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Operational and Safety Effects of the I–95 Variable Speed Limit System in Fredericksburg, Virginia

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16. Abstract:
Variable speed limit (VSL) systems have been broadly deployed to address safety and mobility concerns both in the United States and internationally. In June 2022, the Virginia Department of Transportation (VDOT) activated a VSL system on I–95 northbound about halfway between Washington, D.C., and Richmond, VA. This section of I–95 experiences high traffic volumes and densities, resulting in significant delays and unreliable travel times. There are also a high number of congestion-related crashes and incidents. These problems are particularly prevalent on the weekends in the summer when recreational traffic volumes increase. While many past VSL deployments have attempted to address urban congestion or mitigate safety issues due to inclement weather, this deployment was unique in that it was intended to address traffic congestion created by this weekend traffic by encouraging more uniform speed selection, dampening the effects of shockwaves, and providing advance warning of congestion. Only traditional enforcement was performed on this corridor, and no targeted enforcement or automated speed enforcement was used. This report discusses the characteristics of the deployed system, as well as its safety and operational effects, using approximately 17 months of post-deployment data.

Results show that drivers responded to the VSLs, and that mean speeds and speed distributions changed during transitional flow states. Early safety results also showed reductions in crash severity. Travel time and reliability results showed mixed trends, with travel times and reliability generally improving on weekends, but sometimes worsening during the week as compared to the year prior to system activation. An annual benefit of approximately $2.57 million per year, primarily due to safety improvements, was determined, but this value is very preliminary and should be re-examined as additional data becomes available. This report recommends that VDOT and Virginia Transportation Research Council re-assess the system effects after 3 years of data become available and that the VDOT Traffic Operations Division assess whether other locations are likely to benefit from VSL installation.

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FINAL REPORT

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ABSTRACT

Variable speed limit (VSL) systems have been broadly deployed to address safety and mobility concerns both in the United States and internationally. In June 2022, the Virginia Department of Transportation (VDOT) activated a VSL system on I–95 northbound about halfway between Washington, D.C., and Richmond, VA. This section of I–95 experiences high traffic volumes and densities, resulting in significant delays and unreliable travel times. There are also a high number of congestion-related crashes and incidents. These problems are particularly prevalent on the weekends in the summer when recreational traffic volumes increase. Although many past VSL deployments have attempted to address urban congestion or mitigate safety issues due to inclement weather, this deployment was unique in that it was intended to address traffic congestion created by this weekend traffic by encouraging more uniform speed selection, dampening the effects of shockwaves, and providing advance warning of congestion. Only traditional enforcement was performed on this corridor, and no targeted enforcement or automated speed enforcement was used. This report discusses the characteristics of the deployed system, as well as its safety and operational effects, using approximately 17 months of post-deployment data.

Results show that drivers responded to the VSLs, and that mean speeds and speed distributions changed during transitional flow states. Early safety results also showed reductions in crash severity. Travel time and reliability results showed mixed trends, with travel times and reliability generally improving on weekends, but sometimes worsening during the week as compared with the year prior to system activation. An annual benefit of approximately $2.57 million per year, primarily due to safety improvements, was determined, but this value is very preliminary and should be re-examined as additional data becomes available. This report recommends that VDOT and Virginia Transportation Research Council re-assess the system effects after 3 years of data become available and that the VDOT Traffic Operations Division assess whether other locations are likely to benefit from VSL installation.

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INTRODUCTION

Variable speed limit (VSL) systems, which set speed limits dynamically as a function of traffic and/or roadway conditions, have been used both internationally and in the United States to improve traffic flow and safety. A number of evaluations of VSL systems have been conducted, but generalizing results from past field deployments can be difficult. For example, Virginia may implement VSLs as part of a wider active traffic management strategy in a congested urban area, but separating the VSL effects from other treatments may be is challenging (Mirshahi et al., 2007). Similarly, international deployments often use automated speed enforcement to ensure compliance with the VSLs, but use of that strategy limits the transferability of the speed and safety impacts of international VSL deployments to the United States. Within the United States, the decision whether to use advisory or regulatory VSLs can influence VSL effectiveness.

In June 2022, the Virginia Department of Transportation (VDOT) activated a VSL system on I–95 northbound from milepost (MP)115 to 130 just south of Fredericksburg, VA. This section of I–95 experiences high traffic volumes and densities, resulting in significant delays and unreliable travel times. There are also numerous congestion-related crashes and incidents. These problems are particularly prevalent on summer weekends when recreational traffic volumes increase. The goals of the VSL system were to generate consistent travel speeds in the corridor, which encourages smooth traffic flow and speed harmonization. This system differed from many prior U.S. deployments of VSLs because it was deployed on a major regional through traffic corridor primarily to address off-peak recreational congestion. This kind of application of VSLs had not been examined previously in the literature, so a need existed to assess its effects on safety and operations in the corridor.

Site and System Description

Site Characteristics

The I–95 VSL system was installed between MPs 115 and 130 in the northbound direction of I–95 only. This location is approximately midway between the cities of Richmond, VA, and Washington, D.C., and is just south of Fredericksburg, VA. This section has three interchanges at mileposts 118, 126, and 130 as Figure 1 shows. I–95 has three lanes in the northbound direction that carried a directional annual average daily traffic (AADT) of between 50,000 and 57,000 vehicles in 2022. About 11 percent of traffic was tractor trailers, and 3 percent was buses and single-unit trucks. The base posted speed limit is 70 mph from the southern end of the corridor to MP 124.8, transitioning to 65 mph from that point to the northern end of the corridor. Horizontal and vertical curvature does not exert significant influences on traffic speeds.

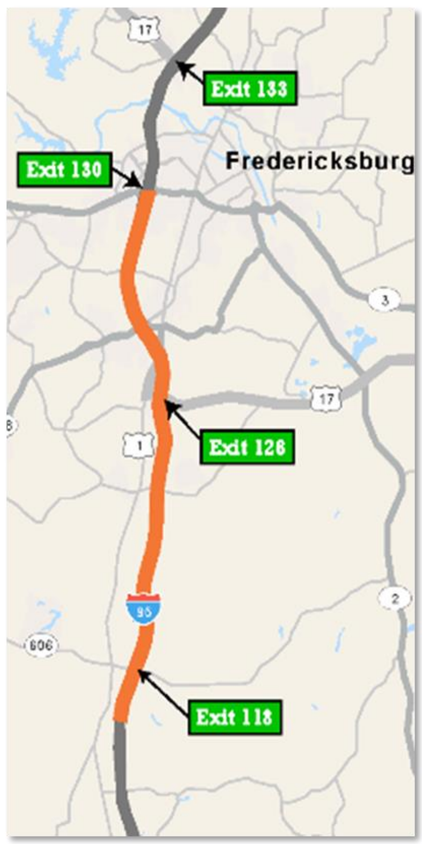


Figure 1. Location of I–95 Variable Speed Limit (VSL) Deployment. The VSL was deployed in the northbound direction only.

This location was selected based on an analysis of crash patterns in the corridor and an examination of congestion patterns using INRIX probe data. I–95 is a major travel corridor for the eastern seaboard of the United States and serves as a major conduit for long-distance travel. An analysis of congestion patterns revealed that this stretch of road experiences relatively low levels of recurring weekday congestion; however, severe congestion frequently occurs from Friday to Sunday during the summer months, indicating that recreational travel is a major cause of congestion. These congestion events were frequently associated with rear-end collisions. The spatial limits of the VSL system were defined to ensure that it included the maximum end of the queue going northbound during the most congested conditions. As a result, the VSL system was designed with the intent of mitigating congestion and safety issues created by these weekend recreational congestion patterns.

Another important characteristic of the corridor was the presence of a large construction project to extend the I–95 Express Lanes located north of the VSL site. This construction project sometimes involved significant activities that created congestion north of the corridor that spilled back into the northern end of the VSL corridor. The project began construction in July 2019 and continued for most of the VSL evaluation period. New northbound express lanes opened on November 18, 2023.

VSL Characteristics

VDOT activated the VSL system on June 22, 2022. The I–95 VSL system consists of 48 individual cutout LED VSL signs that are dual indicated along the corridor. The average spacing of the signs is approximately 0.6 miles. The specific locations of the VSL signs are at mileposts 115.0, 115.5, 116.3, 117.0, 118.1, 119.3, 119.7, 120.2, 120.7, 121.3, 121.9, 122.4, 122.9, 123.4, 123.8, 124.4, 124.9, 125.6, 126.2, 126.8, 127.4, 127.9, 129.0, and 129.9. The posted VSLs are regulatory speeds and enforceable.

Each set of signs dynamically change speed limits based on a predefined algorithm, and a flashing beacon located on top of the sign activates when VSLs display lower speed limits. The same speed is posted on both signs in a pair. A Wavetronix side fire radar installation is co-located at each set of speed limit signs. The Wavetronix units collect per vehicle record (PVR) data, which include timestamped speed data for each vehicle that passes the detector in every lane. Figure 2 shows an example of one location with the VSL signs and detection within the corridor. Cellular communications enable the traffic operations center to communicate with the VSLs. The total cost of the project was approximately $10 million.

Figure 2. Example of Variable Speed Limit Installations Along the Corridor

VSL Control Algorithm

An empirically developed control algorithm was designed to set speed limits in the corridor, and the details of that algorithm are in the VSL algorithm documentation prepared by Kimley Horn and Associates (Kimley Horn and Associates, 2023). Figure 3 shows a conceptual illustration of how a VSL creates an initial recommendation for the posted speed, and Figure 4 shows a summary of the control algorithm with the parameters that were used when the VSL system was initially activated. Highlighted numbers in Figure 4 could be changed so that the system could be calibrated in the future if needed.

The VSL algorithm initially calculates speeds at each set of the 24 VSL sign pair locations. The PVR data are aggregated into 30-second intervals, and the left lane traffic characteristics are examined to set speed limits because that lane is least likely to be impacted by interchange operations. The standard deviation of left lane volume, lane occupancy, and average speed are examined as part of the algorithm. The algorithm operates in both a predictive and a reactive mode. In the predictive mode, the algorithm examines volume, speed, and occupancy to detect instability in the traffic stream and lowers the speed limit in advance of traffic flow breakdown to maintain consistent traffic flow. In the reactive mode, the system lowers the VSL if it detects that traffic is traveling at lower speeds than the currently posted speed. Data collected prior to activation of the system are used to tune thresholds for various parameters using VISSIM simulations that emulate observed data prior to the system going live.

Initially, VSLs are calculated separately at each of the 24 VSL sign pairs along the corridor. The algorithm then smooths and groups speed limits along the corridor by conducting several iterations of smoothing to ensure that drivers do not see too much oscillation in VSLs, thereby ensuring a consistent driver experience in the corridor. VSL signs can display speeds limits of 35, 45, 55, 60, 65, and 70 mph, which can be updated every minute. There is a 10-mph maximum decrease permitted between speed postings when transitioning into congestion, but speed limits can increase by any amount when emerging from congestion. System operations are monitored at the local traffic operations center.

As part of continuing system monitoring, VDOT and consultant staff regularly examined algorithm performance and tuned parameters to improve system performance. The initial algorithm parameters were used from June 2022 to February 2023, when the first update of the algorithm occurred. Major changes instituted in the update included (Figure 4.):

- When conditions are worsening, the value of the standard deviation left lane volume during the state A to state B1 transition decreased from 8.5 to 7.5.
- When conditions are worsening, the value of the threshold for left lane occupancy was decreased from 22 to 20 percent when moving from State B1 to State B2.
- When conditions are improving, the threshold for standard deviation of left lane volume was decreased from 5 to 4.

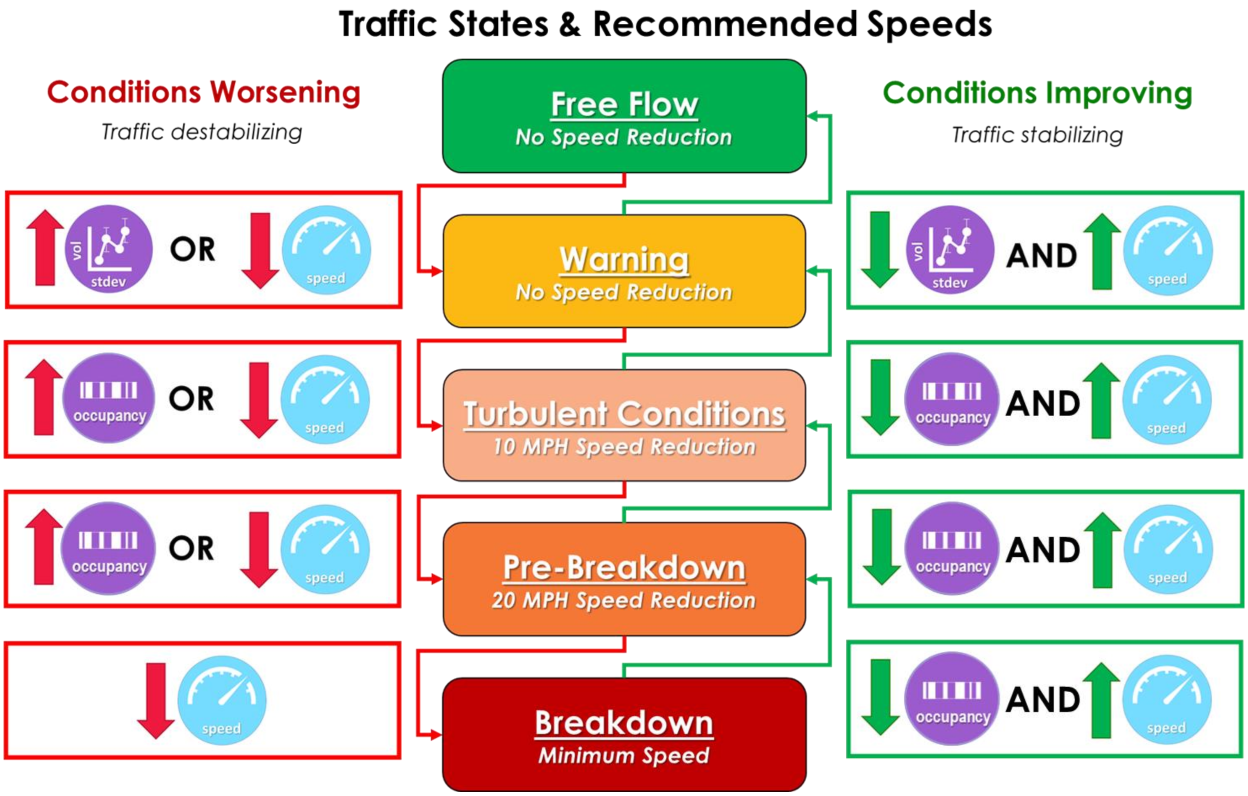


Figure 3. Conceptual Logic for Initial VSL Control Algorithm. Purple denotes cases where the algorithm is operating in predictive mode; blue indicates where it is operating in a reactive mode.

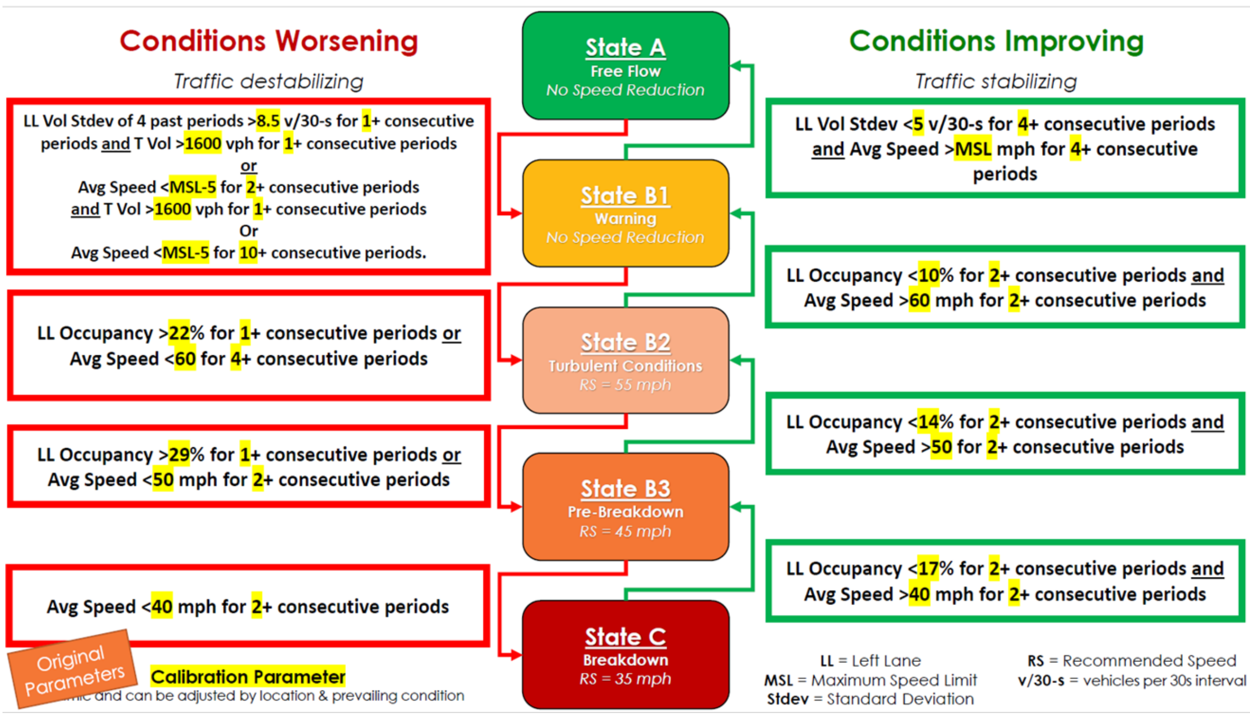


Figure 4. Flowchart of Original Variable Speed Limit Control Algorithm Parameters. Values highlighted in yellow represent configurable parameters that could be calibrated.

Subsequent evaluation by the consultant teams showed that these changes improved system stability. Another modification to the VSL algorithm occurred on November 30, 2023. That algorithm increased the minimum speed limit from 35 mph to 40 mph and decreased the minimum speed limit at the southernmost sites on the corridor to permit 10 mph drops from the 70-mph static speed limit, making transitions into slower speeds rapid. This report includes the February 2023 modification in the evaluation but does not include any data after the November 2023 modification.

VSL Monitoring

No new staff were hired to perform ongoing monitoring of the performance of the VSL system, so system monitoring was conducted by a combination of the consultant staff involved in the development of the VSL algorithm and existing Fredericksburg District staff. That decision to not add staff placed additional demands on District Traffic Engineering and Traffic Operations Center staff beyond their usual duties.

Enforcement

The VSL signs are regulatory, and Virginia has an enabling section of state code that permits enforcement of VSLs. Although VSLs are enforceable, automated speed enforcement of the VSLs is not currently supported by the state code outside of work zones and school zones, so it was not used in this deployment. An application was created to provide enforcement agencies with real-time information on the posted speeds, and a secure archive of speed limits was maintained. All enforcement relied on traditional enforcement by the Virginia State Police, and there was no concentrated enforcement effort in the corridor once the system was activated. The use of traditional enforcement represents a difference in this VSL deployment versus VSL's deployed in many international locations.

Public Education

VDOT conducted several public education and outreach efforts to help the public understand the goals of the VSL project and the way that they should react when they saw reduced speeds in the corridor. Public education efforts included these communications:

- Indoor and outdoor signs at safety rest areas (Figure 5a).
- A billboard on I–95 NB at MP 98 (Figure 5b).
- Social media advertisements on Waze and Facebook that were geofenced so that only travelers traversing the corridor were exposed to them.
- A project website (https://improve95.org/variable/default.asp).
- Media coverage when the system was activated.

(a) **(b)**

Figure 5. Examples of Public Education Signing Including (a) Rest Area Signing and (b) Billboards

PURPOSE AND SCOPE

The purpose of this study was to determine the safety and operational effects of the I–95 VSL system deployed in 2022 Virginia. The specific objectives were to:

- Determine the impact of the VSL on mean speed, speed compliance, and the distribution of high-speed vehicles.
- Identify any changes in capacity or traffic flow because of VSL deployment.
- Assess changes in average travel time and reliability.
- Determine any preliminary changes in safety observed in the corridor.
- Develop a preliminary return on investment estimate for the project.

The analysis used data during approximately 17 months from June 22, 2022, to November 30, 2023, following activation of the VSL. The duration of the before period used for comparison varies depending on the performance measures being examined because some datasets were not available for long periods of time prior to system activation. Before data for periods when traffic was strongly impacted by the COVID pandemic were excluded from all before analyses given the atypical trends in volume and crashes observed during those periods. The analysis documented in this report focuses on macroscopic changes in traffic flow and safety during the course of the VSL deployment. The project team examined more microscopic evaluations, examining specific VSL reduction events through regular project meetings.

METHODS

Literature Review

Using Google Scholar and the Transport Research International Documentation (TRID) database, the research team reviewed literature to identify evaluations of past field deployments of VSLs. The review focused on field deployments; simulation studies of systems were not summarized. In addition, special attention was paid to differentiating VSL deployments in the United States from international installations. Likewise, the team search placed greater emphasis on examining speed harmonization and congestion mitigation VSL applications rather than on those intended to address weather concerns.

Collect VSL System Log Data

The evaluation was designed as a before-after analysis of system performance. A key challenge in this study was the availability of fine-grained data before the system was activated. Following VSL implementation, detector data were available at close spacings throughout the corridor; however, the VSL detectors were online and collecting data for a limited time before the system was turned on. The "before" data were available from 1/1/22 through 3/26/22, and "after" data were available from 6/22/22 through 11/30/23. Given potential seasonality effects, researchers screened volume and events to ensure that before-after comparisons were reasonable.

Collecting VSL system log data involved collecting PVR detector data and posted-speed-limit (PSL) log data generated by the VSL. Raw PVR traffic data (which contained information such as timestamps, vehicle speed, vehicle length, vehicle count, detector ID, and lane, etc.) were collected by Wavetronix detectors and stored in a centralized database (Figure 6).

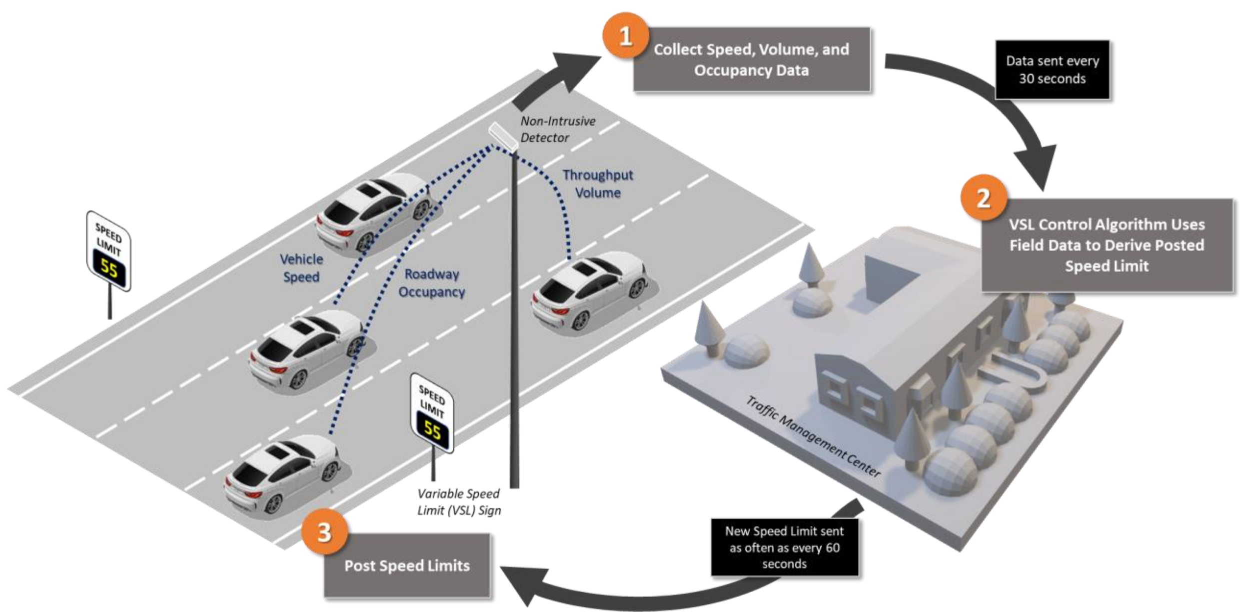


Figure 6. Data Collection Process

Historical data were transferred to the cloud computing platform Azure, so data could be downloaded and analyzed by the team. The team periodically accessed the Azure platform and downloaded PVR and PSL data in a comma-separated values (CSV) file format. Approximately one million records of PVR data were collected each day. The daily data were merged by season, and the aggregated files were imported to PowerBI for further processing. Seasons were defined as:

- Summer 2022: 6/22/22–8/31/22.
- Fall 2022: 9/1/22–11/31/22.
- Winter 2023: 12/1/22–2/28/23.
- Spring 2023: 3/1/23–5/31/23.
- Summer 2023: 6/1/23–8/31/23.
- Fall 2023: 9/1/23–11/29/23.

As mentioned earlier in the VSL algorithm description, there was an update to the VSL algorithm's parameters on 2/10/2023. To differentiate effects of the algorithm change, the winter season was divided into two parts based on the algorithm that was in effect, 12/1/22–2/9/23 (Winter A) and 2/10/23–2/28/23 (Winter B). There was another algorithm update on 11/30/23, which led to excluding that day from the Fall 2023 analysis.

Additional data analysis was performed on the before data (1/1/22–3/26/22). During this time, detailed PVR data were collected, but the VSL system had not been activated. To compare the data before and after the VSL system was activated, the VSL control algorithm was applied to the before data to determine what PSL would have been posted under the recorded traffic conditions. The before PVR data may then be categorized by the PSL that would have been posted had the VSL been active. That categorization enabled direct comparisons under the same traffic conditions with and without the active VSL system. For the rest of the report, the before PSL refers to what the PSL would have been if the VSL system had been actively posting VSLs in the before period.

During the study period, there was long-term construction work (an extension of I–95 express lanes) just north of the study area, which could have affected congestion conditions. As a result, data were separated based on the location within the corridor to examine spatial differences in VSL performance. The study corridor was divided into three sections, taking the presence of onramps and offramps into consideration:

- Northern Section: MP 126.2 (Detector 19)–129.9 (Detector 24).
- Middle Section: MP 119.3 (Detector 6)–125.6 (Detector 18).
- Southern Section: MP 115.0 (Detector 1)–118.1 (Detector 5).

Based on the initial congestion analysis performed before system installation, the research team expected that congestion and VSL use would increase along the corridor moving north. Dividing the corridor into segments enabled the team to examine for any spatial differences.

System Utilization

System utilization was investigated by analyzing the spatial and temporal patterns in VSL activation in the corridor. For the purposes of this analysis, system utilization was defined as the percentage of possible 1-minute intervals where a VSL sign posted a particular speed. The time percentages of VSL activation were calculated and summarized by posted speed limits. Further investigation was performed for reduced speed limits (less than base speed limits) in terms of detector stations, day of week, and time of day to better understand patterns of VSL activation in the corridor. There are 24 locations where VSL sign pairs are placed. Because speed limits can be updated every minute, that meant that in 1 day there were 34,560 possible sign-minutes when a speed limit could be displayed (24 hr/day × 60 min/hr × 24 sign pairs). For example, if reduced speeds were posted for a total of 5,000 minutes across all signs in the corridor, that action would produce a system utilization of 5,000/34,560 = 14.5 percent for that day.

Event and Volume Screening

An important consideration in designing the evaluation of the VSL system was to control for as many external factors as possible to isolate the impact of the VSL system alone. Differences in work zones, weather events, demand volumes, crashes, and incidents could exert influence on various congestion and safety measures. As a result, the researchers attempted to remove time periods that were impacted by disruptive events in the before and after periods when performing comparisons.

Volume was a significant factor that could impact traffic in the corridor, especially given the seasonal differences in the volume data available in the before and after periods. Average daily traffic (ADT) in the study corridor followed weekly and seasonal trends, so ADT also needed to be examined to ensure fair comparisons. A challenge for the evaluation was the availability of detailed predeployment volume and speed data in the corridor. Detailed PVR data from before the VSL activation were available only between January and March 2022, which corresponds with a lower volume period. To mitigate volume impacts, the analysis filtered comparisons with time periods when volumes exceeded specified thresholds to ensure fair comparisons. This value was set at around 2,000 veh/hr across all lanes to correspond with the approximate capacity of a single lane of traffic. This strategy filtered out very low volume periods when free flow speeds tended to dominate.

In addition to mitigating volume impacts, the research team performed extensive event screening to identify timeframes from the data where atypical events occurred. This process included data collection from Fredericksburg District press releases, the VaTraffic database, and VSL system logs. Fredericksburg District press releases were used to identify major work zone and incident events on neighboring facilities that might impact the corridor. All events occurring between mileposts 110 and 140 on I–95 northbound were reviewed. Events 5 miles beyond the bounds of the study corridor were included because researchers expected that congestion from major events could spill back onto the study corridor, especially on the northern end of the corridor. These events were reviewed to determine whether they impacted traffic conditions on the corridor. Events were considered to impact traffic when average speeds dropped below 60 mph for at least 15 minutes in the absence of existing congestion. When events occurred during or leading into congestion on the corridor, researchers could not discern routine congestion from that resulting from an incident; therefore, these events were not screened out. Event screening also included removing timeframes when the VSL system experienced any communications disruptions or outages so that results represented “ideal” VSL performance. If a traffic-impacting event occurred, all data within the corridor during that timeframe were removed from further analysis to be conservative. Time periods impacted by crashes were retained in the data because the VSL could impact safety, so mobility results would reflect benefits attained from reductions in collisions.

Operations Analysis

Once data collection and screening were complete, seasonally merged PVR and PSL data were filtered based on volumes and events, and then processed using PowerBI. The research team selected PowerBI as the analysis tool because it does not have line length limits for import files. Raw PVR data contained a unique vehicle ID, timestamp, detector station ID, lane location, vehicle length, and speed. Raw PSL data elements included timestamp, sign ID, recommended speed, along with several supporting variables that were used in the determination of VSLs.

To evaluate the performance of the VSL system, matching time and location between the PVR and PSL data was crucial to evaluating the performance of the VSL system. The physical locations of each PVR detector (detector station ID) and PSL sign (gantry ID) are identical but use differing notation to represent the location. Those differences were amended by linking separate reference table data. Timestamps of PSL data are uniform and categorized every 30 seconds. However, PVR timestamps are not uniform as each record is created and stored when a vehicle passes a detector. To align PSL and PVR timestamps, an additional timestamp column was added to the PowerBI analysis file that rounded the time of the PVR data down to the nearest 30-second interval. That new timestamp was then matched to the corresponding 30-second increment in the PSL data, with the assumption that passing vehicles recognize and react to the matched PSL.

Average Speed and Speed Limit Compliance

The research team examined both the mean speed and speed limit compliance of vehicles traversing the corridor. Data were analyzed for each PSL (70 or 65 mph, 60 mph, 55 mph, 45 mph, and 35 mph) such that the dataset was mutually exclusive for each PSL and collectively exhaustive in terms of time and space. To realize this, the “CROSSJOIN” function in Power BI matched time and space for the PVR and PSL datasets.

Descriptive statistics of the 30-second average vehicle speeds, such as mean speed, standard deviation, and percentage of activation, were calculated before and after the VSL implementation for each PSL. For 55 mph and 45 mph PSLs, which are transition phases between free-flow and congestion, mean speed by lane were also examined to identify any effects of lateral speed harmonization between lanes. Of note is that raw speed data contain some erroneous data; for example, a very small portion (about 0.03 percent) of vehicle speeds exceeded 150 mph. To remove outliers, vehicle speed was capped at 100 mph.

Speed compliance refers to drivers travelling at or below the PSL. The cumulative percentage of vehicles traveling below the PSL (or what would have been posted by the VSL system for the before data) was calculated in PowerBI. In addition, cumulative percentages of vehicles traveling 5 and 10 mph over the PSL was calculated in PowerBI to better understand the extent and distribution of compliant behavior.

Travel Time and Reliability

The operational measures previously discussed all relied on data derived from the Wavetronix detectors that were deployed as part of the VSL system. Although Wavetronix detectors provided very detailed data at those point detectors, there was not a longtime series of data available prior to system activation to establish a pre-VSL installation baseline. As a result, probe travel time data from the vendor INRIX were used to examine average travel time and planning time index (95th percentile travel time divided by free flow travel time), using the corresponding data from the period 1 year before system activation. Data from INRIX provide data as an average travel time to traverse a vendor-defined link, termed an XD segment, for a particular timestamp. Although these data do not permit evaluation of individual speeds, distribution of vehicle speeds, or compliance, these data are able to make a macroscopic examination of travel time and reliability across the corridor during a longtime horizon. Analyses were conducted for both the entire corridor and subsections based on interchange locations that were described in the VSL system log discussion.

The time periods compared were 6/22/21–6/21/22 (“before”) versus 6/22/22–6/21/23 (“after”), and data were analyzed between milepost 115 and 130. In the case of the travel time and reliability analysis, only the first full year of data following deployment were used to ensure that seasonal volume and weather effects were accounted for. This differs from the time periods used for other operational analyses presented in this report. For the sake of reference, prepandemic data from 6/22/18–6/21/19 were also analyzed to show changes relative to a constant baseline. The analysis used only data with 6 a.m. to 8 p.m. timestamps to focus on the periods when the probe data had the highest availability and the periods when congestion was most prevalent.

The research team also considered the importance of noting that crashes, weather events, and work zones were not filtered from this analysis due to inconsistencies in the amount of event data available at the site in the before versus after period. Thus, the results present a comparison of all time periods before and after VSL implementation, recognizing that differences, in part, could be attributable to differences in the occurrence of various nonrecurring events. This is an important distinction from the detector data evaluation.

Throughput

The research team also examined the impact of VSL on system throughput. For throughput performance measures, a 5-minute aggregation interval was used to smooth fluctuations in flow and converted throughput into an equivalent hourly flow rate. Speed-flow plots were developed for three left-lane detector locations, representing the northern (MP 127.9), middle (MP 123.4), and southern (MP 118.1) subsections, and several metrics were calculated to estimate maximum per-lane throughput. Measures used included maximum observed flow rate, average of the top 20 and top 100 flow rates.

Safety Analysis

A preliminary safety assessment was performed on crashes along the I–95 VSL corridor between MPs 115 and 130. Crashes were compared from 6/22/22 through 6/21/23 (when the VSL system went live) with the same period 1 year prior and before the VSL activation (6/22/21–6/21/22). As of writing this report, Virginia crash data were finalized through September 2023. However, this report summarizes only 1 year of post activation data because analyzing an additional 3 months of data would introduce seasonal biases but would produce findings like the 1-year analysis. Number of crashes, crash severity, and crash types were compared to assess safety impacts of the VSL system. Although 1 year of crash data represent a limited sample for a formal safety analysis, these data may provide some indication of the VSL impact on safety and point to areas to examine more closely as the deployment continues. To provide additional context to the crash data, the research team also reviewed crash trends on nearby sections of I–95. Crashes north (I–95 NB MP 130–140), south (I–95 NB MP 105–115), and parallel to the study corridor (I–95 SB MP 115–130).

Secondary crashes (incidents that occur within the queue of a primary incident) were also reviewed, as the researchers anticipated, the VSL system has the potential to decrease the likelihood of secondary crashes. Secondary crashes were defined as crashes that occurred within 2 hours and 5 miles from the primary crash incident. Some literature defines a secondary crash as occurring within 1 hour and 2 miles from a primary crash (Hirunyanitiwattana and Mattingly, 2006) or within 2 hours and 2 miles of a primary crash (Moore et al., 2004). A slightly more conservative definition was adopted because volumes on the corridor were high, and queues could quickly increase in length.

Benefit-Cost Analysis

This project included performing a planning level benefit-cost analysis of the VSL system. Benefits were calculated using savings from reductions in cost of user delay and crashes. Of note is that this analysis was a rough estimate because only 1 year of crash data following VSL activation were available. The general assumption was that the crash savings observed in that first year would continue to occur moving forward, and any delay changes would also continue to accrue at the same rate in the future. No attempt was made to determine projected traffic growth and ways change in traffic volumes in the future might impact either delay or safety.

The monetary value of crash reductions was calculated using the assumed comprehensive crash costs published by VDOT in 2022 (Cole, 2022):

- Property damage only (PDO) crashes: $13,743.
- Combined fatal and injury crashes: $550,747.

The combined fatal/injury crash value was used rather than specific crash costs by injury severity level due to the greater challenge in predicting future injury severity.

The monetary value of changes in travel time were estimated using the values in the Texas A&M Transportation Institute *Urban Mobility Report* (Glover, 2021). That study estimated the value of changes in travel time to be $30.26 per passenger vehicle hour of delay. A median vehicle occupancy of 1.5 people was assumed based on estimates for I–95 in Spotsylvania County produced by a recent study (Xu, Dougald, and Miller, 2024). The average value of an hour of truck delay was estimated at $55.24 per truck hour based on the *Urban Mobility Report*. Changes in delay were determined based on probe travel time data combined with ADT estimates collected from a continuous count station in the corridor.

An annual estimate of delay and crash savings was generated using the estimated changes during the first year of VSL operation. That value was compared with the initial system installation cost. Ongoing maintenance and operations were not explicitly considered because long-term costs for those items are yet unknown.

RESULTS

Literature Review

VSL systems can be broadly categorized into two groups: (1) VSL systems that adjust speeds to provide better guidance on safe speeds during poor weather conditions or when a work zone is present and (2) VSL systems that attempt to mitigate congestion by encouraging more uniform speed selection as traffic becomes unstable or congested. These congestion mitigation deployments are commonly called speed harmonization VSLs because they attempt to get drivers to travel at consistent speeds.

Weather VSL systems have generally shown high degrees of effectiveness. A VSL system that changed speeds as a function of visibility was installed on I–215 in Utah (Martin et al., 2003). Researchers found that standard deviation of speed decreased due to the VSL system. A study of a VSL system on I–77 in Virginia that reduced speed based on fog visibility found that mean speeds were reduced by 2 to 5 mph following activation (Gonzales and Fontaine, 2018). Furthermore, crashes during fog were reduced by more than 75 percent in the 3 years following activation.

Several studies of speed harmonization VSL systems have been conducted in both Germany and the United Kingdom. A study of a VSL system on the M42 in the United Kingdom compared 1 year of data before and after activation along a 17 km roadway with a 134,000 AADT (Mott McDonald Ltd, 2008). That study found that speed harmonization occurred on the corridor, with capacity increasing by 7 percent and travel time variability decreasing by 22 percent. The VSL was deployed in conjunction with congestion-activated hard shoulder running, so the effect of the VSL alone cannot be isolated. Another study on the A99 in Germany examined a 16 km section of roadway where VSL was deployed without other operational treatments (Weikl et al., 2013). That study found that traffic was more evenly distributed across the available lanes, but there was a slight reduction in capacity. In both cases, automated speed enforcement was present, which likely impacted effectiveness.

In the U.S., VSL speed harmonization deployments have tended to occur in major metropolitan areas, and results have been variable. A study of VSLs on I–5 in Seattle found that travel time reliability improved by 15 to 30 percent (DeGaspari et al., 2013). Studies of VSLs installed on I–35W/I–94 in Minneapolis found that the duration of congestion in the morning peak period was reduced by about 7.6 minutes (Hourdos et al., 2013; Hourdos and Zitzow, 2014). Another study of I–35W found that the buffer time index, a measure of travel time reliability improved by 15 to 30 percent (Kwon and Park, 2015). Other studies found more limited effects. A study of VSLs on I–4 in Orlando determined that changes in speed were more highly correlated with changes in detector occupancy than with the posted VSL (Atkins Consulting, 2009). A study of an active traffic management system on I–66 in the Northern Virginia suburbs of Washington, D.C., found limited benefits on sections of the interstate where VSLs were deployed without any hard shoulder running, although significant benefits were created when dynamic hard shoulder running and VSL were used together (Dutta et al., 2018). That deployment used advisory, rather than regulatory, speed limits. In all cases, these deployments were in large urban areas that potentially had high volumes of commuter traffic, and automated enforcement was not used.

The literature review shows that the effectiveness of VSL systems can vary significantly due to several factors. Based on the literature review, there were no VSL installations in the United States where VSLs were deployed for congestion mitigation/speed harmonization purposes on routes outside urban areas for purposes of off-peak congestion mitigation. This study of the I–95 VSL system helped identify whether speed harmonization systems can be deployed effectively in these situations.

Collect VSL System Log Data and Nonrecurring Event Logs

Approximately 100 million records of PVR data and 5 million records of PSL data were collected for each season during the evaluation. Figures 7 and 8 show examples of raw PVR and PSL data collected periodically by the research team via access to the cloud storage system. Raw PVR data consist of unique vehicle IDs, timestamps, location (detector station ID, lane), speed, and time duration. Raw PSL data also have information about time, location (gantry ID), recommended speed, etc.

UniqueID	DetectorStationID	RequestTime	EntryTimeStamp	Timestamp	Lane	Length	Speed	Duration
274688607	1	2023-09-01 00:00:00.003	2023-09-01 00:00:00.170	2023-08-31 23:59:43.973000-04:00	1	73.92969	69.85547	780
274688609	1	2023-09-01 00:00:00.003	2023-09-01 00:00:00.170	2023-08-31 23:59:43.977000-04:00	2	55.085938	64.72656	643
274688610	1	2023-09-01 00:00:00.003	2023-09-01 00:00:00.170	2023-09-01 00:00:02.733000-04:00	0	81.06641	69.47656	854
274688804	1	2023-09-01 00:00:30.000	2023-09-01 00:00:30.260	2023-09-01 00:00:31.527000-04:00	1	82.15234	73.3125	819
274688965	1	2023-09-01 00:01:00.000	2023-09-01 00:01:00.170	2023-09-01 00:00:38.057000-04:00	1	17.066406	74.12891	212
274688968	1	2023-09-01 00:01:00.000	2023-09-01 00:01:00.170	2023-09-01 00:00:40.467000-04:00	0	70.72656	64.92578	805
274688969	1	2023-09-01 00:01:00.000	2023-09-01 00:01:00.170	2023-09-01 00:00:45.793000-04:00	1	77.49609	65.37109	870
274688973	1	2023-09-01 00:01:00.000	2023-09-01 00:01:00.170	2023-09-01 00:00:55.203000-04:00	1	17.101562	76.76172	205
274688975	1	2023-09-01 00:01:00.000	2023-09-01 00:01:00.170	2023-09-01 00:01:06.480000-04:00	1	14.800781	71.625	197
274689187	1	2023-09-01 00:01:30.000	2023-09-01 00:01:30.250	2023-09-01 00:01:20.547000-04:00	1	39.589844	70.58203	440
274689193	1	2023-09-01 00:01:30.000	2023-09-01 00:01:30.250	2023-09-01 00:01:24.817000-04:00	1	14.761719	66.78906	211
274689200	1	2023-09-01 00:01:30.000	2023-09-01 00:01:30.250	2023-09-01 00:01:28.353000-04:00	0	77.05469	65.87891	859

Figure 7. Example of Raw Per Vehicle Record Data

Timestamp	CorridorID	GantryID	Display_Order	Travel_Order	State	Recommended_Speed	Calculated_Posting_Speed
2023-09-01 00:00:00-04:00		1299	1	23	A	65	65
2023-09-01 00:00:00-04:00		1290	2	22	A	65	65
2023-09-01 00:00:00-04:00		1279	3	21	A	65	65
2023-09-01 00:00:00-04:00		1274	4	20	A	65	65
2023-09-01 00:00:00-04:00		1268	5	19	A	65	65
2023-09-01 00:00:00-04:00		1262	6	18	A	65	65
2023-09-01 00:00:00-04:00		1256	7	17	A	65	65
2023-09-01 00:00:00-04:00		1249	8	16	A	65	65
2023-09-01 00:00:00-04:00		1244	9	15	C	35	35
2023-09-01 00:00:00-04:00		1238	10	14	C	35	35
2023-09-01 00:00:00-04:00		1234	11	13	A	70	45
2023-09-01 00:00:00-04:00		1229	12	12	A	70	55
2023-09-01 00:00:00-04:00		1224	13	11	A	70	65

Figure 8. Example of Raw Posted Speed Limit Data

System Utilization

Table 1 shows the average percentage of time each PSL was shown by season for the entire corridor. The predominant speeds posted were the base speed limits of 65 or 70 mph, accounting for 89 to 97 percent of posted speed limits each season. The congested speed limit of 35 mph was the next most frequent, occurring 2 to 8 percent of the time. Transitional speeds (45 and 55 mph) were posted less frequently as the system moved between free flow and congestion.

Table 1. Average Proportion of Time for Each Posted Speed Limit by Season

VSL[a] Recommended Speed	Before	After							
	Winter 2022	Summer 2022	Fall 2022	Winter A 2023	Winter B 2023	Spring 2023	Summer 2023	Fall 2023	After Overall
65, 70 mph	96.4%	88.8%	94.4%	96.6%	95.8%	91.5%	89.7%	93.7%	92.5%
60 mph	0.0%	0.1%	0.0%	0.0%	0.1%	0.1%	0.1%	0.1%	0.1%
55 mph	0.8%	1.7%	1.0%	0.8%	1.3%	2.0%	2.3%	1.8%	1.6%
45 mph	0.6%	1.5%	0.9%	0.6%	0.5%	1.1%	1.3%	0.9%	1.0%
35 mph	2.2%	8.0%	3.6%	1.9%	2.3%	5.2%	6.6%	3.5%	4.7%

[a]VSL = variable speed limit.

The high proportion of base speed limits in Table 1 may be due to the VSL system being operational around the clock for 24 signs on a 15-mile study corridor. Congestion was often not present, especially on weekdays or at night. To better understand the congestion and VSL activation patterns, Tables 2, 3, and 4 show the percentage of time the VSL system posted reduced speeds (less than 65 mph) by time and location.

Table 2 illustrates the average percentage of time that the VSL reduced speeds below the base PSL during the summer of 2023 by time of day and day of week across the entire corridor. That information represents the proportion of time that VSL signs in the corridor posted a speed other than the base 65 or 70 PSL for that hour during the summer of 2023. For example, on average in the summer of 2023, the VSL signs posted reduced speeds for 61.1 percent (darkest shade) of the time between 1 and 2 p.m. on Sundays. Overall, the table shows the greatest frequency of reduced speed limits on Friday and weekend afternoons. Some higher levels of activation during the week occur during night periods, and those cases correspond to times when work zones were present in the corridor and created congestion.

Table 2. Average Percentage of Time Variable Speed Limit Posts Reduced Speeds by Time of Day and Day of Week for the Entire Corridor during the Summer of 2023

Time	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
12:00 a.m.	7.6%	3.9%	4.6%	10.9%	8.1%	0.0%	0.3%
1:00 a.m.	6.2%	3.7%	5.4%	8.8%	8.2%	0.0%	0.7%
2:00 a.m.	4.9%	2.3%	4.3%	8.0%	7.4%	0.0%	0.0%
3:00 a.m.	5.8%	2.3%	3.6%	8.2%	7.0%	0.1%	0.0%
4:00 a.m.	3.9%	1.0%	2.1%	7.1%	6.2%	0.0%	0.0%
5:00 a.m.	0.4%	0.4%	0.5%	0.5%	1.5%	0.0%	0.0%
6:00 a.m.	0.0%	0.2%	0.7%	0.0%	0.9%	0.0%	0.0%
7:00 a.m.	0.0%	3.2%	4.1%	1.7%	1.3%	0.0%	0.0%
8:00 a.m.	0.4%	6.5%	8.6%	6.8%	2.4%	1.4%	0.0%
9:00 a.m.	0.1%	4.0%	4.9%	5.2%	3.2%	15.3%	2.2%
10:00 a.m.	1.3%	0.6%	5.0%	6.1%	11.0%	28.6%	21.1%
11:00 a.m.	5.2%	0.1%	4.0%	9.0%	21.4%	32.7%	41.1%
12:00 p.m.	12.1%	1.5%	6.7%	15.1%	23.9%	38.8%	52.6%
1:00 p.m.	11.2%	2.0%	10.3%	23.5%	30.2%	42.8%	61.1%
2:00 p.m.	9.0%	5.0%	12.8%	24.0%	37.6%	42.8%	55.7%
3:00 p.m.	12.7%	4.4%	10.4%	19.4%	39.1%	53.6%	51.0%
4:00 p.m.	10.3%	2.8%	8.3%	14.6%	39.7%	56.4%	50.3%
5:00 p.m.	5.9%	0.7%	6.9%	13.8%	35.8%	48.9%	41.4%
6:00 p.m.	5.2%	0.1%	2.1%	8.3%	32.9%	35.4%	36.0%
7:00 p.m.	0.9%	1.5%	1.3%	5.2%	22.2%	17.2%	26.4%
8:00 p.m.	0.1%	0.0%	0.0%	1.7%	13.9%	9.1%	19.2%
9:00 p.m.	1.1%	1.7%	4.6%	4.0%	6.1%	6.3%	11.7%
10:00 p.m.	5.5%	7.6%	11.0%	13.3%	0.3%	0.7%	6.7%
11:00 p.m.	6.6%	7.9%	14.5%	13.0%	0.0%	0.8%	7.7%

Darker colors of red represent higher percentages of time.

Similarly, Table 3 shows the average percentage of reduced speeds during the summer of 2023 by MP and day of week. As an example, the signs at MP 129.9 posted reduced speeds for 37.5 percent of the day on Sundays during the summer of 2023. The northern section of the corridor posted the most reduced speeds, with reductions occurring mostly on weekends.

Table 3. Average Percentage of Time Variable Speed Limit Posts Reduced Speeds by Milepost and Day of Week for Entire Day during the Summer of 2023

Milepost	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
129.9	9.2%	6.5%	13.8%	25.9%	33.2%	37.6%	37.5%
129.0	8.5%	6.3%	12.9%	24.8%	32.6%	37.2%	37.3%
127.9	8.4%	5.9%	12.3%	24.1%	31.9%	37.3%	36.9%
127.4	7.1%	4.3%	9.6%	20.7%	30.3%	36.6%	36.7%
126.8	7.2%	3.4%	8.9%	16.9%	30.4%	37.1%	37.1%
126.2	6.1%	2.4%	6.8%	14.1%	27.4%	35.0%	35.6%
125.6	4.6%	1.7%	4.2%	9.3%	23.8%	30.6%	32.5%
124.9	5.4%	4.0%	6.0%	10.6%	22.3%	27.8%	30.0%
124.4	4.4%	2.7%	4.2%	7.0%	17.2%	21.7%	25.4%
123.8	3.5%	2.3%	3.6%	5.5%	14.1%	18.7%	22.1%
123.4	2.9%	1.8%	3.0%	4.7%	12.1%	16.9%	19.9%
122.9	1.9%	1.4%	2.5%	3.5%	9.9%	13.5%	16.8%

Milepost	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
122.4	1.4%	0.8%	2.2%	3.1%	9.0%	13.3%	16.6%
121.9	1.6%	0.5%	1.7%	3.2%	8.7%	13.4%	17.4%
121.3	1.3%	0.3%	1.7%	2.1%	7.3%	10.5%	13.8%
120.7	4.2%	2.3%	4.6%	6.0%	6.9%	9.3%	12.6%
120.2	6.1%	2.4%	4.6%	6.4%	7.6%	7.2%	11.0%
119.7	6.3%	2.5%	6.2%	8.7%	6.8%	6.3%	8.7%
119.3	6.6%	3.3%	6.7%	9.3%	6.1%	5.0%	7.6%
118.1	6.7%	4.6%	9.1%	10.7%	7.4%	5.1%	8.9%
117.0	5.0%	2.0%	5.1%	5.5%	5.4%	3.3%	6.8%
116.3	4.5%	1.7%	4.6%	4.6%	4.7%	2.5%	5.8%
115.5	2.9%	0.3%	2.8%	1.7%	2.5%	2.4%	5.2%
115.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Darker colors of red represent higher percentages of time.

The VSL location that most frequently posted reduced speeds was at MP 129.9 on the northern end of the corridor (Table 3) because of a combination of construction effects and the bottleneck created by the large volume of merging and diverging traffic near the SR 3 interchange.

Table 4 shows the average percentage of time that a reduced speed was posted at MP 129.9 during the summer of 2023 by time of day and day of week. At MP 129.9, on average, the VSL system was activated more than 90 percent of the time on Sundays between 1 and 4 p.m. This information shows that VSLs were reduced most often on weekend afternoons on the northern end of the corridor.

Table 4. Average Percentage of Time Variable Speed Limit Posts Reduced Speeds by Time of Day and Day of Week at Milepost 129.9 for the Summer of 2023

Time	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
12:00 A.M.	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
1:00 a.m.	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
2:00 a.m.	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
3:00 a.m.	4.0%	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%
4:00 a.m.	0.9%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%
5:00 a.m.	0.0%	0.0%	3.0%	0.0%	1.5%	0.0%	0.0%
6:00 a.m.	0.0%	1.7%	5.9%	0.0%	0.3%	0.0%	0.0%
7:00 a.m.	1.0%	22.8%	17.2%	14.5%	3.1%	0.0%	0.0%
8:00 a.m.	4.5%	32.3%	34.8%	35.6%	4.0%	7.8%	0.3%
9:00 a.m.	0.6%	14.9%	20.9%	24.3%	15.0%	49.3%	13.5%
10:00 a.m.	3.8%	4.5%	12.8%	26.4%	33.8%	67.5%	52.0%
11:00 a.m.	17.6%	0.1%	12.2%	41.8%	65.5%	78.8%	84.3%
12:00 p.m.	45.3%	7.6%	15.4%	68.2%	78.8%	78.9%	86.9%
1:00 p.m.	42.6%	14.1%	43.2%	85.7%	90.2%	91.4%	91.8%
2:00 p.m.	31.7%	24.0%	55.6%	85.6%	91.2%	77.5%	91.0%
3:00 p.m.	20.3%	12.9%	34.9%	72.1%	90.3%	89.0%	91.9%
4:00 p.m.	18.6%	10.2%	30.4%	59.1%	85.7%	90.4%	91.5%
5:00 p.m.	13.0%	5.1%	40.1%	54.0%	84.8%	89.7%	83.1%
6:00 p.m.	11.7%	0.7%	8.0%	44.7%	77.5%	82.7%	79.0%
7:00 p.m.	3.4%	6.7%	0.0%	12.8%	46.5%	57.9%	66.6%
8:00 p.m.	0.0%	0.0%	0.0%	0.4%	21.1%	24.8%	48.8%

Time	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
9:00 p.m.	0.0%	0.0%	0.0%	0.1%	16.8%	18.7%	25.7%
10:00 p.m.	0.1%	0.0%	0.0%	0.6%	0.6%	3.7%	0.4%
11:00 p.m.	3.6%	0.6%	0.0%	0.2%	0.0%	0.0%	0.0%

Darker colors of red represent higher percentages of time.

Tables 5, 6, and 7 show summaries of the average percentage of time reduced speeds were posted for different combinations of season, MP, day of week, and time of day. In addition to showing each season for the after period, the last column shows the overall average percentage utilization in the entire post-activation period. Tables can be read as the marginal probability density functions that ignore other factors and observe only the selected factors. For example, Table 5 considers only MP and season, and other time components (time of day, day of week) are aggregated. The tables show seasonal trends where spring and summer seasons have higher activation times than fall and winter.

Table 5. Average Percentage of Time Variable Speed Limit Posts Reduced Speeds by Milepost and Season for the Entire Study Period

Milepost	Before	After							
	Winter 2022	Summer 2022	Fall 2022	Winter A 2023	Winter B 2023	Spring 2023	Summer 2023	Fall 2023	After Overall
129.9	8.2%	19.0%	13.7%	11.3%	11.2%	23.7%	23.6%	16.0%	17.8%
129	9.0%	19.3%	13.5%	11.1%	9.9%	22.9%	23.0%	15.2%	17.4%
127.9	9.0%	19.6%	13.3%	10.8%	9.4%	22.1%	22.6%	14.6%	17.0%
127.4	7.6%	18.8%	12.0%	7.5%	8.4%	19.7%	20.9%	12.6%	15.2%
126.8	7.5%	18.6%	11.0%	6.4%	9.1%	18.3%	20.3%	12.3%	14.4%
126.2	7.1%	17.8%	9.8%	5.6%	7.6%	16.0%	18.3%	10.8%	13.0%
125.6	6.1%	16.8%	8.5%	4.7%	5.8%	12.0%	15.3%	8.1%	10.8%
124.9	5.4%	16.1%	8.4%	3.9%	5.9%	10.9%	15.2%	6.7%	10.1%
124.4	4.6%	13.6%	6.6%	2.8%	4.4%	8.1%	11.9%	4.5%	7.8%
123.8	4.1%	12.1%	5.4%	2.1%	3.8%	6.7%	10.0%	3.7%	6.6%
123.4	4.0%	11.1%	4.8%	1.7%	3.3%	6.0%	8.8%	3.3%	5.9%
122.9	3.9%	10.0%	4.0%	1.1%	2.8%	5.4%	7.1%	2.9%	5.0%
122.4	4.2%	9.3%	4.0%	1.0%	3.2%	4.8%	6.6%	3.2%	4.8%
121.9	4.2%	8.7%	3.7%	1.1%	3.5%	4.7%	6.7%	4.0%	4.8%
121.3	4.1%	7.7%	3.1%	0.9%	2.1%	3.3%	5.3%	2.9%	3.8%
120.7	3.8%	7.0%	2.4%	1.0%	2.0%	2.9%	6.6%	3.1%	3.8%
120.2	3.6%	6.4%	2.2%	1.0%	1.5%	2.5%	6.5%	3.0%	3.5%
119.7	3.5%	5.7%	1.8%	0.9%	1.2%	2.1%	6.5%	4.6%	3.5%
119.3	3.6%	4.4%	1.4%	0.8%	0.8%	1.9%	6.4%	4.5%	3.1%
118.1	3.5%	6.9%	1.5%	1.0%	1.5%	2.8%	7.5%	4.6%	3.9%
117	3.3%	7.7%	1.7%	1.2%	1.3%	2.3%	4.7%	3.8%	3.4%
116.3	2.9%	6.8%	1.5%	1.1%	1.4%	2.0%	4.1%	2.5%	2.9%
115.5	2.8%	6.2%	1.3%	1.0%	1.3%	0.8%	2.5%	2.0%	2.2%
115	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Darker colors of red represent higher percentages of time.

Table 6. Average Percentage of Time Variable Speed Limit Posts Reduced Speeds by Day of Week and Season for the Entire Corridor for Entire Day

Days	Before	After							
	Winter 2022	Summer 2022	Fall 2022	Winter A 2023	Winter B 2023	Spring 2023	Summer 2023	Fall 2023	After Overall
Monday	8.8%	2.9%	6.0%	4.0%	7.5%	6.2%	4.8%	2.4%	4.6%
Tuesday	7.8%	3.3%	3.5%	2.4%	0.6%	3.0%	2.6%	3.9%	3.0%
Wednesday	1.8%	2.3%	3.2%	3.3%	1.3%	3.1%	5.7%	2.6%	3.3%
Thursday	1.5%	6.4%	3.1%	4.3%	0.1%	5.6%	9.5%	4.2%	5.3%
Friday	1.8%	16.2%	4.8%	4.8%	3.3%	14.8%	14.9%	6.2%	10.1%
Saturday	2.1%	22.2%	4.9%	2.2%	2.7%	8.6%	17.8%	6.9%	10.1%
Sunday	10.8%	23.3%	14.5%	2.2%	11.6%	18.1%	20.1%	17.2%	15.9%

Darker colors of red represent higher percentages of time.

Table 7. Average Percentage of Time Variable Speed Limit Posts Reduced Speeds by Time of Day and Season for the Entire Corridor

Time	Before	After							
	Winter 2022	Summer 2022	Fall 2022	Winter A 2023	Winter B 2023	Spring 2023	Summer 2023	Fall 2023	After Overall
12:00 a.m.	1.4%	2.5%	1.6%	0.2%	0.0%	0.5%	5.1%	1.6%	1.9%
1:00 a.m.	1.5%	2.3%	1.0%	0.2%	0.2%	0.5%	4.8%	0.8%	1.6%
2:00 a.m.	1.5%	2.1%	0.6%	0.2%	0.0%	0.4%	3.9%	0.6%	1.3%
3:00 a.m.	1.2%	2.0%	0.3%	0.2%	0.0%	0.6%	3.9%	0.3%	1.2%
4:00 a.m.	1.2%	1.2%	0.2%	0.4%	0.0%	0.9%	2.9%	0.3%	1.0%
5:00 a.m.	1.4%	0.6%	0.2%	0.2%	0.3%	1.2%	0.5%	0.2%	0.5%
6:00 a.m.	2.5%	0.4%	0.3%	0.4%	0.0%	1.2%	0.2%	0.3%	0.5%
7:00 a.m.	2.9%	0.4%	0.7%	1.2%	1.0%	2.8%	1.4%	2.5%	1.5%
8:00 a.m.	3.1%	0.6%	1.2%	2.1%	2.4%	5.0%	3.7%	3.3%	2.7%
9:00 a.m.	3.3%	2.8%	1.4%	2.4%	1.5%	5.5%	5.0%	2.9%	3.3%
10:00 a.m.	4.2%	9.7%	4.3%	5.0%	2.8%	8.4%	10.6%	5.4%	7.1%
11:00 a.m.	6.9%	17.6%	9.3%	7.5%	7.9%	11.9%	16.4%	10.0%	12.0%
12:00 p.m.	10.3%	24.2%	13.5%	9.1%	10.5%	19.0%	21.7%	12.2%	16.5%
1:00 p.m.	12.4%	29.4%	16.8%	10.1%	13.9%	23.6%	26.2%	14.1%	19.9%
2:00 p.m.	12.0%	31.3%	16.1%	10.2%	16.0%	24.5%	27.0%	16.8%	20.9%
3:00 p.m.	11.0%	31.6%	16.6%	9.6%	13.9%	23.2%	27.6%	16.5%	20.7%
4:00 p.m.	9.7%	29.5%	14.8%	7.1%	13.1%	20.8%	26.2%	16.3%	19.0%
5:00 p.m.	9.6%	27.1%	12.9%	6.3%	8.4%	19.7%	22.0%	17.4%	17.3%
6:00 p.m.	7.8%	20.7%	11.1%	3.8%	6.5%	15.8%	17.2%	13.3%	13.5%
7:00 p.m.	5.0%	12.1%	5.8%	2.1%	1.1%	8.6%	10.7%	7.3%	7.6%
8:00 p.m.	2.5%	7.3%	3.1%	0.7%	0.8%	4.1%	6.3%	5.0%	4.3%
9:00 p.m.	1.8%	5.9%	0.6%	0.5%	0.5%	1.6%	5.1%	1.9%	2.5%
10:00 p.m.	1.3%	4.1%	1.4%	0.4%	0.2%	1.4%	6.5%	2.1%	2.6%
11:00 p.m.	1.4%	3.1%	1.7%	0.2%	0.2%	0.9%	7.3%	1.8%	2.5%

Darker colors of red represent higher percentages of time.

Event and Volume Screening

Following the screening procedure described in the Methods section, traffic-impacting events and system outages were removed from the dataset. The amount of data removed is summarized in Table 8. This process represented a conservative approach, removing data with the goal of obtaining comparable before and after datasets that had both consistently removed events that might influence speeds beyond the operation of the VSL. Some events overlapped in duration; therefore, the total data removed are less than the sum of the individual event types in Table 8.

Table 8. Number of Events and Durations Removed from the Dataset

Event Type	Before (1/1/22–3/26/22)			All After Data (6/2/22–11/29/23)		
	Number of Events	Total Duration (Hours)	Average Hours/Day	Number of Events	Total Duration (Hours)	Average Hours/Day
Collision	28	55.33	0.65	170	288.00	0.55
Weather Condition	4	61.17	0.72	6	14.67	0.03
Construction Work	8	15.00	0.18	136	475.75	0.90
Disabled Vehicle	9	3.17	0.04	71	64.08	0.12
Outage	N/A	N/A	N/A	488	2,143.25	4.07
Total Events	49	134.67	1.58	911	3,158.75	6.01
Non-Overlapping Totals	44	131	1.54	808	2,947.00	5.60

N/A = not applicable because outages did not occur prior to system activation.

Some discussion of the row labeled “outages” is warranted. Events labeled as “outages” typically are disruptions in system communication or data collection at individual locations, and removal of this data is not necessarily indicative of system wide problems. Even though outages often affect only a few signs, data from the entire corridor was removed during these periods to be conservative. The VSL system experienced recurring issues with cellular communications connectivity and message latency that were subject to troubleshooting throughout the initial deployment period. These communications issues could result in VSL missed updates, delayed posting of speed limits, or different speed limits posted on the same VSL sign pair. The prevalence of these issues indicates the need for reliable communications at VSL sites to ensure consistent operations. Also, signs at mileposts 117.0, 120.2, and 120.7 relied on solar power, so prolonged inclement weather could also create disruptions at those locations. No outages were observed in the before period because the VSL system had not been activated.

More data were removed due to weather in the before timeframe, largely due to the January 2022 snowstorm that incapacitated I–95 in this area. More hours were removed in the after period due to work zone activities, which is probably largely attributable to lower levels of construction work during the “before” period since it occurred during winter months.

Volume was also a significant factor that could impact traffic in the corridor, especially given the differences in season between when volume data were available in the before and after periods. ADT on the study corridor followed weekly and seasonal trends as the study corridor experiences a congestion pattern due to recreational trip travel. Weekends, particularly in the spring and summer, experience high ADT (Figure 9).

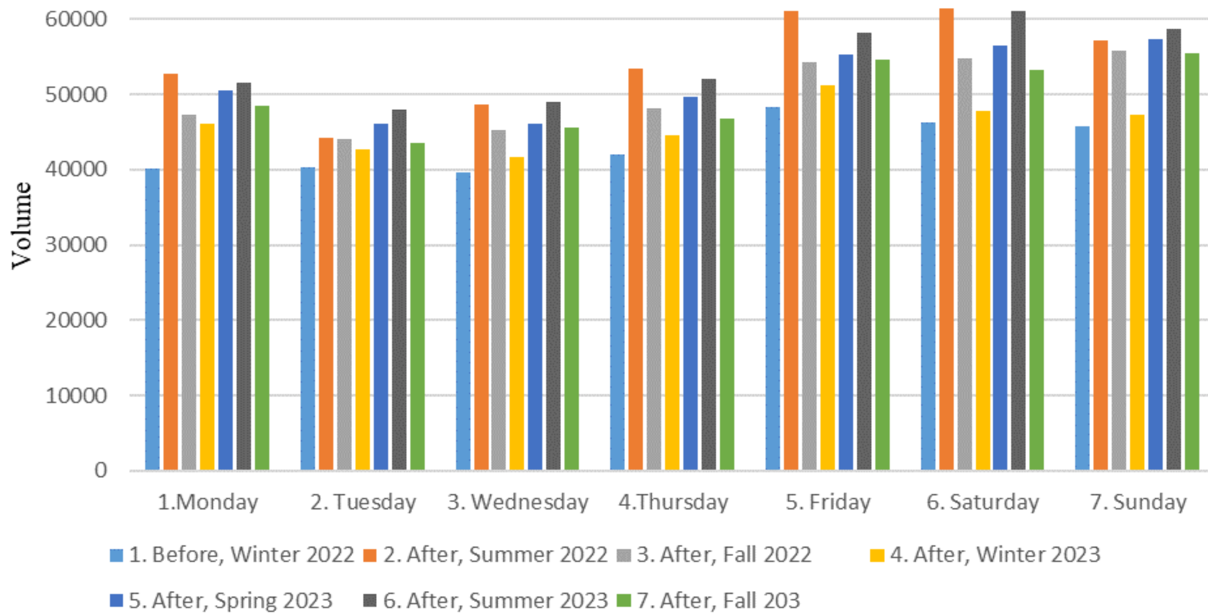


Figure 9. Average Daily Traffic

The PVR and PSL data were subsequently filtered to identify times in the before and after periods when there were no disruptive events, and traffic volumes were similar. Table 9 shows percentages of VSL activation from matching PVR and PSL, excluding periods when work zones, major weather events, or system communications problems were present. Table 9 also includes only time periods where the flow rate across all lanes exceeded 2,000 vehicles per hour (vph). This threshold was set so that low volume periods when flow rate was below the capacity of a single lane would be removed from the data. Because low flow periods were removed from Table 9, it shows a smaller proportion of time where base speed limits (65, 70 mph) were posted than Table 1. Correspondingly, the proportion of time reduced speeds were posted increased in Table 9 versus Table 1.

Table 9. Summary of Seasonal Average Activation Percentages of Posted Speed Limits (All VSL Locations; Work Zones, Weather, and Outages Filtered; Demand Volume > 2,000 vph)

VSL Recommended Speed	Before	After							
	Winter 2022	Summer 2022	Fall 2022	Winter A 2023	Winter B 2023	Spring 2023	Summer 2023	Fall 2023	After Overall
65, 70 mph	93.9%	83.5%	90.7%	93.9%	92.7%	86.0%	84.5%	89.3%	88.1%
60 mph	0.1%	0.1%	0.1%	0.0%	0.2%	0.2%	0.2%	0.2%	0.1%
55 mph	1.3%	2.1%	1.6%	1.3%	2.0%	3.1%	3.1%	2.9%	2.4%
45 mph	0.9%	2.1%	1.4%	1.1%	1.0%	1.9%	1.9%	1.5%	1.6%
35 mph	3.9%	12.1%	6.3%	3.6%	4.2%	8.9%	10.3%	6.2%	7.8%

VSL = variable speed limit.

Note: Winter A 2023 and Winter B 2023 represent data from before and after, respectively, the VSL algorithm changed in February 2023.

Operations Analysis

Average Speed and Speed Limit Compliance

Mean Speed and Standard Deviation for the Entire Corridor

Figure 10 and Table 10 show the average and standard deviation of speed during the before and after periods by PSL, with after speeds separated by season. All figures and tables from this section of the report exclude periods when work zones, major weather events, or system outages were present; they also only include time periods when the flow rate across all lanes exceeded 2,000 vph.

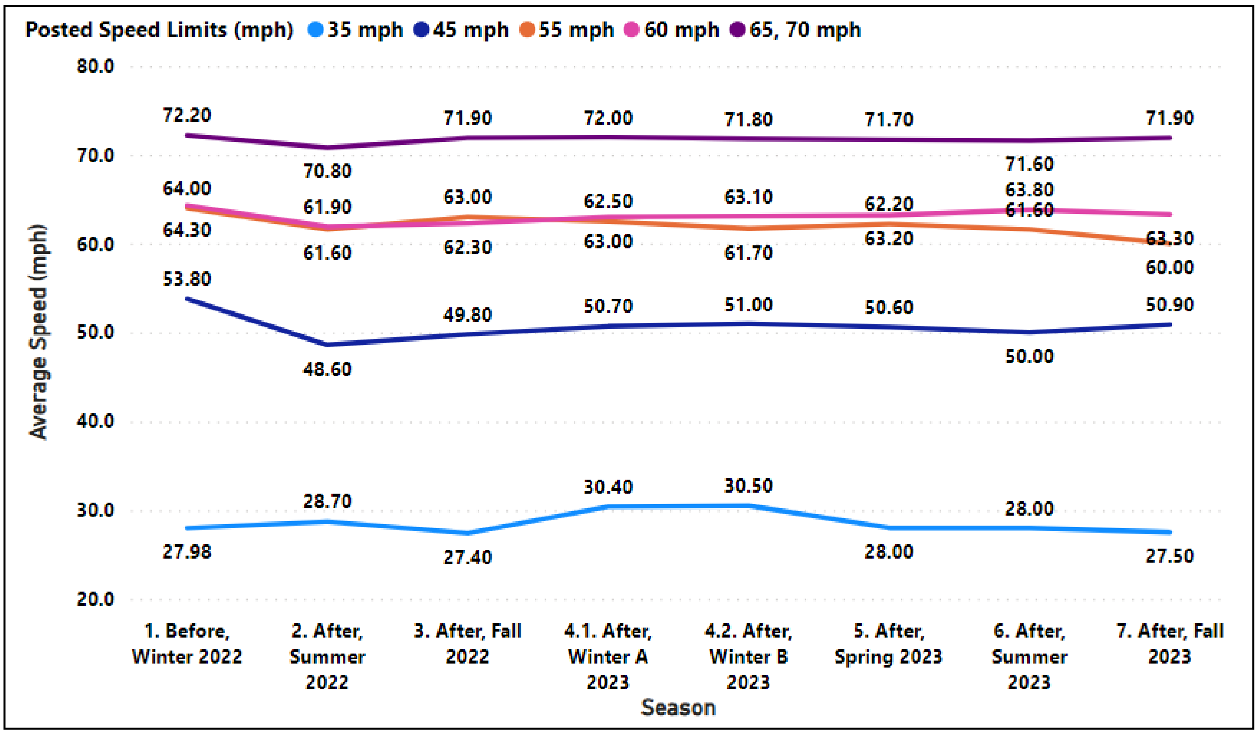


Figure 10. Summary of Seasonal Mean Speed by Posted Speed Limit (All Variable Speed Limit Locations; Work Zones, Weather, and Outages Filtered; Demand Volume > 2,000 vph)

Table 10. Summary of Seasonal Standard Deviation of Posted Speed Limits (All Variable Speed Limit Locations; Work Zones, Weather, and Outages Filtered; Demand Volume > 2,000 vph)

VSL[a] Recommended Speed	Before	After							
	Winter 2022	Summer 2022	Fall 2022	Winter A 2023	Winter B 2023	Spring 2023	Summer 2023	Fall 2023	After Overall
65, 70 mph	5.7	7.9	5.9	5.7	6.0	6.5	7.1	6.0	6.5
60 mph	9.0	7.7	7.9	7.3	6.4	8.9	8.9	7.0	7.9
55 mph	14.2	11.3	11.0	10.9	10.3	12.8	13.0	12.6	11.9
45 mph	17.8	15.6	16.7	16.5	16.8	17.7	17.8	17.2	17.0
35 mph	15.4	13.6	14.0	15.2	14.1	14.2	13.8	13.7	14.1

[a]VSL = variable speed limit.
Note: Winter A 2023 and Winter B 2023 represent data from before and after, respectively, the VSL algorithm changed in February 2023.

In Figure 10, average speeds were relatively alike between the before and after periods during uncongested conditions (65, 70 mph) and during congested conditions (35 mph). The research team expected this similarity, as drivers were traveling at speeds they would typically select during free flow. Likewise, speeds are being controlled by congestion when 35 mph speeds are posted. The 55 and 45 mph cases represent situations of transitional flow, either because traffic was slowing down when approaching stopped traffic or volumes became high, representing instability prior to traffic flow breakdown. Average speeds of those transitional PSLs dropped up to 4 or 5 mph compared with when only static speed limits were present. Comparing before and all after periods (Table 10, first and last columns), the standard deviations of speed also declined for all VSLs below 65 mph.

Utilization, Mean Speed, and Standard Deviation for Corridor Subsections

Table 11 shows activation percentages by season for each subsection of the corridor (northern, middle, southern), using the screened data. The researchers observed that the algorithm change that occurred during the winter of 2023 did not significantly affect activation results, so the Winter A and Winter B 2023 periods were combined for simplicity of presentation in these tables. A comparison of results showed that the northern locations posted reduced speeds far more often than the other sections of the corridor. That fact confirms the utilization data presented earlier. Specifically, in the northern section (Table 11a), VSLs posted reduced speeds 26.6 percent of the time in the overall after period, whereas in the middle (Table 11b) and southern (Table 11c) sections reduced speeds were shown 13.0 and 2.3 percent of the time, respectively. About 71 percent of reduced VSLs in the northern section were 35 mph (congested conditions). and about 27 percent were transitional PSLs (45 mph, 55 mph). The transitional PSLs in the middle and southern sections made up 42 and 82 percent, respectively, of reduced VSLs. The research team expected that result because the recurring bottleneck on weekend afternoons starts downstream of the northern end of the study corridor, and a long queue that covers the northern section of the corridor propagates upstream to the middle and southern sections of the corridor. The step-down requirements for reducing speeds may have also influenced the lower proportion of 35 mph limits posted in the southern end of the corridor.

Table 11. Summary of Seasonal Activation of Posted Speed Limits for (a) Northern, (b) Middle, and (c) Southern Variable Speed Limit (VSL) Locations (Work Zones, Weather, and Outages Filtered; Demand Volume > 2,000 vph)

(a) Northern VSL Locations

VSL[a] Recommended Speed	Before	After						
	Winter 2022	Summer 2022	Fall 2022	Winter 2023	Spring 2023	Summer 2023	Fall 2023	After Overall
65, 70 mph	86.6%	69.3%	79.2%	84.3%	65.8%	64.9%	75.5%	73.4%
60 mph	0.2%	0.4%	0.2%	0.2%	0.5%	0.5%	0.7%	0.4%
55 mph	2.5%	2.6%	2.5%	2.9%	5.4%	4.6%	5.5%	3.9%
45 mph	1.8%	3.3%	2.8%	2.6%	4.1%	3.4%	3.1%	3.2%
35 mph	9.0%	24.3%	15.3%	10.0%	24.2%	26.6%	15.2%	19.1%

(b) Middle VSL Locations

VSL[a] Recommended Speed	Before	After						
	Winter 2022	**Summer 2022**	**Fall 2022**	**Winter 2023**	**Spring 2023**	**Summer 2023**	**Fall 2023**	**After Overall**
65, 70 mph	95.6%	84.3%	93.0%	73.1%	90.6%	88.7%	93.0%	87.0%
60 mph	0.01%	0.01%	0.01%	0.06%	0.03%	0.02%	0.03%	0.0%
55 mph	0.9%	2.1%	1.4%	7.9%	2.7%	3.0%	2.1%	3.3%
45 mph	0.6%	2.1%	1.2%	5.1%	1.5%	1.8%	1.0%	2.2%
35 mph	2.9%	11.5%	4.4%	13.9%	5.2%	6.6%	3.9%	7.6%

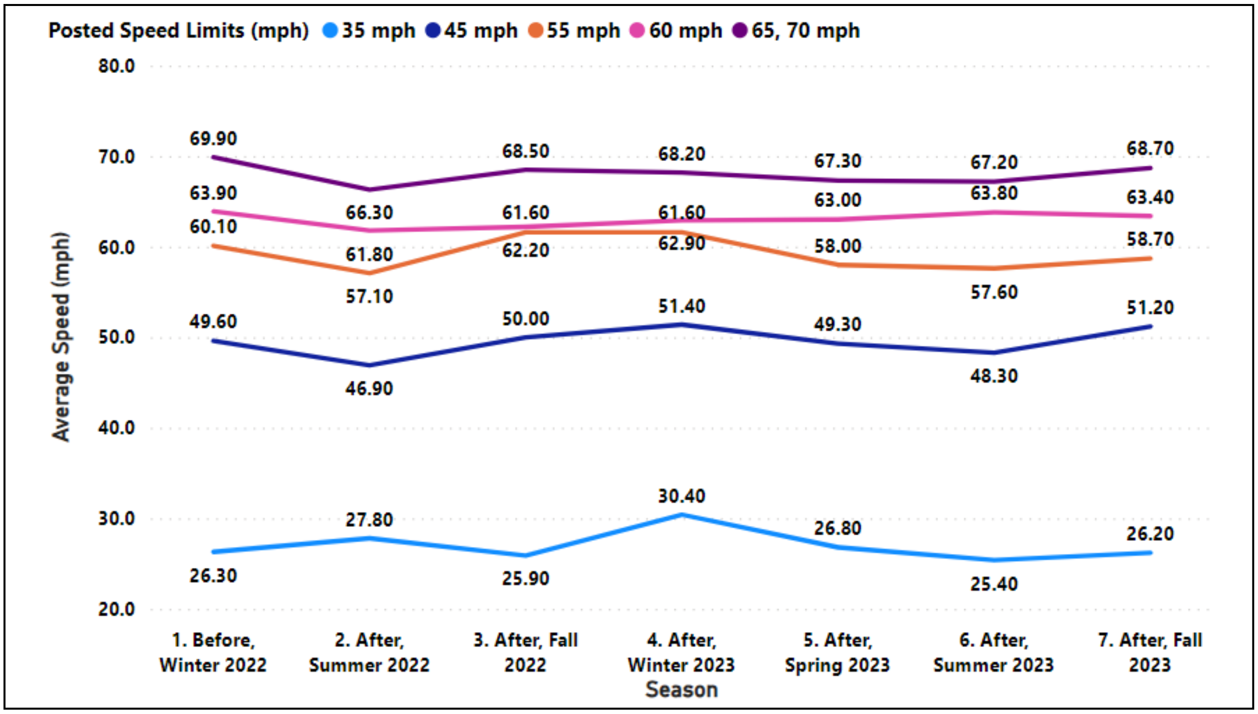
(c) Southern VSL Locations

VSL[a] Recommended Speed	Before	After						
	Winter 2022	**Summer 2022**	**Fall 2022**	**Winter 2023**	**Spring 2023**	**Summer 2023**	**Fall 2023**	**After Overall**
65, 70 mph	98.6%	97.3%	98.2%	98.8%	98.2%	97.6%	96.0%	97.7%
60 mph	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
55 mph	0.7%	1.1%	1.0%	0.6%	1.5%	1.6%	1.9%	1.3%
45 mph	0.4%	1.0%	0.5%	0.3%	0.2%	0.4%	1.1%	0.6%
35 mph	0.3%	0.6%	0.4%	0.2%	0.1%	0.4%	1.1%	0.4%

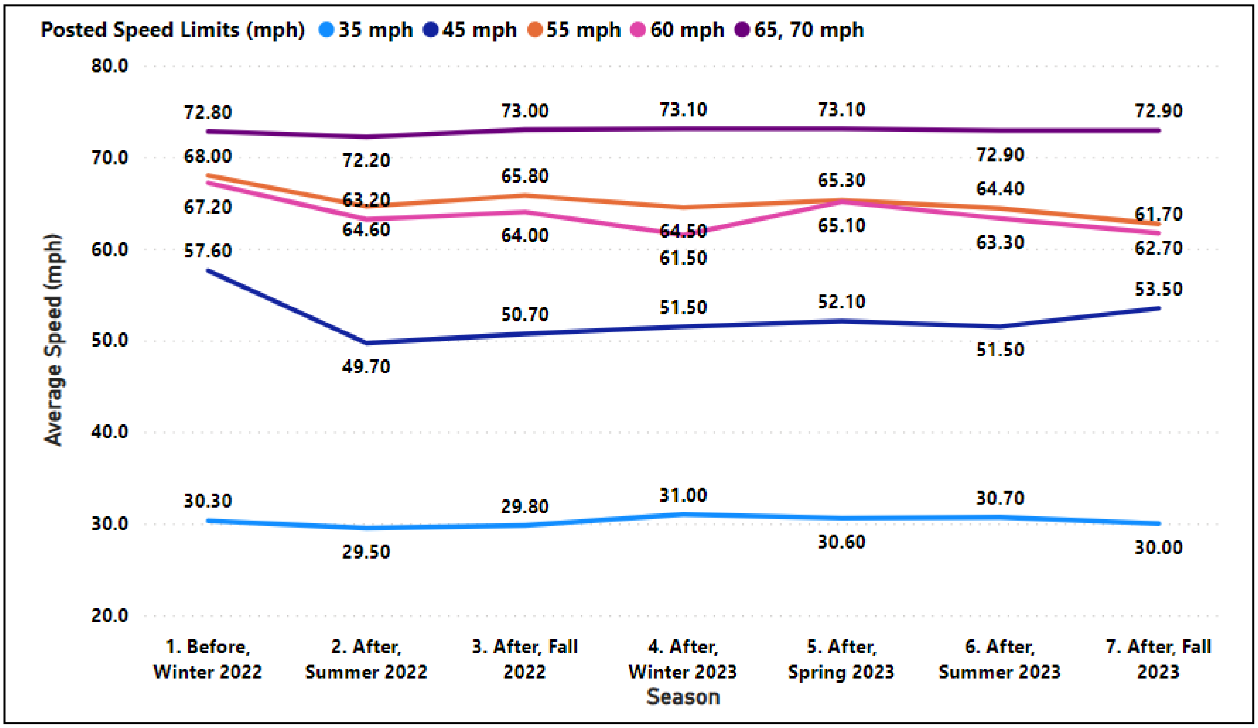
[a]VSL = variable speed limit.
N/A = not applicable because the southern section did not have a 60 mph PSL option.

Figure 11 shows average speeds by season for the three corridor sections. In Figure 11a, the northern sections' average speeds for each VSL did not change much between the before and after periods. However, a reduction in average speeds for transitional PSLs occurred for the middle and southern sections between the before and after periods. In Figures 11b and 11c, a comparison of before (2022) and after (2023) winter seasons shows average speeds reduced by 6–19 mph when transitional VSLs were posted. Figure 11c shows that average speeds increased slightly during spring 2023 but declined in the following seasons. Figure 11b shows the average speeds for the 60 mph PSL were a little less than those for the 55 mph PSL, but that difference may be due to the small sample size (about 0.01–0.06 percent in Table 11b) bias. Of note is that the southern section did not have a 60 mph PSL as a permitted option.

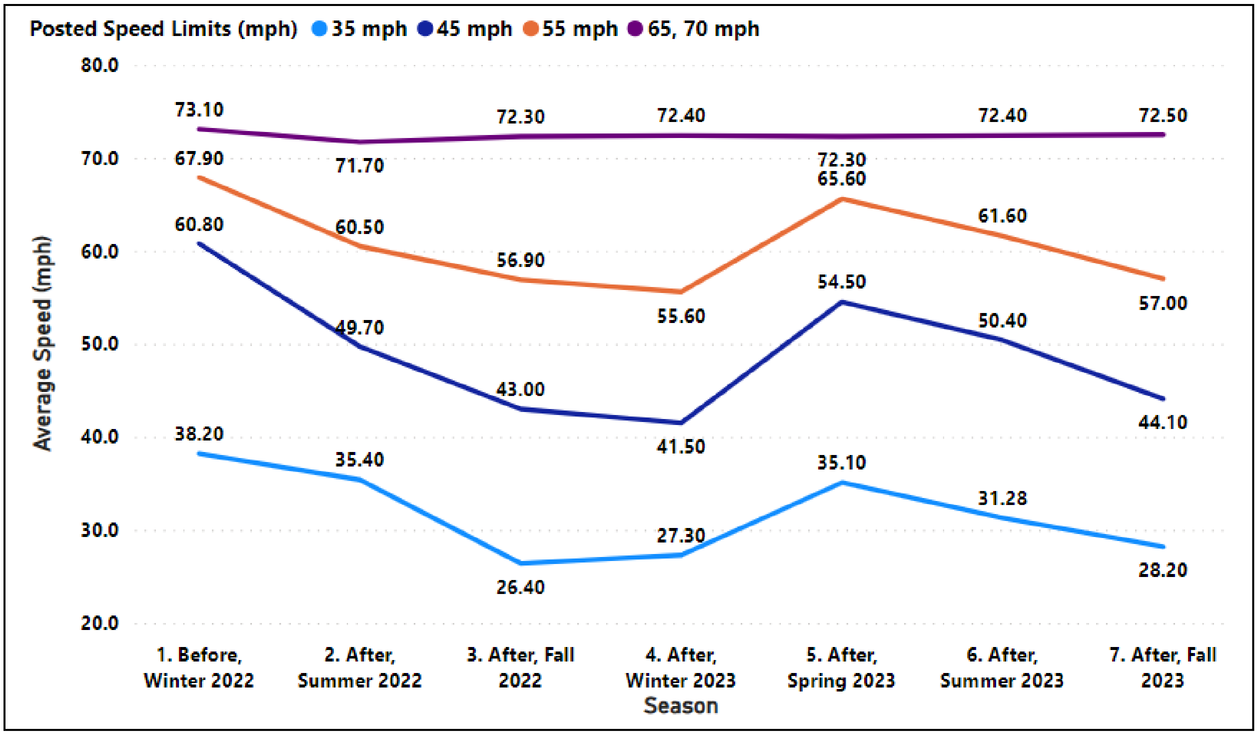
Comparing locations shows average speeds during congested conditions (35 mph) on the northern section of the corridor were lower than speeds on the middle and southern sections. This situation was also expected as the congestion is more severe on the northern end of the corridor. Particularly interesting was that average speeds during uncongested conditions (65, 70 mph) for the northern section of the corridor were also lower than those in the rest of the corridor. However, considering that there was very little change in average speeds during free-flow conditions by season throughout the corridor, the slight change may be explained by the lower base speed limit in the northern section, not a behavioral result of VSL.



(a) Northern VSL Locations



(b) Middle VSL Locations



(c) Southern VSL Locations

Figure 11. Summary of Seasonal Mean Speed by Posted Speed Limits for (a) Northern, (b) Middle, and (c) Southern Variable Speed Limit (VSL) Locations (Work Zones, Weather, and Outages Filtered; Demand Volume > 2,000 vph)

Table 12 shows standard deviations of speed during the study period by season for the three corridor subsections. The standard deviations of speed declined for transitional and congested PSLs for the northern section of the corridor (Table 12a). For the middle (Table 12b) and southern (Table 12c) sections, however, standard deviation of speeds did not decrease much in the after period.

Table 12. Summary of Seasonal Standard Deviation of Posted Speed Limits for (a) Northern, (b) Middle, and (c) Southern VSL Locations (Work Zones, Weather, and Outages Filtered; Demand Volume > 2,000 vph)

(a) Northern VSL Locations

VSL[a] Recommended Speed	Before	After						
	Winter 2022	Summer 2022	Fall 2022	Winter 2023	Spring 2023	Summer 2023	Fall 2023	After Overall
65, 70 mph	6.3	9.9	6.7	6.7	8.2	9.3	6.2	7.8
60 mph	9.3	7.7	8.0	6.7	8.9	9.0	7.1	7.9
55 mph	16.2	12.0	11.0	10.4	14.7	14.7	11.9	12.4
45 mph	17.4	13.5	15.8	15.2	17.5	17.5	15.9	16.0
35 mph	14.3	12.5	13.0	14.5	13.5	12.5	12.9	13.2

[a]VSL = variable speed limit.

(b) Middle VSL Locations

VSL[a] Recommended Speed	Before	After						
	Winter 2022	Summer 2022	Fall 2022	Winter 2023	Spring 2023	Summer 2023	Fall 2023	After Overall
65, 70 mph	5.3	7.1	5.3	5.3	5.5	6.1	5.5	5.8
60 mph	6.3	7.1	6.4	7.6	7.9	8.5	5.7	7.2
55 mph	10.3	9.9	8.9	8.8	10.4	11.3	10.5	9.9
45 mph	17.6	17.1	17.2	17.6	17.9	18.0	17.2	17.5
35 mph	16.6	14.6	15.2	16.2	15.1	15.2	14.9	15.2

[a]VSL = variable speed limit

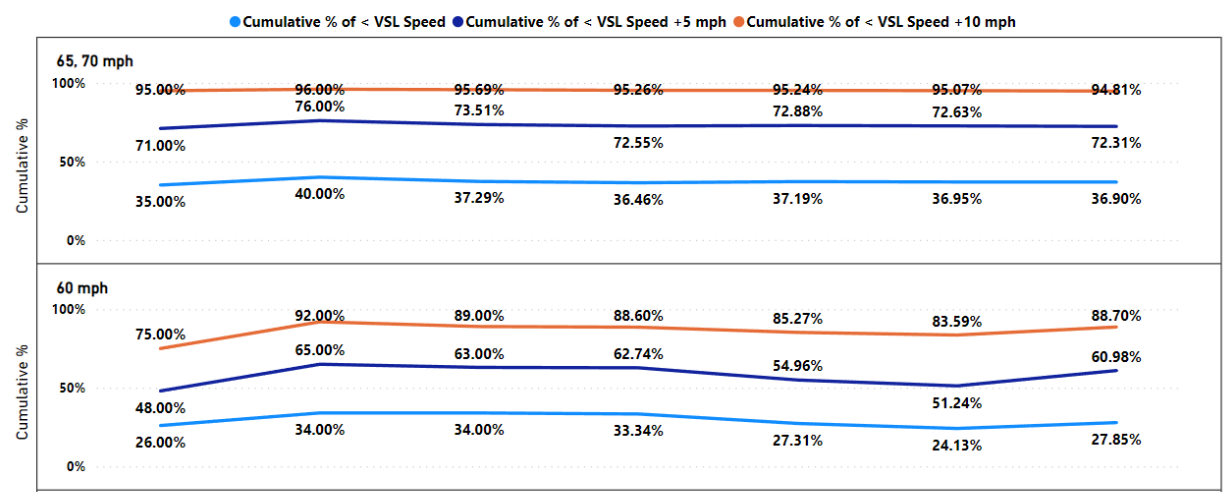
(c) Southern VSL Locations

VSL[a] Recommended Speed	Before	After						
	Winter 2022	Summer 2022	Fall 2022	Winter 2023	Spring 2023	Summer 2023	Fall 2023	After Overall
65, 70 mph	5.2	5.4	5.4	5.4	5.2	5.5	6.2	5.4
60 mph	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
55 mph	11.8	11.0	14.7	15.8	8.2	11.2	17.9	12.1
45 mph	15.5	13.9	17.8	19.7	13.9	16.3	19.7	16.2
35 mph	14.6	12.3	14.3	14.6	15.4	15.2	12.8	14.4

[a]VSL = variable speed limit.
N/A = not applicable because the southern section did not have a 60 mph PSL option.

VSL Compliance and Speed Distribution

Next, researchers examined the proportion of vehicles complying with the recommended VSL. Figure 12 shows the percentage of vehicles that traveled below the PSL, no more than 5 mph over the PSL, or no more than 10 mph over the PSL. The data show that proportions for the before and after periods were similar for both free flow and congested conditions. During the transitional VSLs of 45 and 55 mph, slight improvements in strict compliance with the PSL occurred, but much larger improvements appeared in the proportion of vehicles traveling no more than 5 or 10 mph over the PSL. For example, the proportion of vehicles travelling below 65 mph when a 55-mph speed was posted was between 50 and 62 percent of all traffic compared with 38 percent in the before period. In general, the proportion of high-speed vehicles (traveling more than 10 mph over the VSL) during these transitional speeds declined by at least 10 percent.



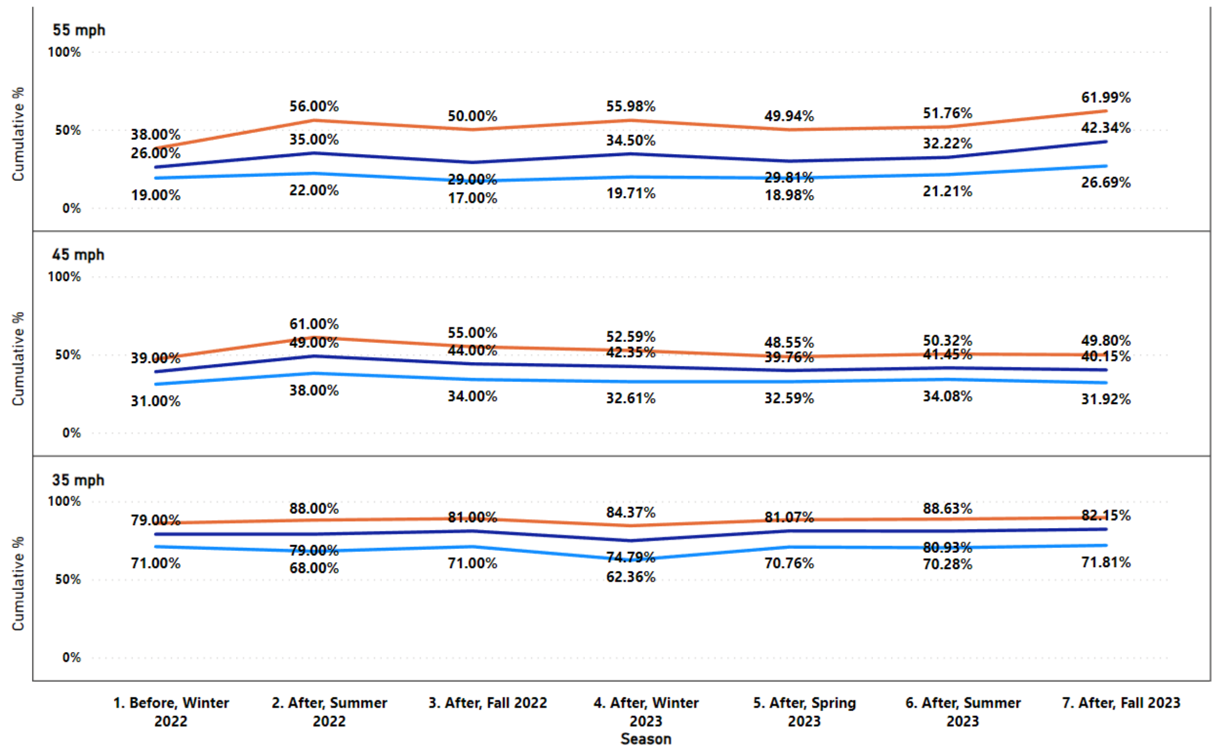
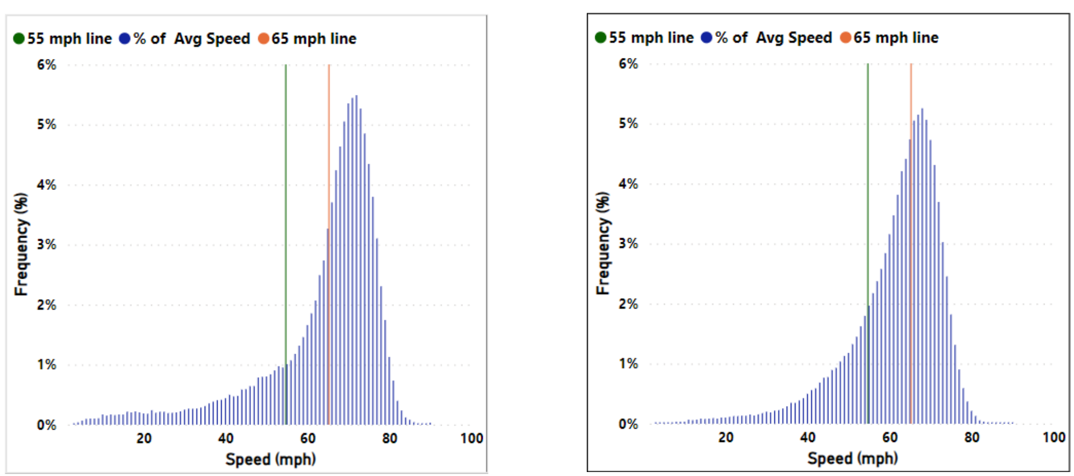
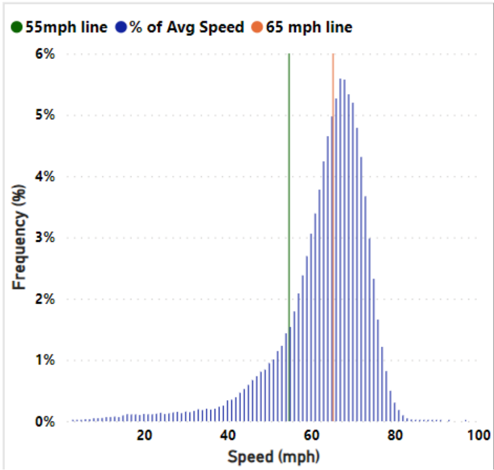


Figure 12. Before and After Speed Limit Compliance Percentages (All Variable Speed Limit Locations; Work Zones, Weather, and Outages Filtered; Demand Volume > 2,000 vph)

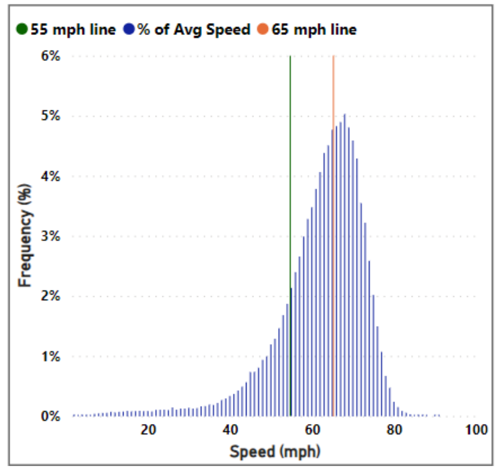
Figure 13 shows the speed distributions of 30-second average speeds for vehicles passing 55 mph VSL signs (or, in the case of the before period, experiencing traffic conditions where a 55 mph VSL would have been posted). In the figure, vertical lines indicate 55 mph and 65 mph as reference points. The area to the left of the 55-mph vertical line is the cumulative percentage of observed speeds less than the PSL, and the area to the left of the 65-mph vertical line is the cumulative percentage of observed speed less than the 65 mph. As the peak of the curves get closer to 65 mph line, the area between vertical lines also increases. In general, the speed distribution curves shifted left, indicating that the distribution of speeds is becoming slower.



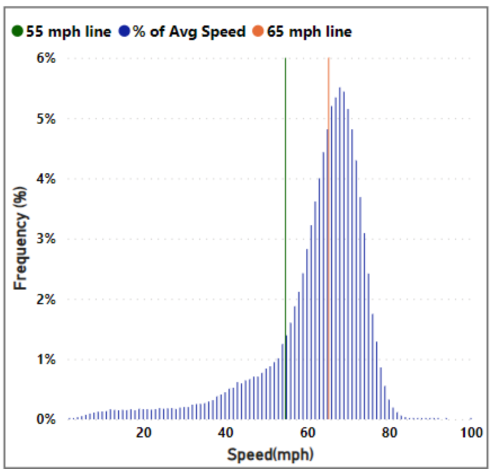
(a) Before, Winter 2022 **(b) After, Summer 2022**



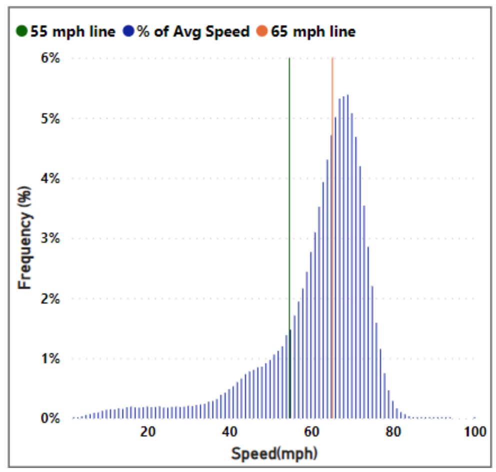
(c) After, Fall 2022



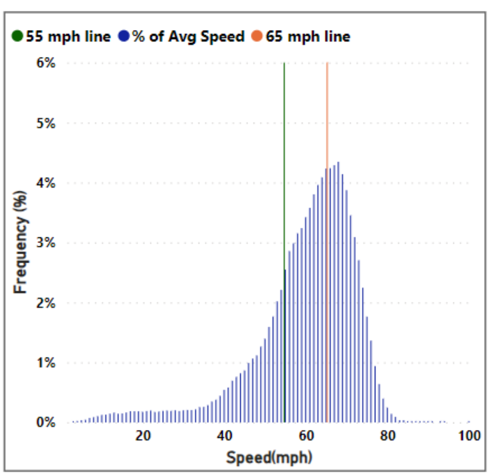
(d) After, Winter 2023



(e) After, Spring 2023



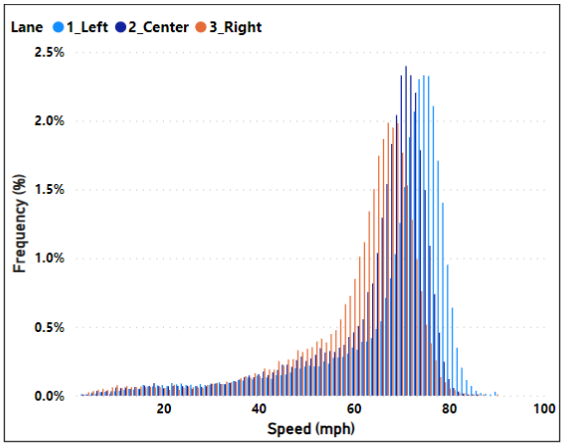
(f) After, Summer 2023



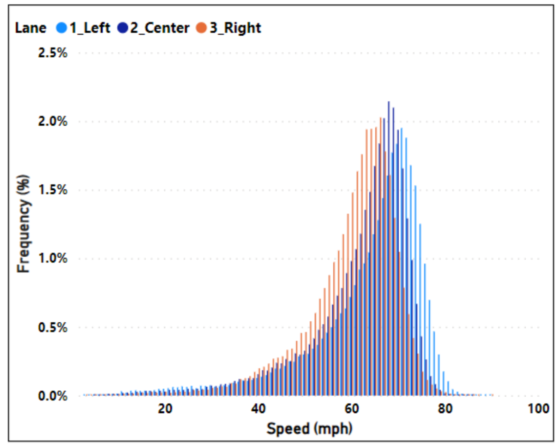
(g) After, Fall 2023

Figure 13. Speed Distributions of 55 mph Posted Speed Limit: (a) Before, Winter 2022, (b) After, Summer 2022, (c) After, Fall 2022, (d) After, Winter 2023, (e) After, Spring 2023, (f) After, Summer 2023, and (g) After, Fall 2023. At all sites, weather, work zones, and outages were filtered out and demand volume was > 2,000 vph. Green line = 55 mph; orange line = 65 mph.

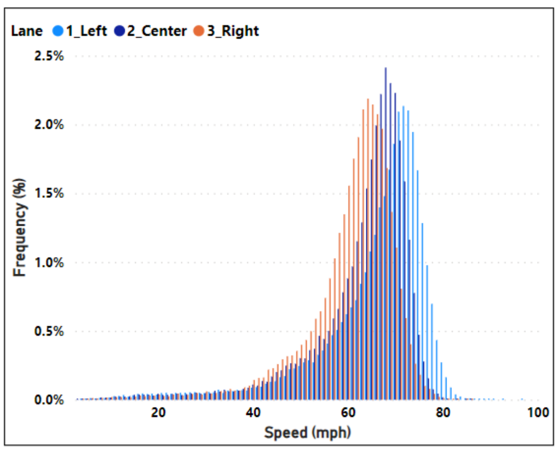
Figure 14 shows the same speed data as Figure 13 but separated by lane (left, center, and right) for the 55 mph PSL. As anticipated, the distributions demonstrate a noticeable shift toward higher speeds when transitioning from the right lane to the left lane. Speed distributions in all three lanes have shifted to the left, indicating lower speeds.



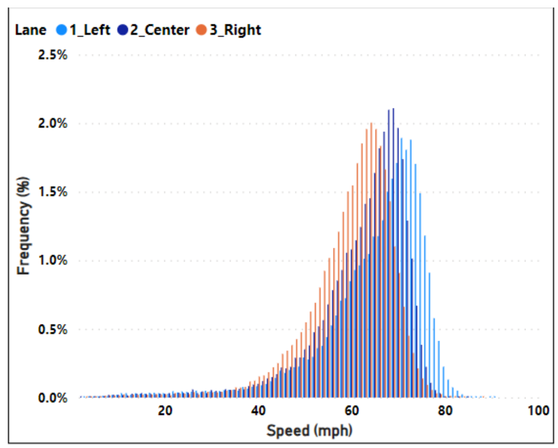
(a) Before, Winter 2022



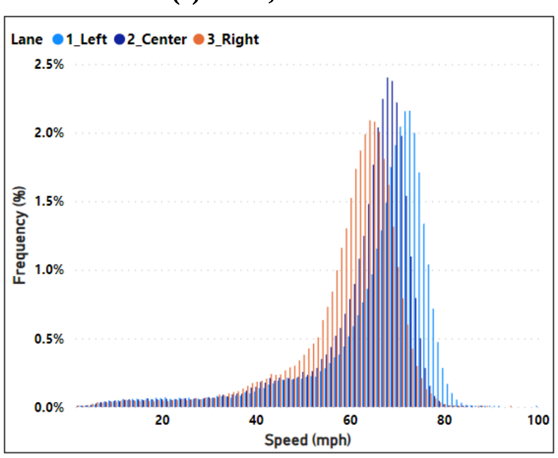
(b) After, Summer 2022



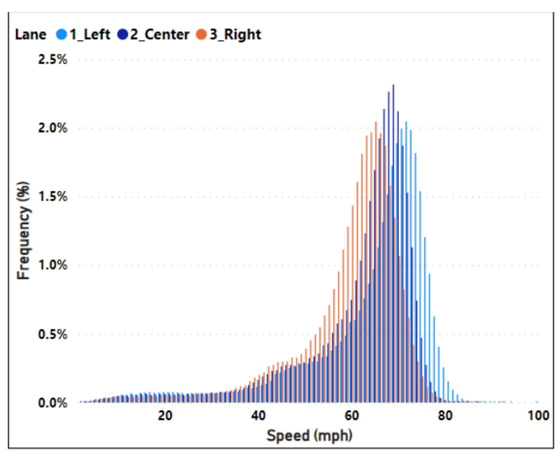
(c) After, Fall 2022



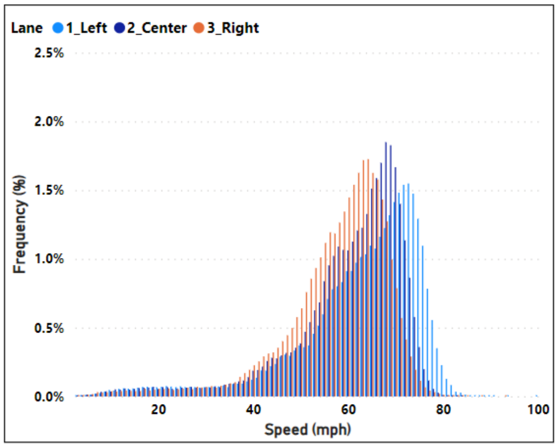
(d) After, Winter 2023



(e) After, Spring 2023



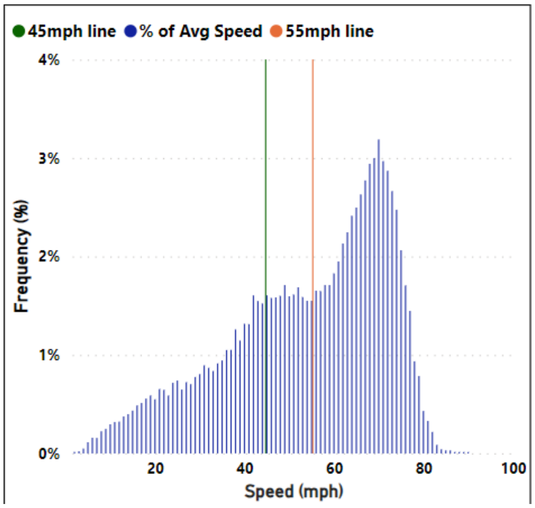
(f) After, Summer 2023



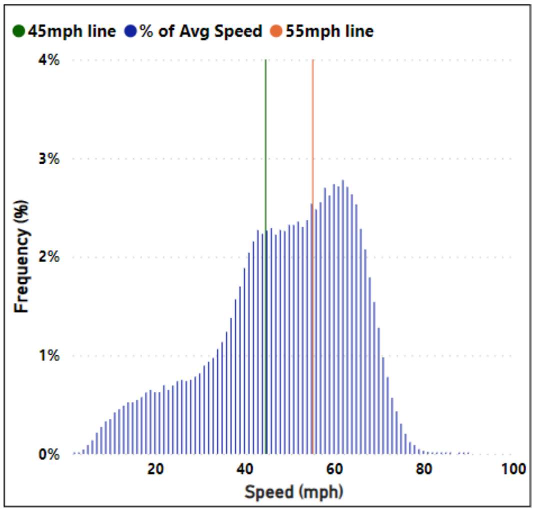
(g) After, Fall 2023

Figure 14. Speed Distribution by Lane of 55 mph Posted Speed Limit: (a) Before, Winter 2022, (b) After, Summer 2022, (c) After, Fall 2022, (d) After, Winter 2023, (e) After, Spring 2023, (f) After, Summer 2023, and (g) After, Fall 2023. At all sites, weather, work zones, and outages were filtered out, and demand volume was > 2,000 vph.

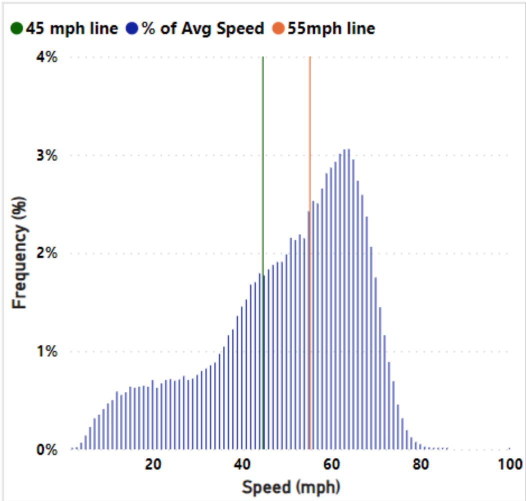
Figure 15 shows speed distributions of 30 second average speeds for vehicles passing 45 mph VSL signs. In the figure, vertical lines represent 45 mph and 55 mph as reference points. Like the 55-mph case, the speed distributions shifted to the left, indicating lower speeds. Differences were particularly noticeable in the first 9 months of operation.



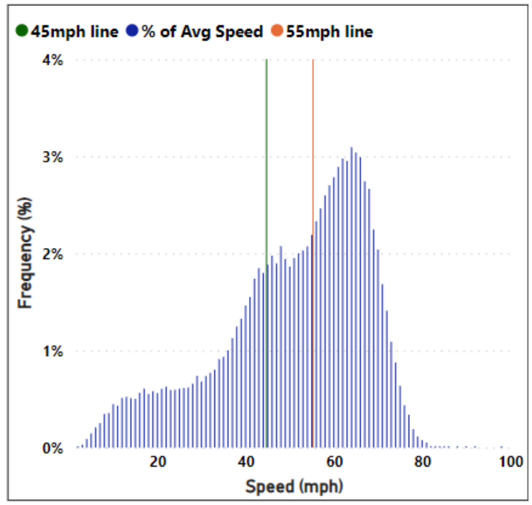
(a) Before, Winter 2022



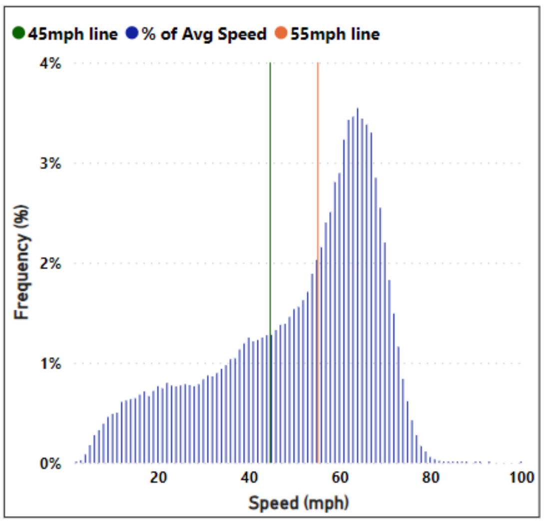
(b) After, Summer 2022



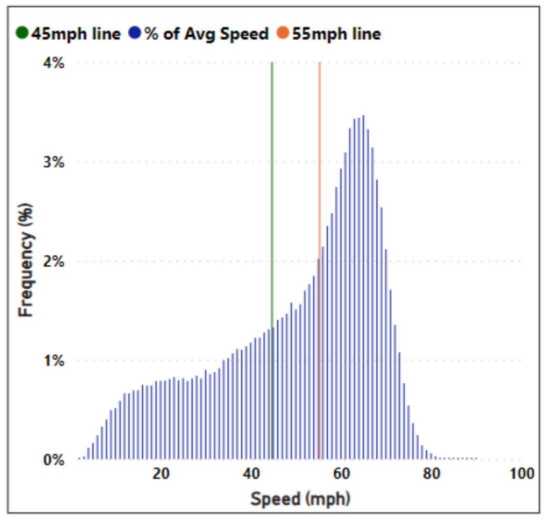
(c) After, Fall 2022



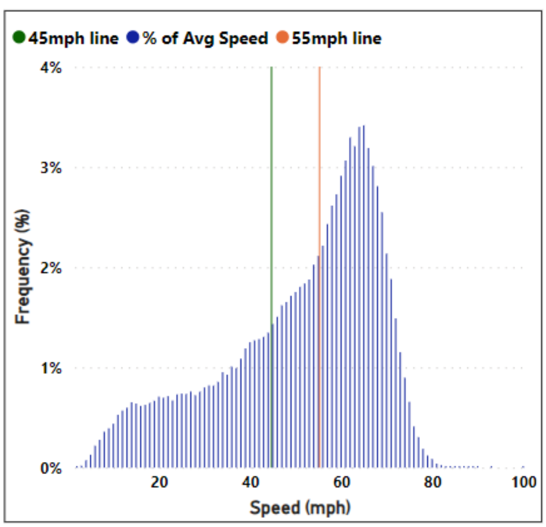
(d) After, Winter 2023



(e) After, Spring 2023



(f) After, Summer 2023

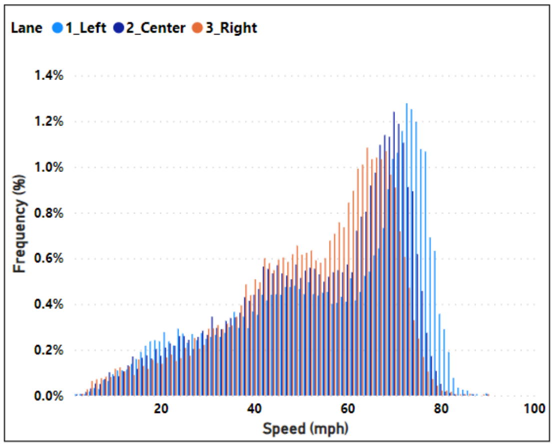


(g) After, Fall 2023

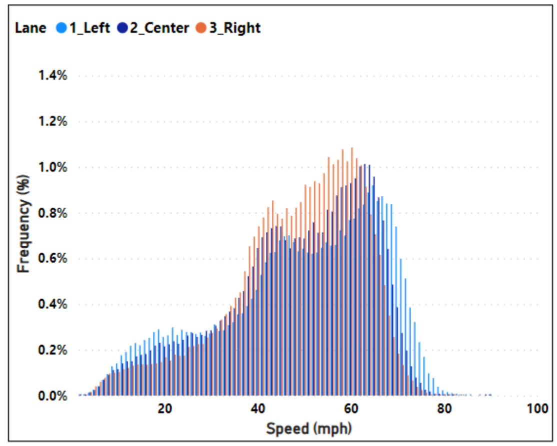
Figure 15. Speed Distributions of 45 mph Posted Speed Limit: (a) Before, Winter 2022, (b) After, Summer 2022, (c) After, Fall 2022, (d) After, Winter 2023, (e) After, Spring 2023, (f) After, Summer 2023, and (g)

After, Fall 2023. At all sites, weather, work zones, and outages were filtered out, and demand volume was > 2,000 vph. Green line = 45 mph; orange line = 55 mph.

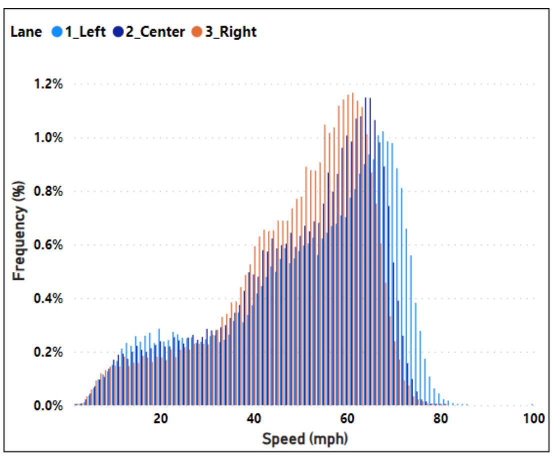
Figure 16 shows the same speed data as Figure 15 but separated by lane (left, center, and right) for the 45 mph PSL. As expected, the distributions shift towards higher speeds moving from the right lane to the left lane.



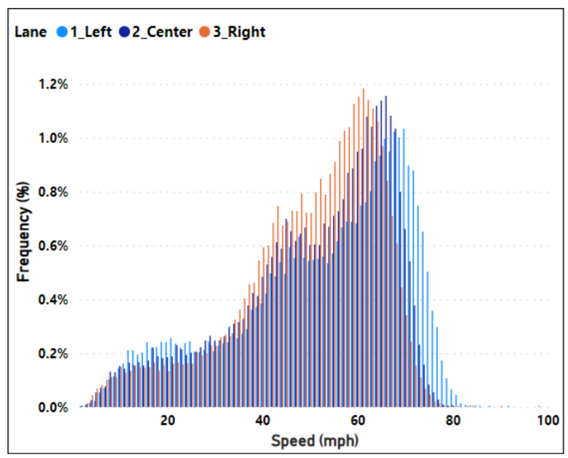
(a) Before, Winter 2022



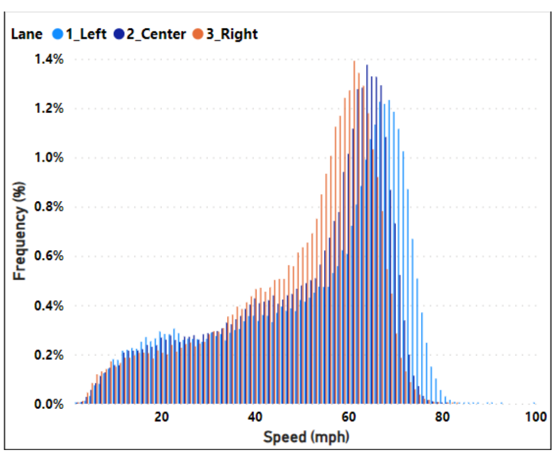
(b) After, Summer 2022



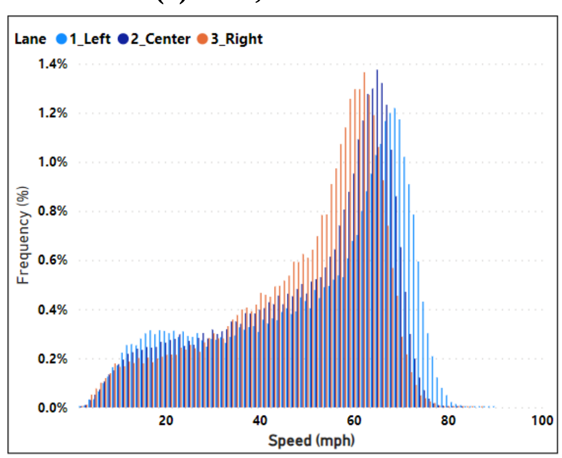
(c) After, Fall 2022



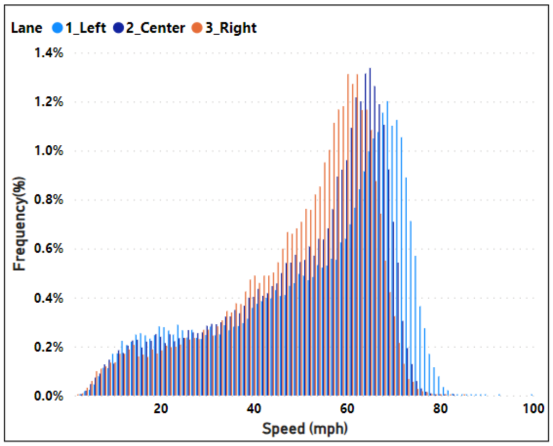
(d) After, Winter 2023



(e) After, Spring 2023



(f) After, Summer 2023



(g) After, Fall 2023

Figure 16. **Speed Distribution by Lane of 45 mph Posted Speed Limit: (a) Before, Winter 2022, (b) After, Summer 2022, (c) After, Fall 2022, (d) After, Winter 2023, (e) After, Spring 2023, (f) After, Summer 2023, and (g) After, Fall 2023. At all sites, weather, work zones, and outages were filtered, out and demand volume was > 2,000 vph.**

It was also hypothesized that VSL might improve speed harmonization across lanes. Tables 13 and 14 show that speed differentials between lanes reduced slightly during the 55 mph and 45 mph transitional PSLs. In every season in the after period, reductions in speed differentials between the left and center lanes and between the center and right lanes are observed compared with the speed differentials in the before period. When the data from Winter 2023 are compared with the before data, the reductions was around 0.5 mph. Although this may not represent a large value in terms of absolute magnitude, it does represent a large change in traffic because millions of observations were used. This indicates an improvement in speed harmonization between lanes, and more uniformity in flow across lanes.

Table 13. Mean Speed (mph) and Speed Differential (mph) by Lane for 55 mph Variable Speed Limit (All Sites, Filtered Out Weather, Work Zones, and Outages; Demand Volume > 2,000 vph)

Period	Mean Speed (mph)			Speed Differential (mph)	
	Left Lane	Center Lane	Right Lane	Δ Left-Center	Δ Center-Right
Before, Winter 2022	67.3	63.9	61.0	3.4	2.9
After, Summer 2022	63.8	61.8	59.9	2.0	1.9
After, Fall 2022	66.6	63.0	60.4	3.6	2.6
After, Winter 2023	65.0	62.2	59.5	2.8	2.7
After, Spring 2023	65.1	62.2	59.5	2.9	2.7
After, Summer 2023	64.1	61.6	59.2	2.5	2.4
After, Fall 2023	62.5	60.0	57.6	2.5	2.4

Table 14. Mean Speed (mph) and Speed Differential (mph) by Lane for 45 mph Variable Speed Limit (All Sites, Filtered Out Weather, Work Zones, and Outages; Demand Volume > 2,000 vph)

Period	Mean Speed (mph)			Speed Differential (mph)	
	Left Lane	Center Lane	Right Lane	Δ Left-Center	Δ Center-Right
Before, Winter 2022	55.9	53.5	52.1	2.4	1.4
After, Summer 2022	49.4	48.4	48.1	1.0	0.3
After, Fall 2022	51.3	49.4	48.6	1.9	0.8
After, Winter 2023	52.3	50.4	49.5	1.9	0.9
After, Spring 2023	52.6	50.3	49.1	2.3	1.2
After, Summer 2023	51.3	49.7	49.1	1.6	0.6
After, Fall 2023	52.8	50.5	49.4	2.3	1.1

Travel Time and Reliability

Entire Corridor

Travel time and reliability were assessed, using INRIX data. The probe data were available continuously in the corridor during both the before and after periods because there are no restrictions related to when detectors were present on the corridor as there was with the previous analysis. Figure 17 and Table 15 show a comparison of the average daily travel times across the entire corridor for a 1-year period beginning on June 22, 2018 (representing a prepandemic baseline), 1 year before VSL activation, and 1 year after VSL activation. Figure 17 shows that mean travel times were generally higher than the prepandemic baseline. Tuesdays through Thursdays generally showed relatively little congestion, with higher congestion observed on the weekends.

When comparing 1 year before activation with 1 year after activation, travel times were within 4 percent of one another on Tuesday, Wednesday, Thursday, and Saturday. The site experienced a 4.7 percent reduction in travel time on Mondays and an 8.5 percent reduction on Sundays. Fridays exhibited a large increase in travel times of 20.5 percent. On aggregate, weekdays experienced a 4.3 percent increase from 14.91 to 15.55 minutes. Weekday travel times remained near free flow on average despite this increase. Weekends experienced a 4.7 percent decrease in travel time from 19.38 to 18.47 minutes.

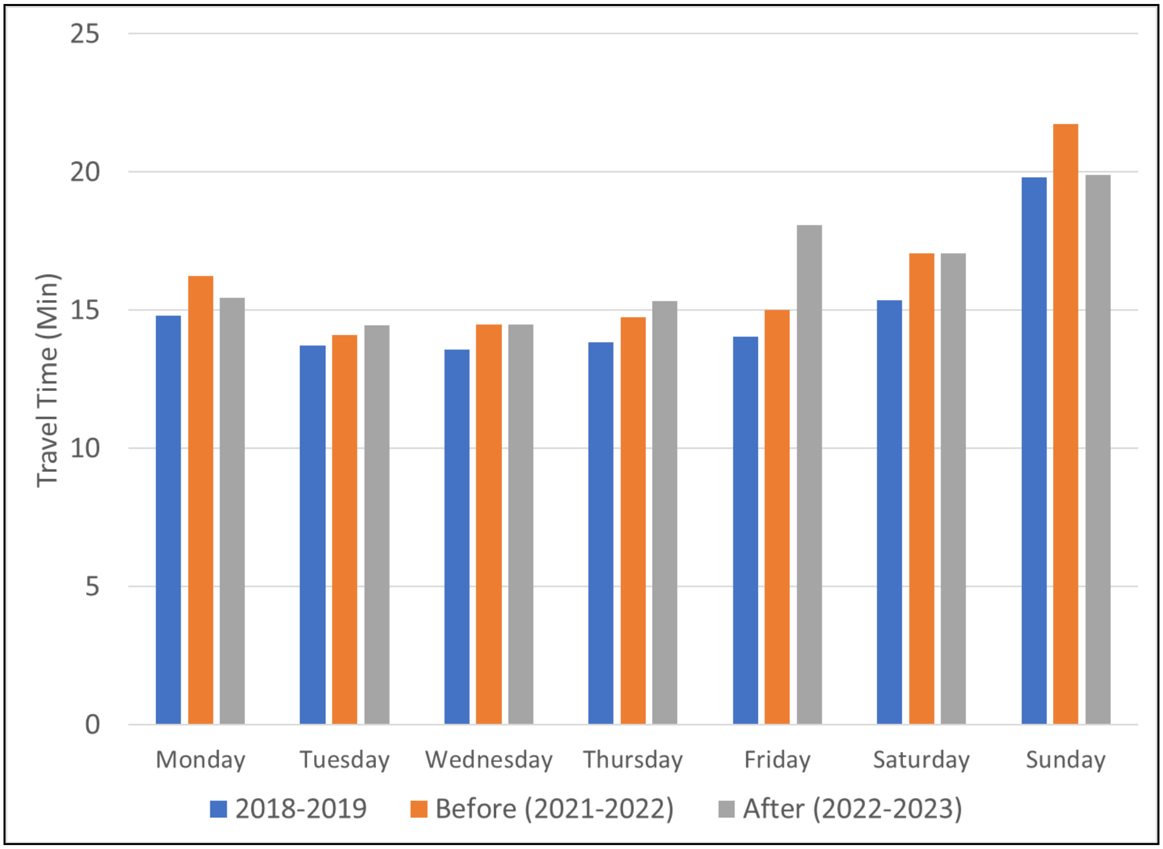


Figure 17. Average Travel Time Comparison Between Mileposts 115–130. Time periods represent 1 year, beginning on June 22 for (1) 2018–2019, (2) 2021–2022 ("before"), and (3) 2022–2023 ("after"). Travel times represent a daily average travel time between 6 a.m. and 8 p.m.

Table 15. Summary of Changes in Average Travel Time and Planning Time Index Across Entire Corridor

Day of Week	Average Travel Time (min)				Reliability (Planning Time Index)			
	Before (2018–2019)	**Before (2021–2022)**	**After (2022–2023)**	**% Change (Last Year)**	**Before (2018–2019)**	**Before (2021–2022)**	**After (2022-2023)**	**% Change (Last Year)**
Monday	14.80	16.22	15.45	-4.7%	1.60	2.36	2.11	-10.6%
Tuesday	13.71	14.10	14.46	+2.6%	1.15	1.35	1.67	+23.7%
Wednesday	13.58	14.49	14.48	-0.1%	1.17	1.70	1.64	-3.5%
Thursday	13.82	14.74	15.33	+4.0%	1.18	1.70	2.00	+17.6%
Friday	14.05	15.00	18.07	+20.5%	1.35	1.90	3.06	+61.1%
Weekdays	***13.99***	***14.91***	***15.55***	***+4.3%***	***1.30***	***1.76***	***2.17***	***+23.3%***
Saturday	15.37	17.06	17.06	0.0%	2.09	2.99	2.97	-0.7%
Sunday	19.80	21.72	19.88	-8.5%	3.32	4.18	3.58	-14.4%
Weekends	***17.61***	***19.38***	***18.47***	***-4.7%***	***2.83***	***3.73***	***3.33***	***-10.7%***
All Week	***15.03***	***16.19***	***16.38***	***+1.2%***	***1.89***	***2.58***	***2.57***	***-0.4%***

Green shading = improvements; yellow shading = degradations.

Travel time reliability was also examined using planning time index (PTI). Figure 18 and Table 15 show daily average PTIs. Trends in reliability were like those observed in the average travel time data. Reliability generally worsened since the prepandemic baseline for both the before and after VSL period. Mid-week continued to exhibit relatively reliable operations, with travel being more variable on weekends, Mondays, and Fridays.

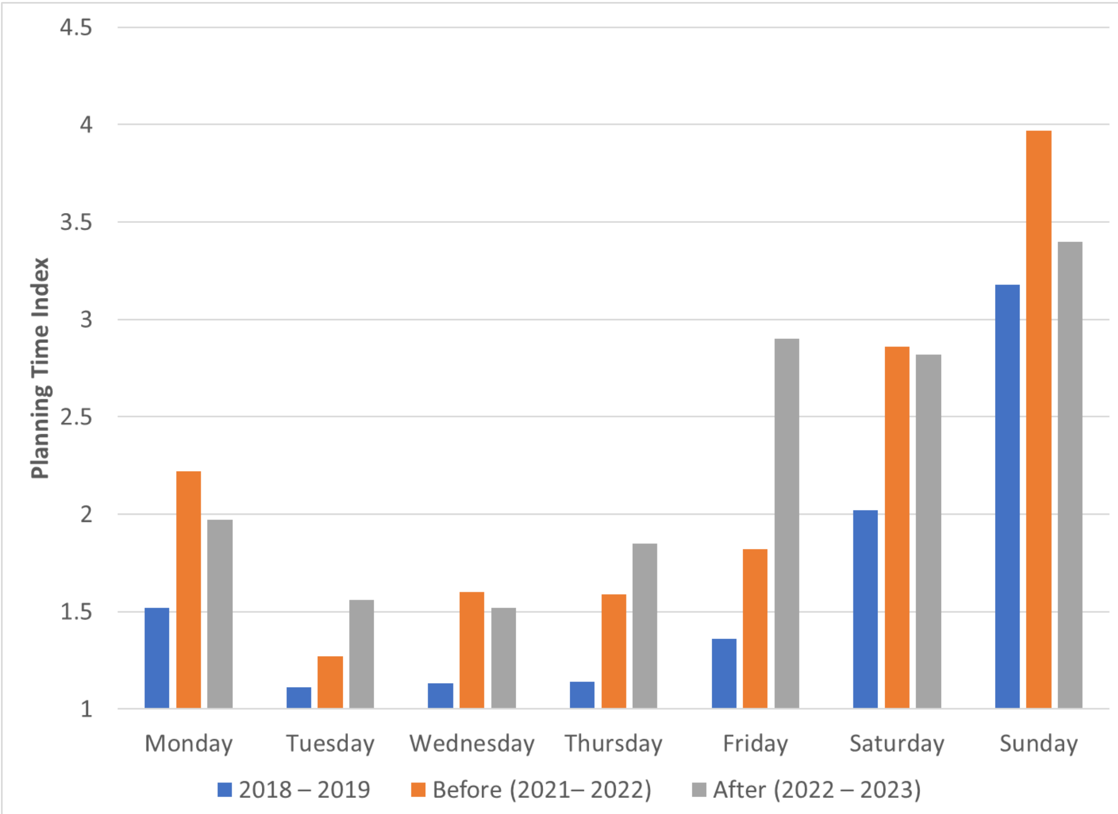


Figure 18. Planning Time Index Comparison Between Mileposts 115–130. Time periods represent 1 year beginning on June 22 for (1) 2018–2019, (2) 2021–2022 ("Before"), and (3) 2022–2023 ("After"). Travel times present a daily average travel time between 6 a.m. and 8 p.m.

When comparing 1 year before activation with 1 year after activation, similar trends emerge for reliability as the average travel times. Mondays (-10.6 percent) and Sundays (-14.4 percent) exhibited significant improvements in reliability, and Fridays exhibited large degradations (+61.1 percent). On average, PTI increased from 1.76 to 2.17 (+23.3 percent) on weekdays and decreased from 3.73 to 3.33 (-10.7 percent) on weekends.

Interestingly, the net effect on operations is relatively flat when the entire week is examined. In general, the corridor operates well during the week, so even large degradations on Fridays are measured relative to a better initial condition so the improvements on Sunday travel times offset Friday's increased travel times. As a result, average travel times during the entire week slightly increased by 1.2 percent, and reliability improved by 0.4 percent.

Performance by Roadway Section

Travel time and PTI were also examined using the south (MP 115–118), middle (MP 119–126), and north (MP 127–130) segmentation to understand where the VSL was creating impacts. Note that when results are broken down by section, the results do not necessarily sum to exactly the values shown in Table 15 because each section may experience degraded travel times on different dates and times. Table 16 shows the southern end of the corridor. The average travel times and PTI values all show this part of the VSL corridor is relatively uncongested. Even though many measures show increases, the system still operated well, with no serious congestion concerns.

Table 16. Summary of Changes in Average Travel Time and Planning Time Index, Southern End of Corridor (Mileposts 115–118)

Day of Week	Average Travel Time (min)				Reliability (Planning Time Index)			
	Before (2018–-2019)	Before (2021–2022)	After (2022–2023)	% Change (Last Year)	Before (2018–2019)	Before (2021–2022)	After (2022-2023)	% Change (Last Year)
Monday	2.81	3.12	2.83	-9.3%	1.02	1.02	1.03	+1.0%
Tuesday	2.73	2.73	2.74	+0.4%	1.01	0.99	1.02	+3.0%
Wednesday	2.72	2.66	2.69	+1.1%	1.01	1.00	1.03	+3.0%
Thursday	2.72	2.78	2.83	+1.8%	1.01	1.01	1.04	+3.0%
Friday	2.79	2.69	2.90	+7.8%	1.02	1.01	1.04	+3.0%
Weekdays	***2.75***	***2.79***	***2.80***	***+0.4%***	***1.01***	***1.00***	***1.03***	***+3.0%***
Saturday	2.87	2.74	2.73	-0.4%	1.10	1.03	1.04	+1.0%
Sunday	3.03	2.72	2.74	+0.7%	1.54	1.05	1.08	+2.9%
Weekends	***2.95***	***2.73***	***2.73***	***0.0%***	***1.31***	***1.03***	***1.06***	***+2.9%***
All Week	***2.81***	***2.77***	***2.78***	***+0.4%***	***1.03***	***1.01***	***1.04***	***+3.0%***

Green shading = improvements; yellow shading = degradations.

Table 17 shows the changes for the middle of the VSL corridor. This section experienced a great amount of congestion, especially on Fridays and weekends. In this case, there were large improvements in reliability and average travel time on Mondays, Saturdays, and Sundays. Fridays experienced a degradation in both measures. This section includes the area where the end of the vehicle queue typically occurs during very congested periods; and, as Table 17 shows, significant improvements occur during many of the most congested periods. Across the entire week, this section of the road exhibited improvements in mean travel times of 2.8 percent and reliability of 9 percent.

Table 17. Summary of Changes in Average Travel Time and Planning Time Index, Middle of Corridor (Mileposts 118–126)

Day of Week	Average Travel Time (min)				Reliability (Planning Time Index)			
	Before (2018–-2019)	Before (2021–2022)	After (2022–2023)	% Change (Last Year)	Before (2018–2019)	Before (2021–2022)	After (2022–2023)	% Change (Last Year)
Monday	6.80	7.52	7.04	-6.4%	1.07	1.90	1.40	-26.3%
Tuesday	6.53	6.51	6.51	0%	1.01	1.00	1.02	+2.0%
Wednesday	6.51	6.64	6.55	-1.4%	1.01	1.02	1.04	+2.0%
Thursday	6.54	6.71	6.68	-0.4%	1.02	1.04	1.06	+1.9%
Friday	6.69	7.15	7.77	+8.7%	1.07	1.58	2.30	+45.6%
Weekdays	***6.61***	***6.91***	***6.91***	***0%***	***1.02***	***1.16***	***1.33***	***+14.7%***
Saturday	7.30	8.15	7.74	-5.0%	1.95	2.94	2.59	-11.9%
Sunday	8.95	9.51	8.51	-10.5%	3.02	3.93	3.06	-22.1%
Weekends	***8.13***	***8.83***	***8.13***	***-7.9%***	***2.61***	***3.53***	***2.85***	***-19.3%***
All Week	***7.05***	***7.46***	***7.25***	***-2.8%***	***1.53***	***2.00***	***1.82***	***-9.0%***

Green shading = improvements; yellow shading = degradations.

Table 18 shows the results from the northern end of the corridor. This section experiences the most severe congestion, and improvements in performance are confined to Sundays and Mondays. Thursdays and Fridays both show large declines in the after period. Performance in this part of the corridor is most likely to be influenced by disruptive work zone events north of the VSL site.

Table 18. Summary of Changes in Average Travel Time and Planning Time Index, Northern End of Corridor (Mileposts 127–130)

Day of Week	Average Travel Time (min)				Reliability (Planning Time Index)			
	Before (2018–2019)	Before (2021–2022)	After (2022–2023)	% Change (Last Year)	Before (2018–2019)	Before (2021–2022)	After (2022–2023)	% Change (Last Year)
Monday	5.19	5.58	5.57	-0.2%	2.87	4.02	3.97	-1.2%
Tuesday	4.46	4.87	5.21	+7.0%	1.49	2.17	3.15	+45.2%
Wednesday	4.35	5.19	5.24	+1.0%	1.52	3.29	3.00	-8.8%
Thursday	4.56	5.25	5.82	+10.9%	1.57	3.25	4.16	+28.0%
Friday	4.58	5.16	7.40	+43.4%	2.05	3.04	5.63	+85.2%
Weekdays	***4.63***	***5.21***	***5.84***	***+12.1%***	***1.96***	***3.26***	***4.29***	***+31.6%***
Saturday	5.20	6.17	6.59	+6.8%	3.01	4.41	4.88	+10.7%
Sunday	7.82	9.49	8.63	-9.1%	5.04	6.74	6.11	-9.3%
Weekends	***6.52***	***7.82***	***7.62***	***-2.6%***	***4.22***	***5.91***	***5.63***	***-4.7%***
All Week	***5.17***	***5.96***	***6.35***	***+6.5%***	***3.06***	***4.60***	***4.82***	***+4.8%***

Green shading = improvements; yellow shading = degradations.

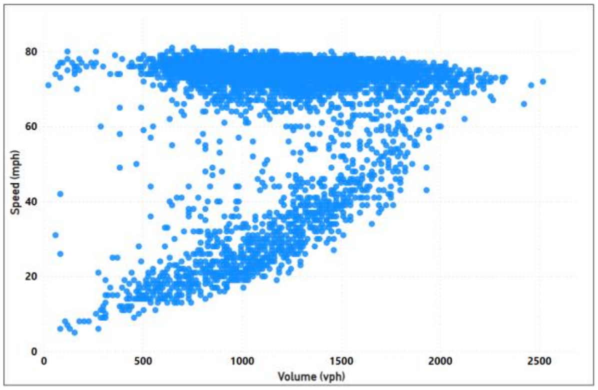
Discussion of Travel Time and Reliability Analysis

It is important to note that the travel time and reliability data analysis was not filtered in the same way as the detector data because real-time volume data were not available before the early 2022 period. As a result, the analysis here is based on all time periods in the study period and has not been filtered based on traffic impacting events or volumes. These results could reflect both the impact of the VSL and the impact of other external events.

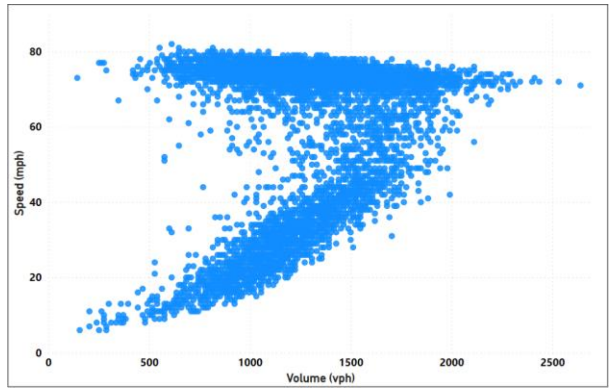
The large degradations in travel times and reliability of Friday were noteworthy and were investigated further. The project to extend I–95 Express Lanes was located just north of the corridor, so there was some concern that congestion from that project may be the source of congestion seen on Fridays. Probe data from MP 130–140 were collected, and there was no evidence that spillback from north of the corridor increased substantially during the first year of VSL operation. Traffic volume data from nearby continuous count stations were also examined to determine if there had been a large increase in volume. Data from two stations within the corridor showed that volumes on Fridays had declined slightly during the first year after VSL operations began. Crash data (discussed in a subsequent section) did show a 23-percent increase in the number of crashes on Fridays during the first year of VSL operation, so it is possible that this had some partial impact on the increase in travel times that day. The number of crashes was still relatively small (about an additional 0.25 crashes/Friday), so the low number of crashes was not the sole cause of the increased travel time. Analysis of the “after” data did not determine a clear direct cause of the large decline in Friday operations, nevertheless, Fridays typically remain less congested than Sundays.

Throughput

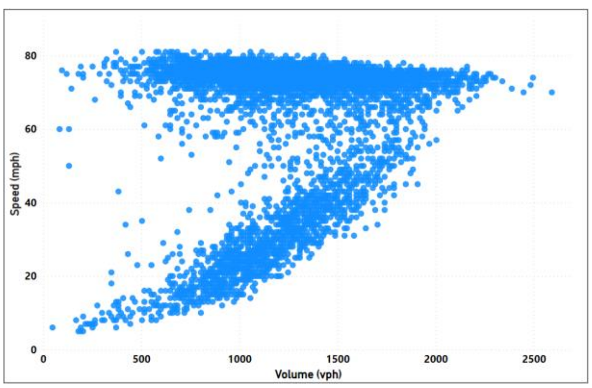
Speed-flow curves were developed for the before period as well as each seasonal after period. Figures 19, 20, and 21 show examples from three sites in the corridor, one from each of the three corridor subsections (located at MPs 127.9, 123.4, and 118.1). Free-flow speeds for the middle site were slightly higher than for the northern and southern sites, and congested regimes were not detected as often at the southern site, which was consistent with previous results.



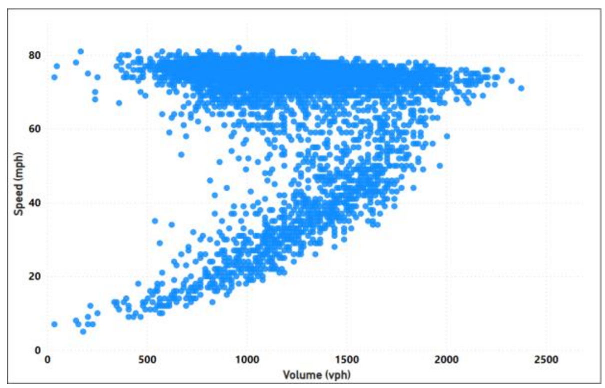
(a) Before, Winter 2022



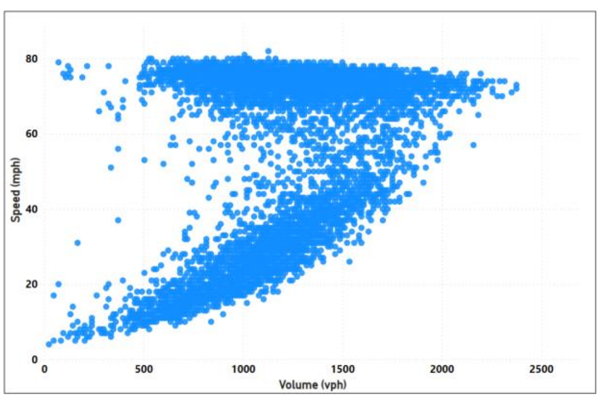
(b) After, Summer 2022



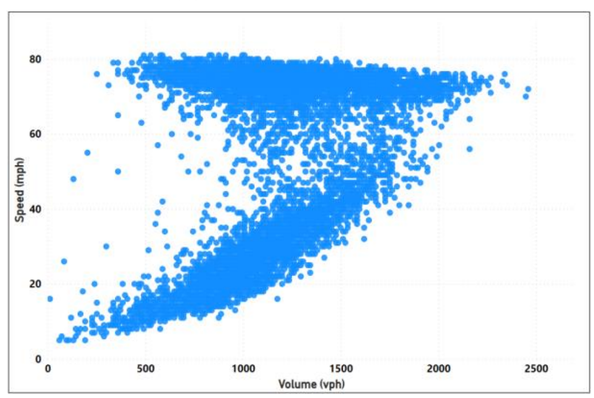
(c) After, Fall 2022



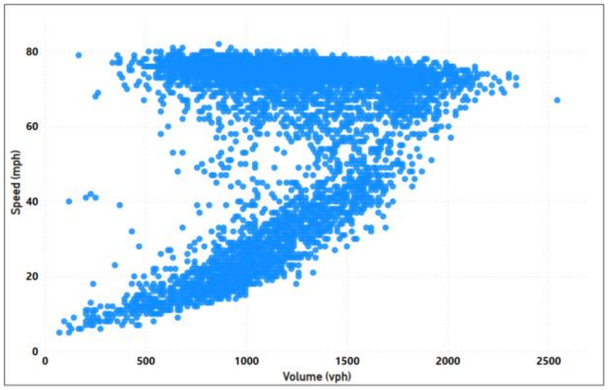
(d) After, Winter 2023



(e) After, Spring 2023

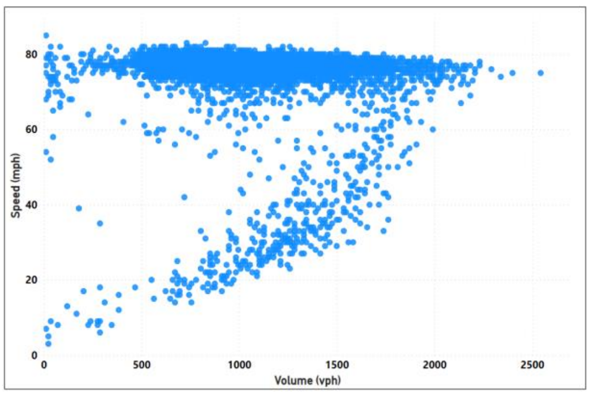


(f) After, Summer 2023

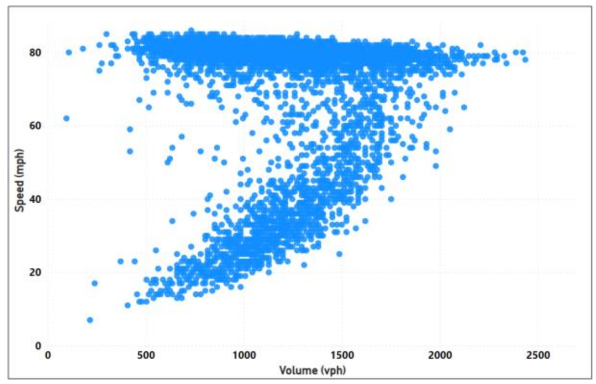


(g) After, Fall 2023

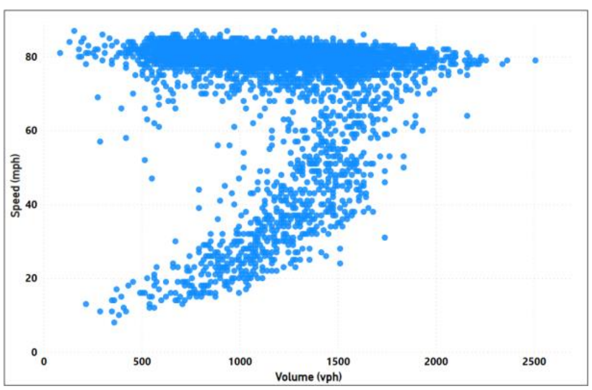
Figure 19. Speed-Flow Curves for Left Lane at MP 127.9: (a) Before, Winter 2022, (b) After, Summer 2022, (c) After, Fall 2022, (d) After, Winter 2023, (e) After, Spring 2023, (f) After, Summer 2023, (g) After, Fall 2023. At all sites, weather, work zones, and outages were filtered out, and demand volume was > 2,000 vph.



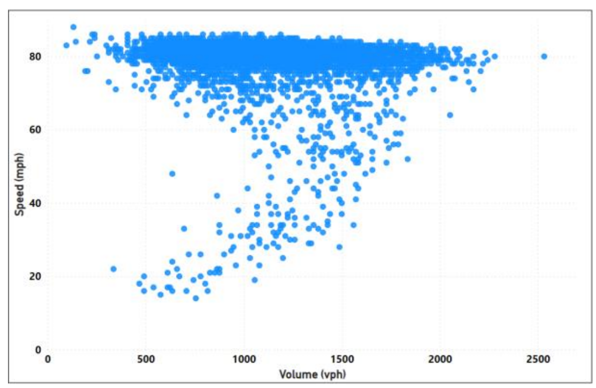
(a) Before, Winter 2022



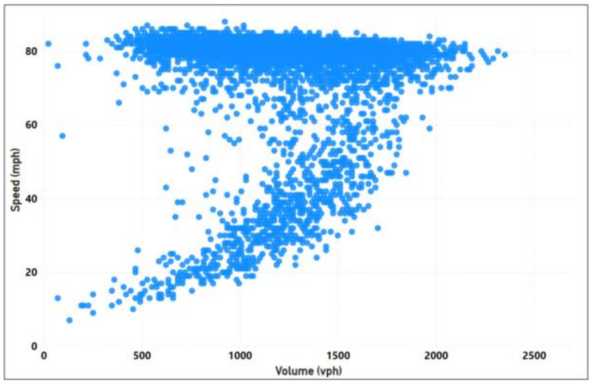
(b) After, Summer 2022



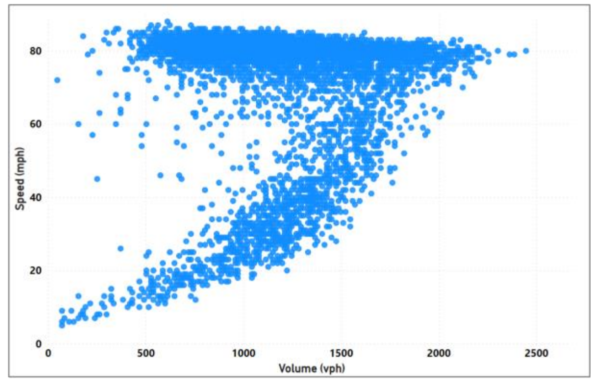
(c) After, Fall 2022



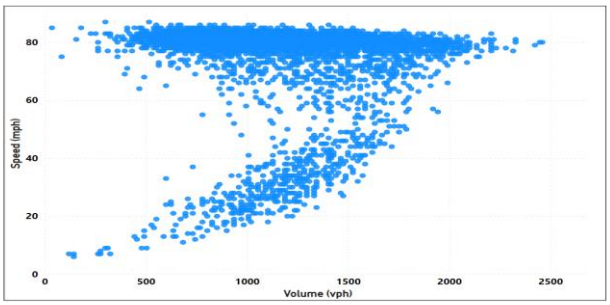
(d) After, Winter 2023



(e) After, Spring 2023

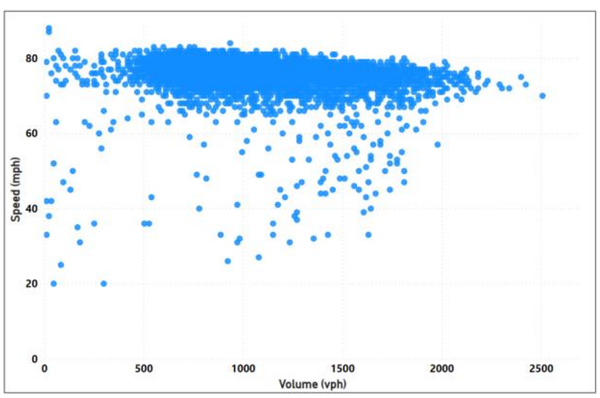


(f) After, Summer 2023

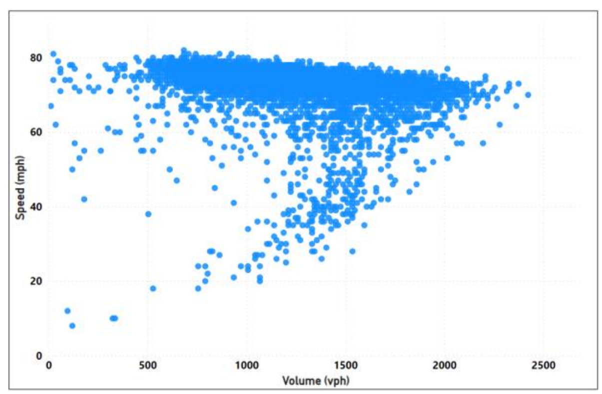


(g) After, Fall 2023

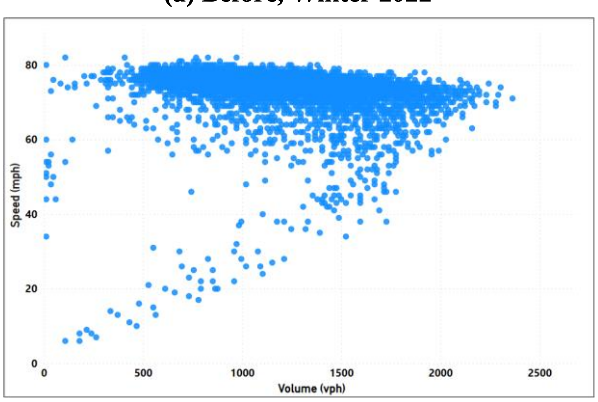
Figure 20. Speed-Flow Curves for Left Lane at MP 123.4: (a) Before, Winter 2022, (b) After, Summer 2022, (c) After, Fall 2022, (d) After, Winter 2023, (e) After, Spring 2023, (f) After, Summer 2023, (g) After, Fall 2023. At all sites, weather, work zones, and outages were filtered out, and demand volume was > 2,000 vph.

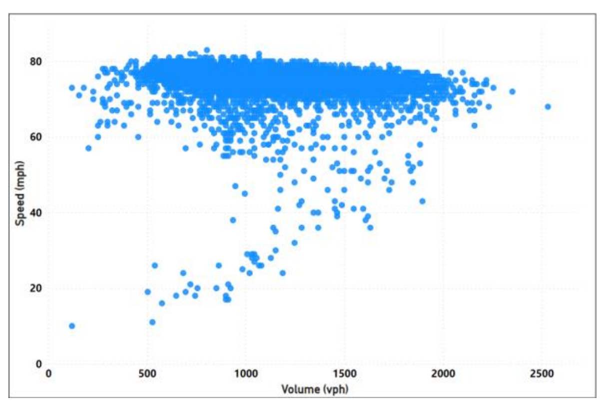


(a) Before, Winter 2022

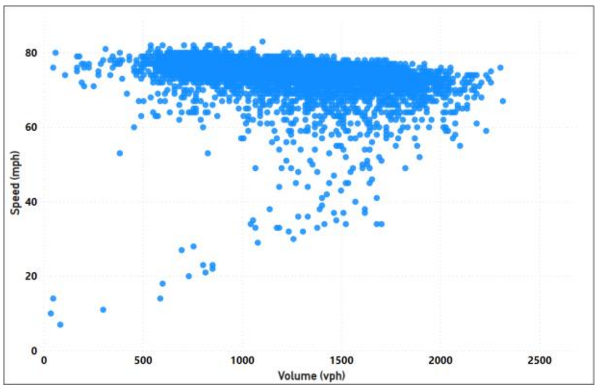


(b) After, Summer 2022

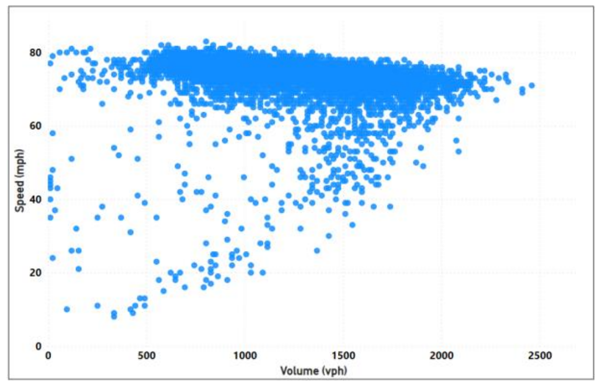




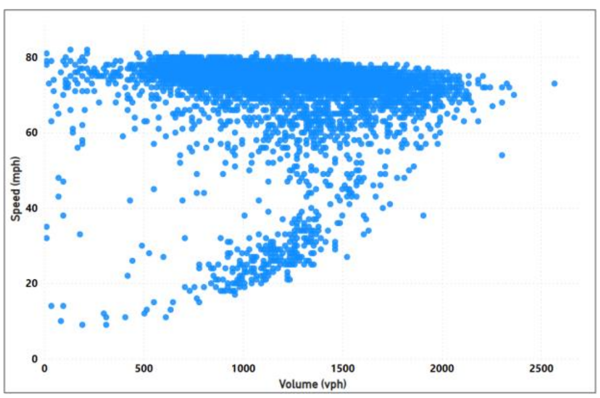
(c) After, Fall 2022 **(d) After, Winter 2023**



(e) After, Spring 2023



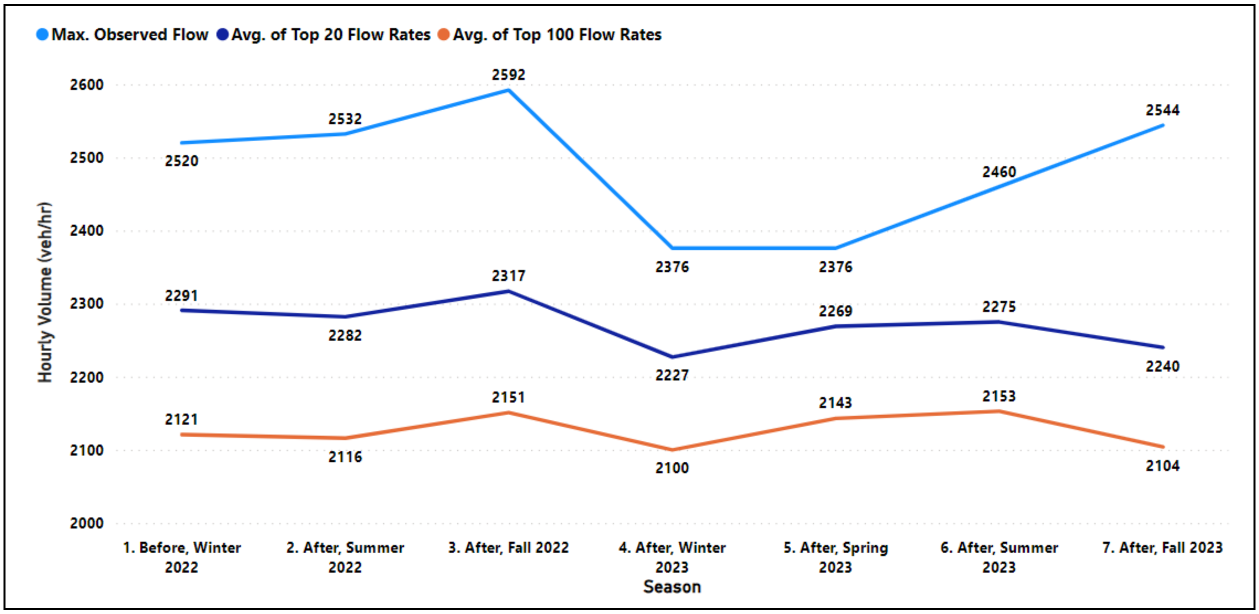
(f) After, Summer 2023



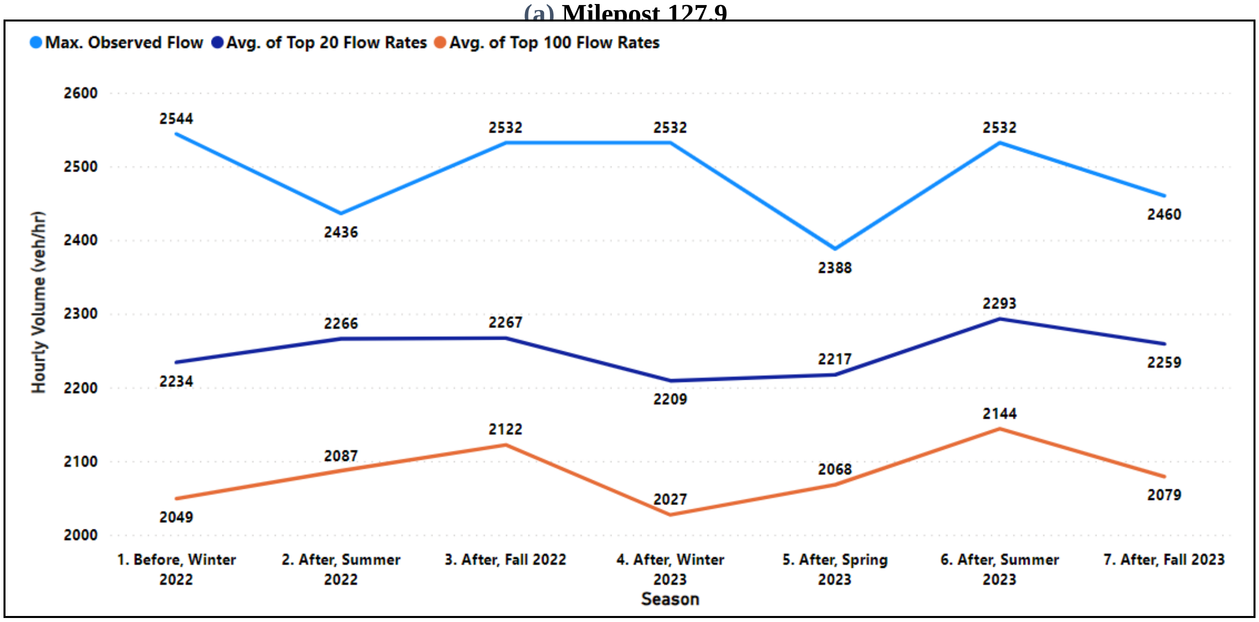
(g) After, Fall 2023

Figure 21. Speed-Flow Curves for Left Lane at MP 118.1: (a) Before, Winter 2022, (b) After, Summer 2022, (c) After, Fall 2022, (d) After, Winter 2023, (e) After, Spring 2023, (f) After, Summer 2023, (g) After, Fall 2023. At all sites, weather, work zones, and outages were filtered out, and demand volume was > 2,000 vph.

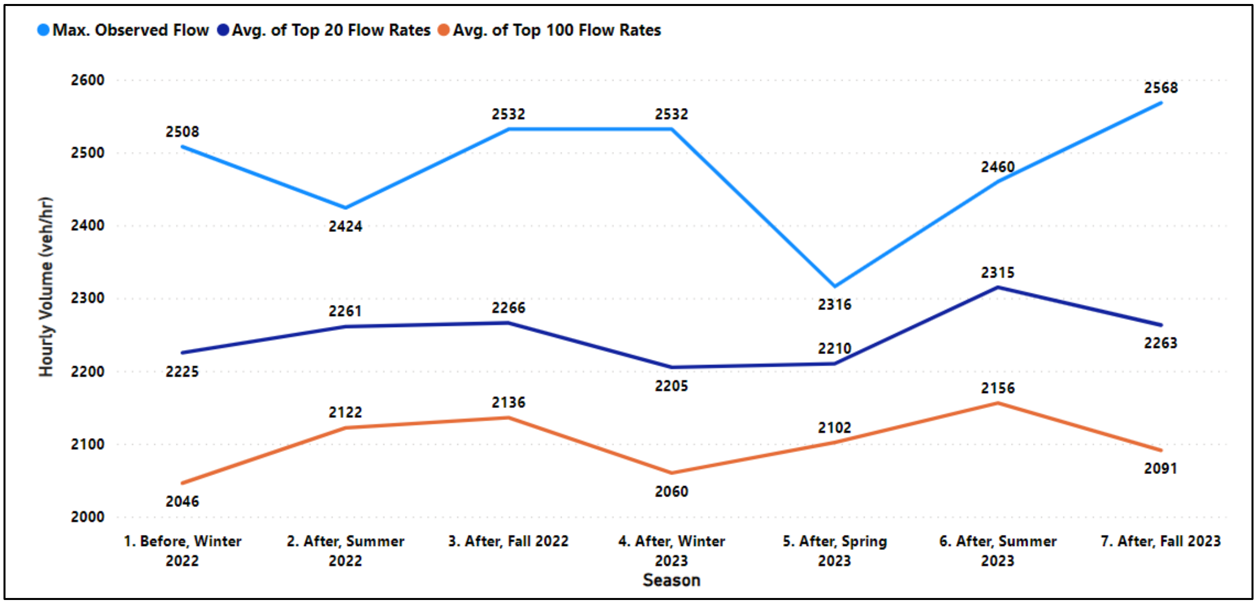
Several flow rate metrics were calculated at the three sites to assess throughput on the corridor (Figure 22). As previously noted, flow rates 5-minute volume counts were converted into equivalent hourly flow rates for ease of interpretation. When maximum throughput was examined, there was some variability in the data because the estimate was based on only a single 5-minute period at the detector. To reduce the potential impacts of extreme outliers of measured flow rates, the average of the top 20 and top 100 flow rates were also calculated. Those two measurements showed a high degree of stability. No sustained, significant differences in maximum throughput were observed following VSL activation.



(a) Milepost 127.9



(b) Milepost 123.4



(c) Milepost 118.1

Figure 22. Maximum Observed Flow Rates, Average of Top 20, 100 Flow Rates at (a) MP 127.9, (b) MP 123.4, and (c) MP 118.1. In the left lane, weather, work zones, and outages were filtered out, and demand volume was > 2,000 mph.

Safety

In the first year after the VSL system was activated (6/22/22–6/21/23), there were 286 crashes, similar to the 291 crashes which occurred during the year prior to the VSL system activation (6/22/21–6/21/22) (Table 19). For context, Virginia crashes have increased year over year since 2020, when crashes fell due to decreased travel during the pandemic (VDOT Crash Dashboard, 2023). In nearby areas on I–95, crashes also increased during the same timeframe (6/22/21–6/21/22 versus 6/22/22–6/21/23). On the section of I–95 northbound just north of the study corridor (mileposts 130–140) crashes increased 23 percent. Just south of the study corridor on I–95 northbound (mileposts 105–115) crashes increased 14 percent. On the parallel section of I–95 southbound (mileposts 115–130) crashes increased 16 percent. Similarly, fatal and injury crashes increased 41, 14, and 44 percent on the sections north of, south of, and parallel to the study corridor respectively. Despite these nearby increases, the total number of crashes have remained stable in the corridor region and fatal and injury crashes have reduced 13 percent, which may be an early positive indicator of safety.

Table 19. Crash Trends on the Study Corridor and Adjacent Sections of I–95 North and I–95 South Before (6/22/21–6/21/22) and After (6/22/22–6/21/23) the Variable Speed Limit System Activation

Corridor Section	Crash Type	Timeframe	Number of Crashes	% Change from Previous Year
I–95N MP 115–130	All Crashes	Before	291	-2%
		After	286	
	Fatal + Injury Crashes	Before	67	-13%
		After	58	
	Property Damage Only	Before	224	+2%
		After	228	
I–95N MP 130–140	All Crashes	Before	262	+23%
		After	322	
	Fatal + Injury Crashes	Before	61	+41%
		After	86	
I–95N MP 105–115	All Crashes	Before	42	+14%
		After	48	
	Fatal + Injury Crashes	Before	7	+14%
		After	8	
I–95S MP 115–130	All Crashes	Before	152	+16%
		After	177	
	Fatal + Injury Crashes	Before	32	+44%
		After	46	

When reviewing crashes by day of week, it may be observed that in both the before and after periods, more crashes occur on Fridays and Sundays than any other day of the week. In the before period, Sunday and Friday crash counts are similar in the after period, Friday exhibits more crashes than Sunday (Table 20), which may also partially explain the increase in travel times on Fridays in the after period discussed in the Travel Time and Reliability section.

Table 20. Crash Trends on the Study Corridor by Day of Week Before (6/22/21–6/21/22) and After (6/22/22–6/21/23) the Variable Speed Limit System Activation

Period	Total Crash Count						
	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
Before	58	42	34	20	34	56	47
After	50	35	27	31	36	69	38

In addition to changes in crash severity between the before and after timeframes, distributions of crash types changed slightly. Rear end and sideswipe—same direction crashes—are the crash types most associated with congestion. Those crash types declined by more than 13 percent (Table 21). The reduction in sideswipe-same direction crashes would correlate with the reduced between-lanes speed differentials observed. As the overall number of crashes remained stable, the proportion of some other crash types, such as fixed object-off road and angle crashes, increased.

Table 21. Crashes Before (6/22/21–6/21/22) and After (6/22/22–6/21/23) the Variable Speed Limit System Activation

Crash Type	Before (6/22/21–6/21/22)	After (6/22/22–6/21/23)	Difference	% Change
Rear End	178	159	−9	−10.7%
Sideswipe (Same Direction)	37	36	−1	−2.7%
During Inclement Weather (Fog/Mist/Rain/Snow/Sleet/Hail)	35	82	+47	+134.3%
Secondary	25	31	+6	+24%

Secondary crashes were reviewed in detail to assess whether the VSL system impacted the frequency of secondary crash occurrence. A secondary crash was defined as occurring within 2 hours and 5 miles of a primary crash, a definition intended to capture the potential queue of a primary crash. Using this definition, 25 secondary crashes occurred from 6/22/21–6/21/22 and 31 secondary crashes occurred between 6/22/22–6/21/23, a 24-percent increase (Table 21). This is a small sample size, and merits further monitoring.

Overall crash characteristics were reviewed, and it was observed that during the after period, more crashes occurred during inclement weather (fog, mist, rain, snow, sleet/hail), 82 (29 percent) compared with 35 (12 percent) during the before period. When examining secondary crashes specifically, 18 (58 percent) in the after period, and 3 (12 percent) in the before period occurred during inclement weather. Carrick et al.'s study (2015) found that weather and wet roadways were factors in 676 secondary crashes in Florida. Due to differences in weather conditions, additional data may be needed to understand VSL impacts on secondary crash occurrence. The initial increase in secondary crashes may be driven by weather effects rather than any VSL impact. The relationship between weather and secondary crashes may also point to an opportunity to examine how the VSL algorithm might be adjusted to address weather events.

Crash density varies along the corridor, but the northern end of the corridor, which is the most congested section (Table 22), had more crashes per mile than the other corridor sections. When crashes are broken down by injury type (fatal and injury crashes, property damage only crashes), crash rates for each injury type are still highest on the northern end of the corridor. When comparing the overall crash density per mile before and after VSL activation, the crash density remained the same in the northern section, declined in the middle section, and increased in the southern section. Injury crash density showed a similar pattern.

Table 22. Crashes by Corridor Section and Severity, South (115–119.3 miles), Middle (119.3–125.6) and North (125.6–130). Before (6/22/21–6/21/22) and After (6/22/22–6/21/23) VSL Activation

Crash Type	Before/After VSL[a]	Number of Crashes (South)	Number of Crashes (Middle)	Number of Crashes (North)	Crashes/ Mile (South)	Crashes/ Mile (Middle)	Crashes/ Mile (North)
All Crashes	**Before VSL**	39	133	119	9.1	21.1	27.0
	After VSL	79	85	122	18.4	13.5	27.7
Fatal + Injury Crashes	**Before VSL**	13	29	25	3.0	4.6	5.7
	After VSL	15	21	22	3.5	3.3	5.0
Property Damage Crashes	**Before VSL**	26	104	94	6.0	16.5	21.4
	After VSL	64	64	100	14.9	10.2	22.7

[a]VSL = variable speed limit.

Although 1 year of data represents a very limited sample for crash analysis, these data do provide some initial indications of possible safety effects. Additional monitoring is needed to determine longer term safety impacts and whether these positive trends will be sustained.

Benefit-Cost Analysis

Benefits were estimated using the process described in the Methods section of the report. As shown in Table 19, the VSL corridor had 4 more PDO crashes and 9 fewer fatal and injury crashes in the first year of operation than the prior year. The crash savings can be monetized using the VDOT comprehensive crash costs detailed in the Methods section of this report:

4 PDO crashes × -$13,743/crash + 9 fatal/injury crashes × $550,747/crash = $4,901,751.

Likewise, changes in travel delay can also be monetized using the values of time described in the “Methods” section. Average travel times were first determined using the INRIX probe data described earlier. The time to traverse the corridor at 65 mph is approximately 13.85 minutes; therefore, any travel time more than that value was determined to be an average delay per vehicle. The ADT on each day of the week in the study period was then based on traffic volume data collected at VDOT continuous count station 060164, which is located near the midpoint of the corridor. The total vehicle hours of delay then were determined by multiplying that day of the week’s ADT by the average delay per vehicle, and then multiplying that by 52 weeks in the year. The value of the change in vehicle hours of delay was then calculated by assuming that 84 percent of traffic was passenger vehicles and 16 percent was trucks, which were the values published by the VDOT Traffic Monitoring System for this link. Table 23 summarizes the results of the analysis.

Table 23. Change in the Cost of Congestion by Day of the Week

Day of Week	Before (2021–2022)			After (2022–2023)			Change in Delay (veh-hrs)	Change in Congestion Cost
	Travel Time (min)	ADT (vpd)	Delay (veh-hr)	Travel Time (min)	ADT (vpd)	Delay (veh-hr)		
Monday	16.22	48,021	98,635.1	15.45	48,857	67,748.4	−30,886.8	−$1,058,082
Tuesday	14.10	44,252	9,587.9	14.46	45,183	23,886.7	14,298.8	$489,832
Wednesday	14.49	45,597	25,291.1	14.48	45,894	25,058.1	−233.0	−$7,982
Thursday	14.74	48,989	37,786.8	15.33	49,179	63,080.3	25,293.4	$866,471
Friday	15.00	56,559	56,370.5	18.07	55,774	203,984.1	147,613.6	$5,056,771
Saturday	17.06	55,416	154,167.3	17.06	55,352	153,989.3	−178.0	−$6,099
Sunday	21.72	55,737	380,163.5	19.88	55,928	292,279.7	−87,883.8	−$3,010,617

ADT = average daily traffic.

In Table 23, positive values represent increases in congestion cost following VSL activation and negative values represent reductions in congestion cost. The table shows large improvements on Sundays and Mondays, but those are offset by increased costs on Tuesday, Thursday, and especially on Friday. In total, the cost due to congestion in the first year of operation was approximately $2,330,294 higher than the year prior to VSL activation. This was largely attributable to the 3-minute increase in average travel time on Fridays.

Although the reason for the large increase in travel times on Friday could not be determined, it is possible that slower speeds created by compliance with posted VSLs might be a partial explanation. If vehicles slow down to comply with VSLs, then travel times would increase and the cost due to congestion would increase. The safety and reliability benefits of the VSL could also impact speeds in the opposite direction, causing travel times to improve. These outcomes can exert opposing forces on the overall cost of congestion.

When considering the savings due to crash reductions and the increased congestion costs, the annual net benefit is approximately $4,901,751 − $2,330,294 = $2,571,457. Assuming that this annual net benefit is maintained year over year, the benefits would exceed the cost of the system in about 4 years.

This is a planning level estimate that does not account for ongoing operations and maintenance. As noted earlier in the system description, the monitoring of the system operations was conducted using existing VDOT staff. The number of person-hours spent monitoring and operating the system by existing staff has not been quantified, partially due to the changing demands of the system as initially deployed. Long-term, average demands on staff need to be quantified to fully understand the potentially significant manpower costs required to effectively operate the system. Likewise, maintenance costs for the field devices are currently unknown and need to be quantified. The upcoming Operations Technology maintenance contract for the devices will provide needed insight that can be used to refine the cost component of the analysis.

This analysis also assumes that changes in travel times and crashes are maintained in the future, and those assumptions are based on only 1 year of post-installation data. Future evaluations of the system could make a better account of long-term safety, mobility, operations, and maintenance costs to gain a more comprehensive picture of the benefit-cost of the system.

CONCLUSIONS

- *Activations of reduced speed limits* (*less than 65 mph*) *are most highly concentrated in northern sections of the corridor on weekend afternoons.* Across the entire corridor, reduced speeds were posted less than 10 percent of the time. Overall, more than 90 percent of posted speed limits were 65 or 70 mph.

- *Several practical operational concerns were identified by the Fredericksburg District and the project team that should be considered in future deployments.* The VSL system sometimes experienced communications disruptions, communications latency issues, and power outages at solar sites that impacted system uptime. Reliable communications and power should be provided at future VSL installations. The District also expressed concerns about whether additional manpower should be provided to support system operations.

- *The VSL system was able to produce reductions in mean speeds and speed differentials between adjacent lanes that occurred when transitional speed limits (45 or 55 mph) were posted.* Average speeds were relatively similar between the before and after periods during uncongested conditions (PSL over 60 mph) and during congested conditions (PSL of 35 mph). Speed reductions were most prominent in the middle of the corridor.

- *Following VSL activation travel times and reliability generally improved on weekends, especially on Sundays, but these improvements were largely offset by degradations during the week***.** The largest improvements in travel time and reliability were observed in the middle of the corridor.

- *No significant changes in maximum throughput were observed.* Multiple locations were evaluated, and none showed consistent increases in throughput.

- *Safety data from the first year after VSL deployment show positive initial results; however, more data need to accumulate before firm safety conclusions can be made.* One year of crash data before and after VSL deployment shows total crashes to be relatively flat and about a 13-percent reduction in fatal and injury crashes. These crash numbers are even more encouraging when put in the context of nearby sections of I–95. On adjacent and parallel sections of I–95, total crashes increased between 14 and 23 precent, and fatal and injury crashes increased between 14 and 44 percent.

- *The VSL system produced an estimated annual benefit of approximately $2.57 million.* This benefit was attained primarily from reductions in severe crashes in the corridor, indicating that queue warning effects of the VSL are the primary benefit at this site. This research did not quantify long-term annual operational and maintenance costs, and these costs could potentially be substantial.

RECOMMENDATIONS

1. *VDOT Fredericksburg District and VTRC should continue to monitor the performance of the VSL system to determine long-term effectiveness.* VTRC can support additional evaluation of the safety and performance of the system after 3 years of deployment to determine whether the effects of the system were sustained. That evaluation will also enable long-term average operational and maintenance costs to be estimated.

2. *VDOT Traffic Operations Division (TOD) should use the operational and safety lessons learned from the I–95 VSL system to identify other locations where VSL deployments are likely to produce positive results.* A system-wide screening could identify locations where VSL or lower cost queue warning systems may be likely to produce benefits. The I–95 VSL experience also offers some guidance on the importance of reliable power and communications and providing staff for monitoring system performance for any future deployments.

IMPLEMENTATION AND BENEFITS

The researchers and the technical review panel (listed in the "Acknowledgments") for the project collaborate to craft a plan to implement the study recommendations and to determine the benefits of doing so. This effort is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. This section provides the following implementation plan and the accompanying benefits.

Implementation

Recommendation 1: Fredericksburg District will continue to regularly monitor the performance of the I–95 VSL system as resources allow to ensure that it is operating as designed. Once at least 3 years have elapsed following initial VSL system activation, VTRC will conduct a follow up technical assistance study that will examine the long-term changes in safety and operations in the corridor. The benefit-cost analysis will be updated, as well, and will include considerations of operations and maintenance costs. This technical assistance study will also enable an examination of the impacts of the express lane expansion.

Recommendation 2: TOD will screen the entire interstate system in Virginia to identify additional locations where VSLs may offer a benefit. Given that the VSL primarily produced safety benefits, alternatives to provide queue warning with a lower infrastructure requirement should also be examined. This work is already underway in TOD and can be considered implemented.

Benefits

Based on the analysis of the first year of operation, the I–95 VSL was estimated to produce an annual benefit of approximately $2.57 million. This benefit was created primarily from a reduction in fatal and injury crashes. Implementation of Recommendation 1 will enable VDOT to expand this initial analysis to ensure that the I–95 VSL system is operating as intended and providing valuable information for future decision making. Continuing monitoring will help ensure that the system is providing benefits to the driving public, and a followup technical assistance will provide data on long-term effectiveness and costs. The followup economic analysis will include better information on maintenance and operations costs that will enable a better accounting of the net benefits of the system. That evaluation will provide useful information to help guide future decision making.

Implementation of Recommendation 2 will help identify other areas likely to benefit from VSL deployment using a data-driven approach. The information from this study can then be used to help ensure that future projects are installed at locations with characteristics that could be improved using VSL.

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