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Evaluation of the Impact of the I-66 Active Traffic Management System

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Abstract:

Construction of a Virginia Department of Transportation project to install an Active Traffic Management (ATM) system on I-66 from U.S. 29 in Centreville to the Capital Beltway (I-495) was completed in September 2015. The project was constructed to improve safety and operations on I-66 through better management of existing roadway capacity. The main components of the ATM system were advisory variable speed limits (AVSL), queue warning systems (QWS), lane use control signs (LUCS), and hard shoulder running (HSR).

Since ATM is still a relatively new approach in the United States, there was a need to analyze the effects of the I-66 ATM. Thus, a before-and-after study was conducted to quantify its effectiveness. The study used "after" data from October 2015-February 2016 (21 weeks) for the operations analysis and data from October 2015-December 2015 (13 weeks) for the safety analysis. Operations and safety evaluations were performed using limited data, so the results should be considered preliminary. The operational measures of effectiveness (MOEs) included ATM utilization rate, average travel time, travel time reliability, and total travel time delay. The safety MOEs included crash rates by type and severity and incident frequency. These MOEs were analyzed using INRIX travel time data, limited traffic volume point sensor data, police crash reports, and iPeMS traffic incident data. Segment-level analysis was performed to determine the segments that benefitted the most from ATM implementation. From this segment-level analysis, it was determined that HSR was the ATM component that led to most of the improvements on I-66.

The results of the study indicate that the ATM produced positive operational and safety benefits across multiple MOEs. The ATM generally had limited operational and safety impacts during the weekday peak periods and some impacts during the midday and off-peak weekday periods. Average weekday travel times during the midday period in the off-peak direction typically improved by 2% to 6%. However, weekday peak period travel times and travel time reliability in the peak direction continued to degrade after ATM installation. This was not surprising given that HSR was already in use during the weekday peak periods before ATM activation and there has been a historic trend of increased travel times on the corridor. There were large operational benefits on weekends, with average travel times and travel time reliability improving by approximately 10% during the weekend peak periods. The weekend improvements were most likely due to the activation of HSR, which had not been active during weekends before ATM implementation, so the additional capacity served to alleviate congestion after activation. The safety analysis showed promising results for weekends, but no solid conclusions could be formed because of the limited data available for the safety analysis.

A planning-level benefit-cost ratio was calculated based on the initial operational and safety benefits. The ATM had a benefit-cost ratio of 1.54 based on conservative assumptions that used only weekend operational improvements. This indicates that the I-66 ATM was a cost-efficient solution for improving operations and safety on I-66. The study recommends expansion of ATM in Virginia and further study.

FINAL REPORT

EVALUATION OF THE IMPACT OF THE I-66 ACTIVE TRAFFIC MANAGEMENT SYSTEM

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(A partnership of the Virginia Department of Transportation
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DISCLAIMER

ABSTRACT

Construction of a Virginia Department of Transportation project to install an Active Traffic Management (ATM) system on I-66 from U.S. 29 in Centreville to the Capital Beltway (I-495) was completed in September 2015. The project was constructed to improve safety and operations on I-66 through better management of existing roadway capacity. The main components of the ATM system were advisory variable speed limits (AVSL), queue warning systems (QWS), lane use control signs (LUCS), and hard shoulder running (HSR).

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INTRODUCTION

According to the Texas A&M Transportation Institute's *Urban Mobility Scorecard*, the Washington, D.C., metropolitan area is consistently ranked as having the worst traffic congestion in the United States in terms of delay, reliability, and fuel consumption (Schrank et al., 2015). I-66 in Virginia is the only interstate running east-west in the region, and it has significant traffic congestion during both peak and off-peak hours. Congestion tends to be the worse in the eastbound (EB) direction during the morning peak period and in the westbound (WB) direction in the afternoon peak period.

Construction of a Virginia Department of Transportation (VDOT) project to install an Active Traffic Management (ATM) system on the I-66 corridor from Centreville (Exit 52/U.S. 29) to the Capital Beltway (Exit 64/I-495) officially began in early 2013 and was completed in September 2015. The project spanned approximately 12.4 miles. TransCore and Parsons Brinkerhoff were selected as design-build contractors, and the approximate total cost for this project was $38.6 million. Of this, approximately $24 million was spent on gantries, sensors, and traffic control devices to implement ATM, with the remainder being spent on upgrades to communications infrastructure and cameras. The ATM system was constructed to improve operations, roadway safety, and incident management through more effective management of the existing roadway. The ATM infrastructure included overhead gantries with lane use control signs, advisory variable speed limit displays, emergency pull-outs, and increased coverage of traffic cameras and sensors. Gantries were spaced approximately 0.6 miles apart so that continuous information could be provided to drivers on I-66 (Iteris, 2011).

ATM components are defined as techniques that dynamically manage recurring and non-recurring congestion based on prevailing traffic conditions, optimizing the capacity of the corridor and improving safety (Mirshahi et al., 2007). The primary ATM components implemented on I-66 included the following:

- *Advisory variable speed limits* (*AVSLs*). AVSLs dynamically change the posted speed based on current traffic or roadway conditions. Variable speed limits (VSLs), sometimes termed "speed harmonization," encourage more uniform speed distributions that can improve traffic operations and safety by providing guidance based on real-time information. They also can provide advance warning of slowed traffic ahead. For the I-66 ATM project, all AVSLs are posted on signs above each lane and are advisory.

- *Queue warning systems (QWSs).* QWSs provide advanced notice to drivers of the cause of congested roadway conditions ahead on variable message signs and work in conjunction with AVSLs to provide notice of slow or stopped traffic ahead. This advance notice was found in other studies to reduce secondary crashes (Fuhs, 2010).

- *Hard shoulder running (HSR).* Before ATM activation, the shoulder lane on I-66 was open to travel during predefined time periods. After ATM activation, the HSR system dynamically opened or closed the shoulder lanes depending on roadway conditions, increasing capacity on I-66 dynamically. Decisions regarding whether to open or close the shoulder were based on the judgment of the operators in the VDOT traffic operations center (TOC). A shoulder lane monitoring system was also installed. The system uses video analytics to monitor blockages on the hard shoulder to facilitate quick opening or closing of the shoulder while protecting disabled motorists temporarily stopped on the shoulder. Before ATM implementation, the operation hours for the system were static from 5:30 to 11:00 AM EB and 2:00 to 8:00 PM WB on non-holiday weekdays.

- *Lane use control signals (LUCSs).* Overhead gantries were deployed with LUCSs to alert drivers to lane blockages. The LUCSs could be used to indicate specific lanes that were closed in advance of the blockage. They were used for incident and work zone management.

During recurring congestion events, such as peak hour traffic, ATM actively manages roadway capacity by dynamically turning on the HSR, AVSL, LUCS, and/or QWS whenever necessary. Ideally, ATM on I-66 will improve the flow of traffic and reduce crashes during the recurring congestion periods and help improve management of non-recurring events.

In Europe, ATM has improved crash rates, crash severity, throughput, and travel times for decades. In both the United States and Europe, ATM projects tend to be implemented in urban areas where recurrent congestion is prevalent and right of way is constrained. Many of the operating characteristics of European ATM deployments differ from those in the United States, however, which may limit the transferability of European results. For example, many European deployments use automated speed enforcement in conjunction with regulatory VSLs, which is not possible in most jurisdictions in the United States. Given the lack of data on U.S. applications of ATM, there was a need to monitor the effects of the I-66 ATM project to determine its impact. Since this was the first ATM deployment in Virginia, there was also a need to capture lessons learned that could be useful for future ATM deployments.

PURPOSE AND SCOPE

The purpose of this study was to quantify changes in traffic operations and safety after the installation of VDOT's I-66 ATM system. Specific objectives included the following:

- Determine the utilization rate of the I-66 ATM system to identify the frequency and spatial distribution of the use of various techniques.
- Identify which component of the I-66 ATM system is most responsible for changes in conditions.
- Assess whether the I-66 ATM system improved average travel time, travel time reliability, and/or total traveler delay.
- Determine if the I-66 ATM system improved crash and incident characteristics, such as frequency, type, severity, and/or rate.

The scope of this study was limited to I-66 between U.S. 29 (Exit 52) and I-495 (Exit 64), where most ATM components were implemented on the I-66 corridor. The study focused on the macroscopic performance of the corridor and assessed whether overall corridor-level operations and safety levels were improved after ATM implementation. Since the ATM system was activated in September 2015, the study assessed its performance from October-February 2016 (21 weeks) for the operational analysis and from October-December 2015 (13 weeks) for the safety analysis.

METHODS

To achieve the study objectives, three major tasks were performed:

1. Investigate documented ATM impacts in Europe and in the United States.
2. Identify and document characteristics of the I-66 site and the ATM system deployed.
3. Perform a before-and-after analysis to evaluate the safety and operational effectiveness of the ATM system on I-66.

Investigate Documented ATM Impacts in Europe and the United States

Studies of ATM field deployments in Europe and in the United States were identified and reviewed. Relevant studies were identified by searching research indexed by the VDOT Research Library and the Transportation Research Board TRID database. Since the effectiveness of ATM is dependent on how drivers respond to the traffic control, simulation studies were not included in the literature review. In each case, the impact of the systems on operations and safety was summarized. Differences in operational strategies were also identified, particularly in cases where the European deployments differed greatly from what would be permitted in Virginia.

Identify and Document Characteristics of I-66 ATM Deployment

The characteristics of the I-66 ATM deployment were reviewed and summarized since the effects of the system will be influenced by the physical infrastructure that was installed. In addition, since different combinations of ATM components were installed on different segments of I-66, it was crucial to identify which segments of I-66 had which ATM components. Some of the steps associated with this task included the following:

- Identify basic project characteristics (e.g., project location on I-66 corridor, ATM characteristics).
- Identify other projects that are under way that may affect operations and safety data (such as major work zones).
- Identify recurring congestion time periods.
- Identify exact locations where ATM techniques were implemented (e.g., gantry locations, DMS locations).
- Determine sensor locations and data elements collected.

The goal of this task was to document the ATM system and identify site characteristics that would influence the before-and-after analysis.

Based on discussions with staff of VDOT's Northern Region Operations (NRO), the scope of the analysis was narrowed to the section of I-66 with the densest ATM implementation: I-66 between U.S. 29 in Centreville and I-495.

Perform Before-and-After Analysis of I-66 ATM

The safety and operational effects of the I-66 ATM in the study section were analyzed at a corridor level and a segment level since the segments of I-66 implement different combinations of ATM techniques. Table 1 shows the measures of effectiveness (MOEs) that were analyzed and the data sources used to conduct the before-and-after ATM evaluation. A planning-level benefit-cost (B/C) ratio analysis was also performed to evaluate the monetary effectiveness of the I-66 ATM.

Table 1. Operations and Safety Measures of Effectiveness for ATM Analysis

Type	Measure of Effectiveness	Data Sources Used for Calculation
Operational	Average travel time	INRIX
	Travel time reliability (i.e., buffer index, planning time index)	INRIX
	Total delay	INRIX + limited point sensors
	Utilization of ATM system (post-deployment only)	VDOT traffic operations center (TOC) logs
Safety	Crash frequency, severity, and rate	VDOT's Roadway Network System (RNS) + limited point sensors
	Traffic incidents	iPeMS traffic incident data

ATM = Active Traffic Management.

Several other operations and safety performance measures (e.g., average volume, maximum throughput, speed limit compliance rate, and speed variance) were initially identified as primary evaluation metrics. These metrics relied on having detailed point detector data from the ATM system detectors. Unfortunately, these data could not be examined because of technical problems with the detector data archive. Configuration problems related to the detector archive resulted in losses of data for the after ATM period initially. Subsequent technical problems with the detector data archive and contractual negotiations between VDOT and the vendor on how to fix the archive made it impossible to query ATM point detectors during the course of this study. Although these measures would have been very valuable for this study, they could not be obtained and analyzed.

Data Description

The analysis of traffic operations impacts was performed using a combination of INRIX travel time data, limited point sensor data, and VDOT TOC ATM utilization log records. For the safety analysis, INRIX travel time data, VDOT's Roadway Network System (RNS) police crash reports, and incident logs were used. This section describes the data sources used in this evaluation.

INRIX

VDOT has access to INRIX real-time probe-based travel time data throughout the I-66 corridor. INRIX is a private company that determines speed and travel time data by mining global position system (GPS) data from smartphones and commercial fleet management systems (Haghani et al., 2009). VDOT currently uses INRIX data to support a variety of performance measurement and traveler information applications. INRIX processes this GPS probe data to estimate speeds, which are reported spatially using Traffic Message Channel (TMC) links. TMC links are spatial representations developed by digital mapping companies for reporting traffic data and consist of homogeneous segments of roadway. On freeways, TMCs typically end and begin at ramp junctions or at locations where the number of mainline lanes change. For the I-66 study section, there were 14 TMCs with a total length of 12.414 miles in the EB direction and 14 TMCs with a total length of 12.345 miles in the WB direction. The length of each TMC varied from 0.22 to 1.85 miles. The data available from INRIX for each TMC included average travel time, length, and average speed for each time interval. The INRIX data provide wide spatial coverage throughout the corridor, which will allow a comprehensive examination of travel times

(Fontaine et al., 2014). Since INRIX calculates segment speeds using GPS probe data, it represents the space mean speed over a segment of road. The validity of INRIX freeway travel time data was previously established by the I-95 Corridor Coalition Vehicle Probe Project through a comparison with Bluetooth travel time data (Haghani et al., 2009).

Since the INRIX data rely on vehicle probes, real-time data may not be available continuously, especially during low flow periods. INRIX provides confidence scores for each 1-minute interval, with a confidence score of 30 representing real-time data and scores of 10 and 20 representing historic data during overnight and daytime periods, respectively. For the purposes of this analysis, average travel times were determined for every 15-minute interval, and that 15-minute travel time interval had to have an average confidence score of 26.67 or higher for at least 85% of the TMC length to be retained for analysis. These thresholds were derived from VDOT Travel Time Business Rules (PBS&J International, Inc., 2010), and time periods that did not meet this threshold were discarded from analysis.

Traffic Volume Data

Since the INRIX data use probe vehicles that represent a sample of the total vehicles on the roadway, INRIX does not provide volume data. As noted earlier, configuration problems related to the ATM detector archive made querying that database impossible. As a result, real-time traffic volume counts after ATM activation were not available for this analysis. However, it was possible to obtain limited archived real-time "before" ATM traffic volume data from the Regional Integrated Traffic Information System (RITIS) detector tools database. Annual average daily traffic (AADT) estimates along the corridor were also available from VDOT throughout the study period, although real-time counts after ATM deployment were not available. For some performance measures, the before ATM traffic volume distributions were used to estimate volume distributions in the after period by assuming a traffic growth rate based on AADT changes. Although it is possible that hourly distributions of traffic did change after ATM installation, no data were available from VDOT to determine whether this was the case. Given observed operational data, especially on weekdays, it was expected that this was a reasonable assumption, however.

VDOT TOC Logs

VDOT TOC logs were reviewed to determine the times when hard shoulders were opened to travel and the time periods when AVSLs and LUCSs were posted. The TOC logs consisted of information on the sign message, the time stamp when the message was posted, and a location identifier for the sign. Thus, the specific message being displayed on each LUCS and AVSL could be tracked over time. This was used to determine the amount of additional time that shoulders were opened to travel and the duration and times of day when AVSL and LUCS were used.

Police Crash Reports

VDOT has records of police crash reports for the corridor in the RNS database. However, the police crash reports are transmitted onto the RNS on a rolling basis with a lag time of 3 to 4 months. Therefore, the most recent police crash reports could not be analyzed in this study, and only crashes through the end of December 2015 were available. Information on crash frequency, severity, crash type, and location was collected from this database.

iPeMS Traffic Incident Data

Traffic incidents such as disabled vehicles and crashes were examined to determine whether changes in incident frequency might impact the operational results. VDOT has records of traffic incidents in a database called iPeMS. Information on the frequency of traffic incidents was collected from this database. The number of incidents before and after ATM activation was assessed.

Operations Analysis

Time Periods Analyzed

The INRIX database contains travel time data from 2010 to the present, which means that there are data for more than 3 years of pre-ATM conditions. However, road characteristics (such as traffic volume) on I-66 have changed over time. Likewise, the quality of INRIX data has continued to improve over time. As a result, analyzing multiple years of data may not provide the most accurate information on pre-deployment baseline conditions. For example, part of I-66 was widened from two lanes in both directions to four lanes between the VA 234 Bypass and U.S. 29 in Gainesville in 2010. This widening decreased the average travel time because of the increase in the physical road capacity. VDOT's NRO staff also indicated that the opening of Phase 1 of the Washington Metro's Silver Line on July 26, 2014, may have created substantial traffic pattern changes on I-66. Phase 1 of the Silver Line was a $2.9 billion project that extended the Metrorail system toward Reston, Virginia, by 23 miles (Metropolitan Washington Airports Authority, 2012). As a result, before-and-after comparisons in this study limited the before period to the time period after the opening of the Silver Line.

ATM on I-66 was first activated in mid-September 2015. Drivers were likely to be unfamiliar with the new system initially; their behavior may change over time as they become more comfortable with the new conditions. The initial adjustment period after ATM activation was defined to be approximately 2.5 weeks, from September 16 to October 4, 2015. In addition, two extreme non-recurring events, i.e., the visit of Pope Francis to Washington, D.C., from September 23 to September 25 and the presence of Hurricane Joaquin in Virginia from October 2 to October 4, were the other contributing factors in the selection of this 2.5-week acclimation period. In total, 21 weeks of after ATM data, from October 5, 2015, through February 28, 2016, were examined in this study. Since a full year of data were not available and traffic patterns are subject to seasonal trends, 21 weeks of before ATM data (October 2014-February 2015) were compared with 21 weeks of after ATM data (October 2015-February 2016). Although 2012-2014 average travel time and crash data were not analyzed for the before-and-after analysis, they were reviewed to show operational and safety trends throughout the years before ATM implementation. This provided an indication of whether the post-ATM data showed changes in trends in crashes or safety from what was the case before system installation.

Analysis was segregated by day of week and time of day (i.e., AM peak, midday, PM peak, overnight). The time-of-day periods were defined based on the pre-ATM shoulder opening hours so that operational results between the before and after periods could be fairly compared. In addition, the corridor was divided into six segments for the segment-level analysis, with the segments ranging from 1.3 to 2.6 miles. These segments were defined based on the locations of interchanges and the use of particular ATM techniques in each analysis section. The definition of these segments is discussed later.

ATM Utilization

It was possible to analyze the utilization rates of the ATM techniques using the activation logs stored at the VDOT TOC. The activation log contained detailed records of ATM usage for each gantry and by individual LUCS, including the time stamp and message displayed every time the LUCS changed.

Since not all gantries are located where shoulders are present, it was necessary to filter out gantries that were not used for HSR for the HSR utilization analysis. The HSR utilization analysis was divided into direction and day of week (i.e., average weekday, average weekend). HSR utilization rates were calculated by adding up the total time of HSR activation for each gantry and then dividing up the total by the number of days in the analysis period. This utilization rate represents average HSR utilization rate per day for each gantry.

All gantries were included in the AVSL utilization analysis. AVSL was deactivated shortly after the system came on line to improve algorithm performance. It was re-activated in mid-January 2016 with an enhanced algorithm, so the dataset in this report includes only AVSL data from mid-January through the end of February 2016. VSL utilization rates were calculated by adding up the total time of AVSL activation per gantry and then dividing the total by the number of days in the analysis period. This utilization rate represents average AVSL utilization rate per day for each gantry. In addition, the use of different speed reduction signs was analyzed by evaluating the utilization of each reduced speed (i.e., 35 to 50 mph in 5-mph increments).

All gantries were also included in the LUCS utilization analysis. The LUCS utilization rate was less than that for AVSL or HSR since it was activated only during lane blocking incidents in a travel lane. Therefore, it made more sense to analyze LUCS based on the total frequency and duration of activation per gantry rather than as an average activation duration per day.

Average Travel Times

INRIX travel time data were acquired in 15-minute temporal aggregations. Data quality screening measures were conducted, and travel times were segregated by appropriate segments, days of the week, and peak and non-peak periods. The travel time data were used to construct average travel time profiles using comparable months for the before and after ATM periods. Paired *t*-tests were conducted at the $\alpha = 0.05$ level to determine if the changes were statistically significant between October 2014-February 2015 and October 2015-February 2016. For each day of the week and average weekday and weekend, the 15-minute average times were divided into time of day for both the before and after ATM periods to set up the paired *t*-test. These groups of average travel times were then matched by their appropriate before and after periods. For example, all of the 15-minute average travel times for the weekday AM peak period from 5:30 to 11:00 AM for the before ATM period were paired and then compared to those of the after ATM period. This guaranteed a one-to-one match for the paired *t*-test, as the number of days for the before-and-after analysis was the same.

Travel Time Reliability

In addition to examining changes in mean travel time, changes in travel time reliability were examined using the planning time index (PTI) and the buffer index (BI). The PTI value shows the total time travelers should account for in order to be on time 95% of the time relative to free flow speeds. The BI value shows the extra time travelers should add to their average travel time to ensure they are on time 95% of the time. Travel time reliability measures were derived directly from INRIX travel time data for both the before and after ATM periods. Equations 1 and 2 were used to calculate the PTI and BI for each 15-minute intervals as follows:

$$\text{Planning time index} = \frac{95th\ Percentile\ average\ travel\ time}{Free\ flow\ average\ travel\ time}$$

[Eq. 1]

$$\text{Buffer index} = \frac{95th\ Percentile\ average\ travel\ time - Average\ travel\ time}{Average\ travel\ time}$$

[Eq. 2]

For PTI calculations, free flow average travel times were calculated by using 55 mph as the free flow speed, which is the posted regulatory speed limit. Paired *t*-tests were conducted at the $\alpha = 0.05$ level to determine if the PTI and BI changes were statistically significant.

Since travelers are usually going faster than the speed limit during low traffic flow hours, it is possible to have a PTI value of less than 1. For the BI, the baseline average travel time value changes, unlike for the PTI. Before and after BI values use their respective before and after average travel time values as the denominator. This means that the after ATM BI value may be calculated using an improved after ATM average travel time, so the calculated after ATM BI value is a conservative number compared to the calculated before ATM BI value. Reductions in the PTI and/or the BI would show that the ATM system has contributed to a more predictable, consistent trip for drivers. Since many of the components of the ATM system may have a greater impact on mitigating the effects of non-recurring congestion, reliability changes may be greater than changes in mean travel time.

Total Delay

Traffic delay for the before and after periods (in vehicle-hours) was examined to determine if the system produced a net benefit for operations. The magnitude of delay can be determined by using Equation 3 for each 15-minute interval:

$$Delay = \begin{cases} 0 & if\ FFTTP \geq ATTP \\ (ATTP - FFTTP) \times Volume \div 60 & if\ FFTTP < ATTP \end{cases}$$

[Eq. 3]

where

FFTTP = free flow travel time profile, defined as the travel time (in minutes) through the corridor at a constant 55 mph speed; speeds faster than 55 mph result in 0 delay, not a negative delay

ATTP = average travel time profile, defined as the average travel time (in minutes) based on the observed data.

Since volume data were not available for after ATM conditions, some assumptions had to be made to calculate total delay. Since volumes were different for the non-HSR and HSR sections of I-66, they were analyzed separately. The daily volume distributions (percentage of traffic in each 15-minute period) for the before and after ATM conditions were assumed to be the same. AADT estimates for the after ATM period were developed using before ATM conditions and average (weighted by length of segment) growth rates across the segments. Once all delay values were calculated for each 15-minute interval, the summations of the respective values represented the average daily delay levels.

Safety Analysis

Time Periods Analyzed

Since RNS police crash reports were not available from January 2016-February 2016, only October 2015-December 2015 data were analyzed for the safety analysis. Although only 3 months (13 weeks) of post-ATM data were available, this analysis using limited data may provide some preliminary insight into the safety effects of the system. These results are not conclusive, but they may help provide insight into performance, particularly when viewed in parallel with operational data.

Since iPeMS traffic incident data are collected in real time, data from October 2015-February 2016 were available. Since data were available throughout the study period, all 21 weeks of data were analyzed for the incident analysis.

Crash Rate Analysis by Severity

Crash rates were analyzed at a corridor level by using weighted average AADT values (weighted by length of segment). Total crash and rear-end and sideswipe crash cases were analyzed, and severity was separated into property damage only (PDO) and injury and fatal types for this analysis. The crash rate, expressed as crashes per 100 million vehicle-miles of travel, is calculated using Equation 4. To analyze the historic crash rate trends, crashes that occurred from October-December of 2012, 2013, 2014, and 2015 were analyzed for the crash rate analysis.

$$\text{Crash rate} = \frac{Crash\ frequency \times 100{,}000{,}000}{AADT \times Days \times Length}$$

[Eq. 4]

Traffic Incident Analysis

Traffic incidents from October-February for 2012-2016 were analyzed. The frequency of incidents was compared before and after ATM activation to determine whether there were any changes in overall frequency or frequency by incident type.

I-66 ATM Benefit-Cost Analysis

A B/C ratio was calculated for the I-66 ATM project. This provided valuable information that can be used when the feasibility of implementing ATM on other corridors or expanding ATM on I-66 is assessed. The B/C analysis was conducted by assigning monetary values to travel time changes resulting from ATM implementation. Values of time from the Texas A&M Transportation Institute's *Urban Mobility Scorecard* (Schrank et al., 2015) were used for this analysis. Differing values of time for freight and passenger vehicles were explicitly considered. These values were combined with project costs to estimate an overall B/C ratio for the project.

RESULTS

Literature Review

ATM has been successful in producing positive operational and safety results in many European countries, but applications in the United States are limited (Fontaine and Miller, 2012). A scan team from the Federal Highway Administration and the American Association of State Highway and Transportation Officials visited and examined the impact of ATM in key European countries (Mirshahi et al., 2007). The conclusion of the scan team was that ATM can be used to improve safety and operations in the United States (Mirshahi et al., 2007). Since the visit of the scan team, there have been more ATM implementations, but ATM is still in its introductory stages in the United States. In many of the U.S. deployments, preliminary evaluations of ATM have been conducted but detailed impact analyses are limited because of the limited availability of data (Jacobson, 2012) or presence of systematic problems (Atkins Consulting, 2009). Since ATM is a relatively new technology in the United States and the effects of ATM in Europe have been very positive, further research regarding the effects of ATM in the United States is necessary.

From the literature review, it is evident that ATM could have both operational and safety benefits. Tables 2 through 4 show a summary of the major European and U.S. deployments of ATM. In Europe, the evaluations showed that travel times, traffic flow, crash rates, and crash severity often improved with the implementation of one or more ATM techniques. In the United States, the literature showed that ATM has the potential to improve operations and safety, although these results are often based on limited data.

Table 2. Summary of ATM Implementation in Germany

Location	ATM Technique	Roadway Characteristics	Research Design	Effect on Operations	Effect on Safety	Research Problems or Comments
Germany, A5 (Sparmann, 2007)	VSL	• 50,000 ADT	N/A	N/A	• 27% reduction in crashes with heavy material damage •29% reduction in crashes with personal damage	• No methodology provided
Germany, A99 (Weikl et al., 2013)	VSL	• 16.3 km (~10 mi) section • 3 lanes each direction	• VSL system • 14 dual-loop detectors • 18 bottleneck cases	• Lane utilization of roadway distributed more evenly at slight cost of capacity • Flow change reduction of 4% when VSL was on and flow change reduction of 3% when VSL was off	N/A	• Gathered only 31 weekdays (25 days when VSL-ON and 6 days when VSL-OFF) for data analysis
Germany, A5 and A3 (Geistefeldt, 2012)	HSR	• 18 km (~11 mi) • 3 lanes each direction • High commuter traffic • Distinct peak volumes	• 40 months of loop detector data • 47 sections of roadway analyzed for duration of congestion analysis	• Median values of capacity 10%-25% higher than capacity of comparable sections without HSR • Duration of congestion reduced from 640 hours/year and 450 hours/year for NB and SB, respectively, to less than 200 hours/year in both directions	N/A	• Did not provide information on comparison sections
Germany A7 (Lemke, 2010)	HSR	• 3 sections of roadway totaling 36 km (~22 mi) •35,000 AADT on each section	• Original hand-written police reports • 3 years before and 3 years after data analyzed	N/A	• Crash rates did not necessarily increase in all cases	N/A

ATM = active traffic management; VSL = variable speed limits; ADT = average daily traffic; N/A = not applicable; HSR = hard shoulder running; AADT = annual average daily traffic.

Table 3. Summary of ATM Implementation in the United Kingdom

Location	ATM Technique	Roadway Characteristics	Research Design	Effect on Operations	Effect on Safety	Research Problems or Comments
U.K., M42 (Mott McDonald, Ltd.,2008)	VSL, HSR	• 17 km (~11 mi) • 134,000 bi-directional AADT • 3 lanes in each direction	• 12 months of before and 12 months of after data analyzed • 1 month settling in period	• Average capacity increased 7% • Total flow increased 6% and 9% on NB and SB directions, respectively • Average travel time increased 9% • Variability of travel time reduced by 22% in both directions	• Average number of crashes per month reduced from 5.08 to 1.83 after ATM implementation • Severity index reduced from 0.16 to 0.14 after ATM implementation	• Additional development and construction work between ATM construction phases, which may underestimate benefit of ATM • Preliminary safety analysis
U.K., M42 (Mott McDonald Ltd., 2011)	VSL, HSR	• 17 km (~11 mi) • 134,000 bi-directional AADT • 3 lanes in each direction	• 36 months of before and 36 months of after data analyzed • 1 month settling in period	N/A	• Average number of crashes per month reduced from 5.08 to 2.25 after ATM implementation • Severity index reduced from 0.16 to 0.07 • Monthly mean number of fatal or seriously injured casualties reduced from 1.15 to 0.19 • Two-way accident rate per billion vehicle miles traveled reduced from 115.92 to 47.98 • Proportion of rear-end crashes remained constant • Proportion of side-impact crashes increased from 16.1% to 30.9%	• Final safety analysis

ATM = active traffic management; VSL = variable speed limits; HSR = hard shoulder running; AADT = annual average daily traffic.

Table 4. Summary of ATM Implementations in the United States

Location	ATM	Roadway	Research Design	Effect on Operations	Effect on Safety	Research Problems or Comments
I-5, Washington (DeGaspari et al., 2013)	VSL, QWS	• 7 miles NB	• Total of 8 months before and after period • 19 loop detectors	• Planning time index improved by 17%-31% • Buffer index improved by 15-27%	N/A	• Solely depended on detector data for analysis of entire roadway
I-4, Florida (Atkins Consulting, 2009)	VSL	• 10 miles • 200,000 AADT	• Study period from 4-6 PM • 21 days of before VSL data and 30 days of after VSL data analyzed	• Speed changes correlated with changes in occupancy rather than changes in posted speed limit	N/A	• Short study period • Before and after periods do not match in season • Studying only 4-6 PM could bias results
I-260 and I-255, Missouri (Kianfar et al., 2010)	VSL	• 38 miles • 3 bottleneck locations	• Inductive loop and acoustic detectors • 150 days of before VSL data and 150 days of after VSL data analyzed • 10 days between before and after VSL deployment for driver normalization	• Pre-queue flow decreased by up to 4.5% • Queue discharge flow decreased by up to 7.7% • Average speed fluctuated but speed variance declined at all bottleneck locations	N/A	• Findings true for bottleneck locations only; not plausible to conclude that results apply to entire roadway
I-35W and I-94, Minnesota (Hourdos and Zitzow, 2014; Hourdos et al., 2013)	VSL	•160,000 AADT	• Single loop detectors, video recordings, crash records • 9 months of before VSL data, 17 months of after VSL data analyzed for operational analysis • 6 months of before VSL data, 6 months of after VSL data analyzed for safety analysis	• During AM peak period, 17% less congestion with the VSL system in operation for speed drop thresholds of 25 mph or more • 7.6 minutes less congestion during average AM peak	• Traffic pattern shows gradual decrease in speeds during onset of congestion • No change in crash rates	• Depended on single loop detector data for analysis of entire roadway
I-35W, Minnesota (Kwon and Park, 2015)	VSL	• Urban location	• Traffic detector data • Sept-Nov 2009 (before), 2010 (after), and 2011 (after) • Apr-Jun 2010 (before), 2011 (after), and 2012 (after)	• Average travel time buffer index improved by 17%-32%	• Maximum deceleration decreased by 10%-22%	• Analysis of 6 months of data may not show full effects of VSL

ATM = active traffic management; VSL = variable speed limits; QWS = queue warning system; NB = northbound; N/A = not applicable; AADT = annual average daily traffic.

It is possible that the reported European ATM implementation benefits may not be fully transferable to the United States, given the differing operating characteristics and driver behavior. For example, many European ATM deployments incorporate automated speed enforcement, which is not legally available in most U.S. jurisdictions. Therefore, a review of implementations and analyses was important as it shed light on the respective operating characteristics on each of the roadways where ATM was installed and analyzed. Results based on field data may be relevant only to the network from which they were derived, making it more important to analyze and compare the operating characteristics of the roadways (Fudala and Fontaine, 2010).

Much of the research regarding ATM techniques was conducted using point detector data, which represent traffic information on a specific point on a roadway. In this study, INRIX real-time probe-based travel time data were used to analyze operational effects of ATM. By using real-time probe-based data, the travel time conditions along the entire corridor were better represented since space mean speeds were used. The ATM system on I-66 is a complex implementation on a unique corridor since I-66 has high occupancy vehicle (HOV) lanes, shoulder lanes, and even Metrorail running in the middle of the corridor. As a result, it was initially unclear how well the results of previous research would translate to the I-66 installation.

I-66 Roadway and ATM Characteristics

Before the results of this study are discussed, it is useful to describe the site conditions on I-66 given its unique characteristics. The ATM system implemented on I-66 used different ATM components along its length. Tables 5 and 6 show a summary of the roadway and operational characteristics of the study sections. Segments C and D from Table 5 were the focus for this study, as these were the segments with the most ATM components installed. The total length of these segments was approximately 13 miles in each direction, with a regulatory speed limit of 55 mph. As shown in Table 6, Segments C and D were further subdivided into six subsegments. The division points for the subsegments were based on the location of major interchanges along the corridor. On the subsegments without HSR (Subsegments 1-3), there was an HOV-2 lane and three general purpose lanes. On the segments with HSR (Subsegments 4-6), there was an HOV-2 lane, two general purpose lanes, and a shoulder lane available for travel using HSR. The 2015 directional AADT varied by segment, ranging from 61,000 to 93,000 vehicles per day.

I-66 Roadway Characteristics

Discussions with staff of VDOT's NRO on July 3, 2014, staff noted that analysis of the ATM system should focus on Segments C and D of the deployment since improvements to the other segments were focused more on improved monitoring. Table 6 and Figures 1 and 2 show the physical roadway characteristics and ATM characteristics of the six subsegments of I-66 that were analyzed. In addition, since multiple techniques were being deployed simultaneously within a section, the before-and-after analysis shows the net effect of the combinations of all ATM techniques for each section.

Table 5. Characteristics of I-66 Roadway Segments

Segment	Location	Length (mi)	AADT (2012)	ATM Component	Additional Features	Physical Roadway Characteristics
A	U.S.15 (Exit 40) to U.S. 29 Gainesville (Exit 43)	2.6	EB: 30,000 WB: 29,000	-	Increased CCTV camera, sensor, and dynamic message sign coverage	Currently in construction to improve from 2 to 4 lanes each direction; upon completion of widening, HOV-2 rules will also apply on segment
B	U.S. 29 (Exit 43) to U.S. 29 Centreville (Exit 52)	8.2	EB: 55,000 to 65,000 WB: 53,000 to 55,000	-	Increased CCTV camera, sensor, dynamic message sign coverage, and enhanced emergency pull-out zones	4 lanes each direction; HOV-2 rules still apply on segment
C	**U.S. 29/Lee Hwy (Exit 52) to U.S. 50 (Exit 57)**	**5.8**	**EB: 64,000 to 71,000** **WB: 62,000 to 72,000**	**AVSL, LUCS, QWS**	**Increased CCTV camera, sensor, dynamic message sign coverage, and enhanced emergency pull-out zones**	**4 lanes each direction; HOV-2 rules still apply on segment**
D	**U.S. 50 (Exit 57) to I-495 (Exit 64)**	**7.2**	**EB: 76,000 to 91,000** **WB: 84,000 to 86,000**	**AVSL, LUCS, QWS, HSR**	**Increased CCTV camera, sensor, dynamic message sign coverage, and enhanced emergency pull-out zones**	**3 lanes + shoulder lane both directions; right shoulder lane used as travel lane during respective peak hours to maintain 3 general travel lanes while leftmost lane acts as HOV-2 lane; median used by heavy rail in sections of segment**
E	I-495 (Exit 64) to DC Line (~Exit 75)	10.2	EB: 33,000 to 65,000 WB: 34,000 to 65,000	Dynamic ramp metering	Increased CCTV camera, sensor, dynamic message sign coverage, and enhanced emergency pull-out zones	2 lanes both directions; additional lane for entry/exit through selected segments; entire roadway reserved for HOV-2 EB in morning and WB in afternoon

AADT = annual average daily traffic; ATM = active traffic management; EB = eastbound; WB = westbound; CCTV = closed circuit television; HOV = high occupancy vehicle; AVSL = advisory variable speed limit; LUCS = lane use control signals; QWS = queue warning system; HSR = hard shoulder running. Segments in bold font indicate which locations were evaluated in this study.

Table 6. Final I-66 Subsegments for Analysis

Segment	Location	Length (mi)	Speed Limit (mph)	AADT (2015)	ATM Component	Physical Roadway Characteristics
1	U.S. 29 (Exit 52) to VA 28 (Exit 53)	1.3	55	EB: 68,000WB: 66,000	AVSL, LUCS, QWS	4 lanes each direction; HOV-2 rules still apply on segment
2	VA 28 (Exit 53) to VA 286 (Exit 55)	1.9	55	EB: 80,000 WB: 82,000	AVSL, LUCS, QWS	4 lanes each direction; HOV-2 rules still apply on segment
3	VA 286 (Exit 55) to U.S. 50 (Exit 57)	2.6	55	EB: 65,000 WB: 61,000	AVSL, LUCS, QWS	4 lanes each direction; HOV-2 rules still apply on segment
4	U.S. 50 (Exit 57) to VA 123 (Exit 60)	1.9	55	EB: 90,000 WB: 93,000	AVSL, LUCS, QWS, HSR	3 lanes and shoulder lane in each direction; right shoulder lane used as travel lane during respective peak hours to maintain 3 general travel lanes while leftmost lane acts as HOV-2 lane
5	VA 123 (Exit 60) to VA 243 (Exit 62)	2.1	55	EB: 93,000 WB: 81,000	AVSL, LUCS, QWS, HSR	3 lanes and shoulder lane in each direction; right shoulder lane used as travel lane during respective peak hours to maintain 3 general travel lanes while leftmost lane acts as HOV-2 lane
6	VA 243 (Exit 62) to I-495 (Exit 64)	3.2	55	EB: 82,000 WB: 86,000	AVSL, LUCS, QWS, HSR	3 lanes and shoulder lane in each direction; right shoulder lane used as travel lane during respective peak hours to maintain 3 general travel lanes while leftmost lane acts as HOV-2 lane; median used by heavy rail (Metrorail)

AADT = annual average daily traffic; ATM = active traffic management; EB = eastbound; WB = westbound; AVSL = advisory variable speed limits; LUCS = lane use control signals; QWS = queue warning system; HSR = hard shoulder running; HOV = high occupancy vehicle.

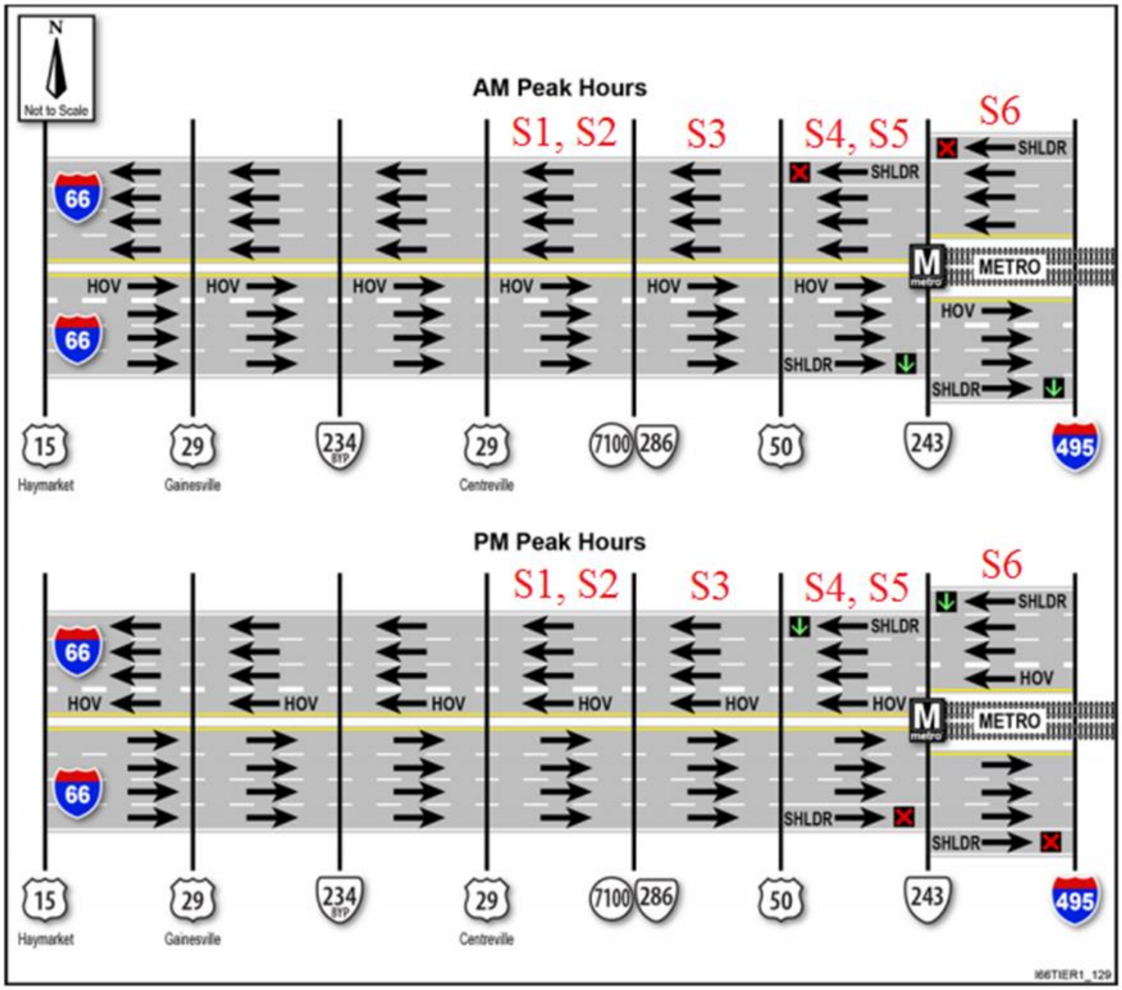


Figure 1. Physical Roadway Characteristics of I-66, With Subsegments Labeled From Table 5

Figure 2. Map of ATM Subsegments From Table 5. ATM = Active Traffic Management.

Most of the I-66 study section had steady traffic volume growth over time. Table 7 shows the generally increasing trend in traffic volume from 2012-2015. The corridor-level AADT growth rate calculated by using weighted averages by length of segment showed an average annual volume growth rate from 2012-2015 of approximately 2% on weekdays and 1% on weekends. With the increase in traffic volumes, the average travel times for the corresponding years also increased. Before ATM implementation, the average travel times along the corridor had increased during peak, midday, and off peak periods. The overnight period was the only period without much average travel time change. Figures 3 and 4 show the trends in increasing average travel time for the years before ATM activation.

Table 7. AADT for 2012-2015 on EB and WB I-66 Segments

Direction	Segment	AADT Average Weekday				AADT Average Weekend			
		2012	2013	2014	2015	2012	2013	2014	2015
EB	1	66,000	70,000	70,000	71,000	59,000	56,000	56,000	60,500
	2	74,000	83,000	82,000	85,000	63,500	65,500	68,000	67,500
	3	68,000	68,000	67,000	68,000	61,000	57,500	60,000	57,500
	4	94,000	93,000	92,000	94,000	76,500	75,500	74,500	80,000
	5	97,000	96,000	96,000	99,000	76,000	78,500	75,000	78,000
	6	80,000	79,000	79,000	86,000	66,000	68,500	65,000	72,000
WB	1	66,000	69,000	68,000	70,000	52,000	55,000	54,000	56,000
	2	76,000	88,000	87,000	87,000	62,000	70,500	69,500	69,500
	3	67,000	66,000	65,000	65,000	53,000	55,500	54,500	51,000
	4	91,000	90,000	89,000	98,000	73,500	72,500	71,500	80,500
	5	91,000	90,000	89,000	85,000	73,500	72,500	71,500	71,000
	6	87,000	86,000	86,000	91,000	76,500	75,500	72,000	73,500

AADT = average annual daily traffic; EB = eastbound; WB = westbound.

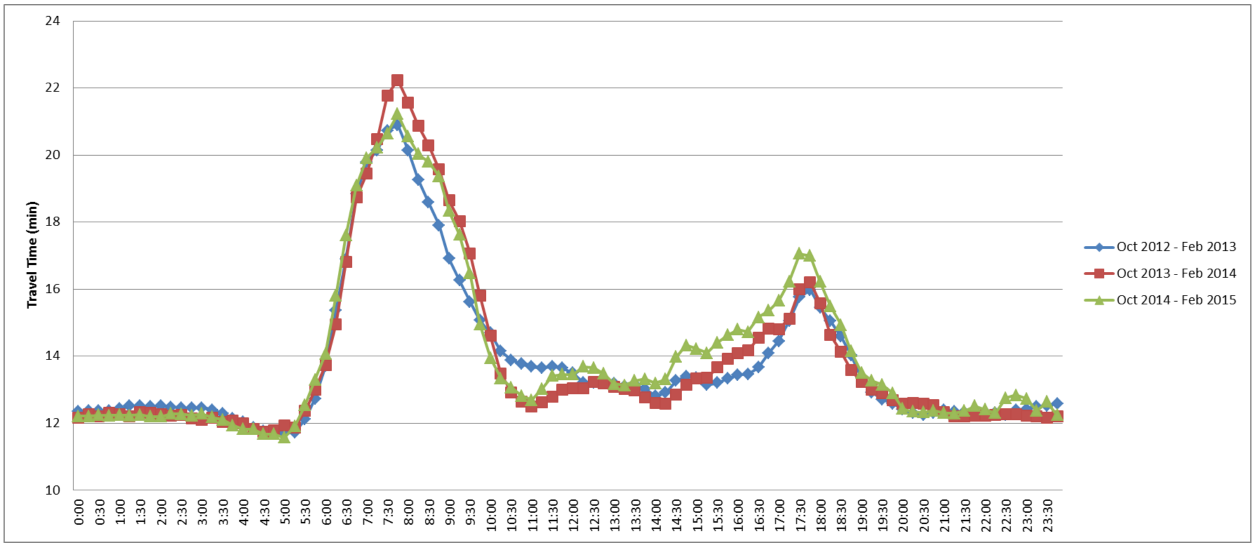


Figure 3. Eastbound Average Weekday Average Travel Time Trend: Corridor Level

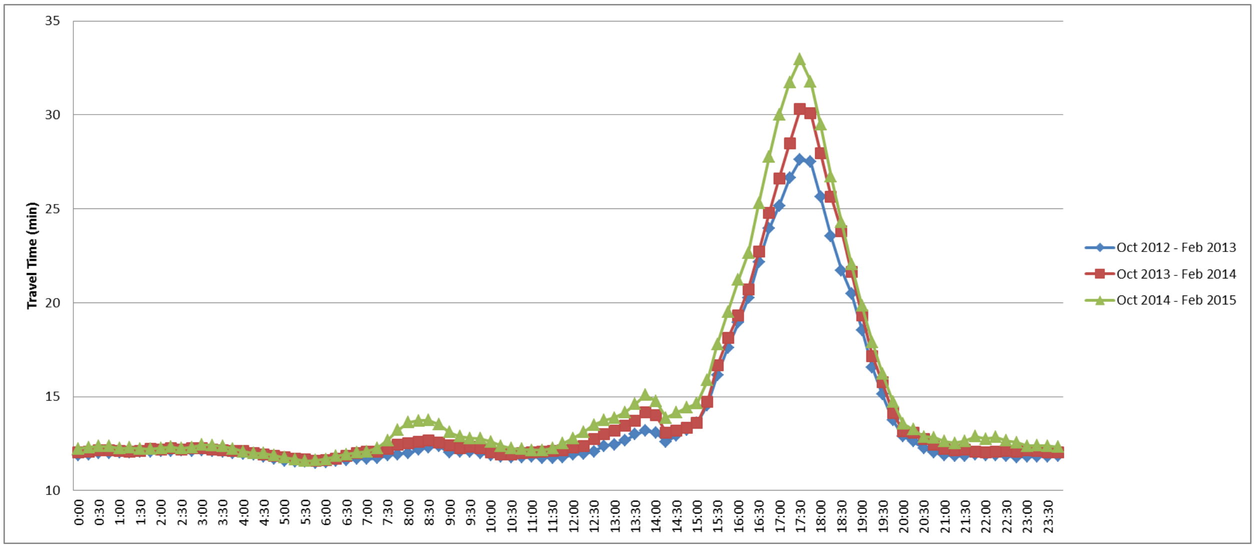


Figure 4. Westbound Average Weekday Average Travel Time Trend: Corridor Level

I-66 Traffic Control Before and After ATM Implementation

This section describes key traffic control characteristics of the study corridor, including those in the before and after ATM periods. The ATM system became active on September 16, 2015. The AVSLs were initially activated but were taken off line after 1 week of operation because of issues with the control algorithm. They were subsequently reactivated in mid-January 2016 with a re-tuned algorithm.

High-Occupancy Vehicle (HOV) Restrictions on I-66

An HOV-2 lane is present in both directions of the study section. The HOV-2 hours did not change between the before and after ATM periods. Outside I-495, the HOV-2 hours are as follows:

- EB: 5:30 to 9:30 AM
- WB: 3:00 to 7:00 PM.

As shown in Figure 1, HOV lanes were present throughout the study section; they were separated only by pavement markings.

Shoulder Opening Hours

Before ATM implementation, the shoulders on Subsegments 4 through 6 were open to travel only during fixed time periods on weekdays. The before ATM static shoulder opening hours were as follows:

- EB: 5:30 AM to 11:00 PM
- WB: 2:00 PM to 8:00 PM.

The shoulders were not opened on federal holidays. After ATM implementation, shoulders continued to be open on the same fixed schedule as during the before ATM peak periods but were also opened dynamically whenever there was a need for additional road capacity. Thus, a major change was that during weekday off peak hours and weekends, the shoulders could be opened when an increase in roadway capacity was warranted. This was to allow the ATM system to add capacity for traffic demands during incidents, work zones, or unusual fluctuations in demand.

ATM Gantry Locations

Twenty-one new gantries were constructed in each direction to house the AVSL signs and the LUCSs. The approximate average distance between gantries was 0.6 miles. Figures 5 and 6 show the locations of the new gantries and whether the new gantry was used for HSR. Each gantry contained dynamic message signs over each lane that could display the AVSL, LUCS, HSR, and/or QWS. Figure 7 shows an example of a gantry installed on the I-66 corridor. This particular gantry employs all of the components of the ATM.

Characteristics of Advisory Variable Speed Limits

AVSL signs were deployed on overhead gantries throughout the corridor once the ATM was installed. Inconsistencies with the AVSL algorithm caused the AVSL component of ATM to be deactivated for fine tuning after 1 week of operation. The AVSL component was reactivated in mid-January 2016 with an enhanced algorithm. The algorithm deployed was developed by Delcan Technologies, and a specific evaluation of the mechanics of the algorithm was not in the scope of this evaluation. Generally, the algorithm examines real-time speed data and then smooths and groups the posted speeds on adjacent signs to develop reasonable transitions into and out of congested conditions. Speeds are gradually lowered approaching congestion in order to reduce conflicts between higher speed approaching vehicles and vehicles in the queue.

The AVSLs have a lower bound of 35 mph. Since the VSLs are advisory, the police cannot enforce the AVSL speed limits, although they can write citations for failure to comply with traffic control. In contrast to European deployments, no automated speed enforcement is present on the corridor.

Characteristics of Lane Use Control Signals

The LUCSs allow the VDOT TOC to provide advance warning of lane closures, allowing better management of roadway incidents and work zones. The LUCSs are located on overhead gantries throughout the corridor, using the same signs as the AVSL signs. Figure 8 shows the traveler educational signs that were placed along the corridor. Figure 9 shows an example of LUCS activation on I-66. Since the diagonal yellow arrow is not a standard indication in accordance with the *Manual on Uniform Traffic Control Devices,* a separate study being conducted by researchers at the Virginia Transportation Research Council (VTRC) is analyzing the effects of those signs on I-66. That study will evaluate the microscopic effects of the behaviors of approaching vehicles attributable to the LUCS.

Figure 5. Gantry Locations for Segments 1-3 (HSR Not Present). HSR = hard shoulder running.

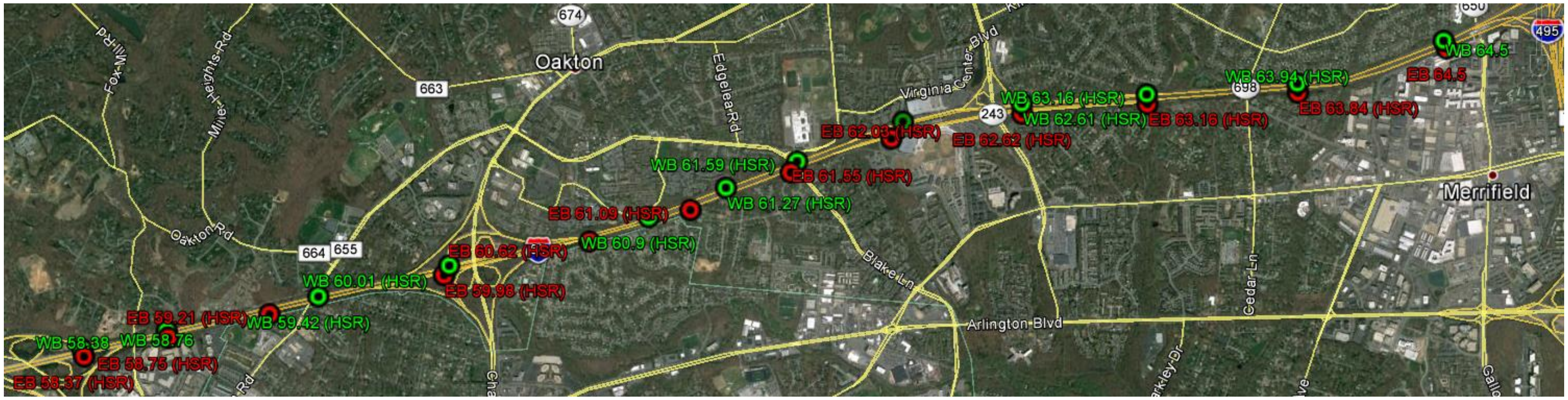


Figure 6. Gantry Locations for Segments 4-6 (HSR Present). HSR = hard shoulder running.

Figure 7. Example of Gantry With ATM Techniques. ATM = Active Traffic Management.

Figure 8. Available Lane Use Control Signals on I-66

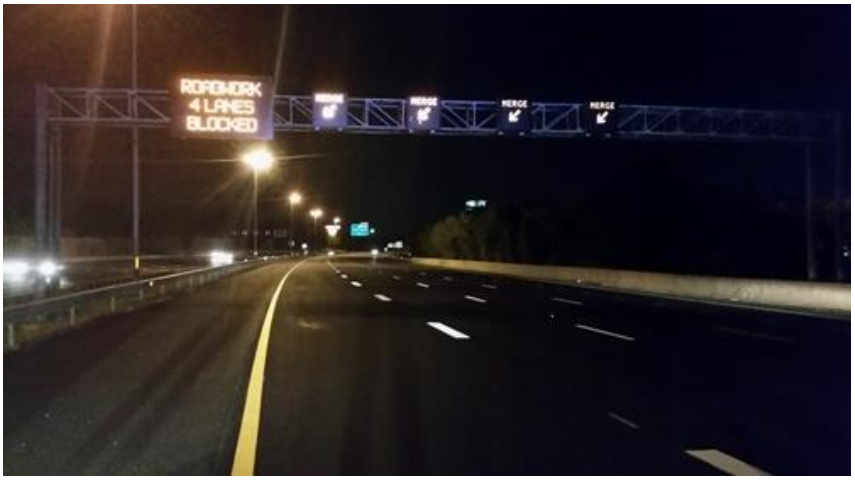


Figure 9. Example of LUCS in Operation. LUCS = lane use control signal.

Figure 10 shows an example of how the gantries work in sequence to manage a crash event that is blocking the right lane (L3) and shoulder during the peak period (Iteris, 2011). The sign sequence, read from the bottom to the top, redirects upstream vehicles out of the closed lane to reduce the effect of the bottleneck as much as possible.

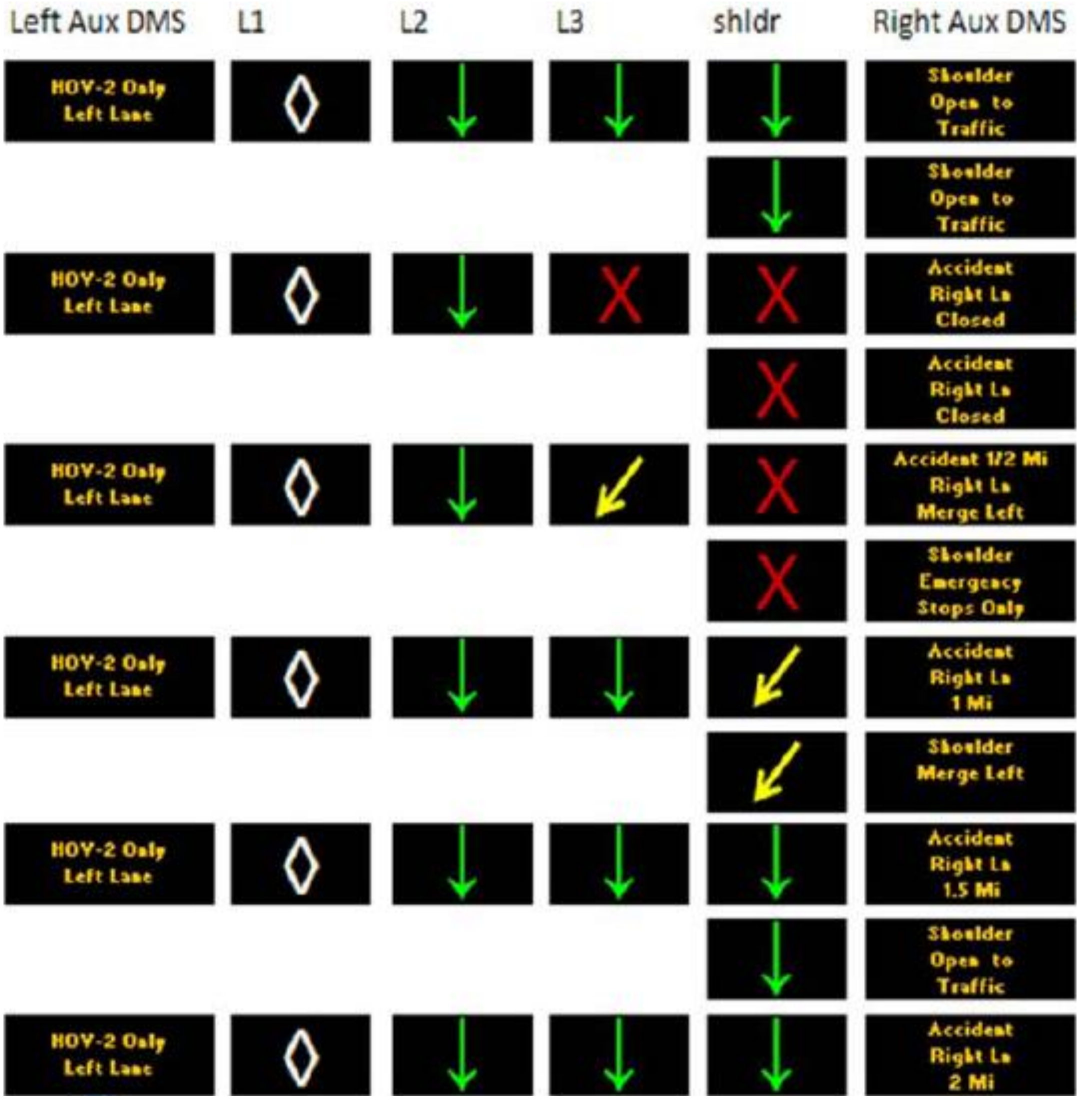


Figure 10. Example of Lane Use Control Signals in Operation When Accident Was on Right Lane of Roadway (Iteris, 2011).

Corridor-Level Operations Analysis

The corridor-level operations analysis focuses on the aggregate impact of the ATM system across the entire 13-mile study section. First, the utilization of each ATM component is reviewed. Second, the impact of the ATM on average travel time and travel time reliability is discussed.

Corridor-Level Utilization Analysis: HSR

Before ATM was implemented, HSR was activated only during pre-defined time periods on weekdays. After ATM implementation, HSR was dynamically opened in response to congestion, in addition to being opened during the regular peak travel times. After ATM was activated, the average weekday HSR operational hours increased from 5.5 hours/day to 7.99 hours/day per gantry in the EB direction. In the WB direction, the average weekday HSR operational hours decreased from 6 hours/day to 5.94 hours/day per gantry. On weekends, EB and WB saw average weekend HSR operational hours increase to 5.92 hours/day and 5.11 hours/day per gantry, respectively, versus not being opened at all during the before period. It should be noted that all of these average durations are skewed by the large number of holidays during the analysis period. Since HSR is not activated on federal holidays, the average in the WB direction declined slightly from the 6-hour baseline from before ATM activation. This means that the HSR utilization rate after ATM implementation is a conservative value, and the long-term actual HSR utilization rate may actually be higher.

Some gantries had more hours of HSR activation than others; these gantries were located on segments with higher AADTs (approximately from Milepost 57 to 62, which correspond to Subsegment 4 to 5). This was not surprising since demand for additional capacity is likely to be highest where volumes are the greatest. Tables 8 through 11 show the average weekday and weekend HSR utilization results for each gantry.

Table 8. EB Weekday Before and After HSR Utilization by Gantry per Day

Gantry Milepost	Average Operational Hours Before (hr/day)	Average Operational Hours After (hr/day)
58.37	5.50	9.53
58.75	5.50	8.99
59.21	5.50	10.07
59.98	5.50	10.09
60.62	5.50	10.12
61.09	5.50	10.00
61.55	5.50	10.25
62.03	5.50	4.71
62.62	5.50	4.73
63.16	5.50	4.73
63.84	5.50	4.68
Average	5.50	7.99

EB = eastbound; HSR= hard shoulder running.

Table 9. WB Weekday Before and After HSR Utilization by Gantry per Day

Gantry Milepost	Average Operational Hours Before (hr/day)	Average Operational Hours After (hr)
59.42	6.00	7.07
60.01	6.00	7.13
60.9	6.00	7.15
61.27	6.00	7.13
61.59	6.00	8.05
62.08	6.00	6.73
62.62	6.00	3.37
63.16	6.00	3.39
63.84	6.00	3.43
Average	6.00	5.94

WB = westbound; HSR= hard shoulder running.

Table 10. EB Weekend Before and After HSR Utilization by Gantry per Day

Gantry Milepost	Average Operational Hours Before (hr/day)	Average Operational Hours After (hr/day)
58.37	0.00	6.71
58.75	0.00	6.64
59.21	0.00	7.10
59.98	0.00	7.01
60.62	0.00	7.19
61.09	0.00	10.66
61.55	0.00	7.18
62.03	0.00	3.15
62.62	0.00	3.15
63.16	0.00	3.17
63.84	0.00	3.13
Average	0.00	5.92

EB = eastbound; HSR= hard shoulder running.

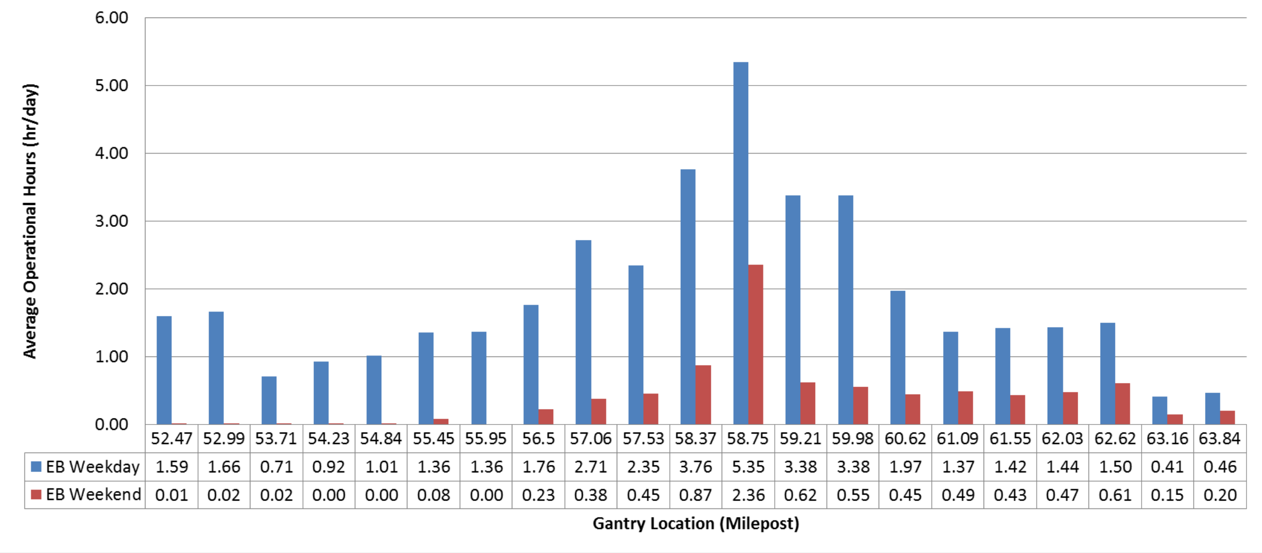
Table 11. WB Weekend Before and After HSR Utilization by Gantry per Day

Gantry Milepost	Average Operational Hours Before (hr/day)	Average Operational Hours After (hr)
59.42	0.00	6.44
60.01	0.00	6.44
60.9	0.00	6.44
61.27	0.00	6.44
61.59	0.00	6.10
62.08	0.00	6.12
62.62	0.00	2.66
63.16	0.00	2.66
63.84	0.00	2.66
Average	0.00	5.11

WB = westbound; HSR= hard shoulder running.

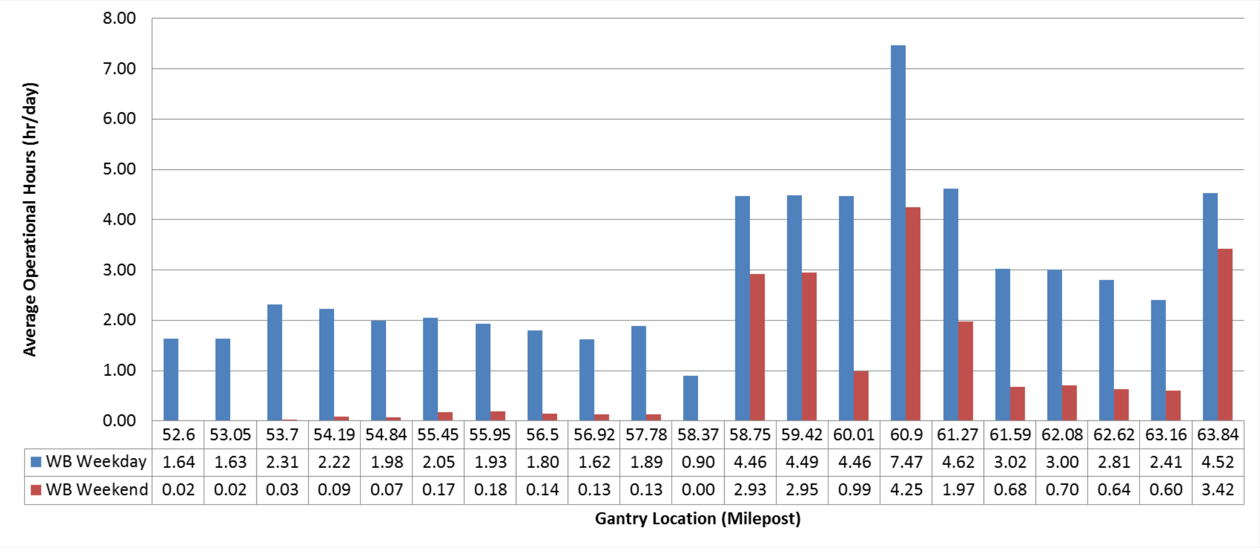
Corridor-Level Utilization Analysis: AVSL

In contrast to HSR, AVSLs are present on all of the study segments of the I-66 corridor with gantries. Since AVSLs with enhanced algorithms were reactivated in mid-January, only mid-January–February data were analyzed for the AVSL utilization analysis. The AVSLs are activated whenever the system detects slowdowns in traffic in order to smooth flow into a reduced speed zone. On average, AVSLs posted reduced speeds on weekdays for 1.90 hours and 2.92 hours in the EB and WB directions, respectively. On weekends, the average durations were 0.40 hours and 0.96 hours for the EB and WB directions, respectively. As with HSR, some gantries had more hours of AVSL activation than others; these gantries were located on segments with higher AADTs (approximately from Milepost 57 to 62, which correspond to Subsegment 4 to 5). Figures 11 and 12 show the average weekday and weekend AVSL operational durations for each gantry.



	52.47	52.99	53.71	54.23	54.84	55.45	55.95	56.5	57.06	57.53	58.37	58.75	59.21	59.98	60.62	61.09	61.55	62.03	62.62	63.16	63.84
🟦 EB Weekday	1.59	1.66	0.71	0.92	1.01	1.36	1.36	1.76	2.71	2.35	3.76	5.35	3.38	3.38	1.97	1.37	1.42	1.44	1.50	0.41	0.46
🟥 EB Weekend	0.01	0.02	0.02	0.00	0.00	0.08	0.00	0.23	0.38	0.45	0.87	2.36	0.62	0.55	0.45	0.49	0.43	0.47	0.61	0.15	0.20

Figure 11. Eastbound AVSL Utilization by Gantry for Weekdays and Weekends. AVSL = Advisory Variable Speed Limit.



	52.6	53.05	53.7	54.19	54.84	55.45	55.95	56.5	56.92	57.78	58.37	58.75	59.42	60.01	60.9	61.27	61.59	62.08	62.62	63.16	63.84
🟦 WB Weekday	1.64	1.63	2.31	2.22	1.98	2.05	1.93	1.80	1.62	1.89	0.90	4.46	4.49	4.46	7.47	4.62	3.02	3.00	2.81	2.41	4.52
🟥 WB Weekend	0.02	0.02	0.03	0.09	0.07	0.17	0.18	0.14	0.13	0.13	0.00	2.93	2.95	0.99	4.25	1.97	0.68	0.70	0.64	0.60	3.42

Figure 12. Westbound AVSL Utilization by Gantry for Weekdays and Weekends. AVSL = Advisory Variable Speed Limit.

Figure 13 shows the distribution of reduced speeds that were posted on the AVSLs based on the duration of the display. For weekdays, the percentages of total time the gantries indicated 35, 40, 45, and 50 mph speed reduction were similar, ranging from 20% to 30%. On the weekends, the percentages of time the gantries indicated 50 mph were highest at 47% and 64% for the EB and WB directions, respectively. This indicates that average speeds on weekends were often higher than on weekdays, and there were not many time periods that required AVSLs to show 45 mph or lower.

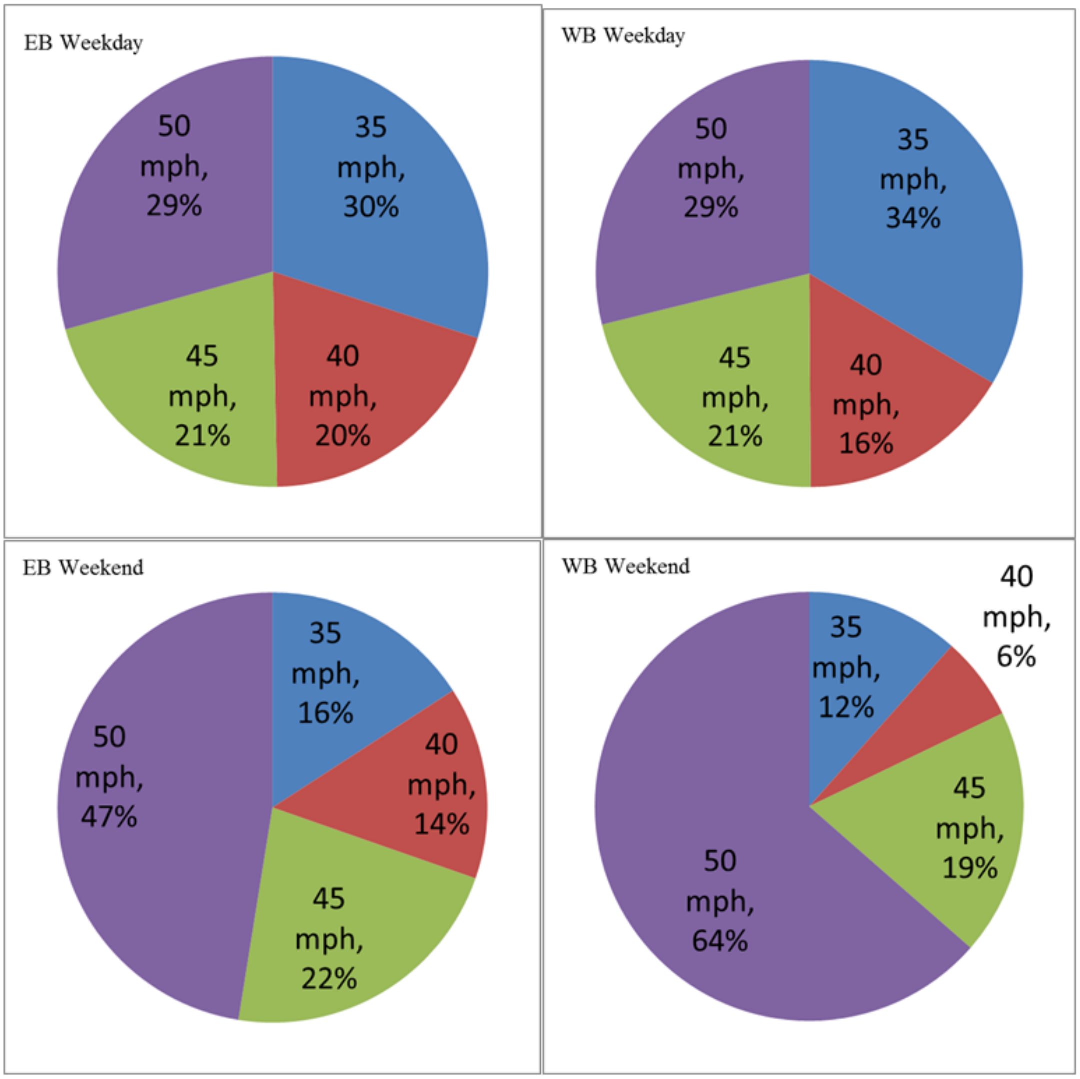


Figure 13. AVSL Utilization by Speed Posted for Eastbound and Westbound Weekdays and Weekends. AVSL = Advisory Variable Speed Limit

Figures 14 through 25 show the average duration of AVSL activation by time of day, along with the posted speed limits. When the utilization durations were broken up into time of day, the analysis showed that, as expected, AVSLs were more active during congested periods. On weekdays, AVSLs were most active in the peak direction (AM for EB, PM for WB). AVSLs were not as active on weekends because of better flow. The magnitude of lowered advisory speed limits indicates the level of congestion on the roadway during each time of day.

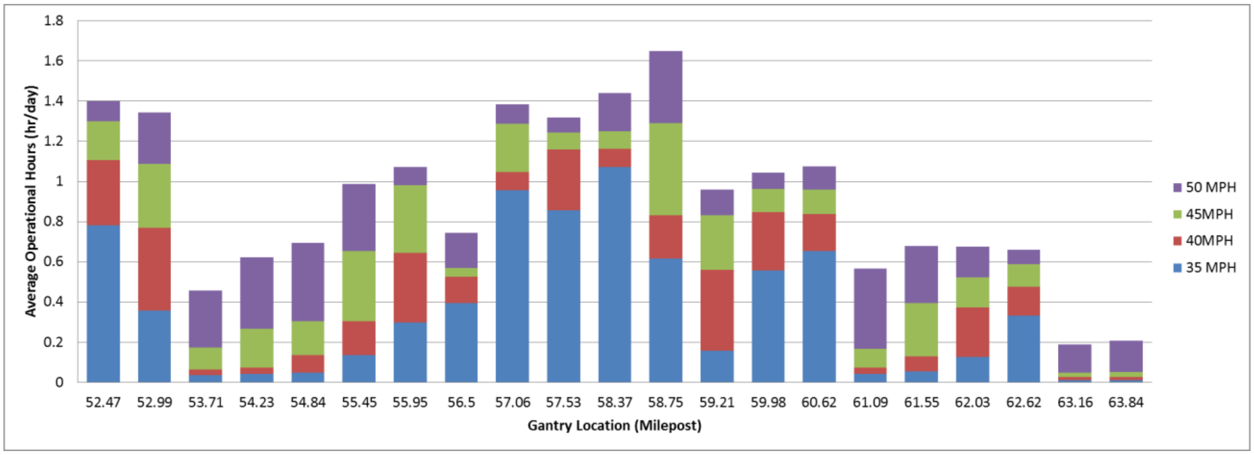


Figure 14. Eastbound AVSL Activation During Weekday AM Peak (5:30-11:00 AM). AVSL = Advisory Variable Speed Limit

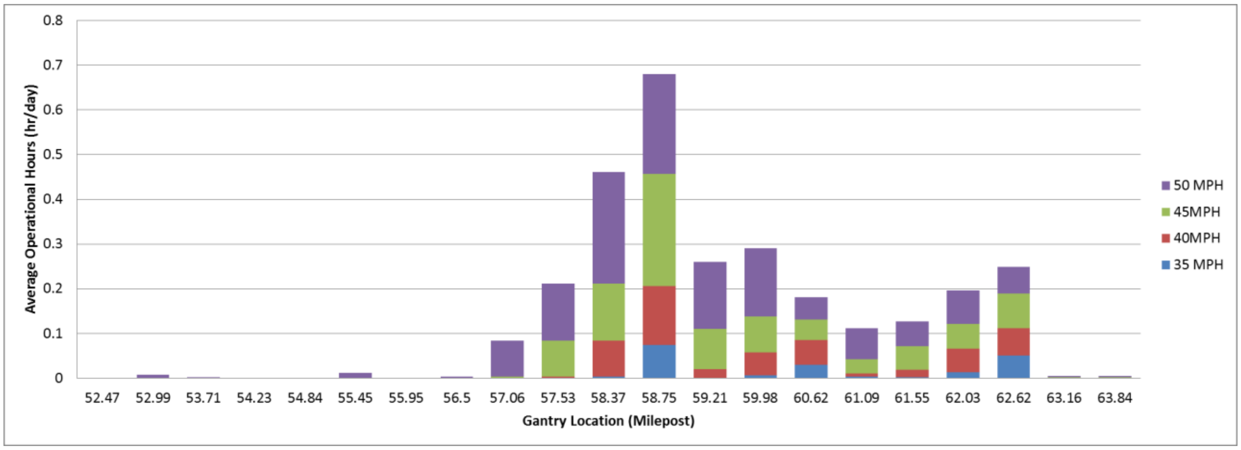


Figure 15. Eastbound AVSL Activation During Weekday Midday (11:00-2:00 PM). AVSL = Advisory Variable Speed Limit

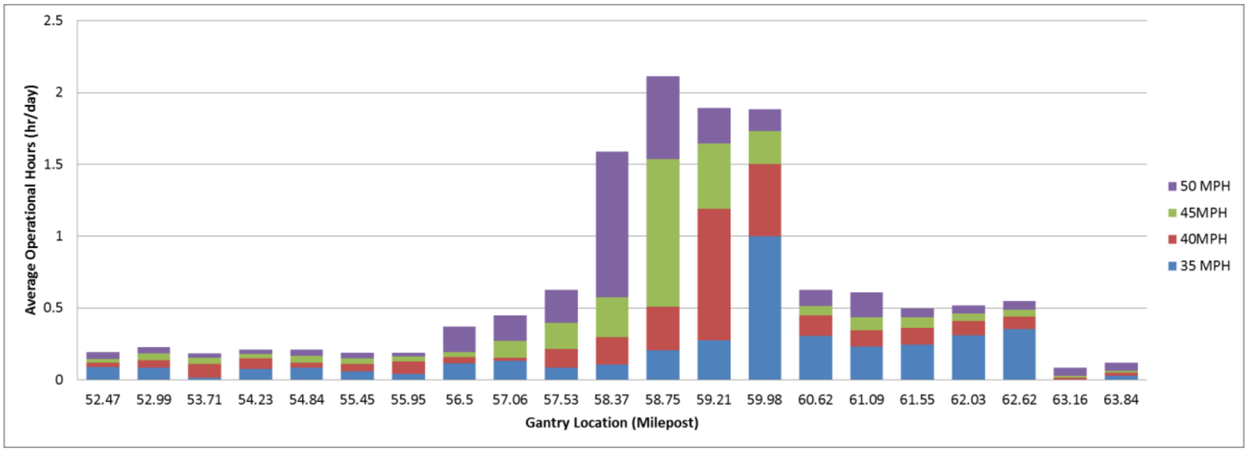


Figure 16. Eastbound AVSL Activation During Weekday PM Peak (2:00-8:00 PM). AVSL = Advisory Variable Speed Limit.

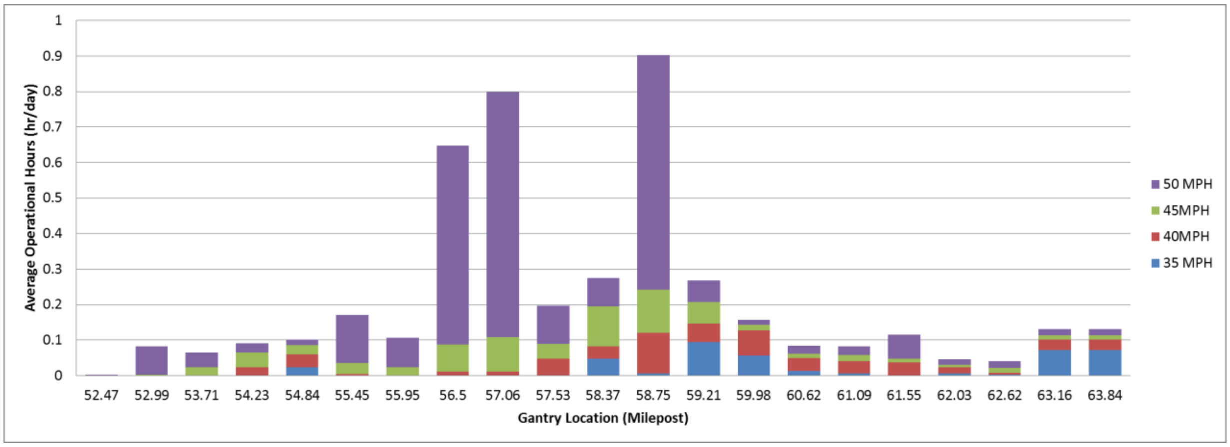


Figure 17. Eastbound AVSL Activation During Weekday Overnight (8:00 PM-5:30 AM). AVSL = Advisory Variable Speed Limit.

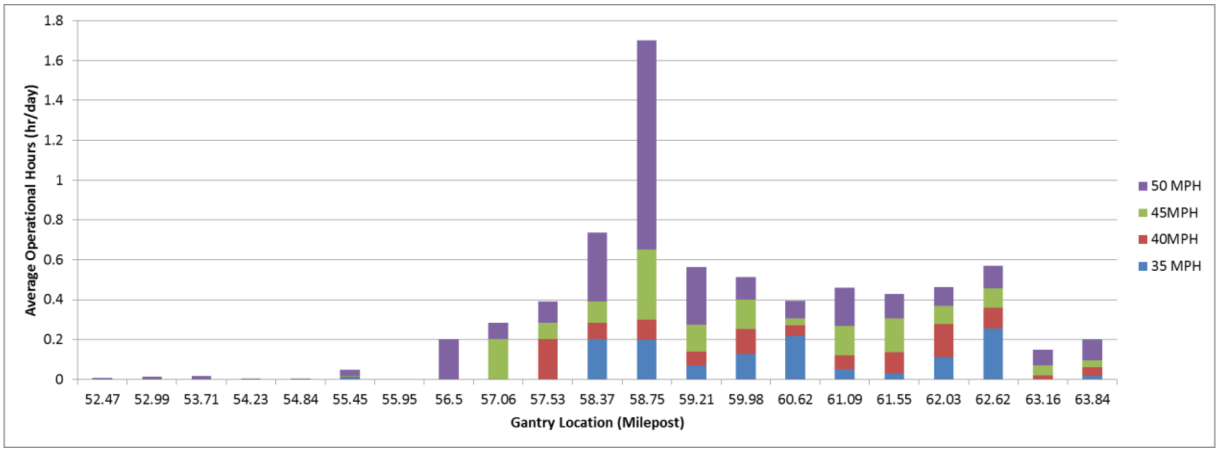


Figure 18. Eastbound AVSL Activation During Weekend Peak (10:00 AM-8:00 PM). AVSL = Advisory Variable Speed Limit.

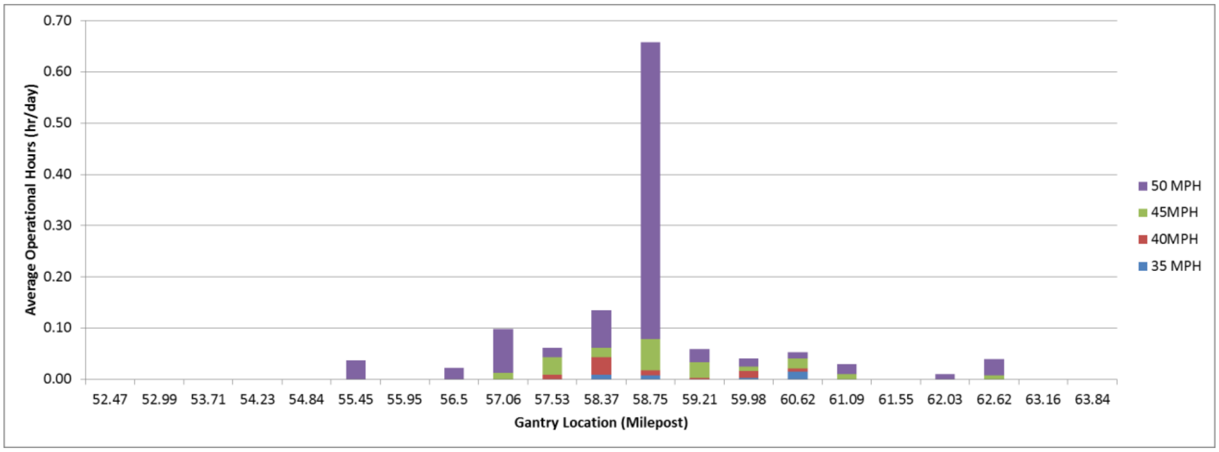


Figure 19. Eastbound AVSL Activation During Weekend Off-Peak (8:00 PM-10:00 AM). AVSL = Advisory Variable Speed Limit.

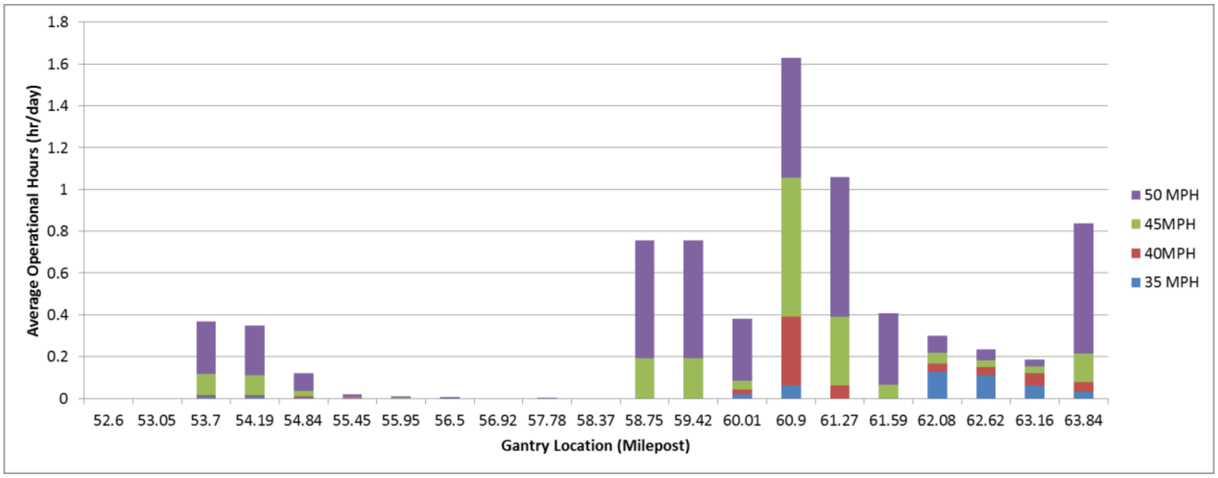


Figure 20. Westbound AVSL Activation During Weekday AM Peak (5:30-11:00 AM). AVSL = Advisory Variable Speed Limit.

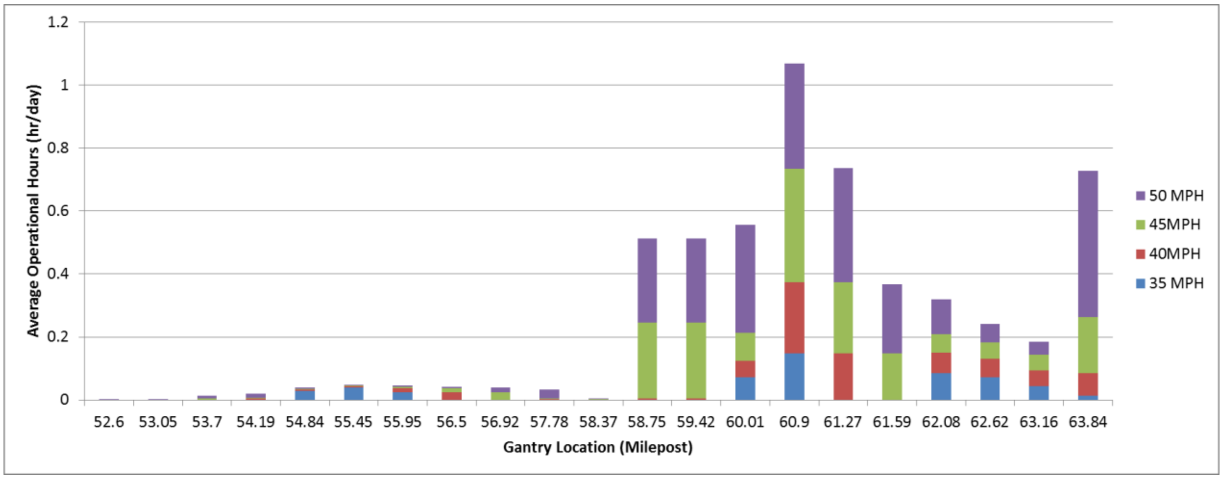


Figure 21. Westbound AVSL Activation During Weekday Midday (11:00 AM-2:00 PM). AVSL = Advisory Variable Speed Limit.

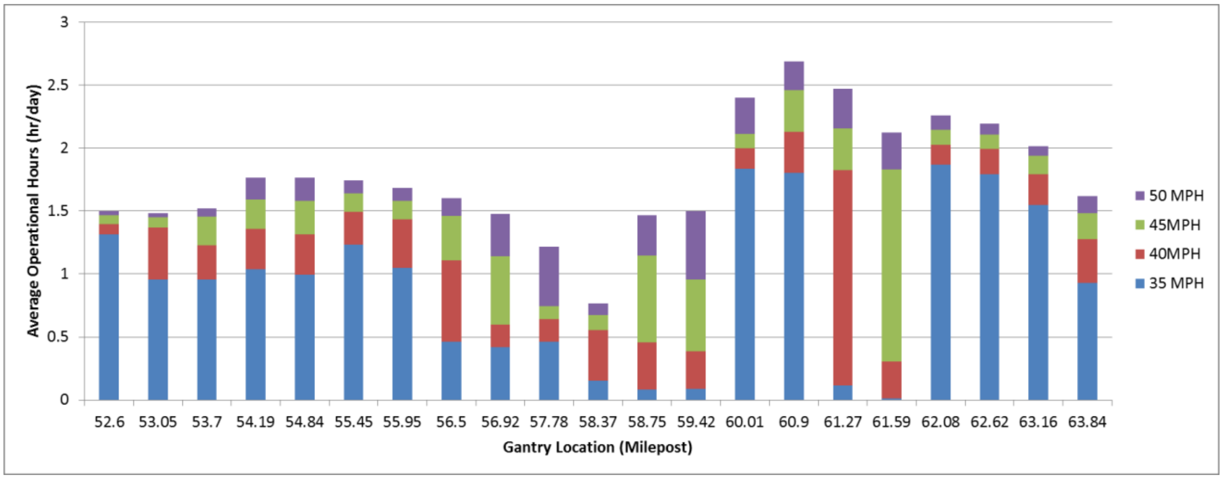


Figure 22. Westbound AVSL Activation During Weekday PM Peak (2:00-8:00 PM). AVSL = Advisory Variable Speed Limit.

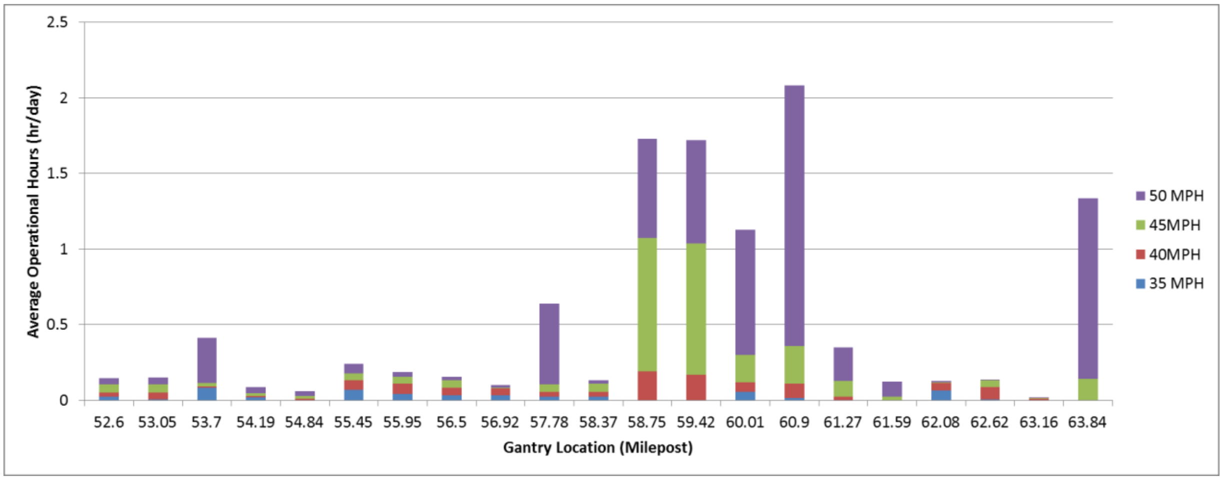


Figure 23. Westbound AVSL Activation During Weekday Overnight (8:00 PM-5:30 AM). AVSL = Advisory Variable Speed Limit.

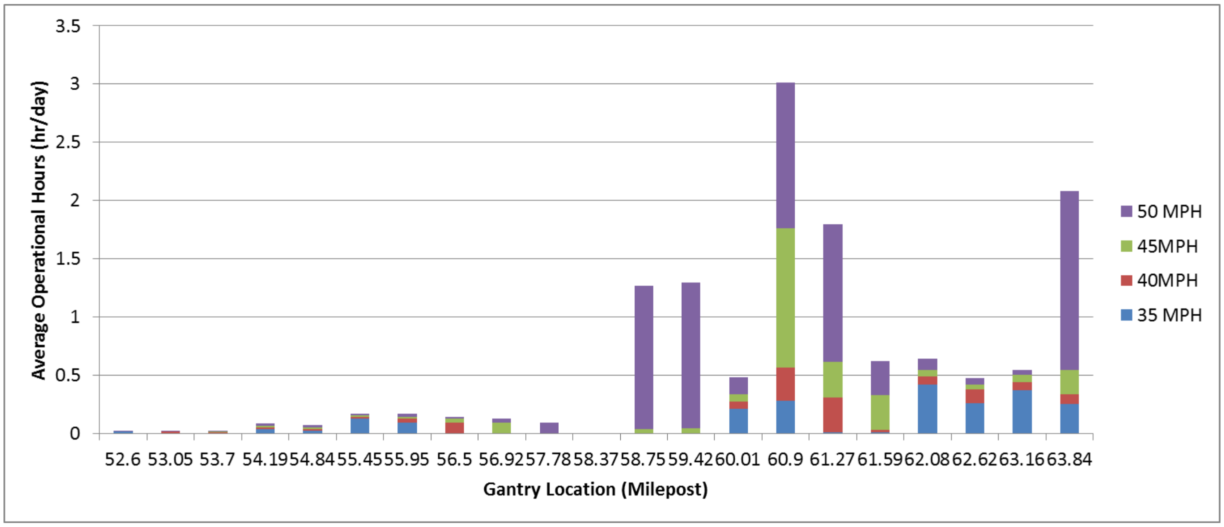


Figure 24. Westbound AVSL Activation During Weekend Peak (10:00 AM-8:00 PM). AVSL = Advisory Variable Speed Limit.

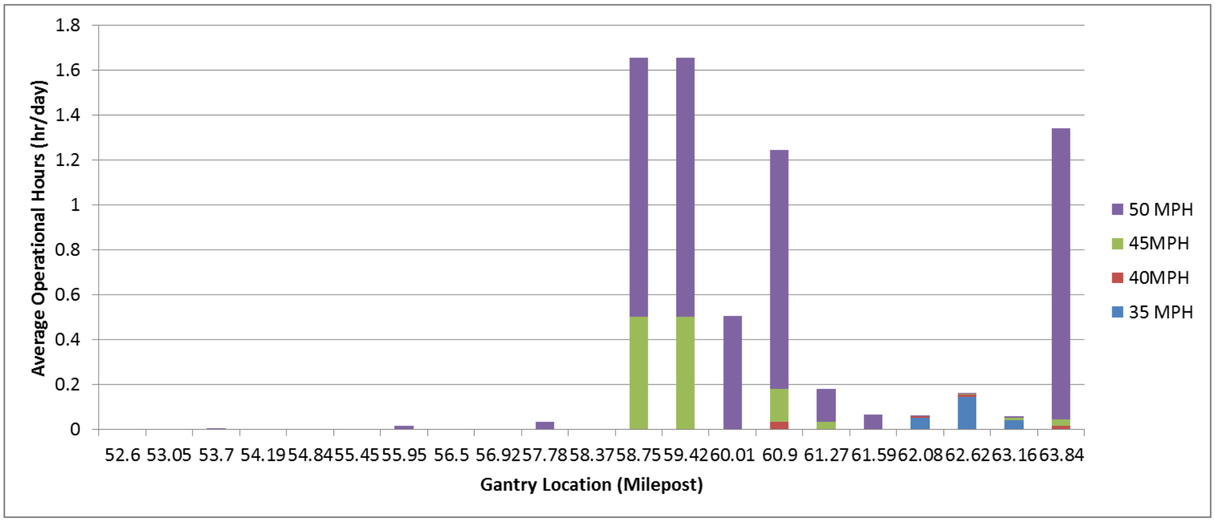


Figure 25. Westbound AVSL Activation During Weekend Off-Peak (8:00 PM-10:00 AM). AVSL = Advisory Variable Speed Limit.

Corridor-Level Utilization Analysis: LUCS

LUCSs were activated when there were lane blockages on the corridor because of incidents, crashes, or work zones. The LUCSs would show diagonal yellow arrow signs that were used to reroute the regular traffic into the open lanes from the blocked lanes. Red X indications were then used to indicate closed lanes. Since LUCSs are activated only when there is a problem on the roadway (e.g., disabled vehicle, crash, work zone), they do not activate as frequently as HSR or AVSL. The full LUCS utilization results are shown in Tables 12 through 15. In these tables, Lane 1 is the leftmost lane and Lane 4 is the rightmost lane. As expected, the total duration and frequency of LUCS activation for EB and WB weekday and weekend periods were low. Although the VDOT TOC operators have anecdotally indicated that the LUCSs have provided some incident management benefits, the LUCSs were not activated very frequently as compared to AVSL or HSR. As a result, it is difficult to assign specific benefits to these systems. A parallel study at VTRC is currently investigating the microscopic benefits of the LUCS in a more detailed manner.

Weekday Corridor-Level Average Travel Time Analysis

For weekday average travel times, there were small but statistically significant ($\alpha = 0.05$) degradations after ATM activation during the peak periods in the peak directions (AM for EB, PM for WB). For the EB AM peak period, weekday average travel times increased from 17.03 to 18.19 minutes (6.80% increase) and for the WB PM peak period, weekday average travel times increased from 21.65 to 22.54 minutes (4.12% increase). This trend was generally consistent across most days of the week (Monday-Friday). The increase in weekday average travel times during peak periods was not surprising, however. Peak period weekday average travel time profiles for both the EB and WB, shown in Figures 26 and 27, had been generally increasing during the 3 years before ATM installation. Since shoulder lanes were already open to travel before ATM activation, no capacity was added to the network when ATM was activated. Thus, it appears that travel times continued to degrade during the peak periods.

Table 12. EB Weekday Total Duration and Frequency of LUCS Activation

Gantry Milepost	Utilization of Sign in Lane 1		Utilization of Sign in Lane 2		Utilization of Sign in Lane 3		Utilization of Sign in Lane 4	
	Total Minutes	Total Count	Total Minutes	Total Count	Total Minutes	Total Count	Total Minutes	Total Count
52.47	14.85	1	15.88	1	0.00	0	2.32	1
52.99	0.00	0	1.03	1	24.12	1	43.15	1
53.71	0.00	0	0.00	0	51.00	1	61.22	2
54.23	14.52	1	0.00	0	31.20	4	147.83	6
54.84	38.80	2	21.10	2	0.00	0	0.00	0
55.45	21.33	1	0.00	0	2.55	1	7.28	2
55.95	29.18	4	3.97	1	5.23	2	9.28	4
56.5	35.52	3	0.00	0	2.80	2	2.80	2
57.06	29.40	3	19.80	3	1.60	1	0.00	0
57.53	128.75	5	37.37	1	73.65	3	131.78	3
58.37	4.47	1	28.75	4	49.95	4	125.22	9
58.75	80.73	4	96.73	6	72.88	5	146.98	8
59.21	232.48	10	75.25	8	58.50	6	135.87	11
59.98	86.37	4	38.50	4	0.00	0	17.87	4
60.62	15.33	2	38.80	3	312.50	6	157.95	11
61.09	55.48	5	41.23	4	296.53	4	350.10	17
61.55	14.97	2	8.95	1	52.03	4	64.10	4
62.03	72.05	3	1.87	2	22.20	6	16.58	4
62.62	2.38	2	37.25	4	49.63	5	18.30	3
63.16	0.12	1	47.82	5	190.02	10	416.42	13
63.84	0.35	2	11.08	4	11.20	4	74.63	2
Total	877.08	56	525.38	54	1307.60	69	1929.68	107

EB = eastbound; LUCS = lane use control signal.

Table 13. WB Weekday Total Duration and Frequency of LUCS Activation

Gantry Milepost	Utilization of Sign in Lane 1		Utilization of Sign in Lane 2		Utilization of Sign in Lane 3		Utilization of Sign in Lane 4	
	Total Minutes	Total Count	Total Minutes	Total Count	Total Minutes	Total Count	Total Minutes	Total Count
52.47	0.00	0	0.00	0	0.00	0	0.00	0
52.99	0.00	0	28.82	1	2.93	1	0.00	0
53.71	42.62	1	0.00	0	0.00	0	0.00	0
54.23	113.23	9	90.38	6	40.95	4	12.27	3
54.84	93.13	4	99.75	3	46.75	2	74.13	3
55.45	5.48	3	0.00	0	0.00	0	240.03	3
55.95	68.35	5	4.38	2	3.02	1	11.10	1
56.5	35.87	2	45.38	2	40.52	2	38.88	1
57.06	9.52	1	152.13	3	105.72	2	0.00	0
57.53	75.40	1	32.93	1	0.00	0	0.00	0
58.37	84.78	2	68.37	2	6.22	1	0.00	0
58.75	50.30	1	0.00	0	0.00	0	31.37	1
59.21	51.55	3	0.00	0	0.00	0	2.73	1
59.98	32.35	2	472.02	1	2.02	1	148.25	7
60.62	82.47	2	0.00	0	29.28	1	58.95	5
61.09	130.37	4	43.72	2	0.00	0	54.60	2
61.55	14.00	1	0.00	0	44.47	1	119.63	4
62.03	141.48	1	0.00	0	0.00	0	46.93	6
62.62	75.82	4	30.00	5	59.15	5	70.45	4
63.16	63.17	6	0.42	3	0.38	3	50.42	6
63.84	11.38	3	36.38	8	37.08	8	271.07	6
Total	1181.27	55	1104.68	39	418.48	32	1230.82	53

WB = westbound; LUCS = lane use control signal.

Table 14. EB Weekend Total Duration and Frequency of LUCS Activation

Gantry Milepost	Utilization of Sign in Lane 1		Utilization of Sign in Lane 2		Utilization of Sign in Lane 3		Utilization of Sign in Lane 4	
	Total Minutes	Total Count	Total Minutes	Total Count	Total Minutes	Total Count	Total Minutes	Total Count
52.47	0.00	0	29.93	1	42.20	1	67.17	1
52.99	0.00	0	0.00	0	0.00	0	4.77	1
53.71	0.00	0	0.00	0	0.00	0	46.47	3
54.23	0.00	0	0.00	0	0.93	1	36.37	1
54.84	0.00	0	0.00	0	32.95	1	32.95	1
55.45	0.00	0	0.00	0	32.95	1	0.00	0
55.95	0.00	0	0.00	0	0.00	0	0.33	1
56.5	0.00	0	0.00	0	0.00	0	42.52	1
57.06	0.00	0	0.00	0	0.00	0	0.00	0
57.53	0.00	0	0.00	0	0.00	0	0.00	0
58.37	0.00	0	0.00	0	0.00	0	46.23	2
58.75	9.47	1	0.00	0	65.25	1	0.00	0
59.21	2.07	1	0.00	0	0.00	0	1.12	1
59.98	9.62	2	10.30	2	4.37	1	0.00	0
60.62	7.83	1	0.00	0	0.00	0	0.00	0
61.09	44.28	1	71.45	2	84.57	4	75.85	4
61.55	3.07	1	26.45	1	40.12	3	20.92	4
62.03	11.22	1	25.90	1	25.90	1	7.32	1
62.62	84.30	1	147.75	2	0.00	0	0.00	0
63.16	0.00	0	0.00	0	0.00	0	89.68	2
63.84	0.00	0	0.00	0	0.00	0	0.00	0
Total	171.85	9	311.78	9	329.23	14	471.68	23

EB = eastbound; LUCS = lane use control signal.

Table 15. WB Weekend Total Duration and Frequency of LUCS Activation

Gantry Milepost	Utilization of Sign in Lane 1		Utilization of Sign in Lane 2		Utilization of Sign in Lane 3		Utilization of Sign in Lane 4	
	Total Minutes	Total Count	Total Minutes	Total Count	Total Minutes	Total Count	Total Minutes	Total Count
52.47	0.00	0	0.00	0	0.00	0	0.00	0
52.99	13.32	1	13.32	1	0.00	0	0.00	0
53.71	0.00	0	0.00	0	0.00	0	0.00	0
54.23	10.93	2	7.22	2	0.00	0	0.00	0
54.84	15.48	1	6.23	1	64.28	1	93.88	2
55.45	0.00	0	0.00	0	36.17	2	43.00	2
55.95	0.00	0	0.00	0	0.00	0	0.00	0
56.5	0.00	0	0.00	0	0.00	0	0.00	0
57.06	0.00	0	3.25	1	0.00	0	0.00	0
57.53	0.00	0	10.92	1	0.00	0	0.00	0
58.37	0.00	0	1.18	1	0.00	0	0.00	0
58.75	0.00	0	4.20	1	0.00	0	22.98	1
59.21	0.00	0	0.00	0	0.00	0	0.00	0
59.98	64.08	1	0.00	0	0.52	1	15.48	3
60.62	73.85	1	0.00	0	0.00	0	0.00	0
61.09	0.00	0	0.00	0	0.00	0	0.00	0
61.55	73.72	1	0.00	0	0.00	0	0.00	0
62.03	2.38	1	0.00	0	0.00	0	0.00	0
62.62	0.00	0	0.00	0	0.00	0	0.00	0
63.16	0.00	0	0.00	0	0.00	0	0.00	0
63.84	0.00	0	0.00	0	0.00	0	0.00	0
Total	253.77	8	46.32	8	100.97	4	175.35	8

WB = westbound; LUCS = lane use control signal.

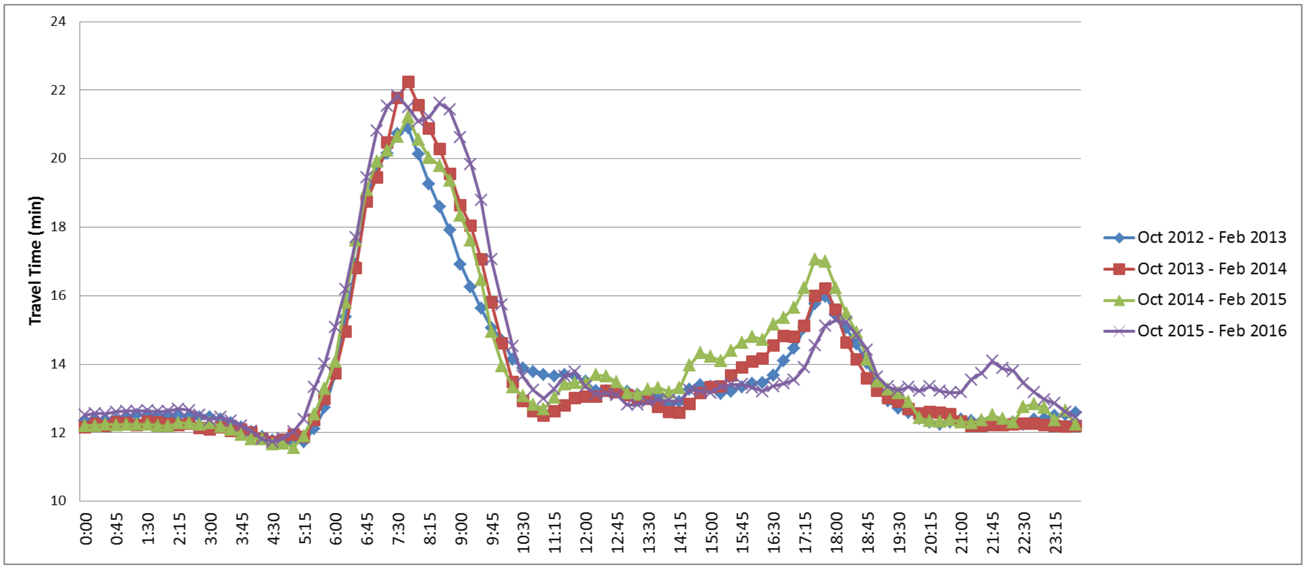


Figure 26. Eastbound Average Weekday Average Travel Time Trend (Corridor Level)

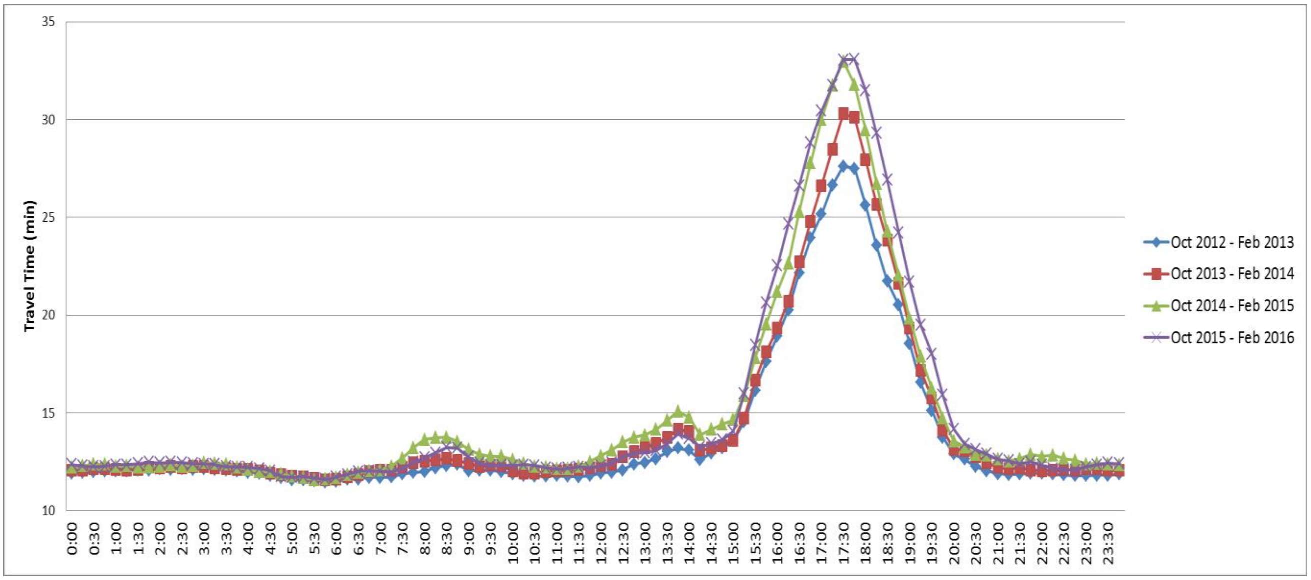


Figure 27. Westbound Average Weekday Average Travel Time Trend: Corridor Level

Table 16 shows the general increasing trend of the average travel times for average weekdays for several years before ATM implementation. The WB peak period average travel time trend showed continual increases in travel time. However, after ATM implementation, the rate of increase may have slowed. For the EB direction, the case for ATM improvements is not as strong since the average travel time change between October 2013-February 2014 and October 2014-February 2015 improved, possibly because the impact of the opening of the Metro Silver Line, which may have removed drivers from I-66 that previously accessed the Metro in Vienna.

Table 16. Weekday Average Travel Time Percent Changes for 2012-2016: Oct-Feb Only, Peak Directions

Direction	Oct 2012-Feb 2013 to Oct 2013-Feb 2014	Oct 2013-Feb 2014 to Oct 2014-Feb 2015	Oct 2014-Feb 2015 to Oct 2015-Feb 2016 (After ATM Activation)
EB Peak (AM)	+3.2%	-1.1%	+6.8%
WB Peak (PM)	+5.2%	+7.1%	+4.1%

EB = eastbound; WB = westbound.

Figures 28 and 29 show the before and after ATM EB and WB corridor-level average travel time profiles. The error bars represent the confidence interval of the average travel time values at the 95% confidence level. Reliability measures are discussed in more detail later.

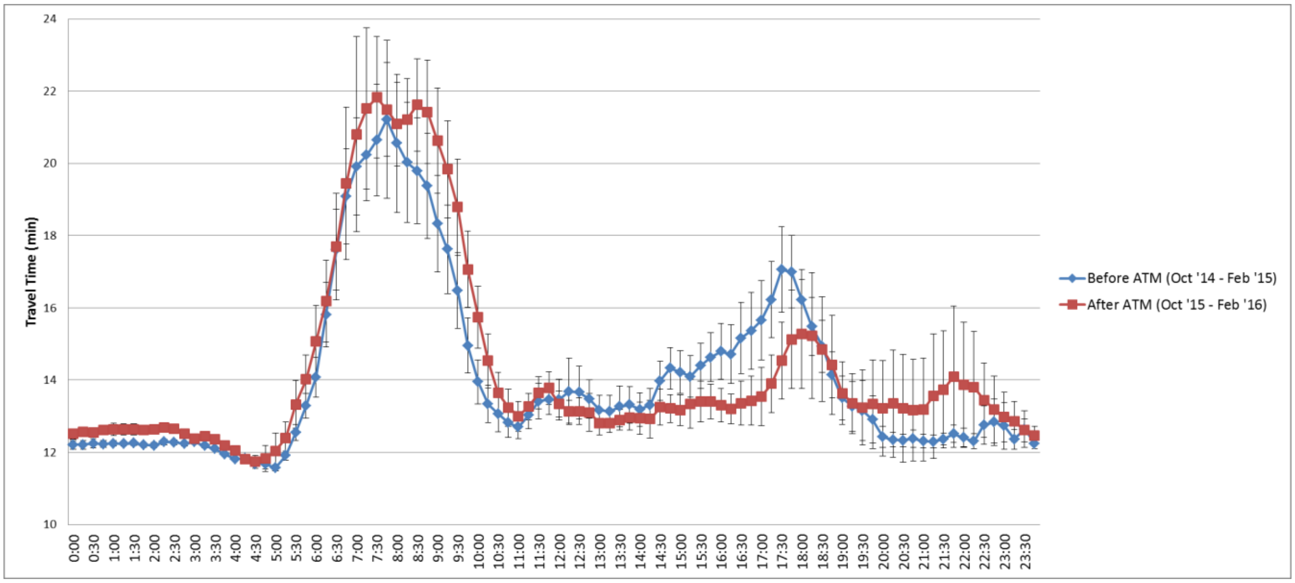


Figure 28. Eastbound Before and After Average Weekday Average Travel Time Profile: Corridor Level

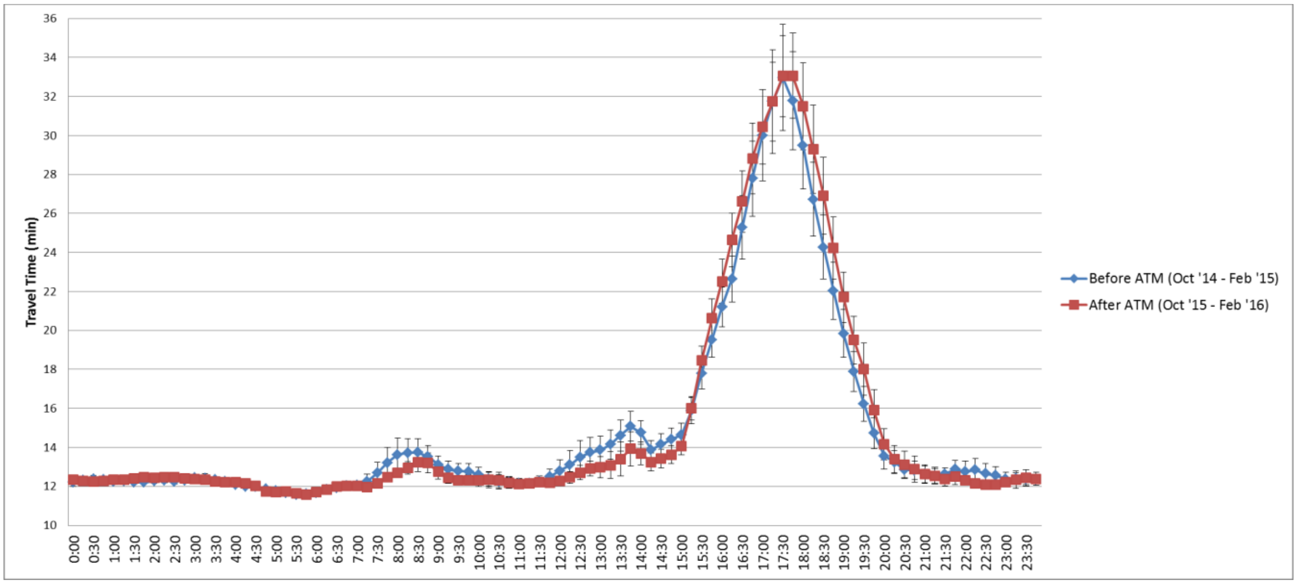


Figure 29. Westbound Before and After Average Weekday Average Travel Time Profile: Corridor Level

For the off-peak directions (PM for EB, AM for WB), there were statistically significant improvements in weekday average travel times even though the off-peak weekday average travel times for both directions had been increasing during the 3 years before ATM activation. For the EB PM off-peak period, weekday average travel times decreased from 14.66 to 13.73 minutes (6.35% improvement) and for the WB AM off-peak period, average weekday travel times decreased from 12.57 to 12.29 minutes (2.20% improvement). For the midday transition period, there were also small but statistically significant improvements in weekday average travel times in both directions. For the EB midday period, average weekday travel times decreased from 13.31 to 13.16 minutes (1.17% improvement), and for the WB midday period, average weekday travel times decreased from 13.33 to 12.70 minutes (4.66% improvement). Although these small improvements are likely not detectable by motorists, the accumulation of these benefits over time and all users can create aggregate system level benefits. For these off-peak and midday transition periods when the roadway was often not operating at maximum capacity, the dynamic opening of the shoulders may have contributed to faster travel times along the corridor and mitigated any incident and non-recurring congestion impacts. The improvements in weekday average travel times were generally consistent across weekdays for both off-peak and midday transition periods. Once again, the reductions in the weekday average travel times in the off-peak and midday periods represented a reversal from the year-over-year increases in the 3 years before ATM activation.

The weekday average travel time changes during the overnight period were negligible as average travel times were free flow for both the before and after conditions. The full average weekday average travel times are shown in Tables 17 and 18.

Weekend Corridor-Level Average Travel Time Analysis

ATM impacts were more pronounced on the weekends than on weekdays. Table 19 shows that for both the EB and WB weekend peak periods, there were statistically significant improvements in travel times. For the EB direction, the weekend average travel times were reduced from 14.53 to 13.06 minutes (10.13% improvement). In the WB direction, the average weekend travel times were reduced from 13.71 to 12.25 minutes (10.66% improvement). Both improvements were statistically significant. As mentioned previously, before ATM implementation, shoulders were not used during the weekend. However, after ATM implementation, shoulders were opened for travel whenever demands for additional capacity were warranted. This additional roadway capacity brought on by HSR likely contributed to the improvements in travel times along the corridor. After ATM implementation, for both EB and WB, the travel times often approached free flow during the weekend peak period. These improved trends can be seen from the yearly weekend average travel time profiles shown in Figures 30 and 31. The improvements in weekend average travel times were consistent across the weekend days for both the peak and off-peak periods. The weekend average travel time changes during the overnight off-peak period were negligible, as average travel times were already free flow for both the before and after conditions.

Table 17. Weekday Before-and-After Average Travel Time Comparisons: Entire Corridor AM and PM Peaks

Direction	Average Travel Time (min)										
	Day	**AM Peak Period Oct 2014-Feb 2015**	**AM Peak Period Oct 2015-Feb 2016**	**Change in AM Peak Period (min)**	**Change in AM Peak Period (%)**	**Statistical Significance at α = 0.05**	**PM Peak Period Oct 2014-Feb 2015**	**PM Peak Period Oct 2015-Feb 2016**	**Change in PM Peak Period (min)**	**Change in PM Peak Period (%)**	**Statistical Significance at α = 0.05**
EB	Mon	16.370	17.068	+0.698	+4.264	Sig (<0.05)	14.873	13.848	-1.025	-6.892	Sig (<0.05)
	Tues	18.176	20.178	+2.002	+11.015	Sig (<0.05)	14.084	13.119	-0.965	-6.852	Sig (<0.05)
	Wed	17.620	18.806	+1.186	+6.731	Sig (<0.05)	13.718	14.911	+1.193	+8.697	Sig (<0.05)
	Thur	18.751	19.855	+1.104	+5.888	Sig (<0.05)	15.001	13.105	-1.896	-12.639	Sig (<0.05)
	Fri	14.316	14.959	+0.643	+4.491	Sig (<0.05)	15.580	13.663	-1.917	-12.304	Sig (<0.05)
	Average	17.034	18.192	+1.158	+6.798	Sig (<0.05)	14.656	13.725	-0.931	-6.352	Sig (<0.05)
WB	Mon	12.331	12.282	-0.049	-0.397	Not Sig (0.324)	20.392	22.194	+1.802	+8.837	Sig (<0.05)
	Tues	13.118	12.415	-0.703	-5.359	Sig (<0.05)	20.202	22.538	+2.336	+11.563	Sig (<0.05)
	Wed	12.868	12.340	-0.528	-4.103	Sig (<0.05)	21.773	23.028	+1.255	+5.764	Sig (<0.05)
	Thur	12.454	12.193	-0.261	-2.096	Sig (<0.05)	23.227	22.769	-0.458	-1.972	Not Sig (0.155)
	Fri	12.095	12.220	+0.125	+1.033	Not Sig (0.094)	22.624	22.179	-0.445	-1.967	Not Sig (0.137)
	Average	12.567	12.290	-0.277	-2.204	Sig (<0.05)	21.653	22.544	+0.891	+4.115	Sig (<0.05)

AM Peak Period = 5:30-11:00 AM; PM Peak Period = 2-8 PM; EB = eastbound; WB = westbound; Sig = significant.

Table 18. Weekday Before-and-After Average Travel Time Comparisons: Entire Corridor Midday and Overnight Periods

	Average Travel Times (min)									
Direction	**Day**	**Midday Period Oct 2014-Feb 2015**	**Midday Period Oct 2015-Feb 2016**	**Change in Midday Period (min)**	**Change in Midday Period (%)**	**Statistical Significance at α = 0.05**	**Over-night Period Oct 2014-Feb 2015**	**Over-night Period Oct 2015-Feb 2016**	**Change in Over-night Period (min)**	**Change in Over-night Period (%)**	**Statistical Significance at α = 0.05**
EB	Mon	14.093	12.946	-1.147	-8.139	Sig (<0.05)	12.240	12.476	+0.236	+1.928	Sig (<0.05)
	Tues	13.039	13.050	+0.011	+0.084	Not Sig (0.393)	12.194	12.777	+0.583	+4.781	Sig (<0.05)
	Wed	12.788	13.380	+0.592	+4.629	Sig (<0.05)	12.174	13.583	+1.409	+11.574	Sig (<0.05)
	Thur	13.766	13.410	-0.356	-2.586	Not Sig (0.085)	12.283	12.593	+0.310	+2.524	Sig (<0.05)
	Fri	12.862	12.987	+0.125	+0.972	Not Sig (0.166)	12.283	12.395	+0.112	+0.912	Not Sig (0.128)
	Average	13.312	13.156	-0.156	-1.172	Sig (<0.05)	12.238	12.768	+0.530	+4.331	Sig (<0.05)
WB	Mon	12.554	12.459	-0.095	-0.757	Not Sig (0.329)	12.363	12.292	-0.071	-0.574	Sig (<0.05)
	Tues	13.390	12.512	-0.878	-6.557	Sig (<0.05)	12.483	12.450	-0.033	-0.264	Not Sig (0.205)
	Wed	14.361	12.503	-1.858	-12.938	Sig (<0.05)	12.240	12.589	+0.349	+2.851	Sig (<0.05)
	Thur	12.466	12.873	+0.407	+3.265	Sig (<0.05)	12.556	12.380	-0.176	-1.402	Sig (<0.05)
	Fri	13.853	13.193	-0.660	-4.764	Sig (<0.05)	12.399	12.250	-0.149	-1.202	Sig (<0.05)
	Average	13.325	12.704	-0.621	-4.660	Sig (<0.05)	12.410	12.390	-0.020	-0.161	Not Sig (0.202)

Midday Period = 11 AM-2 PM; Overnight Period = 8:00 PM-5:30 AM; EB = eastbound; WB = westbound; Sig = significant.

Table 19. Weekend Before-and-After Average Travel Time Comparisons: Entire Corridor Peak and Off-Peak Periods

Direction	Average Travel Times (min)										
	Day	**Peak Period Oct 2014-Feb 2015**	**Peak Period Oct 2015-Feb 2016**	**Change in Peak Period (min)**	**Change in Peak Period (%)**	**Statistical Significance at α = 0.05**	**Off-Peak Period Oct 2014-Feb 2015**	**Off-Peak Period Oct 2015-Feb 2016**	**Change in Off-Peak Period (min)**	**Change in Off-Peak Period (%)**	**Statistical Significance at α = 0.05**
EB	Sun	13.617	12.663	-0.954	-7.006	Sig (<0.05)	12.068	12.351	+0.283	+2.345	Sig (<0.05)
	Sat	15.487	13.481	-2.006	-12.953	Sig (<0.05)	12.128	12.227	+0.099	+0.816	Sig (<0.05)
	Average	14.534	13.062	-1.472	-10.128	Sig (<0.05)	12.098	12.287	+0.189	+1.562	Sig (<0.05)
WB	Sun	12.460	11.971	-0.489	-3.925	Sig (<0.05)	12.000	12.076	+0.076	+0.633	Not Sig (0.115)
	Sat	14.991	12.544	-2.447	-16.323	Sig (<0.05)	11.988	12.043	+0.055	+0.459	Sig (<0.05)
	Average	13.710	12.249	-1.461	-10.656	Sig (<0.05)	11.995	12.055	+0.060	+0.500	Sig (<0.05)

Peak Period = 10 AM-8 PM; Off-Peak Period = 8:00 PM-10:00 AM; EB = eastbound; WB = westbound; Sig = significant.

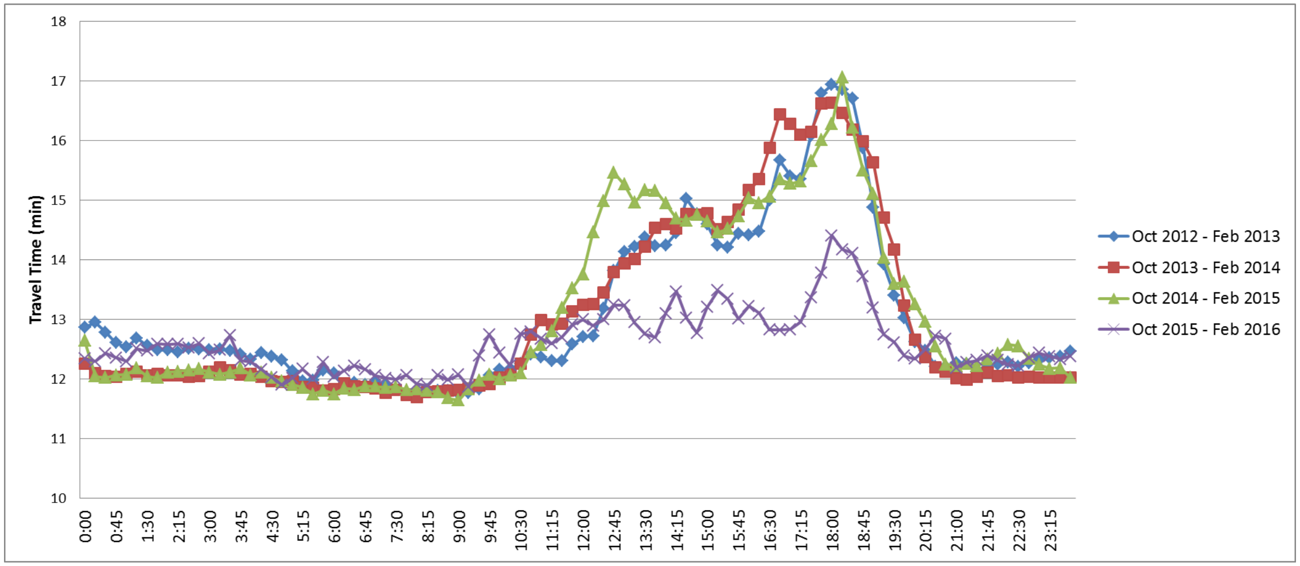


Figure 30. Eastbound Average Weekend Average Travel Time Trend: Entire Corridor

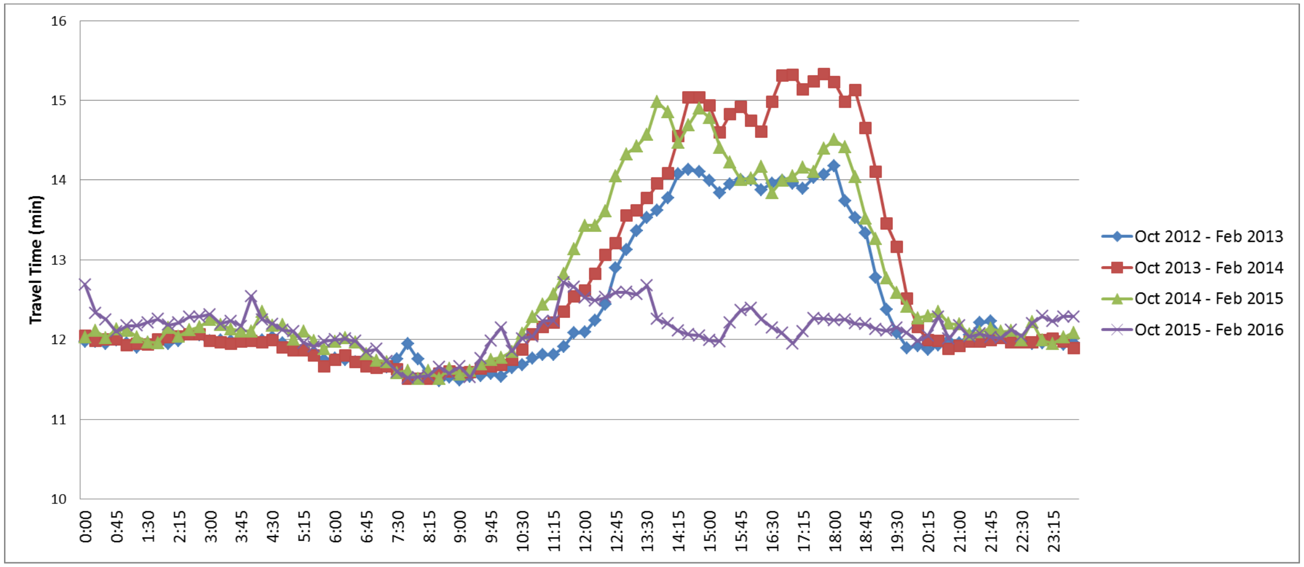


Figure 31. Westbound Average Weekend Average Travel Time Trend: Entire Corridor

Figures 32 and 33 show the corridor-level travel time profiles for an average weekend day for the before and after ATM periods. The error bars represent the confidence interval of the average travel time values at the 95% confidence level. The confidence intervals tightened during the average weekday conditions after ATM implementation, which indicates less variance in travel times and more reliable trips. This is discussed in more detail later.

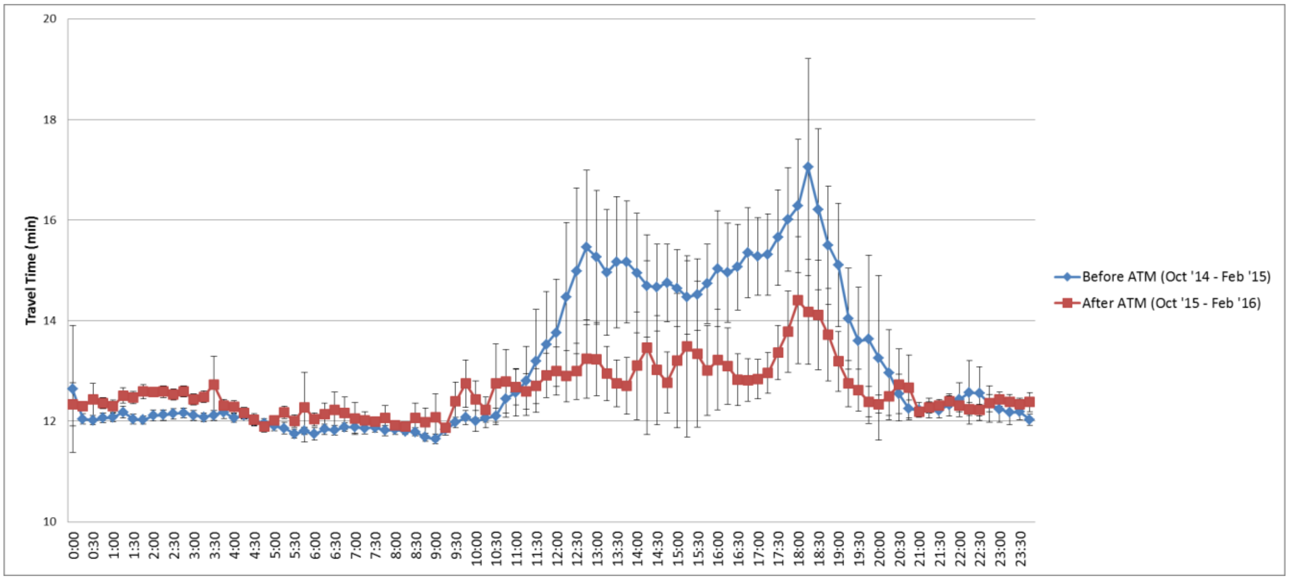


Figure 32. Eastbound Before-and-After Average Weekend Average Travel Time Profile: Entire Corridor

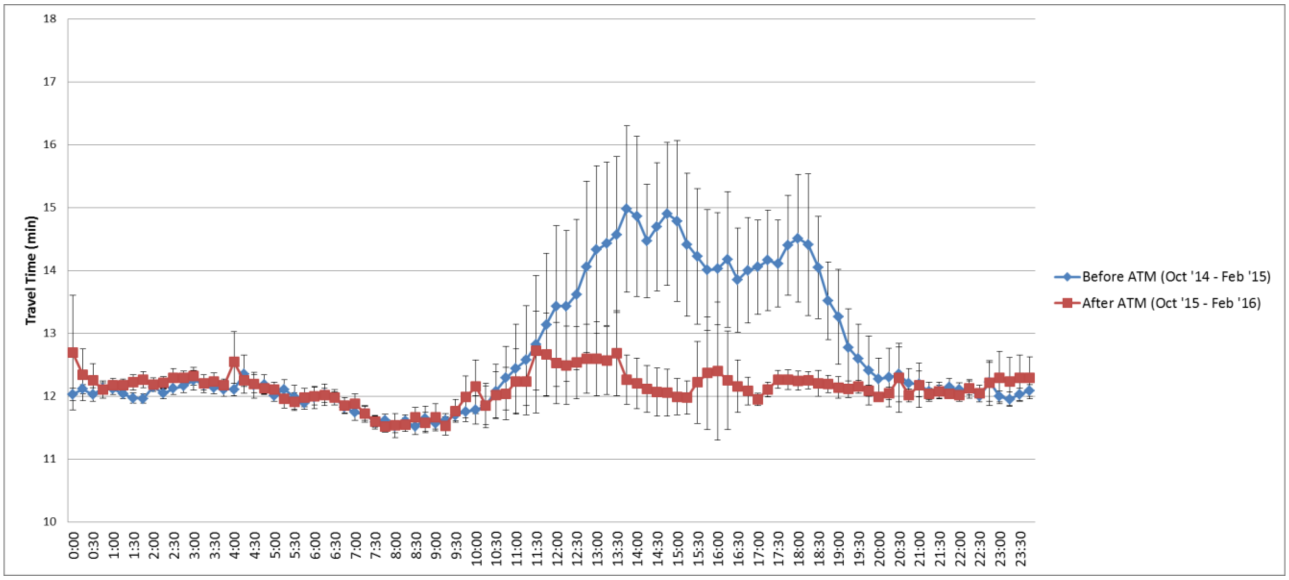


Figure 33. Westbound Before-and-After Average Weekend Average Travel Time Profile: Entire Corridor

Weekday Corridor-Level Travel Time Reliability Analysis

The travel time reliability results were similar to the average travel time results for the respective peak, midday, off-peak, and overnight periods. For the EB AM peak period, average weekday PTI and BI worsened by 0.10 (7.48%) and 0.01 (13.33%), respectively. For the WB PM peak period, average weekday PTI and BI worsened by 0.07 (3.81%) and <0.01 (3.45%), respectively. The changes, although relatively small, were statistically significant ($\alpha = 0.05$). This trend was consistent across most days of the week. These results mirror the trends in average travel time. Again, since HSR was already in use in the before period during the peak periods, there was no capacity added during these times after ATM activation. Conditions continued to deteriorate during the peak periods.

Generally, there were statistically significant improvements in PTI and BI for the off-peak directions (PM for EB, AM for WB). For the EB PM off-peak period, average weekday PTI improved by 0.06 (5.45%) but average weekday BI deteriorated by 0.01 (17.65%). The deterioration in BI was a result of the mean travel time improving at a higher rate than the 95th percentile travel time, although both were reduced from the before period. This is a known limitation of the BI metric. For the WB AM off-peak period, average weekday PTI and BI improved by 0.03 (3.33%) and 0.01 (36.67%), respectively.

For the midday transition period, there were also small but statistically significant improvements in average PTI and BI. For the EB midday period, average weekday PTI and BI improved by 0.02 (2.25%) and 0.01 (28.21%), respectively. For the WB midday period, average weekday PTI and BI improved by 0.06 (5.62%) and 0.01 (25.00%), respectively.

The magnitudes of the off-peak and midday travel time reliability changes were minimal or practically insignificant as the PTI values were close to 1 or less than 1 during these time periods for both EB and WB. The average weekday PTI and BI changes during the overnight period were negligible, as average travel times were free flow–like for both the before and after conditions. The full average weekday PTI and BI results and trends are shown in Tables 20 through 23.

Table 20. Weekday Before-and-After Average PTI Comparisons: Entire Corridor AM and PM Peak Periods

Direction	Day	AM Peak Period Oct 2014-Feb 2015	AM Peak Period Oct 2015-Feb 2016	Change in AM Peak Period (min)	Change in AM Peak Period (%)	Statistical Significance at α = 0.05	PM Peak Period Oct 2014-Feb 2015	PM Peak Period Oct 2015-Feb 2016	Change in PM Peak Period (min)	Change in PM Peak Period (%)	Statistical Significance at α = 0.05
EB	Mon	1.357	1.394	+0.037	+2.727	Sig (<0.05)	1.254	1.147	-0.107	-8.533	Sig (<0.05)
	Tues	1.534	1.748	+0.214	+13.950	Sig (<0.05)	1.115	1.035	-0.080	-7.175	Sig (<0.05)
	Wed	1.446	1.574	+0.128	+8.852	Sig (<0.05)	1.078	1.312	+0.234	+21.707	Sig (<0.05)
	Thur	1.648	1.732	+0.084	+5.097	Not Sig (0.140)	1.276	1.046	-0.230	-18.025	Sig (<0.05)
	Fri	1.133	1.197	+0.064	+5.649	Sig (<0.05)	1.269	1.146	-0.123	-9.693	Sig (<0.05)
	Average	1.337	1.437	+0.100	+7.479	Sig (<0.05)	1.138	1.076	-0.062	-5.448	Sig (<0.05)
WB	Mon	0.956	0.958	+0.002	+0.209	Not Sig (0.357)	1.705	1.918	+0.213	+12.493	Sig (<0.05)
	Tues	1.075	0.959	-0.116	-10.791	Sig (<0.05)	1.709	1.872	+0.163	+9.538	Sig (<0.05)
	Wed	1.036	0.948	-0.088	-8.494	Sig (<0.05)	1.856	1.936	+0.080	+4.310	Sig (<0.05)
	Thur	0.967	0.928	-0.039	-4.033	Sig (<0.05)	1.988	1.915	-0.073	-3.672	Sig (<0.05)
	Fri	0.923	0.946	+0.023	+2.492	Not Sig (0.071)	1.919	1.864	-0.055	-2.866	Not Sig (0.079)
	Average	0.962	0.930	-0.032	-3.326	Sig (<0.05)	1.708	1.773	+0.065	+3.806	Sig (<0.05)

PTI = planning time index; AM Peak Period = 5:30-11:00 AM; PM Peak Period = 2-8 PM; EB = eastbound; WB = westbound; Sig = significant.

Table 21. Weekday Before-and-After Average BI Comparisons: Entire Corridor AM and PM Peak Periods

Direction	Day	AM Peak Period Oct 2014-Feb 2015	AM Peak Period Oct 2015-Feb 2016	Change in AM Peak Period (min)	Change in AM Peak Period (%)	Statistical Significance at $\alpha = 0.05$	PM Peak Period Oct 2014-Feb 2015	PM Peak Period Oct 2015-Feb 2016	Change in PM Peak Period (min)	Change in PM Peak Period (%)	Statistical Significance at $\alpha = 0.05$
EB	Mon	0.116	0.101	-0.015	-12.931	Sig (<0.05)	0.140	0.117	-0.023	-16.429	Not Sig (0.078)
	Tues	0.138	0.171	+0.033	+23.913	Sig (<0.05)	0.070	0.068	-0.002	-2.857	Not Sig (0.396)
	Wed	0.107	0.133	+0.026	+24.299	Sig (<0.05)	0.063	0.183	+0.120	+190.48	Sig (<0.05)
	Thur	0.174	0.164	-0.010	-5.747	Not Sig (0.362)	0.145	0.080	-0.065	-44.828	Sig (<0.05)
	Fri	0.066	0.081	+0.015	+22.727	Sig (<0.05)	0.103	0.127	+0.024	+23.301	Not Sig (0.054)
	Average	0.060	0.068	+0.008	+13.333	Not Sig (0.078)	0.051	0.060	+0.009	+17.647	Sig (<0.05)
WB	Mon	0.043	0.050	+0.007	+16.279	Not Sig (0.061)	0.122	0.149	+0.027	+22.131	Sig (<0.05)
	Tues	0.101	0.038	-0.063	-62.376	Sig (<0.05)	0.128	0.114	-0.014	-10.938	Sig (<0.05)
	Wed	0.080	0.034	-0.046	-57.500	Sig (<0.05)	0.140	0.132	-0.008	-5.714	Not Sig (0.212)
	Thur	0.044	0.025	-0.019	-43.182	Sig (<0.05)	0.136	0.120	-0.016	-11.765	Sig (<0.05)
	Fri	0.027	0.041	+0.014	+51.852	Not Sig (0.055)	0.133	0.120	-0.013	-9.774	Sig (<0.05)
	Average	0.030	0.019	-0.011	-36.667	Sig (<0.05)	0.058	0.056	-0.002	-3.448	Not Sig (0.136)

BI = buffer index; AM Peak Period = 5:30-11:00 AM; PM Peak Period = 2-8 PM; EB = eastbound; WB = westbound; Sig = significant.

Table 22. Weekday Before-and-After Average PTI Comparisons: Entire Corridor Midday and Overnight Periods

Direction	Day	Midday Period Oct 2014-Feb 2015	Midday Period Oct 2015-Feb 2016	Change in Midday Period (min)	Change in Midday Period (%)	Statistical Significance at α = 0.05	Over-night Period Oct 2014-Feb 2015	Over-night Period Oct 2015-Feb 2016	Change in Over-night Period (min)	Change in Over-night Period (%)	Statistical Significance at α = 0.05
EB	Mon	1.176	1.009	-0.167	-14.201	Sig (<0.05)	0.927	0.950	+0.023	+2.481	Sig (<0.05)
	Tues	1.020	1.030	+0.010	+0.980	Not Sig (0.255)	0.920	1.004	+0.084	+9.130	Sig (<0.05)
	Wed	0.984	1.062	+0.078	+7.927	Sig (<0.05)	0.914	1.200	+0.286	+31.291	Sig (<0.05)
	Thur	1.130	1.057	-0.073	-6.460	Sig (<0.05)	0.933	0.980	+0.047	+5.038	Sig (<0.05)
	Fri	0.985	0.999	+0.014	+1.421	Not Sig (0.223)	0.942	0.948	+0.006	+0.637	Not Sig (0.381)
	Average	1.022	0.999	-0.023	-2.250	Sig (<0.05)	0.917	0.987	+0.070	+7.634	Sig (<0.05)
WB	Mon	0.999	0.983	-0.016	-1.602	Not Sig (0.246)	0.954	0.939	-0.015	-1.572	Not Sig (0.107)
	Tues	1.094	0.971	-0.123	-11.243	Sig (<0.05)	0.972	0.964	-0.008	-0.823	Not Sig (0.201)
	Wed	1.235	0.963	-0.272	-22.024	Sig (<0.05)	0.934	0.989	+0.055	+5.889	Sig (<0.05)
	Thur	0.965	1.020	+0.055	+5.699	Sig (<0.05)	0.978	0.959	-0.019	-1.943	Not Sig (0.151)
	Fri	1.094	1.094	0.000	0.000	Not Sig (0.481)	0.961	0.934	-0.027	-2.810	Sig (<0.05)
	Average	1.033	0.975	-0.058	-5.615	Sig (<0.05)	0.940	0.939	-0.001	-0.106	Not Sig (0.380)

PTI = planning time index; Midday Period = 11 AM-2 PM; Overnight Period = 8:00 PM-5:30 AM; EB = eastbound; WB = westbound; Sig = significant.

Table 23. Weekday Before-and-After Average BI Comparisons: Entire Corridor Midday and Overnight Periods

Direction	Day	Midday Period Oct 2014-Feb 2015	Midday Period Oct 2015-Feb 2016	Change in Midday Period (min)	Change in Midday Period (%)	Statistical Significance at α = 0.05	Overnight Period Oct 2014-Feb 2015	Overnight Period Oct 2015-Feb 2016	Change in Overnight Period (min)	Change in Overnight Period (%)	Statistical Significance at α = 0.05
EB	Mon	0.127	0.055	-0.072	-56.693	Sig (<0.05)	0.026	0.031	+0.005	+19.231	Not Sig (0.104)
	Tues	0.059	0.069	+0.010	+16.949	Not Sig (0.132)	0.021	0.060	+0.039	+185.714	Sig (<0.05)
	Wed	0.042	0.074	+0.032	+76.190	Sig (<0.05)	0.017	0.175	+0.158	+929.412	Sig (<0.05)
	Thur	0.111	0.067	-0.044	-39.640	Sig (<0.05)	0.028	0.051	+0.023	+82.143	Sig (<0.05)
	Fri	0.037	0.041	+0.004	+10.811	Not Sig (0.147)	0.036	0.033	-0.003	-8.333	Not Sig (0.403)
	Average	0.039	0.028	-0.011	-28.205	Sig (<0.05)	0.014	0.046	+0.032	+228.571	Sig (<0.05)
WB	Mon	0.069	0.062	-0.007	-10.145	Not Sig (0.305)	0.038	0.028	-0.010	-26.316	Not Sig (0.089)
	Tues	0.100	0.044	-0.056	-56.000	Sig (<0.05)	0.048	0.041	-0.007	-14.583	Not Sig (0.104)
	Wed	0.154	0.037	-0.117	-75.974	Sig (<0.05)	0.027	0.055	+0.028	+103.704	Sig (<0.05)
	Thur	0.041	0.067	+0.026	+63.415	Sig (<0.05)	0.047	0.042	-0.005	-10.638	Not Sig (0.340)
	Fri	0.061	0.111	+0.050	+81.967	Sig (<0.05)	0.043	0.027	-0.016	-37.209	Sig (<0.05)
	Average	0.044	0.033	-0.011	-25.000	Sig (<0.05)	0.020	0.020	0.000	0.000	Not Sig (0.460)

BI = buffer index; AM Peak Period = 5:30-11:00 AM; PM Peak Period = 2-8 PM; EB = eastbound; WB = westbound; Sig = significant.

Weekend Corridor-Level Travel Time Reliability Analysis

The travel time reliability for the weekend peak period improved the most of all periods for both directions. In the EB direction, the average peak period PTI and BI improved by 0.13 (11.32%) and .01 (19.12%), respectively. In the WB direction, the average peak period PTI and BI improved by 0.15 (13.62%) and 0.03 (50.75%), respectively. All of these improvements were statistically significant. The average weekend PTIs were reduced from above 1 to close to or less than 1, which indicates that the 95th percentile travel time approaches free-flow conditions. The average weekend PTI and BI changes during the overnight off-peak period were negligible since average travel times were already approaching free flow for both the before and after conditions. The full average weekend PTI and BI results are shown in Tables 24 and 25.

Corridor-Level Total Traveler Delay Analysis

Next, an estimated total delay measure was computed. The components required to calculate travel delay were the yearly AADT and average 15-minute volume distributions. Data from October-February were used for the before and after periods to define average delay changes on weekdays and weekends. Since the 2016 AADT was not yet available, AADT growth rates from 2014-2015 were used to estimate a 2016 AADT, and the calculation results are shown in Table 26. The weekday weighted average growth rate was 3.92% and 2.86% for EB and WB, respectively. The weekend weighted average growth rate by length of segment was 4.13% and 1.59% for EB and WB, respectively.

The total traveler delay calculation results are shown on Table 27. For an average weekday EB and WB, total traveler delay increased 12.96% and 9.01%, respectively, after ATM activation. In this case, the small improvements during off-peak and midday periods were not sufficient to overcome the increases in peak period travel time on weekdays. For an average weekend day EB and WB, the total traveler delay levels improved by 58.12% and 67.76%, respectively. The additional use of HSR during weekends, which dramatically improved average travel times, translated to large improvements in traveler delay levels for the weekend period. The values from Table 27 should be interpreted as daily levels in vehicle-hours. For example, total traveler delay for the EB weekday before ATM period should be interpreted as 2968.5 hours of traveler delay occurring on this corridor per day on a weekday.

When aggregated across the entire week, the large delay improvements on weekends served to offset the increases in delay during the week. The EB direction had a -0.2% reduction in delay per week, and the WB direction had a +2.0% increase in delay. Delay increases would likely have been much larger had ATM not been in place to mitigate off-peak and weekend congestion.

Table 24. Weekend Before-and-After Average PTI Comparisons: Entire Corridor Peak and Off-Peak Periods

Direction	Day	Peak Period Oct 2014-Feb 2015	Peak Period Oct 2015-Feb 2016	Change in Peak Period (min)	Change in Peak Period (%)	Statistical Significance at α = 0.05	Off-Peak Period Oct 2014-Feb 2015	Off-Peak Period Oct 2015-Feb 2016	Change in Off-Peak Period (min)	Change in Off-Peak Period (%)	Statistical Significance at α = 0.05
EB	Sun	1.094	0.989	-0.105	-9.598	Sig (<0.05)	0.909	0.936	+0.027	+2.970	Sig (<0.05)
	Sat	1.257	1.083	-0.174	-13.842	Sig (<0.05)	0.917	0.920	+0.003	+0.327	Not Sig (0.380)
	Average	1.148	1.018	-0.130	-11.324	Sig (<0.05)	0.909	0.923	+0.014	+1.540	Sig (<0.05)
WB	Sun	0.978	0.912	-0.066	-6.748	Sig (<0.05)	0.904	0.915	+0.011	+1.217	Sig (<0.05)
	Sat	1.227	0.986	-0.241	-19.641	Sig (<0.05)	0.905	0.914	+0.009	+0.994	Sig (<0.05)
	Average	1.087	0.939	-0.148	-13.615	Sig (<0.05)	0.901	0.909	+0.008	+0.888	Sig (<0.05)

PTI = planning time index; Peak Period = 10 AM-8 PM; Off-Peak Period = 8 PM-10 AM; EB = eastbound; WB = westbound; Sig = significant.

Table 25. Weekend Before-and-After Average BI Comparisons: Entire Corridor Peak and Off-Peak Periods

Direction	Day	Peak Period Oct 2014-Feb 2015	Peak Period Oct 2015-Feb 2016	Change in Peak Period (min)	Change in Peak Period (%)	Statistical Significance at α = 0.05	Off-Peak Period Oct 2014-Feb 2015	Off-Peak Period Oct 2015-Feb 2016	Change in Off-Peak Period (min)	Change in Off-Peak Period (%)	Statistical Significance at α = 0.05
EB	Sun	0.086	0.056	-0.030	-34.884	Sig (<0.05)	0.020	0.026	+0.006	+30.000	Sig (<0.05)
	Sat	0.097	0.086	-0.011	-11.340	Not Sig (0.171)	0.023	0.019	-0.004	-17.391	Not Sig (0.236)
	Average	0.068	0.055	-0.013	-19.118	Sig (<0.05)	0.017	0.017	0.000	0.000	Not Sig (0.401)
WB	Sun	0.055	0.026	-0.029	-52.727	Sig (<0.05)	0.015	0.020	+0.005	+33.333	Sig (<0.05)
	Sat	0.102	0.058	-0.044	-43.137	Sig (<0.05)	0.017	0.022	+0.005	+29.412	Not Sig (0.073)
	Average	0.067	0.033	-0.034	-50.746	Sig (<0.05)	0.012	0.016	+0.004	+33.333	Sig (<0.05)

BI = buffer index; Peak Period = 10 AM-8 PM; Off-Peak Period = 8 PM-10 AM; EB = eastbound; WB = westbound; Sig = significant.

Table 26. Observed AADT (2014-2015) and Estimated AADT (2016)

Route Label	Link Length (mi)	Segment	2014 Weekday AADT	2015 Weekday AADT	% Change	Weighted Avg % Change	Est. 2016 Weekday AADT	2014 Weekend AADT	2015 Weekend AADT	% Change	Weighted Avg % Change	Est. 2016 Weekend AADT
EB	1.25	1	70,000	71,000	1.43	3.92	73,783	56,000	60,500	8.04	4.13	62,999
	1.86	2	82,000	85,000	3.66		88,332	68,000	67,500	-0.74		70,288
	2.57	3	67,000	68,000	1.49		70,666	60,000	57,500	-4.17		59,875
	1.85	4	92,000	94,000	2.17		97,685	*74,500*	80,000	7.38		83,304
	2.13	5	96,000	99,000	3.13		102,881	75,000	78,000	4.00		81,221
	2.98	6	79,000	86,000	8.86		89,371	65,000	72,000	10.77		74,974
WB	0.83	1	68,000	70,000	2.94	2.86	72,002	54,000	56,000	3.70	1.59	56,890
	3.03	2	87,000	87,000	0.00		89,488	69,500	69,500	0.00		70,605
	2.20	3	65,000	65,000	0.00		66,859	54,500	51,000	-6.42		51,811
	2.01	4	89,000	98,000	10.11		100,803	71,500	80,500	12.59		81,780
	1.41	5	89,000	85,000	-4.49		87,431	71,500	71,000	-0.70		72,129
	3.62	6	86,000	91,000	5.81		93,603	72,000	73,500	2.08		74,669

AADT = annual average daily traffic; EB = eastbound; WB = westbound.

Table 27. Day of the Week Traveler Delay Levels: Entire Corridor

Direction	Day of the Week	Total Traveler Delay (vehicle-hour)		
		Before ATM	After ATM	Change (%)
EB	Weekday	2,968.5	3,353.4	+12.96%
	Weekend	1,682.5	704.7	-58.12%
	Entire Week	18,207.5	18176.4	-0.2%
WB	Weekday	5,121.6	5,583.3	+9.01%
	Weekend	1,292.5	416.8	-67.76%
	Entire Week	28,193.0	28,750.1	+2.0%

ATM = Active Traffic Management; EB = eastbound; WB = westbound.

Corridor-Level Safety Analysis

Corridor-Level Crash Rate Analysis

The ATM system could have conflicting safety impacts. Although the ATM system could mitigate congestion and improve safety by providing better advance warning of lane closures and congestion, the removal of the shoulder in the HSR section could have negative consequences since there would be more potential conflicts between disabled vehicles and through traffic. Although only 3 months of crash data from after ATM implementation were available, it is useful to examine preliminary trends in safety after system activation to identify any early safety concerns. These initial trends may not be sustainable but could provide some indication of initial reactions to the system. According to RNS police crash report data, the total number of crashes had generally been increasing for the before ATM conditions, as shown in Tables 28 and 29. Table 30 shows trends in AADT during the analysis period.

Table 28. Corridor-Level Crash Frequency Results for All Crashes

Direction	Length (mi)	Weekday				Weekend			
		Oct-Dec 2012	Oct-Dec 2013	Oct-Dec 2014	Oct-Dec 2015	Oct-Dec 2012	Oct-Dec 2013	Oct-Dec 2014	Oct-Dec 2015
EB	12.41	87	99	108	106	32	41	45	33
WB	12.35	59	65	91	106	14	28	22	14

EB = eastbound; WB = westbound.

Table 29. Corridor-Level Crash Frequency Results for Rear-end and Sideswipe Crashes

Direction	Type	Weekday				Weekend			
		Oct-Dec 2012	Oct-Dec 2013	Oct-Dec 2014	Oct-Dec 2015	Oct-Dec 2012	Oct-Dec 2013	Oct-Dec 2014	Oct-Dec 2015
EB	PDO	49	62	65	64	20	21	20	20
	Injury + Fatal	29	26	28	26	10	13	13	7
WB	PDO	40	40	60	54	9	8	11	7
	Injury + Fatal	8	18	18	28	3	6	6	2

EB = eastbound; WB = westbound; PDO = property damage only.

Table 30. Corridor-Level Weekday and Weekend AADT for 2012-2015

Direction	Length (mi)	2012 Weekday	2013 Weekday	2014 Weekday	2015 Weekday	2012 Weekend	2013 Weekend	2014 Weekend	2015 Weekend
EB	12.41	80,206	81,376	80,879	84,071	67,145	67,295	66,610	69,434
WB	12.35	80,811	83,071	82,347	84,806	66,864	68,903	67,212	68,492

AADT = annual average daily traffic; EB = eastbound; WB = westbound.

Rear-end and sideswipe crashes, which make up approximately 70% to 90% of all crashes in the study area, comprise one of the main safety concerns and are most likely to be impacted by ATM. ATM is known to be effective in mitigating rear-end and sideswipe crashes as speed harmonization and expansion of roadway capacity help to reduce the number of vehicle-to-vehicle interactions (Fontaine and Miller, 2012). The crash rate, which accounts for annual AADT growth in the safety analysis, was analyzed for the corridor, and the crash rate results are shown on Table 31. For the average weekdays both EB and WB, during the before ATM years of 2012-2014 (October-December), the crash rates increased annually by 6% to 34%. For the average weekends both EB and WB, during the before ATM years of 2012-2014 (October-December), the crash rates showed slight increasing trends.

Given the differing operational impacts between weekdays and weekends, the crash trends were examined separately by those two time periods. This further reduces the amount of after data available, however, so these results should again be viewed with caution. The trends indicate that crash rates either decreased or the rate of crash rate increase had been reduced after ATM activation. For all crash severities and rear-end and sideswipe crashes only, crash rates increased every year from 2012-2014 except for the EB weekend period during 2013-2014. As shown in Figure 34, EB weekdays had a reduction in rear-end and sideswipe crashes of 6.90% after ATM implementation whereas there was a crash rate increase of 6.33% in the before ATM period. WB weekdays had crash rate increases of only 2.08% after ATM implementation, whereas there was a crash rate increase of 35.66% immediately before ATM activation. The crash rate improvements were much more evident on weekends after ATM implementation, as EB and WB weekends saw crash rate improvements of 21.51% and 48.05% versus the before ATM period. The improvement trends were similar even when the rear-end and sideswipe crashes were divided into PDO and fatal and injury crashes except for WB weekday fatal and injury crashes. These results are shown in Figures 35 and 36.

Table 31. Corridor-Level Crash Rate Results for Rear-end and Sideswipe Crashes

		Weekday				**Weekend**			
Direction	**Type**	**Oct-Dec 2012**	**Oct-Dec 2013**	**Oct-Dec 2014**	**Oct-Dec 2015**	**Oct-Dec 2012**	**Oct-Dec 2013**	**Oct-Dec 2014**	**Oct-Dec 2015**
EB	PDO	33.40	41.65	43.93	41.62	16.28	17.06	16.41	15.75
	Injury + Fatal	19.77	17.47	18.93	16.91	8.14	10.56	10.67	5.51
	Total	53.16	59.12	62.86	58.52	24.42	27.62	27.08	21.26
WB	PDO	27.19	26.45	40.02	34.98	7.39	6.38	8.99	5.61
	Injury + Fatal	5.44	11.90	12.01	18.14	2.46	4.78	4.90	1.60
	Total	32.63	38.35	52.03	53.11	9.86	11.16	13.89	7.22

EB = eastbound; WB = westbound; PDO = property damage only.

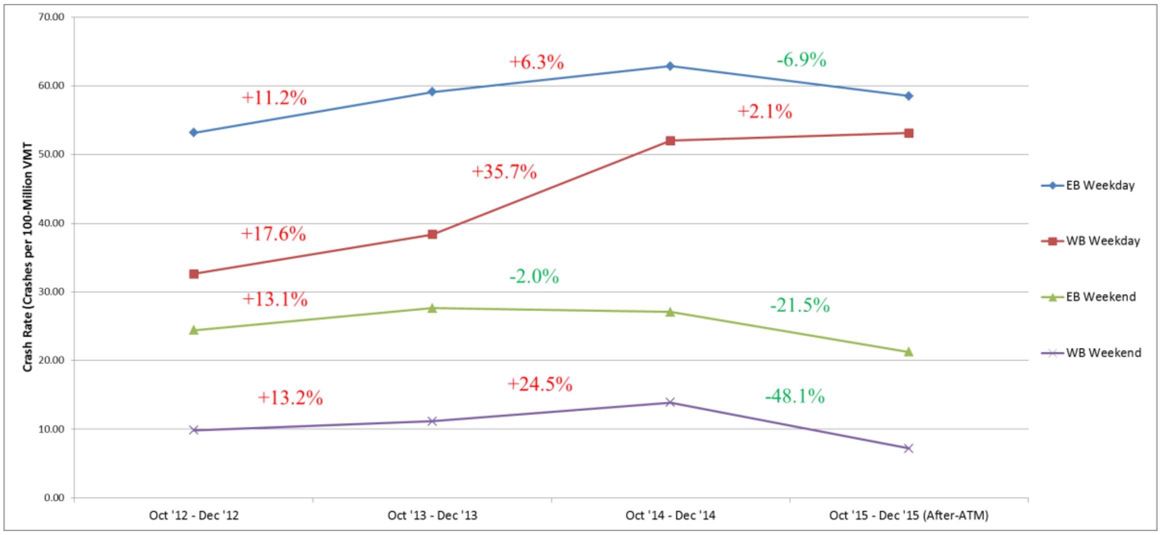


Figure 34. Crash Rate Trends for 2012-2015 for Rear-end and Sideswipe Crashes, All Severities: Entire Corridor

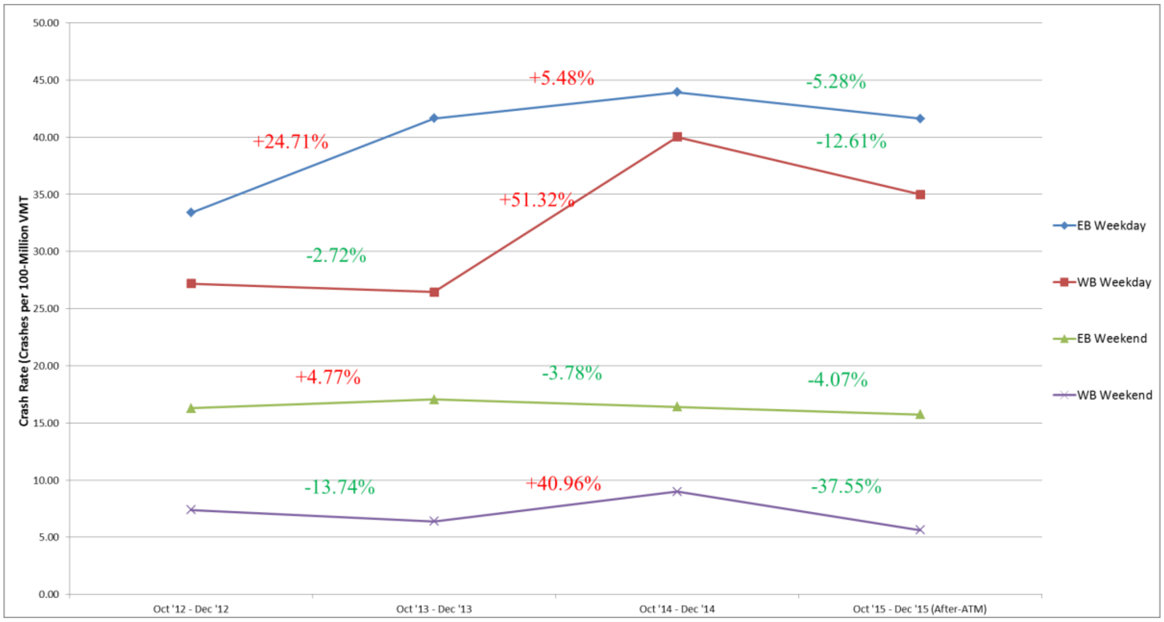


Figure 35. Crash Rate Trends for 2012-2015 for Rear-end and Sideswipe Crashes, Property Damage Only: Entire Corridor

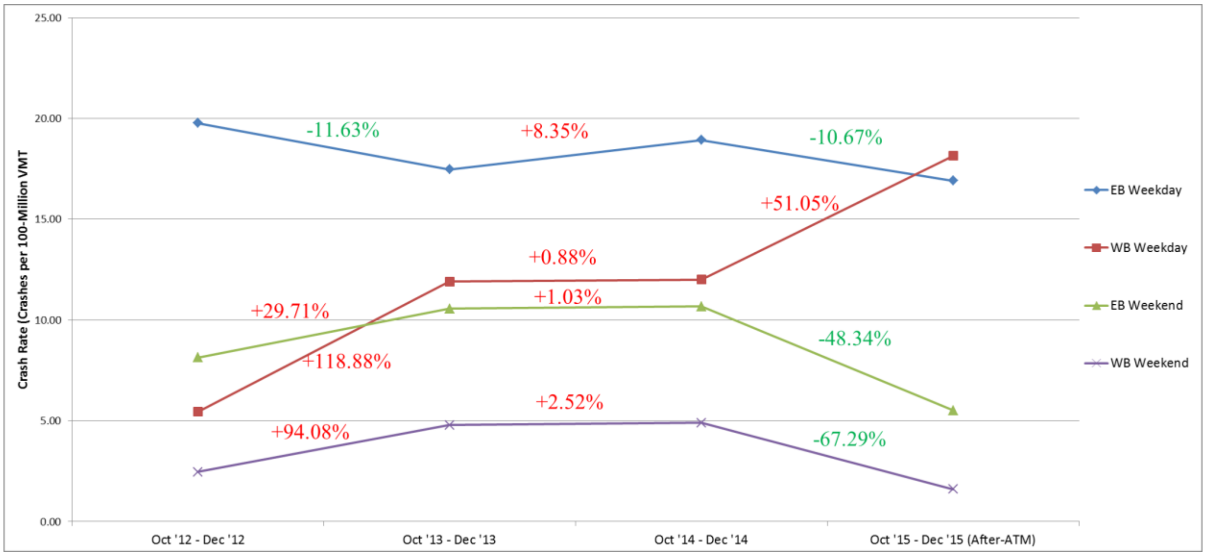


Figure 36. Crash Rate Trends for 2012-2015 for Rear-end and Sideswipe Crashes, Fatal and Injury Crashes: Entire Corridor

The crash rates were calculated using only October-December crash data for each year, so the full yearly trends may not be represented by this analysis. However, the consistent improvements in crash rates over all conditions especially on weekends show that there may have been noticeable safety improvements along the corridor as a result of ATM implementation. Since AVSL was activated only starting in mid-January, most of the safety benefits that may have come from ATM in this time period are likely to have been due to LUCS and HSR operation. As a result, the initial empirical safety evidence shows promising results because of decreased congestion on the corridor, although this is based on limited data. This will need to continue to be monitored over time to reach a definitive conclusion, but the preliminary analysis seems to indicate that ATM did not produce any adverse safety impact.

Corridor-Level Traffic Incident Analysis

The number of traffic incidents generally increased after ATM implementation, but this may have been attributable to increased monitoring along the corridor after ATM installation. Tables 32 through 34 show the traffic incident data for the corridor.

Table 32. Weekday Number of Traffic Incidents: Entire Corridor AM and PM Peak Periods

Direction	Incident Type	AM Peak Period Oct 2012-Feb 2013	AM Peak Period Oct 2013-Feb 2014	AM Peak Period Oct 2014-Feb 2015	AM Peak Period Oct 2015-Feb 2016	PM Peak Period Oct 2012-Feb 2013	PM Peak Period Oct 2013-Feb 2014	PM Peak Period Oct 2014-Feb 2015	PM Peak Period Oct 2015-Feb 2016
EB	Disabled Vehicle	107	78	122	172	130	108	121	164
	Accident	60	57	46	108	94	89	88	74
	Other	5	2	3	6	5	6	5	14
	Total	172	137	171	286	229	203	214	252
WB	Disabled Vehicle	101	112	172	167	155	137	155	229
	Accident	51	64	64	40	103	109	94	171
	Other	9	3	7	8	6	4	6	17
	Total	161	179	243	215	264	250	255	417

AM Peak Period = 5:30-11:00 AM; PM Peak Period = 2-8 PM; EB = eastbound; WB = westbound.

Table 33. Weekday Number of Traffic Incidents: Entire Corridor Midday and Overnight Periods

Direction	Incident Type	Midday Period Oct 2012-Feb 2013	Midday Period Oct 2013-Feb 2014	Midday Period Oct 2014-Feb 2015	Midday Period Oct 2015-Feb 2016	Overnight Period Oct 2012-Feb 2013	Overnight Period Oct 2013-Feb 2014	Overnight Period Oct 2014-Feb 2015	Overnight Period Oct 2015-Feb 2016
EB	Disabled Vehicle	33	41	77	71	85	79	100	146
	Accident	16	23	35	24	21	28	23	24
	Other	2	1	4	9	5	3	7	12
	Total	51	65	116	104	111	110	130	182
WB	Disabled Vehicle	31	71	64	107	86	97	145	208
	Accident	14	11	27	29	24	20	33	46
	Other	3	5	6	7	2	3	7	15
	Total	48	87	97	143	112	120	185	269

Midday Period = 11 AM-2 PM; Overnight Period = 8:00 PM-5:30 AM; EB = eastbound; WB = westbound.

Table 34. Weekend Number of Traffic Incidents: Entire Corridor Peak and Off-Peak Periods

Direction	Incident Type	Peak Period Oct 2012-Feb 2013	Peak Period Oct 2013-Feb 2014	Peak Period Oct 2014-Feb 2015	Peak Period Oct 2015-Feb 2016	Off-Peak Period Oct 2012-Feb 2013	Off-Peak Period Oct 2013-Feb 2014	Off-Peak Period Oct 2014-Feb 2015	Off-Peak Period Oct 2015-Feb 2016
EB	Disabled Vehicle	48	63	54	93	51	52	143	90
	Accident	29	67	32	47	16	12	58	19
	Other	6	3	6	5	6	7	6	4
	Total	83	133	92	145	73	71	207	113
WB	Disabled Vehicle	66	82	90	100	61	69	100	97
	Accident	44	52	49	28	16	12	15	17
	Other	3	1	8	11	1	2	9	9
	Total	113	135	147	139	78	83	124	123

Peak Period = 10 AM-8 PM; Off-Peak Period = 8 PM-10 AM; EB = eastbound; WB = westbound.

Greater camera coverage of the corridor after ATM activation means that a greater number of traffic incidents, particularly disabled vehicles, would be detected and logged. The large increase in the number of disabled vehicles after ATM implementation likely indicates that improved camera coverage created the increase in recorded incidents, rather than a true increase in the number of incidents. With greater coverage, traffic incidents that were once not within the camera coverage area could be captured and appropriate measures could be taken more quickly to mitigate the congestion caused by those events.

Otherwise, there were no other trends for the number of traffic events throughout the years. There was no strong evidence of deterioration or improvement of roadway conditions. The lack of a large decrease in incidents after ATM activation implies that the travel time improvements were not due to changes in incident occurrence.

Subsegment-Level Operations Analysis

VDOT staff anecdotally indicated that the HSR component of the ATM has been the most active ATM technique in operation since initial deployment, especially on weekends. HSR is present only on Subsegments 4 through 6, and this analysis will determine if these subsegments had more operational improvements than other segments. Total delay was used to determine whether benefits produced by the ATM system were disproportionately created by the subsegments where HSR was present and if the net total delay decreased along the entire corridor.

The segment-level total delay analysis shows that Segments 4 and 5 (U.S. 50 to VA 243) had the most improvements in terms of mitigating traffic delay. With regard to the overall delay improvements alone, Subsegments 4 and 5 far outperformed other segments. Tables 35 and 36 show the full subsegment-level delay analysis. The total delay improvements for both directions and all days of the week on Subsegments 4 and 5 were 2173.7 and 1355.2 vehicle-hours per week, respectively. Subsegments 4 and 5 were the only subsegments with an improvement in total delay, and this is important as they are locations where the heaviest congestion persists on I-66. Subsegment 6 had a large increase in total delay; however, this was due to an abnormal total delay growth during EB weekdays. In addition, Segments 4 through 6 showed the greatest improvements in mitigating delay over weekends both EB and WB after ATM implementation, which is consistent with the fact that average travel times became almost free flow–like for all weekend hours both EB and WB.

Most, if not all, traffic operations improvements seemed to occur because of HSR. Although LUCS and AVSL may have provided some incident management benefits, they did not appear consistently to produce large reductions in traveler delay. Given the limited crash data available, safety improvements were not analyzed at a subsegment level. It is possible, however, that AVSL and LUCS generated additional safety benefits.

Table 35. Subsegment-Level Analysis of Total Delay (vehicle-hours): Segments 1-3, Non-HSR

Segment	Direction	Day of Week	Before ATM	After ATM	Change
1	EB	Weekday	129.3	175.1	+45.8
		Weekend	51.7	43.8	-7.9
	WB	Weekday	372.7	594.6	+221.9
		Weekend	5.9	7.9	+2.0
	Total Delay/Week				+1,326.7
2	EB	Weekday	268.7	244.5	-24.2
		Weekend	76.1	75.3	-0.8
	WB	Weekday	580.0	803.1	+223.1
		Weekend	37.5	56.9	+19.4
	Total Delay/Week				+1,031.7
3	EB	Weekday	911.8	830.3	-81.5
		Weekend	125.5	46.6	-78.9
	WB	Weekday	512.3	622.2	+109.9
		Weekend	12.1	47.9	+35.8
	Total Delay/Week				+55.8

HSR = hard shoulder running; ATM = Active Traffic Management; EB = eastbound; WB = westbound.

Table 36. Segment-Level Analysis of Total Delay (vehicle-hours): Segments 4-6, Hard Shoulder Running

Segment	Direction	Day of Week	Before ATM	After ATM	Change
4	EB	Weekday	891.3	681.4	-209.9
		Weekend	468.2	122.8	-345.4
	WB	Weekday	375.9	328.1	-47.8
		Weekend	118.2	21.0	-97.2
	Total Delay/Week				-2,173.7
5	EB	Weekday	447.4	643.0	+195.6
		Weekend	527.1	158.0	-369.1
	WB	Weekday	1,873.0	1,747.6	-125.4
		Weekend	615.4	131.4	-484.0
	Total Delay/Week				-1,355.2
6	EB	Weekday	320.0	779.2	+459.2
		Weekend	433.9	258.1	-175.8
	WB	Weekday	1,407.7	1,487.7	+80.0
		Weekend	503.4	151.7	-351.7
	Total Delay/Week				+1,641.0

ATM = Active Traffic Management; EB = eastbound; WB = westbound.

CONCLUSIONS

- *Weekday peak periods often had slightly degraded operations after ATM activation, but several possible explanations exist for this trend.* First, peak period weekday average travel times both EB and WB had been generally increasing during the 3 years before ATM activation. The shoulders were already open to travel in the peak direction before the ATM system was deployed, so the ATM system did not offer any physical capacity beyond what was already in use during pre-ATM conditions. Second, real-time volume data were unavailable for analysis. It is possible that volumes have increased along the corridor, mitigating any operational improvement from ATM. This cannot be examined until the data archive becomes available. Third, the AVSL system was active for only 1.5 months during the analysis period. Thus, its effects were not fully included in the analysis. Further analysis using more data with the AVSL active is needed.

- *After ATM activation, weekday off-peak periods generally had reduced average travel times and improved reliability.* There was a statistically significant reduction in weekday off-peak average travel times in the EB direction, from 14.66 to 13.73 minutes/vehicle (6.35% improvement). In the WB direction, average travel times were reduced from 12.57 to 12.29 minutes/vehicle (2.20% improvement). Further, there was a statistically significant improvement in PTI of 0.06 (5.45%) in the EB direction and 0.03 (3.33%) in the WB direction in the respective off-peak periods (PM for EB, AM for WB). Although these improvements were small, they represent a statistically significant change from the increases in travel time during the pre-ATM installation period.

- *For weekend peak periods, the operational benefits were even more evident after ATM implementation. The average weekend conditions became almost free flow–like throughout the day.* For the weekend peak period, there was a statistically significant improvement in average travel times for the EB direction from 14.53 to 13.06 minutes/vehicle (10.13% improvement). For the WB direction, average travel times improved from 13.71 to 12.25 minutes/vehicle (10.66% improvement). There were also statistically significant improvements in PTI of 0.13 (11.32%) in the EB direction and 0.15 (13.62%) in the WB direction. The average travel delay savings was estimated to be 977.8 vehicle-hours EB and 875.7 vehicle-hours WB per weekend day.

- *For rear-end and sideswipe crashes, the corridor had either a crash rate reduction or a slowed rate of increase after ATM activation based on 3 months of data.* The potential crash rate improvements were much more evident on weekends after ATM implementation as weekends had crash rate improvements of 21.51% EB and 48.05% WB compared to those of the before ATM period. Although this is based on limited data, the results seem to be consistent with the operational improvements. This provides a preliminary indication that the use of HSR did not result in large adverse impacts.

- *No conclusions can be drawn with regard to the rate of incident occurrence on I-66.* Although the number of incidents generally increased after ATM activation, this may be wholly or partially attributable to the improved camera coverage on the corridor. Increases in the number of disabled vehicles logged likely indicate that improved coverage created much of the change in incident frequency.

- *The data showed that HSR, present in only Segments 4 through 6 of the study corridor, was likely the primary component of the ATM that contributed to the operations and safety improvements during the first 5 months of operation.* This additional lane provided improvements in average travel times and travel time reliability and may have reduced the frequency of vehicle-to-vehicle interaction that led to a reduction in rear-end and sideswipe crashes. Only 1.5 months of data after AVSL activation were available for analysis, however, so the impact of AVSL is unclear at this time.

- *Based on this analysis, it can be concluded that the I-66 ATM had a positive impact on safety and operations during weekend peak and weekday off-peak periods (PM for EB, AM for WB).* The reported operational and safety benefits for I-66 after ATM implementation were similar to those in Europe and other U.S. states. This is a promising sign as it further supports the effectiveness of ATM in improving operations and safety if implemented on a viable corridor. The system did not create substantial changes during peak periods that were already operating in oversaturated conditions, however. In those cases, shoulders were already open to travel before ATM activation so no capacity was added during peak periods.

RECOMMENDATIONS

1. *Given the results of this evaluation, VDOT should consider implementing ATM systems that use HSR on congested corridors where feasible. VDOT should examine shoulder depth, lateral clearances, structure locations, proximity to supporting utilities, and crash history to determine where HSR could be implemented without significant infrastructure changes or safety concerns.* HSR use is obviously inferior to adding a lane of regular capacity, but it can be a cost-effective solution where construction costs or right of way prohibit further expansion. HSR use would appear potentially to offer great benefits at locations where it is not presently used during peak periods and during non-recurring congestion events during off-peak periods. Potential operational benefits should be weighed against safety concerns related to the removal of the emergency shoulder at these locations. Based on this preliminary analysis of I-66, there were no major safety concerns related to the removal of the shoulder. Data on the effectiveness of AVSL and LUCS are inconclusive based on the initial 5 months of operation.

2. *Since this study used only 5 months of after ATM data for the operations and safety analysis, it is imperative that analyzing and monitoring the operations and safety effects of the ATM on I-66 should continue. VTRC and VDOT's NRO should continue to monitor the corridor.* It is important to know if the improvements from implementing the ATM will be maintained over an extended period of time. For a more comprehensive operations and safety analysis, 1-year and 3-year after ATM operations and safety effectiveness evaluations are recommended. These would be required in order to assess the effect of AVSL on safety and operations.

3. *The I-66 point sensor database was out of service during the after ATM period in this study. It is important to analyze the traffic volume changes on I-66 after ATM implementation that might have had an impact on operations and safety. VTRC and VDOT's NRO should include this analysis in future evaluations as data become available.* Once the point sensor data can be acquired, it is critical that traffic volume changes be examined for the after ATM condition to support the findings of this study. VDOT's NRO has been working with the contractor to get the system on line, and it should be available sometime in 2016.

4. *VTRC should conduct an additional study to examine travel behavior during AVSL activation.* The segment-level analysis in this study showed HSR to have operational and safety

improvements on a macro level. It is important to understand the specific AVSL effects since speed harmonization is a key component of ATM that has been shown to mitigate non-recurrent and recurrent congestions in Europe. Additional analysis of driver behavior on I-66 is needed as greater experience is gained with the AVSL system. Point sensor data will be required to conduct further analysis of driver compliance and reactions. This information could potentially be used to refine further the performance of the AVSLs.

BENEFITS AND IMPLEMENTATION

Benefits

A B/C analysis was performed at a planning level to quantify the benefits of the ATM on I-66. The traveler delay improvements were primarily used to show the ATM benefits. As noted earlier, most of the benefits observed to date seem to be attributable to the use of HSR, although limited data on AVSL usage were analyzed in this study. Since there was strong evidence that there were improved operations on weekends and it is difficult to quantify weekday benefits given historic increasing pre-ATM travel time trends on the corridor, only weekend benefits were analyzed for this B/C analysis. To have a conservative estimate for this B/C analysis, any improvement in the weekday deterioration rate after ATM implementation was not considered for this analysis. Safety benefits were also not quantified given the limited amount of data available.

Several assumptions were made to develop the B/C analysis. First, it was assumed that the benefits observed during the first 5 months of operation could be extrapolated to the entire year. This may or may not be true given that the AVSL was not fully active throughout the analysis period. Second, it was assumed that the benefits observed would remain level over time. It is likely that traffic volumes will continue to increase on the corridor, which would in turn impact future year delays and safety. Given the difficulty in forecasting those future year ATM impacts, the assumption for this analysis was to hold benefits level to be conservative. Only user delay benefits were calculated, and no benefits due to decreased emissions or fuel consumption were determined. Likewise, only initial capital costs were considered. VDOT data systems make it difficult to track ongoing maintenance costs for the ATM system, so those were not included.

Using the value of travel time delay used by the Texas A&M Transportation Institute, the operations benefit was quantified (Schrank et al., 2015). The value of travel time delay was estimated at $17.67 per hour of person travel and $94.04 per hour of truck time (Schrank et al., 2015). To be conservative, each vehicle on I-66 was considered to have one passenger. Overall, there was an improvement of approximately 3,707 hours of traveler delay combined in both directions of I-66 every weekend. If it is assumed that the trends during the 5-month study period extend over the entire year, this translates to an improvement of approximately 192,778 hours of traveler delay per year (3,707 hours multiplied by 52 weeks). VDOT AADT data from 2015 estimated that truck traffic was approximately 2% of all traffic on I-66. Using this percentage, truck delay was determined to be approximately 3,856 hours and the delay for passenger vehicles was determined to be approximately 188,922 hours. The total operations benefits were calculated to be approximately $3.7 million per year based only on weekend improvements.

According to VDOT's NRO, the cost of implementing the gantries and relevant ATM control and sensor systems was $24 million. The total cost of the project was listed at $39 million, but $15 million that was allocated for this project was used to upgrade sensors and cameras that were due for updates. This means that in less than 7 years, the benefits of the ATM will eclipse the cost of ATM implementation. If the project life of the ATM is assumed to be 10 years, the B/C ratio is 1.54, which shows that the ATM would be a cost-efficient solution in improving operations and safety on the I-66 corridor. Again, it should be noted that HSR was initially responsible for most of these benefits, and incremental benefits of AVSL are less clear. Likewise, the costs used in the B/C calculations are for the entire system, not just HSR, so the B/C estimate may be conservative versus that for an HSR system alone. This estimate should be considered a planning level estimate of the B/C ratio for the system given the number of assumptions. Since the conservatively calculated B/C ratio exceeded 1, it appears that the system produced a positive overall net benefit to traffic in the region. Again, this is likely a very conservative estimate since it does not reflect any potential weekday impacts or safety benefits and does not contain a full evaluation of AVSL benefits. Additional research is needed to determine what benefit, if any, AVSL provided to operations.

Implementation

1. *VTRC will initiate a follow-up study to continue to evaluate the I-66 ATM system focusing on the effects of the AVSLs.* Recommendations 2, 3, and 4 all involve continued evaluation and monitoring of the I-66 ATM deployment. VTRC has already begun conducting additional analyses focusing on the period since February 2016. The goal of that analysis is to examine the impact of the ATM system now that VDOT's NRO has gained greater familiarity with the system. The specific focus is on quantifying the AVSL impacts now that more time has passed. VDOT's NRO has also reached a contractual agreement with the vendor to modify the sensor data archive, and that data will also be evaluated by VTRC once they become available. VTRC will continue to work with VDOT's NRO to monitor performance trends on I-66 until the ATM gantries are removed for the I-66 High Occupancy Toll Lane Project in the summer of 2017.

2. *Depending on the outcomes of the follow-up analysis on I-66, VDOT's Operations Division will issue guidance on the use of ATM.* This will include guidance on the use of HSR as described in Recommendation 1. This will be implemented after the completion of the follow-up analysis in late 2017.

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