique has not reduced the number of vehicles being processed.
5. Check the ramp queuing to ensure arterials are not being adversely affected at the cost of a mainline congestion reduction.
6. Once the location specific benefits are confirmed, check that the entire system’s measures of effectiveness (MOE) have not been degraded.
7. If the preceding analysis generally indicates improvement, then it is suggested that the particular congestion mitigation technique be identified as having the highest likelihood of success at reducing congestion for the simulated segment.

These steps were repeated for each combination of congestion mitigation techniques.

RESULTS AND DISCUSSION

Literature Review

A majority of the congestion mitigation solutions identified placed a great emphasis on traffic management systems. The simple solution to recurring congestion is to increase freeway capacity by adding lanes; however, this is very expensive, it requires a lot of time, and the increase in congestion attributable to construction activities can be detrimental.⁵

Several themes became apparent with regard to congestion mitigation solutions, including a continued emphasis on Intelligent Transportation Systems (ITS), European innovation and VSL use, and ramp metering using advanced algorithms.⁵ The European experience with congestion mitigation is reported a great deal in the literature.⁶

A number of systems are currently being used for congestion mitigation: however, not all of them are being used in conjunction with one another. Appendix C provides the findings of studies of various congestion mitigation systems found in the literature. VSLs are used extensively and with great success in Europe, but their use in the United States has been limited. In addition, the use of HS is a proven technique for congestion mitigation in Northern Virginia, and the extension of its use is recommended.¹⁵

Simulation Results

The results of the simulation analysis focus on highlighting the performance measures developed in the methodology. They were used to identify improvements in vehicle throughput, traffic smoothing, reductions in travel time, and improvements in overall freeway performance.

The control scenario conditions reflected as best as possible actual conditions on I-95 and I-66. The models are based on actual flow, speed, routing, and geometric characteristics of the selected interstates. The control scenarios are representative of heavily traveled commuter routes and have recorded average occupancies more than 30 percent, speeds at or below 30 mph, and decreased flows, all of which occur for durations greater than 30 min. Ramp queuing and mainline backups occur at every major interchange on I-95 and I-66.

It should be noted that although ramp metering was selected as a strategy to be evaluated in this study, detailed discussions of the scenarios that included ramp metering are not presented here. Initial evaluations of ramp metering indicated that the geometric and traffic flow characteristics of the study segments would require a much more in-depth evaluation, integrating both freeway and arterial operations, to be effective. Since such a complex evaluation was not within the scope of this study, ramp metering as a strategy was eliminated from further consideration.

I-66 Results

Westbound

The simulated VSL system proved to be the most efficient at smoothing the traffic flow, which was indicated by the more consistent overall average speeds, increased overall average occupancy, and increase in the overall average flow. Because speeds were lowered using the VSL system, dangerous speed differentials were eliminated at the Route 29 and Route 123 interchanges. At both of these locations, for the control condition, speeds were dropping from 55 to 15 mph in less than ¼ mi. Conversely, when the VSL system was used, speeds remained consistently at 25 mph through both bottlenecks. Other improvements included the delay of the onset of congestion and the shortening of queues. At the last Route 29 interchange just before the end of the study area, congestion was delayed by a full 20 min before it began forming. Further, a major queue was reduced in length by 0.4 mi in the vicinity of the heavily congested Route 7100 interchange. Overall, the benefits of the VSL system on I-66 westbound came in the form of smoother flowing traffic, delays of congestion, and reductions in queues.

Eastbound

The VSL system on the eastbound direction of I-66 performed in a similar fashion with respect to reductions in speed differentials and traffic smoothing. However, reductions in queues were less apparent. Despite this, there was one reported instance of congestion being delayed from forming by a full 65 min in the vicinity of the Route 28 interchange. As for the control conditions, speed reductions from 60 to 15 mph occurred within ¼ mi approaching the Route 234 and Route 29 interchanges; speeds remained constant at around 25 to 35 mph through both interchanges with the VSL system, indicating that speed variation is reduced over control conditions when the VSL system is used. By calculating the standard deviation in speed over the entire network, the dispersion of speeds helped identify speed harmonization conditions on the freeway. The standard deviation of speeds over the entire freeway for the test period under the control conditions was 17 mph, versus 9 mph for the VSL system. Taken as a whole, speed harmonization, traffic smoothing, and a delay in congestion were all observed with the VSL system on the simulated I-66 eastbound segment.

Vehicle Miles Traveled

In both directions of I-66, decreases in VMT were recorded for each segment. Although there were decreases in VMT, the difference was small, with just a 1 percent and a 1.5 percent difference in VMT for the westbound and eastbound directions, respectively. The I-66 VMT results are presented in Figure 4. Although there was a decrease in VMT, for comparison purposes, the decrease was minimal at less than 1.5 percent; therefore, the simulated network maintained an acceptable level of vehicle processing ability.

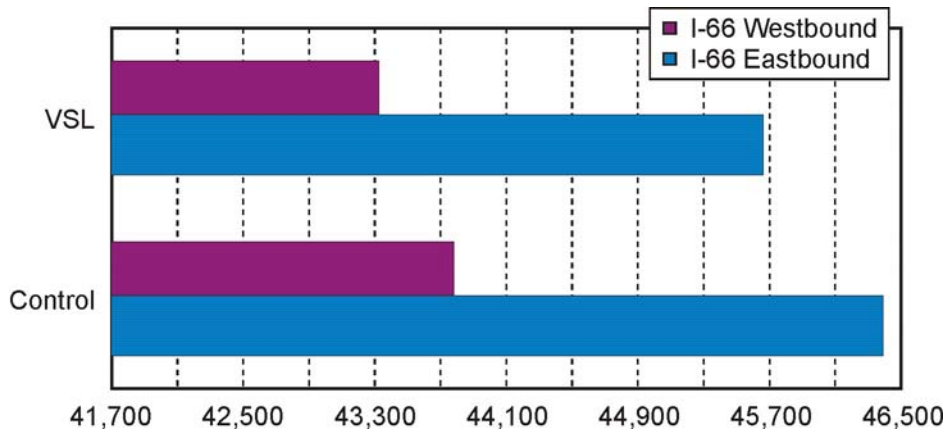


Figure 4. I-66 Graph of Vehicles Miles Traveled. VSL = variable speed limit system.

Travel Delay

The VSL system for the eastbound direction performed poorly with regard to reducing travel delay; the time it would take to traverse the entire 20-mi segment in congested conditions increased by a little more than 1 min. This increase in travel time was due to the fact that the average speed recorded for the entire eastbound simulation segment was a full 17 mph slower than for the control condition. Conversely, for the westbound direction, a 1-min reduction in total travel time over the entire segment was reported using the VSL system. Since the changes

in travel delay for the eastbound and westbound segments were not large, at just a 1-min difference, the VSL system had little impact on the overall travel time on the simulated eastbound and westbound segments of I-66. The mainline detectors were placed across all lanes at 0.2-mi increments, and the average of each of these adjacent lane detectors was taken; therefore, individual improvements in lane performance such as with the HS could not be identified.

Average Fuel Economy

The calculation used for the average fuel economy is described in the Texas Transportation Institute’s *The 2005 Urban Mobility Report* and is one performance measure used to rank congestion on a national level.³ Although the gains in fuel economy using the simulation were modest, they were gains nonetheless, and daily commuters would realize the effects of these over time.

The average fuel economy for I-66 westbound and eastbound is shown in Figure 5. There was little with regard to gains in fuel economy. In fact, for the eastbound segment, the average fuel economy decreased due to the fact that the overall average speed decreased by 17 mph from the control condition. Since the variation in average fuel economy was less than 0.5 mpg, any advantages or disadvantages over using VSL were not large. The variation in fuel economy from control conditions was less than 1 percent for the eastbound and westbound segments; therefore, the VSL system is more akin to the control condition with regard to average fuel economy.

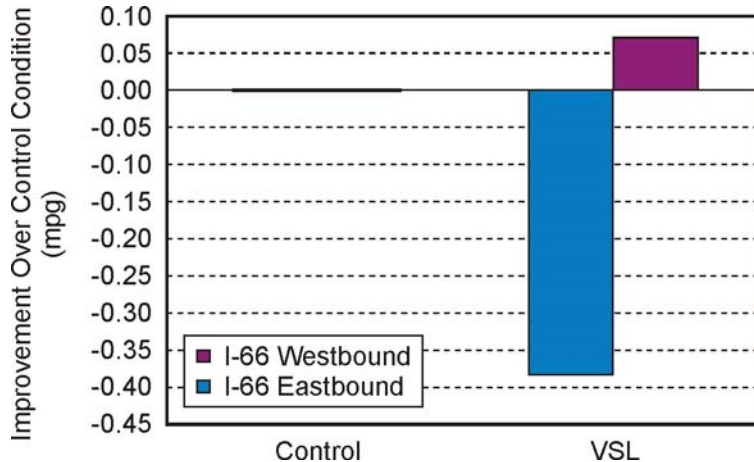


Figure 5. I-66 Average Fuel Economy. VSL = variable speed limit system.

I-95 Results

Northbound

There was one major difference between the I-95 northbound simulations and the I-66 simulations: the addition of an HS system, which improved the overall speed and occupancy results. Increases of 14 percent in average speed over the entire segment were achieved using the HS system and of 16 percent using the combination HS and VSL system. The VSL system was tested alone on I-95; however, the degree of improvement was not seen using only the VSL

system as compared to the combination VSL and HS system. An in-depth analysis of the VSL system alone is not included here since there were better performing systems, such as the combination VSL and HS system.

A 4-mi segment between the Route 234 and Route 784 interchanges saw a reduction in occupancy levels of 66 percent. The combination HS and VSL system performed similarly to the HS system with regard to overall average speed and overall average flow. Table 2 shows the overall average speeds and flows for the entire length of the freeway for the control, HS, and combination HS and VSL scenarios. One difference between the control condition and the combination HS and VSL scenario was the 4.8 percent variation in flow. This difference can be explained by the fact that the overall average flow was more consistent and smoothed using the combination HS and VSL system whereas the control condition had large differences in flow throughout the entire segment, which decreased the average. In addition, the overall average speed for these segments was improved by 14 percent using the HS and combination HS and VSL systems.

The most substantial improvement over the control conditions for the combination HS and VSL system was the reduction of a queue by 3.4 mi, which originated in the vicinity of the Route 123 interchange. Stemming from the Route 234 interchange, a 2.5-mi-long backward propagating shockwave, affecting traffic for more than 75 min, was eliminated on this segment. Numerous other shockwaves were reduced or eliminated using the combination HS and VSL system; in total, five minor shockwaves were mitigated. For comparison purposes, the smallest of the five shockwaves located just prior to the I-495 interchange underwent a 15-min reduction in total activation time and was shortened in length by 0.6 mi. Another noticeable improvement over the control condition was the reduction in overall average occupancy using the combination HS and VSL system. The average occupancy dropped by more than 10 percent, from 40 to 30 percent, using the combination HS and VSL system. All in all, the combination HS and VSL system showed a marked improvement over the control condition, with reductions in the number and impact of shockwaves, increases in average speeds, and overall decreased occupancies.

Table 2. Average Total Segment Flow and Speeds for I-95 Northbound Simulation

System	Average Flow (veh/hr)	Average Speed (mph)
VSL + HS	6,608	44
HS	6,416	43
Control	4,716	37

VSL = variable speed limit, HS = hard shoulders.

Southbound

With regard to queue reduction, the combination HS and VSL system had similar results as the HS system alone. Both systems were effective at removing a 4.8-mi-long queue and a 1.8-mi-long queue further downstream between the Route 619 and Route 234 interchanges. Table 3 shows the overall average speed and flow for the entire length of the freeway for the control, HS, and combination HS and VSL scenarios.

One improvement seen over the control condition was a 14.5 percent increase in average speed for the entire freeway segment. As with the northbound segment of I-95, the southbound segment saw another dramatic decrease in average occupancy for the entire freeway.

Table 3. Average Total Segment Flow and Speeds for I-95 Southbound Simulation

System	Average Flow (veh/hr)	Average Speed (mph)
VSL + HS	6,800	55
HS	6,064	52
Control	4,524	47

VSL = variable speed limit, HS = hard shoulders.

A 9 percent drop in occupancy from the overall average of 27 to 18 percent was recorded for the combination HS and VSL system. Substantial improvements in shockwave reduction occurred with the combination HS and VSL system. The greatest improvement in queue reduction came with the elimination of a 6.2-mi-long backup stemming from the Route 123 interchange. In total, five queues were either eliminated or reduced to include the 6.2-mi-long queue previously mentioned. The next most substantial backup removed developed in the vicinity of the Route 619 interchange. This particular queue extended upstream a total of 1.6 mi, affecting traffic for more than 2 hr. The combination HS and VSL system was the most effective in increasing overall average speeds and reducing overall average occupancies; in addition, it removed every large backup identified from the simulated control conditions.

Vehicle Miles Traveled

Similar results occurred with the I-95 simulations as with the I-66 simulations with regard to the VSL alone scenario remaining consistent with the control condition VMT. For the northbound segment, there was a slight decrease in VMT; for the southbound segment, there was a slight increase in VMT; however, both were rather small changes with respect to the control condition. VMT results are provided in Table 4, which highlights the VMT for each segment and displays the percent difference in VMT over the control condition.

With the addition of the HS system, larger increases in VMT were seen. The HS and combined HS and VSL systems performed at or near the same level for the northbound and southbound segments. The northbound segment using the HS and combination HS and VSL systems showed the greatest improvements in VMT over the control condition, with a 26 percent increase in VMT. This increase may be due in part to the increased number of vehicles serviced by the northbound segment over any other simulated segment. It is clear that the HS system and any combination thereof perform very well and do not degrade system performance by reducing the number of vehicles that the simulated segments process.

Table 4. Results for Vehicle Miles Traveled (VMT) for I-95 Simulation

Parameter	Control	VSL	HS	HS + VSL
<i>I-95 Northbound</i>				
VMT	35,276	35,120	44,607	44,696
% difference over control	0.0%	-0.4%	25.5%	26.7%
<i>I-95 Southbound</i>				
VMT	34,432	34,453	39,402	39,931
% difference over control	0.0%	0.1%	14.4%	16.0%

VSL = variable speed limit system, HS = hard shoulder system, HS + VSL = combination HS + VSL system.

Travel Time Savings

The travel time savings for the I-95 southbound and northbound directions are provided in Figures 6 and 7, respectively. Characteristic of previous performance measure results, the HS system continued to outperform any other system tested. The VSL system performed as it did on the I-66 network, with only minimal savings in travel time for the northbound and southbound directions. However, when the VSL system was used in combination with the HS system, a much greater travel time savings occurred. The VSL system provided additional time savings over the HS system, and this was especially evident for the northbound segment, where the VSL system provided an additional 4-min reduction in travel time. The combination HS and VSL system showed the greatest savings in travel time by nearly 12 min for the northbound segment and 7 min for the southbound segment.

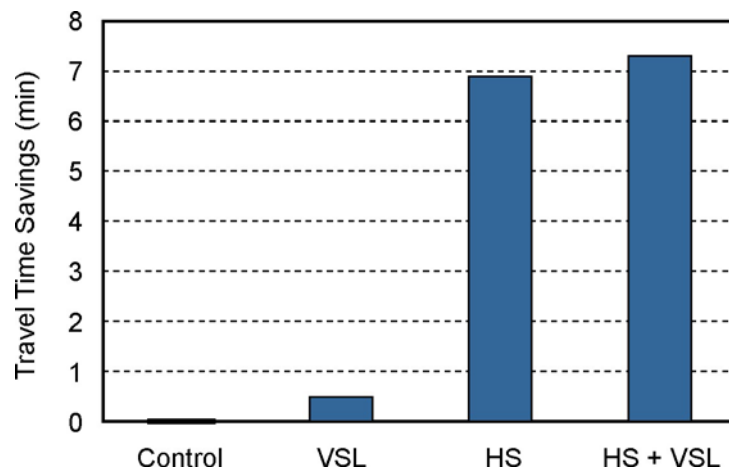


Figure 6. I-95 Southbound Travel Time Savings. VSL = variable speed limit system, HS = hard shoulder system, HS + VSL = combination HS and VSL system.

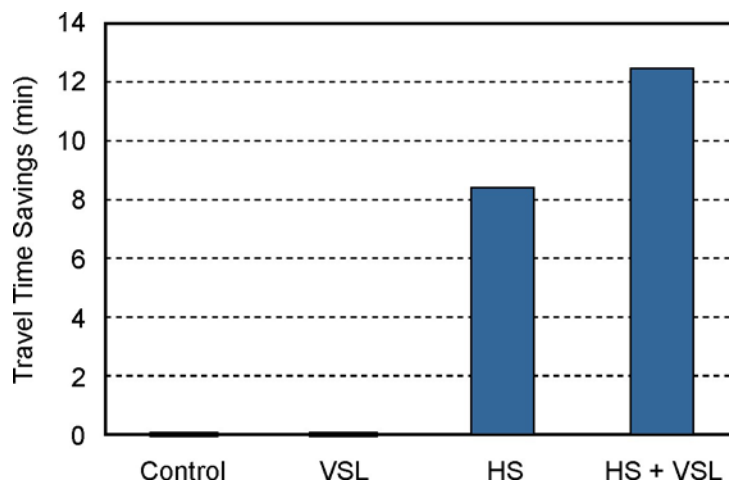


Figure 7. I-95 Northbound Travel Time Savings. VSL = variable speed limit system, HS = hard shoulder system, HS + VSL = combination HS and VSL system.

Average Fuel Economy

In comparison to I-66, the increase in fuel economy was substantial for the northbound direction of I-95 and even more so for the southbound direction. The average fuel economy for I-95 is shown in Figure 8. Since the overall speeds recorded were much slower for the northbound direction than for the southbound direction, the southbound VSL system did not perform as well. Again, because of the reduction in congestion using the HS system, the VSL system was able to increase further the average fuel economy for the southbound segment. This, however, was not the case for the northbound segment as the HS and combination HS and VSL systems had similar average fuel economy results. The best performing congestion mitigation system simulated on I-95 was the combination HS and VSL system, which resulted in an increase of 2 and 4.5 mpg for the northbound and southbound segments, respectively.

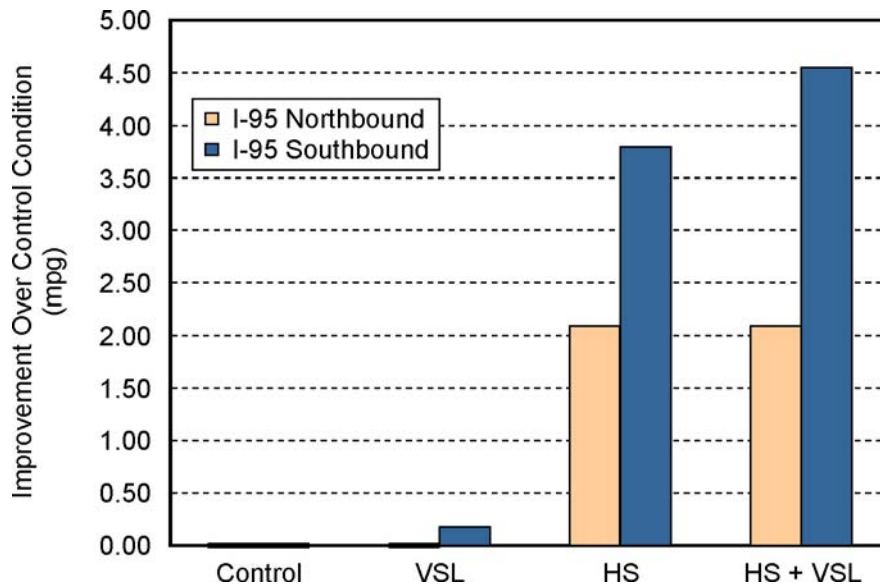


Figure 8. I-95 Average Fuel Economy. VSL = variable speed limit system, HS = hard shoulder system, HS + VSL = combination HS and VSL system.

Congestion Fail Points

Although the congestion mitigation systems tested on each segment showed overall improvements, there were selected portions where congestion was beyond the ability of any of the tested operational improvements to mitigate. In the instances where a congestion fail point existed, this location may have been beyond the ability of any operational improvements and might have required significant geometric expansion to alleviate recurring congestion issues. The following were the specific segments identified as congestion fail points:

- *I-66 Westbound*
 - between mile markers 42 and 45
 - between mile markers 50 and 51.

- *I-66 Eastbound*
 - between mile markers 53 and 44
 - between mile markers 63 and 59.
- *I-95 Southbound*: between mile markers 157 and 153.

No congestions fail points were identified for I-95 Northbound.

CONCLUSIONS

- The primary impact of variable speed limit (VSL) systems in congestion reduction is through delaying the onset of congestion and smoothing traffic flows. Further, VSLs are beneficial at eliminating dangerous speed differentials and subsequently smoothing vehicle speeds through bottlenecks.
- VSL systems do not operate well after heavy congestion forms; they provide relief before this state is reached and delay its occurrence.
- Temporary capacity upgrades such as the use of hard shoulders (HS) are the most effective at increasing average speeds, shortening queue lengths, lowering occupancies, improving average fuel economy, and reducing travel delay.
- VSL and HS systems work well together because HS systems are capable of reducing the congestion level to a point that is opportune for VSLs to operate effectively. The combination of VSL and HS reduces congestion more so than HS alone.
- Ramp metering remains a viable alternative for the Northern Virginia region; however, an integrated analysis of freeway and arterial facilities should be undertaken to quantify the potential benefits
- Some bottleneck locations on the simulated I-66 and I-95 segments are beyond the ability of any operational changes tested to mitigate congestion and may require substantial construction to remove them.
- A standard congestion mitigation strategy for all bottlenecks is not feasible because of the variability in congestion characteristics and driver behavior.
- PTV Vision's VISSIM is an effective freeway simulation tool. VISSIM's ability to be programmed allows for congestion mitigation strategies to be easily customized and integrated into a network model.

RECOMMENDATIONS

1. *Based on the results of the simulation model for I-95, staff of VDOT's Northern Region Operations should further consider the combination of hard shoulders and variable speed limits as a potential solution to reduce travel delay, delay the onset of congestion, reduce queue length, increase average speed, and increase average fuel economy. Specific design and safety issues related to shoulder use should also be investigated.*
2. *Based on the results of the simulation model for I-66, staff of VDOT's Northern Region Operations should consider variable speed limits as a potential solution for reducing queue lengths, delaying the onset of congestion, smoothing the traffic flow, and reducing speed differentials.*

COSTS AND BENEFITS ASSESSMENT

This simulation study demonstrated the benefits of the use of HS running and VSLs in reducing delay on congested roadways. Although the cost of implementing these systems is great, the delay savings they would provide to motorists would result in a positive return on investment.

A recent study conducted for the staff of Northern Region Operations estimated the cost of an enhanced shoulder use system for I-66 at approximately \$6 million.²¹ The VSL system deployed as part of the Woodrow Wilson Bridge project (a leased system) has an estimated cost of \$1.5 million per year.²² Given the synergies between the systems (both involve the deployment of cameras, signs, and detectors), a combination HS and VSL system similar to that tested in this study could cost approximately \$8 million in capital costs.

This study estimated delay savings of approximately 7 min per vehicle on I-95, which equates to approximately \$9.5 million in delay savings for a 4-hr commute period (morning and evening) over the course of 1 year. Although the return on investment in the first year would be relatively small at \$500,000, subsequent years would see very high returns, even after operating and maintenance costs were considered.

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APPENDIX A
STUDY AREA MAPS

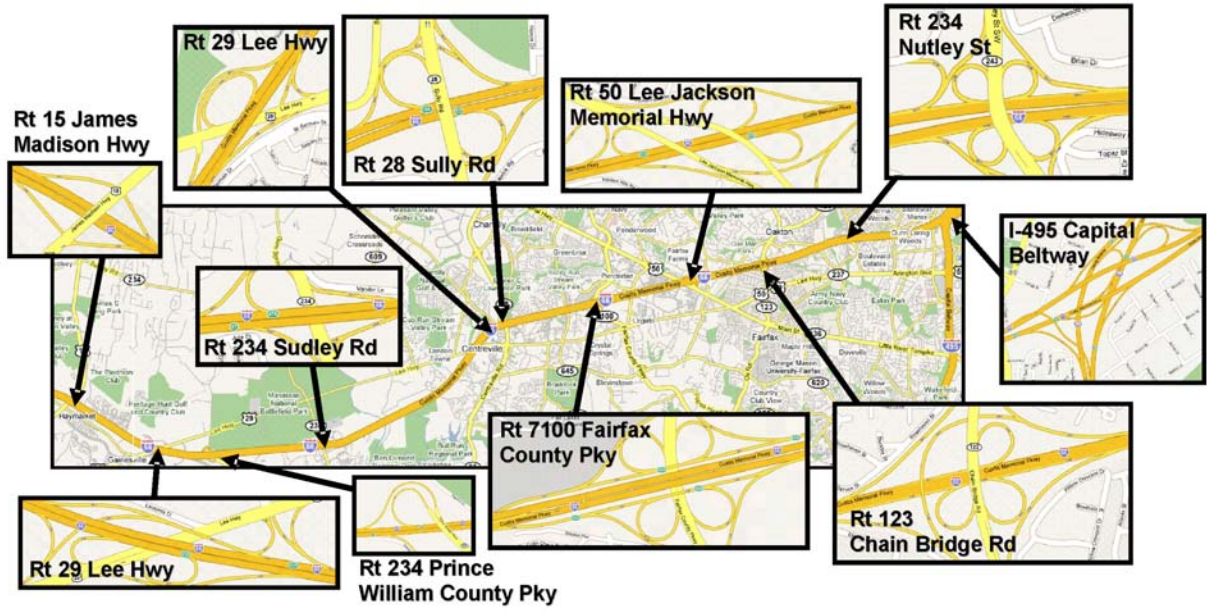


Figure A-1. Map of I-66 Study Area with Interchange Locations and Configurations

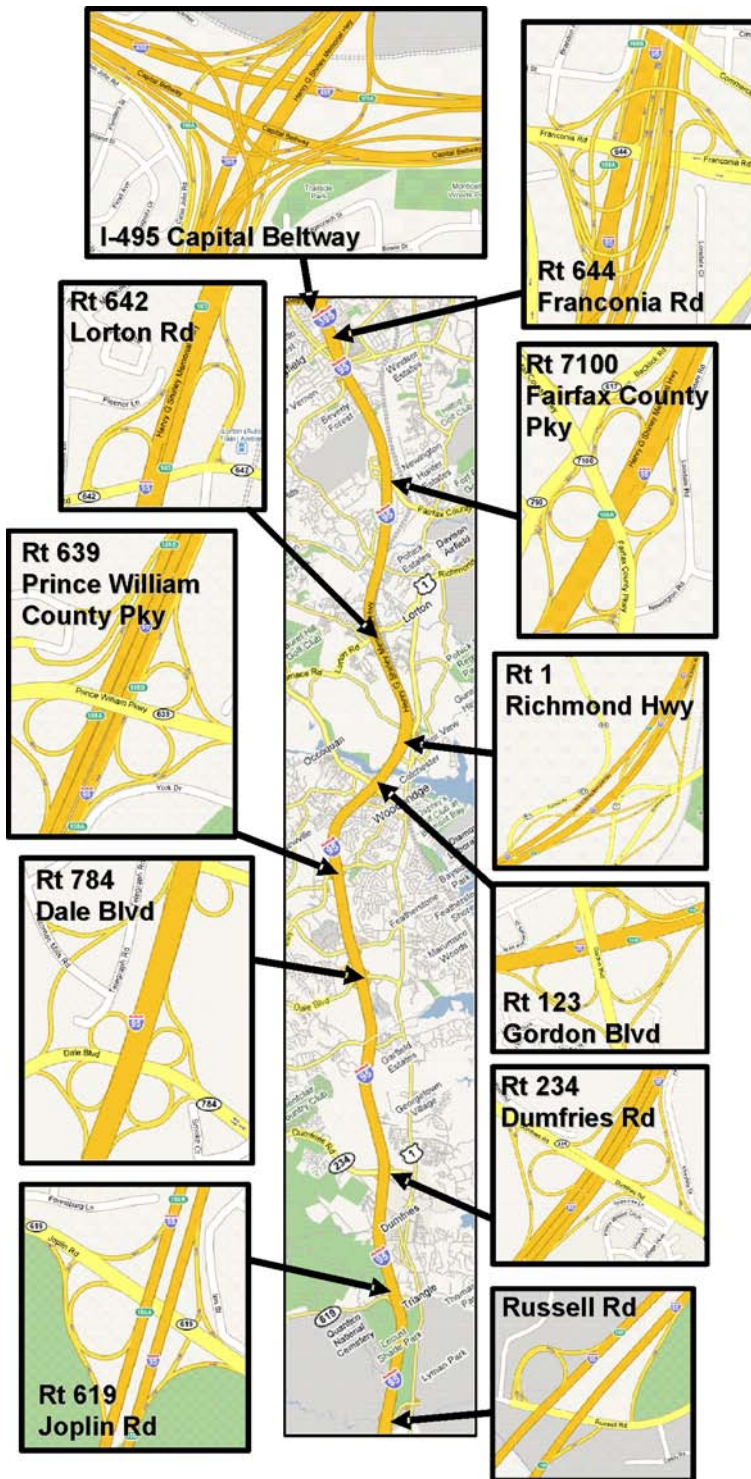


Figure A-2. Map of I-95 Study Area with Interchange Locations and Configuration

APPENDIX B

CONGESTION MITIGATION SYSTEMS AND THEIR ASSOCIATED BENEFITS

Association/ Project Name	Technologies	Benefits	Reference No.
Amsterdam's Lane Management System (The Netherlands)	Lane control signs, VSL, dynamic message signs	23% decrease in accidents, high compliance rate	7
Make Better Use, The Highways Agency (U.K.)	Tidal flow, dedicated lanes, ramp metering, VSL, HS running, dynamic lanes	5% to 10% increase in freeway throughput	18
London's Ring Road (U.K.)	VSL, managed lanes	10% to 15% reduction in accidents, high driver approval rating	18
Optimal Coordination of VSL to Suppress Shockwaves (The Netherlands)	VSL	Minimized total time vehicle spends in network	19
University of Maryland	VSL	Reduced queue lengths, increased vehicle throughput	10
University of Virginia	VSL	Reduced speed variances	17
University of Waterloo (Canada)	VSL	Significantly reduced total potential for crash	20
A9 Outside Munich (Germany)	VSL	Dissipated upstream forming shockwaves, reduced intensity of shockwaves	21
Delaware DOT	VSL	Reduced pollution on ozone-alert days, lowered speed limits during adverse weather and construction	11
Colorado DOT	Ramp metering	60% increase in mainline speeds, 37% decrease in vehicle hours of travel, significant drops in emissions and accidents	12
Texas DOT	Ramp metering	Savings of almost 3,000 vehicle hours over control condition	12
Texas DOT	Ramp metering	8% increase in throughput, 60% increase in mainline speeds	12
The Highways Agency (U.K.)	Ramp metering	20-min reduction in peak period	12
Dutch Ministry of Transport (The Netherlands)	Ramp metering	3% increase in bottleneck capacity, 13% reduction in travel time	12
Oregon DOT	Ramp metering	Increased average vehicle speeds from 16 to 41 mph	12
Washington State DOT	Ramp metering	Decreased average travel time from 22 to 11 min	12
Minnesota DOT	Ramp metering	25% increase in vehicle throughput	12
VDOT	HS	No increase in accident rates	15
Transportation Research Board	HS	No increase in accident rates	14

VSL = variable speed limits; HS = hard shoulders.

APPENDIX C

CONGESTION MITIGATION TECHNIQUES

Retiming signals/signal optimization
HOV ramp bypass
Changeable lane assignments
Event management
Real time traveler information
Transportation management center operations
Incident management
Lane controls
Managed lanes
Temporary hard shoulders
Work zone management
Ramp closers
Bottleneck removal
Building additional lanes
Variable speed limits
Speed over distance enforcement
Electronic toll collection
Mainline metering
Dynamic lanes
Vehicle diversion
HOV ramp bypass
Traffic control center operations
Automatic incident identification system
High occupancy toll lanes
Helper ramp algorithm
Zone algorithm
Isolated ramp metering
Coordinated systemwide ramp metering
Dynamic late merge
Restriping lanes for more narrower lanes
Minor geometric improvements
Increased shoulder width
Queue detection
No lane change zones
Heavy merge area signage