VTRC
Virginia Transportation Research Council

We Bring Innovation to Transportation

# Evaluation of the Impact of the I-66 Active Traffic Management System: Phase II

http://www.virginiadot.org/vtrc/main/online_reports/pdf/19-r7.pdf

**NANCY DUTTA**
**Graduate Research Assistant**
**Virginia Transportation Research Council**

**MICHAEL D. FONTAINE, Ph.D., P.E.**
**Associate Director**
**Virginia Transportation Research Council**

**RICHARD ATTA BOATENG**
**Graduate Research Assistant**
**University of Virginia**

**MEGAN CAMPBELL**
**Undergraduate Research Assistant**
**Virginia Transportation Research Council**

Final Report VTRC 19-R7

VIRGINIA TRANSPORTATION RESEARCH COUNCIL
530 Edgemont Road, Charlottesville, VA 22903-2454
vtrc.virginiadot.org

**Standard Title Page—Report on State Project**


| Report No.: | Report Date: | No. Pages: | Type Report: Final Contract | Project No.: RC00122 |
|---|---|---|---|---|
| VTRC 19-R7 | October 2018 | 51 | Period Covered: | Contract No.: |


Title:
Evaluation of the Impact of the I-66 Active Traffic Management System: Phase II


Key Words:
Active Traffic Management, Hard Shoulder Running, Variable Speed Limits, Lane Use Control Signals



Authors:
Nancy Dutta, Michael D. Fontaine, Ph.D., P.E., Richard Atta Boateng, and Megan Campbell

Performing Organization Name and Address:
Virginia Transportation Research Council
530 Edgemont Road
Charlottesville, VA 22903



Sponsoring Agencies' Name and Address:
Virginia Department of Transportation
1401 E. Broad Street
Richmond, VA 23219

Supplementary Notes:



Abstract:

In early 2013, construction began on a Virginia Department of Transportation (VDOT) project to install an Active Traffic Management (ATM) system on I-66 from US 29 in Centreville to the Capital Beltway (I-495). Construction was completed in September 2015. This project was intended to improve safety and operations on I-66 without physically expanding the roadway through better management of the existing facility. The main components of the installed system included advisory variable speed limits (AVSL), lane use control signals (LUCS), and hard shoulder running (HSR).

In 2016, the Virginia Transportation Research Council completed a Phase I evaluation of the system, covering its first 5 months of operation. A before-after study to quantify the effectiveness of the system was performed using "after" data from October 2015–February 2016 (21 weeks) for the operational analysis and data from October 2015–December 2015 (13 weeks) for the safety analysis. Since the operational and safety analyses were performed using limited amounts of data, the results were preliminary. The analysis showed several benefits attributable to dynamic HSR, but only 1.5 months of data were available with the AVSL active.

In Phase II, the project was expanded to evaluate the long-term effects of the I-66 ATM system. For this phase, data from October 2015–November 2017 were used for the operational analysis and data from October 2015–December 2016 were used for the safety analysis. The operational measures of effectiveness were the same as for Phase I and included the ATM utilization rate, average travel time, and travel time reliability. In order to evaluate the safety impacts, the empirical Bayes method was used with safety performance functions developed for Virginia. Segment-level analysis was performed to determine the segments that had benefitted the most from the implementation of the ATM system. From this segment-level analysis, it was determined that HSR was the ATM component that created most of the improvements on I-66.

The operational analysis showed that travel time improved significantly during off-peak hours after the ATM system was activated but that travel time during peak periods in the peak direction of travel generally did not improve. Further analysis revealed that most of these improvements occurred on the sections with HSR. The safety evaluation showed 6%, 10%, and 11% reductions in total (all severity), multiple-vehicle (all severity), and rear-end (all severity) crashes, respectively. Segment-level analysis again showed that the most safety benefits were found for locations with HSR (crash reductions of 25% to 40%), and no statistically significant reductions were found for sections with only AVSL and LUCS. The results of the analysis showed that HSR could produce statistically significant operational and safety benefits but that the effects of other ATM components were more limited. The study recommends that VDOT's Operations Division and regions use the results from I-66 to inform decisions about future ATM and HSR use in Virginia.

**FINAL REPORT**

# EVALUATION OF THE IMPACT OF THE I-66 ACTIVE TRAFFIC MANAGEMENT SYSTEM: PHASE II

**Nancy Dutta**
**Graduate Research Assistant**
**Virginia Transportation Research Council**

**Michael D. Fontaine, Ph.D., P.E.**
**Associate Director**
**Virginia Transportation Research Council**

**Richard Atta Boateng**
**Graduate Research Assistant**
**University of Virginia**

**Megan Campbell**
**Undergraduate Research Assistant**
**Virginia Transportation Research Council**

Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
And the University of Virginia since 1948)

Charlottesville, Virginia

October 2018
VTRC 19-R7

## DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Virginia Department of Transportation, the Commonwealth Transportation Board, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation. Any inclusion of manufacturer names, trade names, or trademarks is for identification purposes only and is not to be considered an endorsement.

## ABSTRACT

In early 2013, construction began on a Virginia Department of Transportation (VDOT) project to install an Active Traffic Management (ATM) system on I-66 from US 29 in Centreville to the Capital Beltway (I-495). Construction was completed in September 2015. This project was intended to improve safety and operations on I-66 without physically expanding the roadway through better management of the existing facility. The main components of the installed system included advisory variable speed limits (AVSL), lane use control signals (LUCS), and hard shoulder running (HSR).

In 2016, the Virginia Transportation Research Council completed a Phase I evaluation of the system, covering its first 5 months of operation. A before-after study to quantify the effectiveness of the system was performed using "after" data from October 2015–February 2016 (21 weeks) for the operational analysis and data from October 2015–December 2015 (13 weeks) for the safety analysis. Since the operational and safety analyses were performed using limited amounts of data, the results were preliminary. The analysis showed several benefits attributable to dynamic HSR, but only 1.5 months of data were available with the AVSL active.

In Phase II, the project was expanded to evaluate the long-term effects of the I-66 ATM system. For this phase, data from October 2015–November 2017 were used for the operational analysis and data from October 2015–December 2016 were used for the safety analysis. The operational measures of effectiveness were the same as for Phase I and included the ATM utilization rate, average travel time, and travel time reliability. In order to evaluate the safety impacts, the empirical Bayes method was used with safety performance functions developed for Virginia. Segment-level analysis was performed to determine the segments that had benefitted the most from the implementation of the ATM system. From this segment-level analysis, it was determined that HSR was the ATM component that created most of the improvements on I-66.

The operational analysis showed that travel time improved significantly during off-peak hours after the ATM system was activated but that travel time during peak periods in the peak direction of travel generally did not improve. Further analysis revealed that most of these improvements occurred on the sections with HSR. The safety evaluation showed 6%, 10%, and 11% reductions in total (all severity), multiple-vehicle (all severity), and rear-end (all severity) crashes, respectively. Segment-level analysis again showed that the most safety benefits were found for locations with HSR (crash reductions of 25% to 40%), and no statistically significant reductions were found for sections with only AVSL and LUCS. The results of the analysis showed that HSR could produce statistically significant operational and safety benefits but that the effects of other ATM components were more limited. The study recommends that VDOT's Operations Division and regions use the results from I-66 to inform decisions about future ATM and HSR use in Virginia.

## FINAL REPORT

# EVALUATION OF THE IMPACT OF THE I-66 ACTIVE TRAFFIC MANAGEMENT SYSTEM: PHASE II


**Nancy Dutta**
**Graduate Research Assistant**
**Virginia Transportation Research Council**

**Michael D. Fontaine, Ph.D., P.E.**
**Associate Director**
**Virginia Transportation Research Council**

**Richard Atta Boateng**
**Graduate Research Assistant**
**University of Virginia**

**Megan Campbell**
**Undergraduate Research Assistant**
**Virginia Transportation Research Council**


## INTRODUCTION

In early 2013, construction began on a Virginia Department of Transportation (VDOT) project to install an Active Traffic Management (ATM) system on I-66 from US 29 in Centreville (Exit 52/US 29) to the Capital Beltway (Exit 54/I-495). Construction was completed in September 2015. The project spanned approximately 12.4 miles. The main goals of the project were to improve operations, roadway safety, and incident management through more effective management of the existing roadway.

The installed ATM infrastructure included overhead gantries with lane use control signals, shoulder and lane use control signals, 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 the drivers traveling on I-66 (Iteris, 2011). The total project cost was approximately $38.6 million. Of this cost, approximately $24 million was spent on gantries, sensors, and traffic control devices to implement ATM, with the remainder being spent on upgrades to existing infrastructure such as cameras and communications systems.

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 (AVSL).* AVSL dynamically changes the posted speed based on current traffic or roadway conditions. For the I-66 ATM system, AVSL are posted on signs above each lane. The normal posted speed limit on I-66 is 55 mph, but the AVSL can post speeds between 35 mph and 50 mph based on traffic conditions (Chun and Fontaine, 2016). An automated algorithm determines the desirable posted speed limit based on observed traffic speeds from sensors, which are then processed, smoothed, and grouped to create transitions into and out of congestion.

- *Hard shoulder running (HSR).* Prior to ATM activation, the shoulder lane on I-66 was open to travel on a fixed time-of-day basis from 5:30 to 11:00 AM eastbound (EB) and from 2:00 to 8:00 PM westbound (WB) on non-holiday weekdays. After ATM activation, the HSR system dynamically opened or closed the shoulder lanes depending on roadway conditions, increasing capacity on I-66 dynamically. Decisions on whether to open or close the shoulder were based on the judgment of the operators in the traffic operations center (TOC). The HSR implemented by the I-66 ATM system could be activated at any time of the day or day of the week, in contrast to pre-ATM operations.

- *Lane use control signals (LUCS).* Overhead gantries were deployed with LUCS to alert drivers to lane blockages. LUCS could be used to indicate specific lanes that were closed in advance of the blockage. Drivers are advised that a lane is open (down green arrow), a lane is closed ahead (diagonal down yellow arrow), or a lane is closed (red X) (Dutta et al., 2017). This was used for incident and work zone management.

These components of ATM have been implemented in different combinations along I-66. Figure 1a shows an example of AVSL activation while the hard shoulder is closed to travel. Although the entire ATM corridor had LUCS and AVSL, Figure 1b shows which sections also had HSR.

In 2016, the Virginia Transportation Research Council completed an evaluation of the I-66 ATM system, covering its first 5 months of operation. A before-after study to quantify the effectiveness of the system was performed using “after” data from October 2015–February 2016 (21 weeks) for the operational analysis and data from October 2015–December 2015 (13 weeks) for the safety analysis. Since the operational and safety analyses were performed using limited amounts of data, the results were preliminary. That analysis showed several benefits attributable to HSR, but only 1.5 months of data were available with AVSL active. A more detailed discussion of the ATM system deployed and the preliminary evaluation are provided in the Phase I report by Chun and Fontaine (2016).


**Figure 1. ATM Components on I-66: (a) AVSL activation with HSR closed; and (b) HSR locations. AVSL = advisory variable speed limits; HSR = hard shoulder running.**

## PURPOSE AND SCOPE

The purpose of this study was to quantify the operational and safety improvements that occurred as a result of the I-66 ATM system using data from more than 1 year of operation. This was done to ensure that the trends observed in the Phase I study (Chun and Fontaine, 2016) were sustainable. The objectives were as follows:

- Determine the utilization rate of the ATM on I-66 to identify the frequency and spatial distribution of the use of various ATM techniques.

- Assess whether the I-66 ATM system improved average travel time and travel time reliability along the corridor.

- Determine the effect of the ATM system on segments of the I-66 corridor in terms of travel time and travel time reliability.

- Assess the safety effects of the ATM system.

- Determine to the maximum extent possible the degree to which different ATM components were responsible for operational and safety effects observed at the site.

Since the ATM system was activated in September 2015, this study covered its performance from October 2015–November 2017 for the operational analysis and from October 2015–December 2016 for the safety analysis.

# METHODS

## Review Relevant Literature

Publications related to the operational and safety effects of ATM were reviewed. The literature review focused on evaluations of field deployments, with an emphasis on those in the United States.

## Conduct the Operational Analysis

### Description of Data Sources

*INRIX Travel Time Data*

Probe-based travel time data from INRIX were used for the operational analysis. INRIX develops travel time estimates using GPS data from trucks and passenger vehicles, creating segment travel times based on these probe data. VDOT currently uses INRIX data to support a variety of performance measurement and traveler information applications, and several evaluations have supported the accuracy of the travel time data for freeways (Haghani et al., 2009). These data are reported spatially using Traffic Message Channel (TMC) links, which typically span segments between interchanges. At this study site, there were 14 TMCs with a total length of 12.41 miles in the EB direction and 14 TMCs with a total length of 12.34 miles in the WB direction. The length of each TMC varied from 0.22 to 1.85 miles.

INRIX provides confidence scores for each 1-minute interval travel time, 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 during the study period. Each 15-minute travel time interval had to have an average confidence score of 26.67 or higher for at least 85% of the TMCs composing the analysis section for it to be included in the analysis. These thresholds were derived from VDOT travel time business rules, and time periods that did not meet this threshold were discarded from the analysis (VDOT, 2015).

*TOC Logs*

The TOC keeps a log of the messages that were displayed on AVSL and LUCS. The TOC logs were reviewed to determine the times when HSR opened the shoulder to travel and the time periods when AVSL and LUCS 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 every individual sign could be tracked over time.

## Calculation of Performance Measures

*Analysis Time Periods and Data Aggregation*

The Phase I analysis of the ATM system used 21 weeks of before-ATM data (October 2014–February 2015) and 21 weeks of after-ATM data (October 2015–February 2016) for comparison (Chun and Fontaine, 2016). Although those results provided a preliminary examination of system effectiveness, they may have been influenced by seasonal factors. In this study, annual data were divided into four parts to be consistent with the seasonal variation in traffic: October-November, December-February, March-May, and June-August. Since the ATM system was activated on September 15, 2015, data from the month of September were not used in the analysis. In addition, four time periods were considered in this analysis:

1. Pre-ATM period: October 2014–August 2015
2. ATM Year 1: October 2015–August 2016
3. ATM Year 2: October 2016–August 2017
4. ATM Year 3: October–November 2017.

No operational data were analyzed after November 2017 because the I-66 Express Lanes inside the Capital Beltway opened in December 2017. This affected travel patterns in the area, making comparisons with prior periods invalid.

The analysis was also segregated by day of week and time of day. Time-of-day periods were defined as follows:

- *Weekdays*
  - AM peak (5:30-11:00 AM)
  - Midday (11:00 AM–2:00 PM)
  - PM peak (2:00-8:00 PM)
  - Overnight (8:00 PM–5:30 AM).

- *Weekends*
  - Daytime peak (10:00 AM–8:00 PM)
  - Off-peak (8:00-10:00 AM).

These time periods were selected to match the time periods when the static time of day HSR was used in the pre-ATM period (5:30-11:00 AM EB and 2:00-8:00 PM WB).

Even though the analysis was separated by season, factors beyond the presence of the ATM system may have affected travel on I-66. In June 2016, the Metrorail system in the Washington, D.C., area implemented the SafeTrack program to improve the safety and reliability of the system (Washington Metropolitan Area Transit Authority, no date). SafeTrack was an accelerated track work plan to address safety recommendations and rehabilitate the Metrorail system to improve safety and reliability. This plan created periods of disruption or complete shutdowns of portions of the Metrorail system, resulting in reduced service. This led to changes in travel behavior such as mode shifts, changes in departure time, telecommuting, and trip cancellations (Ali and Murray-Tuite, 2018). SafeTrack was active for some part of the analysis period used in this study and may have increased traffic on I-66 during the study period. The full effect of this disruption on traffic could not be easily isolated in this study, however, but readers should be cognizant that the effects reported may be related to this disruption.

*ATM Utilization*

The activation log maintained by the TOC contained detailed records of ATM usage for each individual sign on each gantry. Of the 22 gantries in each direction, 11 gantries were used for HSR in the EB direction and 9 gantries were used for HSR in the WB direction. Average HSR utilization rates were calculated by adding up the total time of HSR activation per gantry and then dividing the total by the number of days in the analysis period. This was calculated by direction and for weekdays and weekends.

All 22 gantries were included for the AVSL utilization analysis. AVSL 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.

All gantries were also included for the LUCS utilization analysis. The utilization of LUCS was far less frequent than the activation of AVSL or HSR since LUCS was activated only when there was a lane-blocking incident. Given the lower utilization, LUCS activations are not documented in this report, but interested readers can consult related work by Dutta et al. (2017).

*Average Travel Times*

INRIX travel time data were acquired using a 15-minute temporal aggregation; data quality screening measures were applied to the travel times, and travel times were segregated by segment, season, day of week, and time of day. Paired *t*-tests were conducted at $\alpha = 0.05$ to determine if any changes were statistically significant between the pre-ATM time period and ATM Year 1, Year 2, and Year 3, when applicable. For each day of the week, the 15-minute average times were divided into time of day for the before- and after-ATM periods to set up the paired *t*-test. Time periods with incidents were not screened out since those affect both average travel time and reliability. Since ATM is expected to help manage non-recurring events, it was important to include incident impacts in the analysis.

*Travel Time Reliability*

In addition to changes in mean travel time, changes in travel time reliability were examined using the planning time index (PTI) and 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 in order to ensure they are on time 95% of the time. Travel time reliability measures were derived directly from INRIX travel time data for the before and after ATM periods. The equations used to calculate PTI and BI for each 15-minute interval are as follows:

$$\text{Planning time index} = \frac{\text{95th percentile average travel time}}{\text{Free flow average travel time}} \qquad \text{[Eq. 1]}$$

$$\text{Buffer index} = \frac{\text{95th percentile average travel time} - \text{Average travel time}}{\text{Average travel time}} \qquad \text{[Eq. 2]}$$

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 analyze the statistical significance of the PTI and BI changes.

Since travelers are usually going faster than the speed limit during hours of low traffic flow, it is possible to have a PTI value of less than 1. For the BI, the baseline average travel time value changes, unlike 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 PTI and/or 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 was examined to determine if the system produced a net benefit on operations. The magnitude of delay can be determined by calculating Equation 3 for each 15-minute interval:

$$Delay = \begin{cases} 0 & if\ FFTTP \geq ATTP \\ (ATTP - FFTTP) \times Volume \div 60 & if\ FFTTP < ATTP \end{cases} \qquad \text{[Eq. 3]}$$

where

Delay is in vehicle-hours

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

FFTTP = free flow travel time profile, which is 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.

The daily volume distribution (percentage of traffic in each 60-minute period) was calculated based on AADT data from the VDOT Traffic Monitoring System by direction. Seasonal variation in traffic was addressed by calculating different seasons separately, and weekdays and weekends were also treated differently. Since AADT data had not been finalized for 2017 as of the writing of this report, the 2017 AADT estimates were developed using data from 2015 and 2016 (weighted by length of segment) using average growth rates across the segments.

## Safety Analysis

The safety analysis of the I-66 ATM system was limited to basic freeway segments, and safety within the interchange areas was not specifically analyzed. The reason for this is that AADT data from interchange ramps were not available at most sites during the study period. Without that traffic exposure data, any safety analysis of the interchanges would not adequately account for the volumes that were merging and diverging at the site.

### Description of Data Sources

#### *Crash Data*

Crash data for the study were collected from the VDOT Roadway Network System (RNS) between 2011-2014 (before) and 2016 (after) along I-66. Data from 2015 were not used in the analysis since the AVSL was not fully activated until early 2016 and the 2017 data could not be analyzed since 2017 AADTs had not yet been finalized by VDOT.

#### *Segment Traffic and Geometric Data*

The I-66 corridor was reviewed to ensure compliance with the *Highway Safety Manual* (HSM) base conditions for freeway segments (AASHTO, 2010). The EB and WB directions of the study corridor were sub-segmented into homogeneous sections based on the traffic and geometric characteristics of the roadway and the presence or absence of HSR. Road inventory data for the corridor were obtained from VDOT, and only data from segments outside the interchange area along the corridor were used. An interchange area was defined as an area between gores of entrance/exit ramps (Kweon and Lim, 2014). Additional data collected included length of horizontal curves, lane widths, inside/outside shoulder widths, median widths, and length of median barriers. Traffic data were collected before (2011-2014) and after (2016) implementation of the ATM system, and the year of activation was omitted from the analysis.

### Safety Analysis Methods

In order to evaluate the safety impacts of ATM on I-66, the empirical Bayes method with safety performance functions (SPFs) described by Gross et al. (2010) was used. This method is well known for its robustness and ability to calculate statistically defensible crash modification factors (CMFs). It is also able to account for key changes in traffic and geometric conditions that occurred during the study period while also controlling for regression-to-the-mean effects (Goh et al., 2012). Hauer (1980) described SPFs as being representative of the safety performance of a roadway or an intersection, and they are used to correct for regression-to-the-mean bias when calculating the safety effectiveness of a countermeasure. They relate crash frequencies, traffic volume, and roadway and land use characteristics to one another. The SPFs include an overdispersion parameter that is developed from a negative binomial model as a measure of precision of the model in predicting crashes that would have occurred at the treatment sites if the treatment had not been implemented. This factor is used in conjunction with the observed crash frequency before the treatment was applied to weight computations and to predict the expected crashes at each site.

Virginia statewide SPFs developed by Kweon and Lim (2014) for freeway segments with six lanes and eight+ lanes were used to develop the CMFs for the I-66 ATM system. By use of the Virginia SPFs, predictions can better account for jurisdictional trends in factors such as driving behavior, weather, and reporting thresholds than the national models in the HSM. More generalized SPFs can also lead to erroneous computation of the safety effect of the treatment (Garber et al., 2006). Relevant base condition CMFs were computed based on the geometric data collected earlier using equations and coefficients described in the HSM for freeways. These data were used to develop CMFs, and they were applied to the Virginia SPFs in the empirical Bayes computation. HSM coefficients for horizontal curves, median width, and median barrier were used. Lane width and inside and outside shoulder widths met the base conditions, so they were not corrected for in the computations.

The Virginia SPFs developed by Kweon and Lim (2014) used in this study were as follows:

$$N_{Total\ Crashes,6\ Lanes} = e^{-12.85} AADT_{Directional}^{1.45} Segment\ Length_{Directional};\ (k = 0.59) \quad \text{[Eq. 4]}$$

$$N_{Fatal+\ Injury\ Crashes,6\ Lanes} = e^{-15.64} AADT_{Directional}^{1.6} Segment\ Length_{Directional};\ (k = 0.47) \quad \text{[Eq. 5]}$$

$$N_{Total\ Crashes,8\ Lanes} = e^{-2.17} AADT_{Directional}^{0.48} Segment\ Length_{Directional};\ (k = 0.58) \quad \text{[Eq. 6]}$$

$$N_{Fatal+\ Injury\ Crashes,8\ Lanes} = e^{-5.94} AADT_{Directional}^{0.71} Segment\ Length_{Directional};\ (k = 0.50) \quad \text{[Eq. 7]}$$

Gross et al. (2010) described the computation of expected crashes without the treatment for a site as follows:

$$N_{exp,T,B} = w \times \left(N_{pred,T,B}\right) + (1 - w) \times (N_{obs,T,B}) \quad \text{[Eq. 8]}$$

where

$N_{exp,T,B}$ = an estimate of the expected crashes in the before period without the treatment

$N_{obs,T,B}$ = observed crash frequency in the before period at the treated sites

$N_{pred,T,B}$ = an estimate of the predicted crashes in the before period from the SPF

$w$ = weight, which is based on the overdispersion parameter (k) from the applicable SPF model and is calculated as follows:

$$w = \frac{1}{1+k*\Sigma N_{pred,TB}}$$ , k = overdispersion parameter [Eq. 9]

Expected crashes after the implementation of the treatment ($N_{exp,T,A}$) is computed as:

$$N_{exp,T,A} = (N_{exp,T,B}) \times \left(\frac{N_{pred,T,A}}{N_{pred,T,B}}\right)$$ [Eq. 10]

where

$N_{pred,T,A}$ = an estimate of the predicted crashes in the after period from the SPF.

The variance of the expected number of treatment crashes in the after period is:

$$var(N_{exp,T,A}) = \left[(N_{exp,T,A}) \times \left(\frac{N_{pred,T,A}}{N_{pred,T,B}}\right) \times (1-w)\right]$$ [Eq. 11]

$$CMF = \frac{(N_{Obs,T,A}/N_{exp,T,A})}{\left(1+(var(N_{exp,T,A})/N_{exp,T,A}{}^2)\right)}$$ [Eq. 12]

The standard error is computed as follows:

$$Standard\ Error = \sqrt{\left(\frac{CMF^2*\left[\left(\frac{1}{N_{Obs,T,A}}\right)+(var(N_{exp,T,A})/N_{exp,T,A}{}^2)\right]}{\left[1+(var(N_{exp,T,A})/N_{exp,T,A}{}^2)\right]^2}\right)}$$ [Eq. 13]

The standard error is used in conjunction with the calculated CMF to determine whether the results are statistically significant.

CMFs for multiple-vehicle and rear-end crash types were also estimated by computing their proportions of total (all severity levels) and fatal and injury (FI) crashes during the before period. The factors for the proportions (x) were then applied to the sum of the predicted crashes in the before and after period $(x\Sigma N_{pred,TB}, x\Sigma N_{pred,T,A})$ to obtain the predicted crashes for multiple-vehicle and rear-end crashes. These proportional factors (x) were again applied to the expected crashes $(xN_{exp,T,B}, xN_{exp,T,A})$ to compute the expected number of crashes before and after the ATM activation for the multiple-vehicle and rear-end crash types.

# RESULTS AND DISCUSSION

## Literature Review

Although ATM deployments in the United States are relatively new as compared to those in Europe, U.S. data show some promising operational and safety results. Evaluation results of ATM deployments in Europe have shown improvements in operational measures (throughput, travel times, and travel time reliability) and safety (Mirshahi et al., 2007). Since driving behavior and operational conditions (such as the presence of automated speed enforcement) are often different in Europe than in the United States, those results may be difficult to translate to U.S. applications. Given the limited U.S. experience with ATM using HSR, there is still a need to continue to document and evaluate U.S. ATM systems. Table 1 summarizes selected ATM field deployments in Europe and the United States.

## Operational Analysis

### Corridor-Level ATM Utilization

Table 2 summarizes the average utilization of AVSL, HSR, and LUCS during the first 2 years after ATM activation. Before ATM was implemented, HSR was activated only on weekdays from 5:30 to 11:00 AM in the EB direction and from 2:00 to 8:00 PM in the WB direction. After ATM activation, HSR was dynamically opened in response to congestion, in addition to being opened during the regular peak travel periods.

Usage of the different components generally increased over time as operators became more comfortable with ATM. During weekdays, HSR utilization increased from pre-ATM to after ATM Year 1 and further increased from Year 1 to Year 2 in most cases. For the weekends, utilization decreased slightly in Year 2 in the EB direction but increased in the WB direction. AVSL utilization rates were also analyzed, but AVSL was used less often than HSR. AVSL utilization increased in the second year. LUCS utilization followed the same trend as AVSL utilization. The Appendix includes detailed utilization charts for HSR, LUCS, and AVSL by gantry. In general, utilization increased as operators gained experience with using the system.

There was a particularly noteworthy change in how LUCS was deployed in the second year of operation. On November 15, 2016, VDOT started using diagonal downward yellow arrow indications on the lane use control signals to manage ramp traffic in the vicinity of major interchanges at three locations in the EB direction: Mile Marker (MM) 58.75 (I-66 and US 50 interchange); MM 60.62 (I-66 and SR 123 interchange); and MM 63.16 (I-66 and SR 243 interchange). The objective was to improve merging of vehicles entering I-66 from an entrance ramp. For this reason, the number and total hours of activations increased considerably for these particular gantries in the EB direction. The tables in the Appendix reflect this change in utilization.

**Table 1. Summary of ATM Deployments**

| Location | ATM Technique | Roadway Characteristics | Research Design | Effect on Operations | Effect on Safety |
|---|---|---|---|---|---|
| Germany, A99 (Weikl et al., 2013) | VSL | • 16.3 km (~10 mi) section of A99<br>• 3 lanes each direction | • VSL system<br>• 14 dual-loop detectors<br>• 18 bottleneck cases | • Flow change reduction of 4% when VSL was on and flow change reduction of 3% when VSL was off | N/A |
| Germany, A5 and A3 (Geistefeldt, 2012) | HSR | • 18 km (~11 mi)<br>• 3 lanes each direction<br>• High commuter traffic<br>• Distinct peak volumes | • 40 months of loop detector data<br>• 47 sections of the roadway analyzed for duration of congestion analysis | • Median values of the capacity 10%-25% higher than the capacity of comparable sections without HSR<br>• Duration of congestion reduced from 640 hr/yr and 450 hr/yr for NB and SB, respectively, to less than 200 hr/yr in both directions | N/A |
| Germany A7 (Lemke, 2010) | HSR | • 36 km (~22 mi)<br>• 35,000 AADT on each of the 3 sections | • Hand-written police reports<br>• 3 years of before and 3 years of after data analyzed | N/A | • Mixed results, with some increases and some declines |
| I-5, Washington (DeGaspari et al., 2013) | VSL, QWS | • 7-mile NB | • Total of 8 months before and after period<br>• 19 loop detectors | • PTI improved by 17%-31%<br>• BI improved by 15%-27% | N/A |
| I-260 and I-255, Missouri (Kianfar et al., 2010) | VSL | • Total of 38 miles<br>• 3 bottleneck locations | • Inductive loop and acoustic detectors<br>• 150 days of before and 150 days of after data<br>• 10 days in between before and after VSL deployment for driver normalization | • Pre-queue flow decreased by up to 4.5%<br>• Queue discharge flow decreased by up to 7.7%<br>• Average speed fluctuated, but speed variance declined at all bottleneck locations | N/A |
| 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<br>• 9 months of before and 17 months of after data | • During AM peak period, 17% less congestion with VSL system in operation<br>• 7.6 minutes less congestion during the average AM peak | • Traffic pattern shows gradual decrease in speeds during the onset of congestion<br>• No change in crash rates |
| I-35W, Minnesota (Kwon and Park, 2015) | VSL | • Urban location | • Traffic detector data<br>• Sept.-Nov. 2009 (before), 2010 (after), and 2011 (after)<br>• April-June 2010 (before), 2011 (after), and 2012 (after) | • Average travel time buffer index improved by 17%-32% | • Maximum deceleration decreased by 10%-22% |

**Table 2. ATM Utilization (Average Hours of Operation/Day per Gantry)**

| Direction | Day of Week | AVSL | | | LUCS | | | HSR | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Before ATM | Year 1 | Year 2 | Before ATM | Year 1 | Year 2 | Before ATM | Year 1 | Year 2 |
| EB | Weekday | N/A | 2.1 | 2.9 | N/A | 0.4 | 0.7 | 5.5 | 9.4 | 10.3 |
| | Weekend | N/A | 0.6 | 1.0 | N/A | 0.3 | 0.4 | N/A | 6.3 | 7.0 |
| WB | Weekday | N/A | 2.7 | 3.8 | N/A | 0.5 | 0.6 | 6.0 | 7.8 | 7.6 |
| | Weekend | N/A | 0.6 | 0.8 | N/A | 0.2 | 0.3 | N/A | 8.5 | 6.9 |

ATM = active traffic management; AVSL = advisory variable speed limit; LUCS = lane use control signal; HSR = hard shoulder running; EB = eastbound; WB = westbound.

## Corridor-Level Travel Time Analysis

*Weekday Average Travel Time Analysis*

Figures 2 and 3 show the EB and WB corridor-level average travel time profiles, respectively, for weekdays before and after ATM activation. For weekday peak period average travel times, there were statistically significant degradations after ATM activation in the peak directions during the peak period (AM for EB, PM for WB). Since HSR was already in use during these time periods before ATM was activated and I-66 operates far over capacity in these periods, no additional capacity was added during these periods by the ATM. As a result, it is probably not surprising that travel times did not improve in these periods. Even though average travel time increased in the peak period, the increase was larger in the first year of using the ATM system compared to the second year.

For the midday transition period and off-peak periods (PM for EB, AM for WB), there were small but statistically significant improvements in weekday average travel times. The differences in trends between weekday peak periods and other times also highlight the effectiveness of the ATM system in managing non-recurring congestion that might have occurred during off-peak periods if the facility had not been dynamically managed. All the changes were statistically significant in the WB direction but were mixed in the EB direction. The full average weekday average travel time results are shown in Table 3.

*Weekend Corridor-Level Average Travel Time Analysis*

ATM impacts were more pronounced on the weekends than on weekdays. Table 4 shows that there were statistically significant improvements in travel times for both the EB and WB weekend daytime peak periods. Before the ATM system was implemented, the shoulders were not used for travel during the weekends, even if there was demand for increased roadway capacity. After the ATM system was implemented, shoulders were opened for travel whenever additional capacity was needed. This additional roadway capacity brought on by the HSR likely contributed to the improvements in travel times along the corridor. After the implementation of the ATM, for both the EB and WB directions, the travel times improved during the weekend peak period. These improved trends can be seen from the yearly weekend average travel time profiles shown in Figures 4 and 5. Although travel times did improve, congestion was still present during the late afternoon.

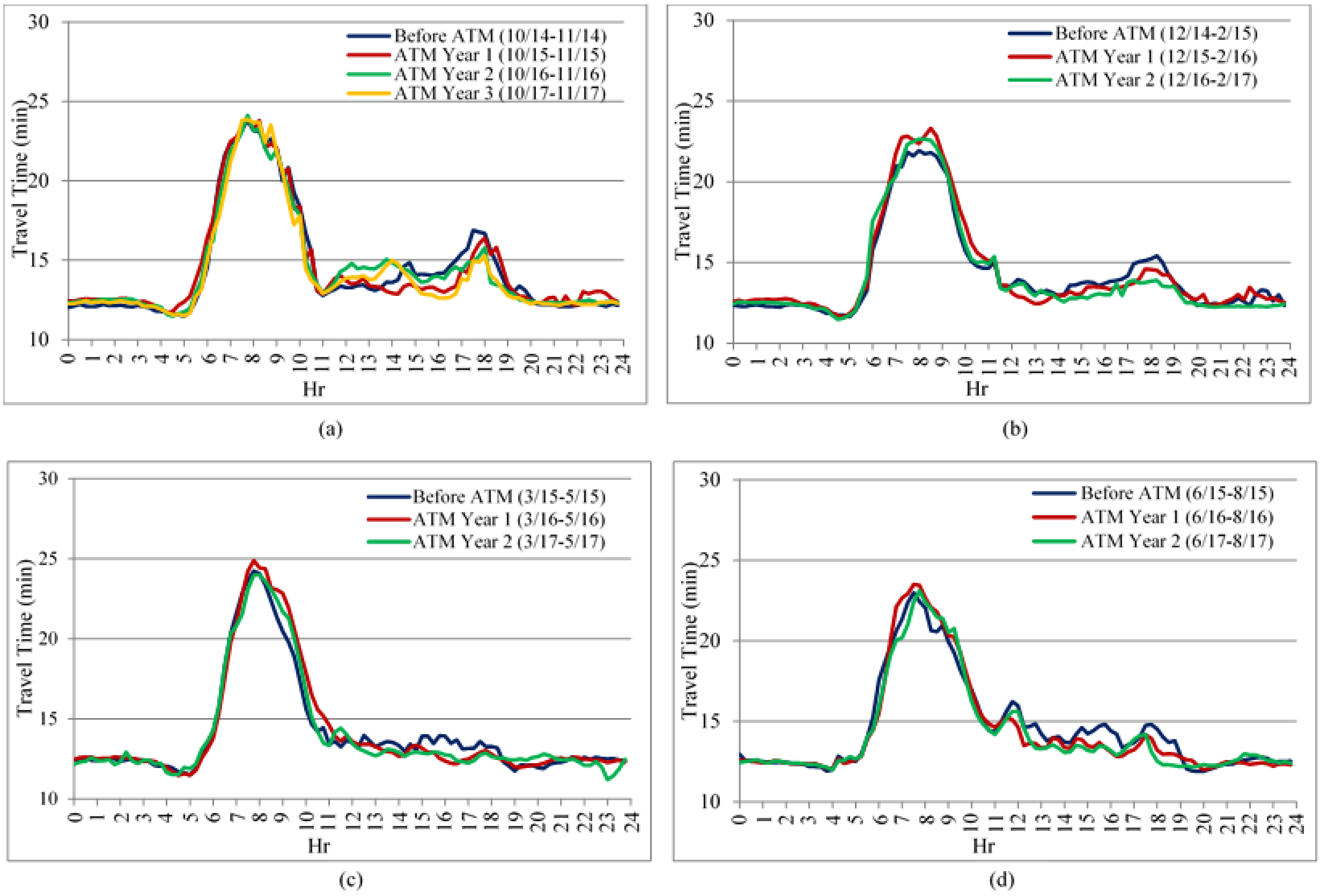
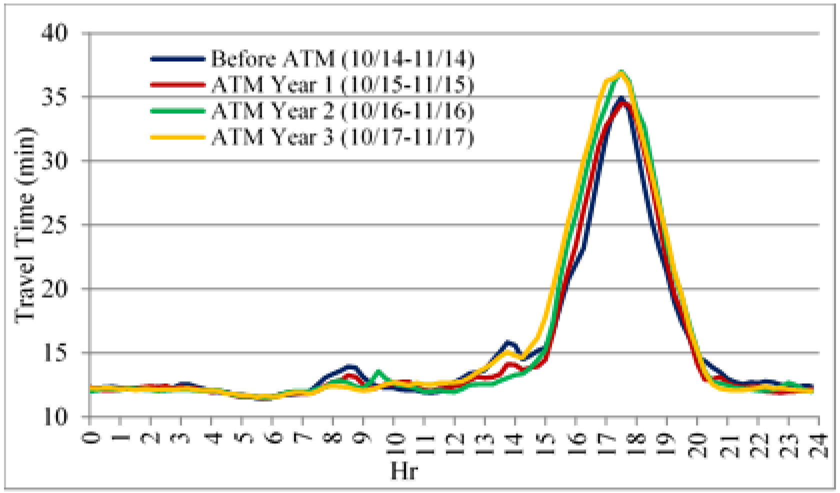
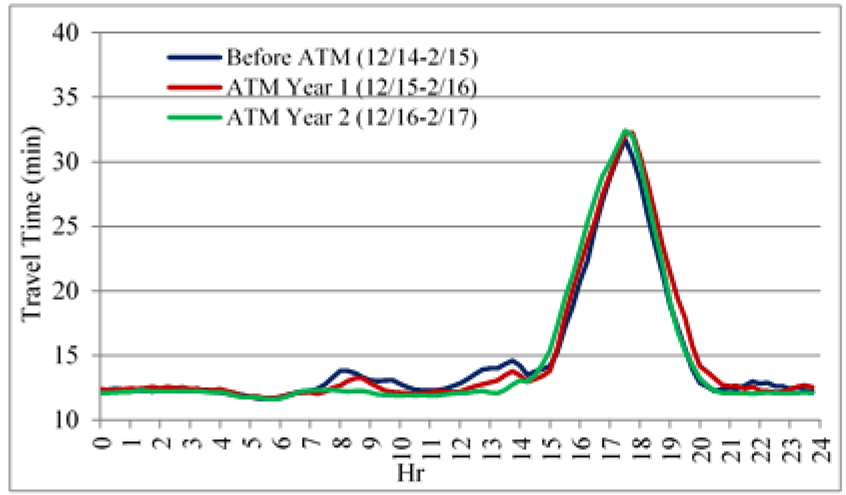


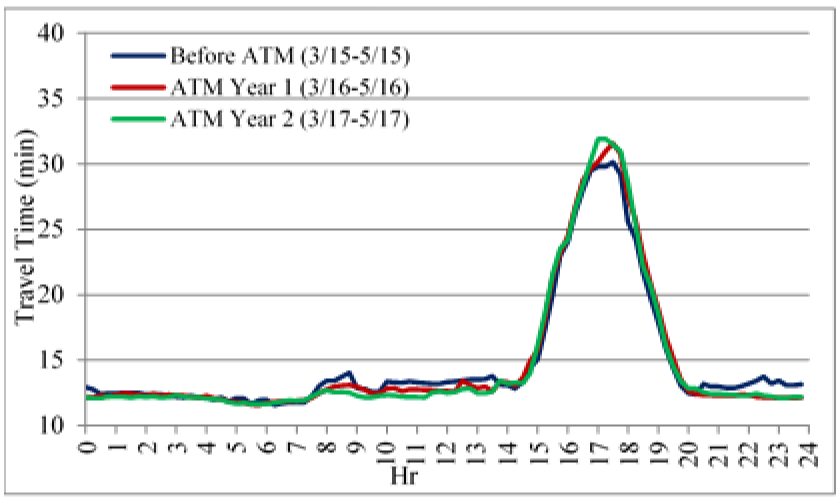

**Figure 2. Before and After Average Travel Time Profiles for Eastbound Average Weekday: (a) October-November; (b) December-February; (c) March-May; and (d) June-August**



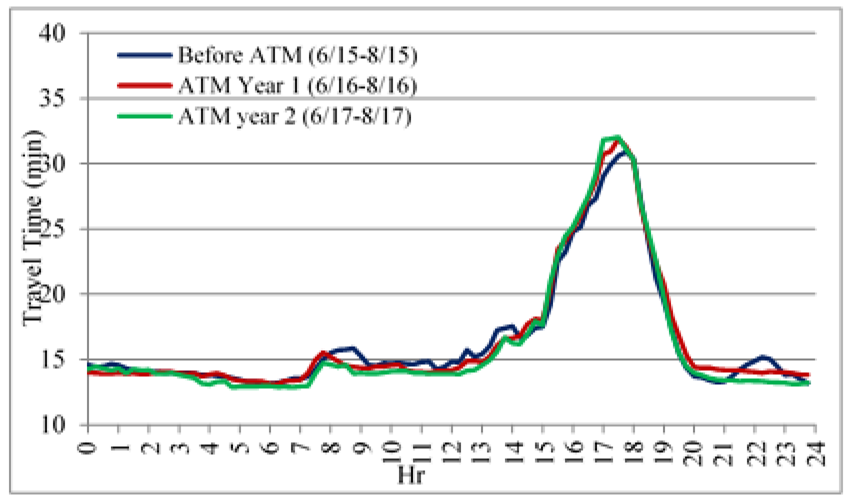

**(a)**




**(b)**




**(c)**




**(d)**

**Figure 3. Before and After Average Travel Time Profiles for Westbound Average Weekday: (a) October-November, (b) December-February, (c) March-May; and (d) June-August**

**Table 3. Before and After Average Travel Time Changes (Minutes) for Average Weekday (Entire Corridor)**

| Time Period | Comparison | Eastbound | | | | Westbound | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | AM Peak (5:30 AM–11 AM) | Midday (11 AM–2 PM) | PM peak (2 PM–8 PM) | Overnight (8 PM–5:30 AM) | AM Peak (5:30 AM–11 AM) | Midday (11 AM–2 PM) | PM peak (2 PM– 8 PM) | Overnight (8 PM–5:30 AM) |
| October-November | Before vs. After Year 1 | 0.98 (+5.35%) | 0.24 (+1.81%) | -1.09 (-7.31%) | 0.62 (+5.15%) | -0.13 (-1.06%) | -0.55 (-4.11%) | 0.69 (+3.04%) | -0.25 (-1.98%) |
| | Before vs. After Year 2 | 0.33 (+1.80%) | 1.01 (+7.56%) | -1.06 (-7.08%) | 0.2 (+1.62%) | -0.1 (-0.84%) | -0.95 (-7.17%) | 2.08 (+9.10%) | -0.24 (-1.95%) |
| | Before vs. After Year 3 | 0.71 (+3.87%) | 0.53 (+3.97%) | -1.55 (-10.34%) | 0.11 (+0.89%) | -0.27 (-2.17%) | 0.04 (+0.30%) | 2.93 (+12.84%) | -0.26 (-2.07%) |
| December-February | Before vs. After Year 1 | 1.25 (+7.69%) | -0.41 (-3.07%) | -0.83 (-5.73%) | 0.45 (+3.66%) | -0.37 (-2.91%) | -0.67 (-5.02%) | 1.13 (+4.79%) | 0.13 (+1.00%) |
| | Before vs. After Year 2 | 0.92 (+5.66%) | -0.08 (-0.60%) | -1.64 (-11.35%) | -0.09 (-0.74%) | -0.64 (-4.98%) | -1.19 (-8.95%) | 1.04 (+4.99%) | -0.19 (-1.58%) |
| March-May | Before vs. After Year 1 | 1.07 (+5.85%) | -1.05 (-7.31%) | -1.81 (-12.37%) | + 0.03 (+0.25%) | -0.91 (-6.89%) | -1.54 (-10.98%) | 0.17 (+0.78%) | -0.36 (-2.85%) |
| | Before vs. After Year 2 | 0.33 (+1.77%) | -1.41 (-9.56%) | -1.99 (-13.65%) | 0.08 (0.66%) | -0.23 (-1.88%) | -1.78 (-12.50%) | 0.93 (+4.25%) | -0.41 (-3.28%) |
| June-August | Before vs. After Year 1 | 0.78 (+4.46%) | -0.62 (-4.30%) | -1.36 (-9.34%) | -0.06 (-0.46%) | -0.24 (-1.67%) | -2.01 (-11.95%) | 1.54 (+6.80%) | -0.47 (-3.26%) |
| | Before vs. After Year 2 | 0.18 (+1.00%) | -0.56 (-3.92%) | -1.57 (-10.77%) | 0.04 (+0.36%) | -2.24 (-15.58%) | -3.87 (-23.09%) | 0.002 (+0.01%) | -2.18 (-15.10%) |

Green cells indicate statistically significant reductions at α = 0.05. Blue cells indicate statistically significant increases at α = 0.05.

**Table 4. Before and After Average Travel Time Changes (Minutes) for Average Weekend (Entire Corridor)**

| Time Period | Comparison | Eastbound | | Westbound | |
|---|---|---|---|---|---|
| | | Peak (10 AM–8 PM) | Off-peak (8 PM–10 AM) | Peak (10 AM–8 PM) | Off-peak (8 PM–10 AM) |
| October-November | Before vs. After Year 1 | -2.24 (-14.59%) | -0.21 (-1.77%) | -1.92 (-13.74%) | 0.06 (+0.47%) |
| | Before vs. After Year 2 | -0.85 (-7.05%) | 0.26 (+1.71%) | -1.09 (-7.77%) | -0.03 (-0.23%) |
| | Before vs. After Year 3 | -0.63 (-4.11%) | 0.14 (+1.19%) | -1.27 (-9.12%) | 0.03 (+0.21%) |
| December-February | Before vs. After Year 1 | -0.97 (-6.95%) | 0.16 (+1.33%) | -1.19 (-8.78%) | -1.28 (-9.44%) |
| | Before vs. After Year 2 | -1.36 (-9.72%) | 0.18 (+1.44%) | 0.07 (+ 0.58%) | -0.001 (-0.01%) |
| March-May | Before vs. After Year 1 | -1.89 (-12.36%) | 0.01 (+0.09%) | -2.4 (-16.18%) | 0.02 (+0.13%) |
| | Before vs. After Year 2 | -2.16 (-13.50%) | -0.01 -0.09% | -2.18 (-14.06%) | -0.07 (-0.54%) |
| June-August | Before vs. After Year 1 | -1.58 (-10.42%) | -0.01 (-0.11%) | -1.9 (-11.49%) | 0.04 (+0.29%) |
| | Before vs. After Year 2 | -2.51 (-17.07%) | -0.09 (-0.82%) | -4.3 (-25.97%) | -1.76 (-12.85%) |

Green cells indicate statistically significant reductions at $\alpha = 0.05$. Blue cells indicate statistically significant increases at $\alpha = 0.05$.

## Corridor-Level Travel Time Reliability Analysis

*Weekday Corridor-Level Travel Time Reliability Analysis*

For the EB AM peak period, statistically significant improvements in BI occurred in certain months. A similar trend occurred for the PM peak period in the WB direction. The results for the PM period in the EB direction and the AM period in the WB direction were mixed, in terms of both change and statistical significance. The same was true for the midday and overnight periods in the EB direction. However, other than the winter months in Year 1, there was steady improvement in both the midday and overnight periods in the WB direction in terms of BI.

For PTI, there were no improvements during the EB AM peak or WB PM peak periods. For the EB PM peak period, PTI improved for all months and the change was statistically significant. For the WB AM peak period, PTI decreased for all months, but not all of the decreases were statistically significant. PTI improved in the midday and overnight off-peak periods in the WB direction compared to the EB direction.

Tables 5 and 6 show the change in BI and PTI for the average weekday for both directions. Based on these results, reliability generally improved during the off-peak periods but continued to degrade during the peak periods. 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.

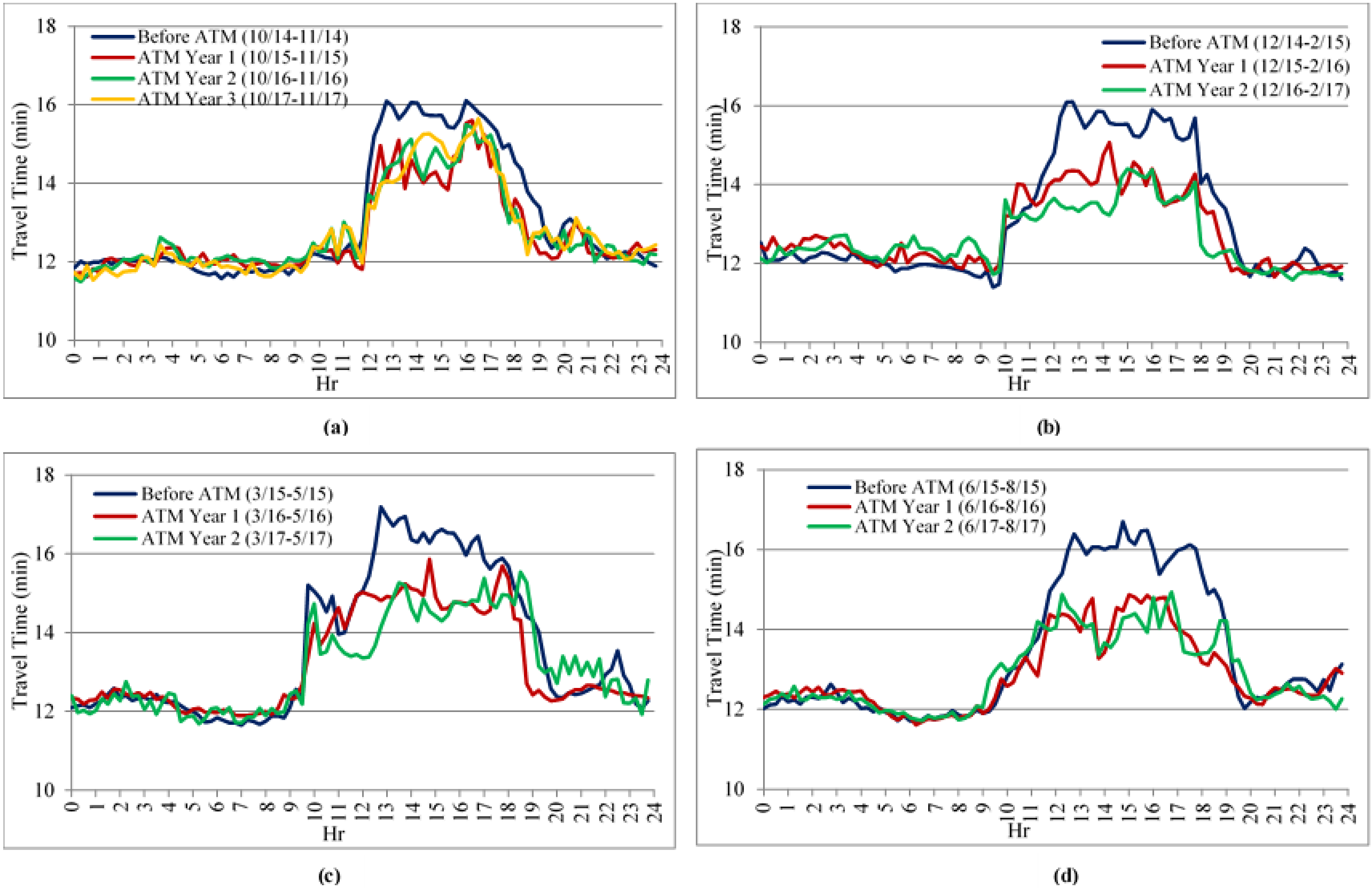
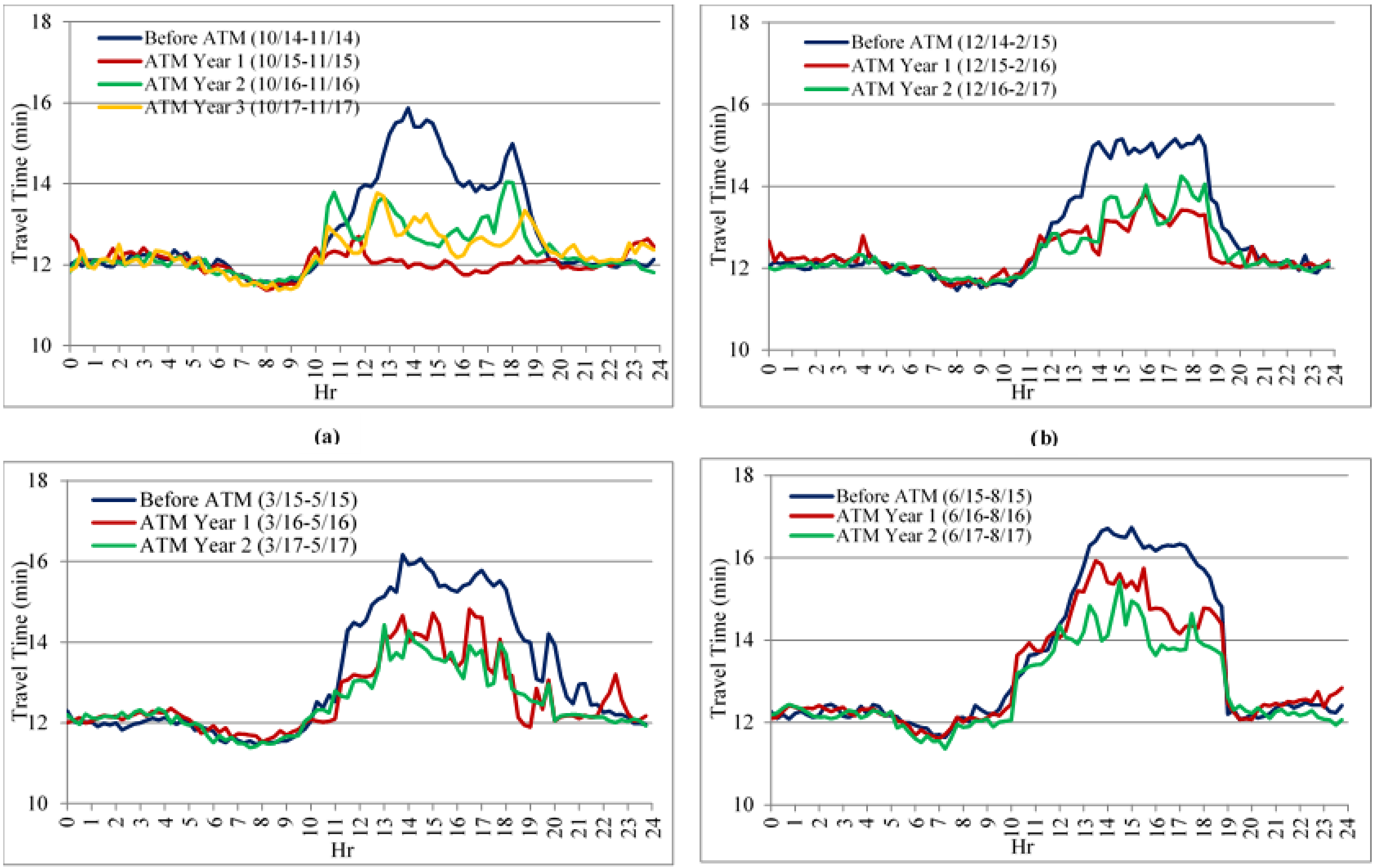



**Figure 4. Before and After Average Travel Time Profiles for Eastbound Average Weekend: (a) October-November; (b) December-February; (c) March-May; and (d) June-August**




(c) (d)

**Figure 5. Before and After Average Travel Time Profiles for Westbound Average Weekend: (a) October-November; (b) December-February; (c) March-May; and (d) June-August**

**Table 5. Weekday Before and After Changes in Average BI (Entire Corridor)**

| Time Period | Comparison | Eastbound | | | | Westbound | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | AM Peak (5:30 AM–11 AM) | Midday (11 AM–2 PM) | PM peak (2 PM–8 PM) | Overnight (8 PM–5:30 AM) | AM Peak (5:30 AM–11 AM) | Midday (11 AM–2 PM) | PM peak (2 PM–8 PM) | Overnight (8 PM–5:30 AM) |
| October-November | Before vs. After Year 1 | 0.01 (+7.59%) | 0.01 (+13.54%) | 0.01 (+8.87%) | 0.03 (+23.12%) | 0.002 (+6.81%) | -0.03 (-45.42%) | -0.01 (-9.83%) | -0.02 (-47.08%) |
| | Before vs. After Year 2 | -0.04 (-39.11%) | 0.01 (+54.10%) | -0.001 (-1.17%) | -0.004 (-31.46%) | 0.01 (+18.43%) | -0.05 (-59.01%) | -0.01 (-12.83%) | -0.09 (-47.69%) |
| | Before vs. After Year 3 | -0.04 (-35.7%) | 0.02 (+42.22%) | -0.03 (-34.3%) | -0.003 (-25.6%) | 0.002 (+7.84%) | -0.002 (-3.36%) | -0.003 (-0.38%) | -0.02 (-53.44%) |
| December-February | Before vs. After Year 1 | 0.01 (+22.40%) | -0.03 (-47.69%) | *0.02 (+18.62%)* | 0.05 (+22.42%) | -0.02 (-53.56%) | -0.001 (-13.62%) | -0.0003 (-0.02%) | 0.01 (+50.47%) |
| | Before vs. After Year 2 | 0.01 (+10.05%) | 0.002 (+3.57%) | -0.03 (-46.87%) | -0.01 (-62.52%) | -0.02 (-66.04%) | -0.04 (-56.50%) | -0.01 (-18.56%) | -0.02 (-53.55%) |
| March-May | Before vs. After Year 1 | 0.02 (+30.73%) | -0.01 (-9.17%) | -0.03 (-57.11%) | -0.002 (-23.52%) | -0.02 (-46.58%) | -0.02 (-42.95%) | -0.02 (-26.11%) | -0.02 (-69.93%) |
| | Before vs. After Year 2 | -0.01 (-13.95%) | -0.001 (-1.61%) | -0.01 (-20.12%) | 0.001 (+9.94%) | -0.02 (-57.46%) | -0.03 (-59.18%) | -0.002 (-3.06%) | -0.02 (-59.52%) |
| June-August | Before vs. After Year 1 | -0.01 (-14.37%) | 0.003 (+8.55%) | 0.004 (+9.57%) | -0.004 (-30.39%) | 0.003 (+11.57%) | -0.03 (-47.90%) | -0.002 (-4.49%) | -0.02 (-60.29%) |
| | Before vs. After Year 2 | -0.02 (-20.92%) | 0.02 (+49.06%) | 0.02 (+45.16%) | 0.002 (+16.93%) | -0.01 (-34.51%) | -0.04 (-54.38%) | -0.001 (-0.94%) | -0.02 (-53.18%) |

BI = Buffer index. Green cells indicate statistically significant reductions at α = 0.05. Blue cells indicate statistically significant increases at α = 0.05.

**Table 6. Weekday Before and After Changes in Average PTI (Entire Corridor)**

| Time Period | Comparison | Eastbound AM Peak (5:30 AM–11 AM) | Eastbound Midday (11 AM–2 PM) | Eastbound PM peak (2 PM–8 PM) | Eastbound Overnight (8 PM–5:30 AM) | Westbound AM Peak (5:30 AM–11 AM) | Westbound Midday (11 AM–2 PM) | Westbound PM peak (2 PM–8 PM) | Westbound Overnight (8 PM–5:30 AM) |
|---|---|---|---|---|---|---|---|---|---|
| October-November | Before vs. After Year 1 | 0.08 (+5.63%) | 0.03 (+2.45%) | -0.08 (-6.42%) | 0.08 (+8.44%) | -0.01 (-0.88%) | -0.08 (-7.17%) | 0.04 (+2.14%) | -0.04 (-3.79%) |
| | Before vs. After Year 2 | -0.04 (-2.58%) | 0.16 (+15.23%) | -0.09 (-7.19%) | 0.01 (+1.17%) | -0.003 (-0.29%) | -0.123 (-11.64%) | 0.14 (+7.81%) | -0.04 (-3.77%) |
| | Before vs. After Year 3 | 0.001 (+0.09%) | 0.06 (+6.04%) | -0.15 (-12.79%) | 0.005 (+0.52%) | -0.02 (-1.97%) | -0.001 (-0.06%) | 0.23 (+12.28% | -0.04 (-4.10%) |
| December-February | Before vs. After Year 1 | 0.12 (+9.17%) | -0.06 (-5.56%) | -0.05 (-4.66%) | 0.08 (+8.55%) | -0.05 (-5.21%) | -0.06 (-5.65%) | 0.08 (+4.58%) | 0.02 (+2.03%) |
| | Before vs. After Year 2 | 0.06 (+4.88%) | -0.004 (-0.43%) | -0.16 (-13.88%) | -0.02 (-2.02%) | -0.08 (-7.76%) | -0.13 (-12.62%) | 0.06 (+3.43%) | -0.02 (-2.61%) |
| March-May | Before vs. After Year 1 | 0.11 (+7.30%) | -0.1 (-8.80%) | -0.19 (-16.71%) | -0.001 (-0.07%) | -0.11 (-11.05%) | -0.16 (-14.05%) | -0.05 (-2.89%) | -0.06 (-5.72%) |
| | Before vs. After Year 2 | 0.02 (+1.05%) | -0.11 (-9.59%) | -0.17 (-14.68%) | 0.01 (+0.78%) | -0.12 (-11.72%) | -0.17 (-15.25%) | 0.09 (+5.03%) | -0.05 (-5.31%) |
| June-August | Before vs. After Year 1 | 0.05 (+3.47%) | -0.04 (-3.96%) | -0.11 (-9.05%) | -0.01 (-0.88%) | -0.01 (-1.26%) | -0.17 (-14.68%) | 0.1 (+6.52%) | -0.05 (-5.01%) |
| | Before vs. After Year 2 | -0.003 (-0.23%) | -0.02 (-1.90%) | -0.1 (-9.12%) | 0.01 (+0.7%) | -0.16 (-16.59%) | -0.3 (-25.82%) | 0.01 (+0.08%) | -0.16 (-16.47%) |

PTI = planning time index. Green cells indicate statistically significant reductions at α = 0.05. Blue cells indicate statistically significant increases at α = 0.05.

*Weekend Corridor-Level Travel Time Reliability Analysis*

The travel time reliability for the weekend peak period improved for most periods in the WB direction. In the EB direction, peak period PTI improved more than BI. 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 Table 7.

*Comparison Between HSR and Non-HSR Segments*

Although the corridor-level analysis showed that the ATM system provided some travel time improvements during weekday off-peak and weekend operations, it was unclear what role the different ATM elements played in these improvements. Anecdotally, TOC staff indicated that they believed the addition of dynamic HSR was responsible for the majority of the observed benefits. As a result, the operational performance of the sections with HSR, AVSL, and LUCS was compared with that of sections with only AVSL and LUCs.

For this, the corridor level data were divided into segments with an HSR section and without an HSR section. The change in travel time was analyzed for both sections to assess whether benefits were uniformly distributed. A paired *t*-test was conducted to determine if the change was significant. Before ATM was implemented, HSR was activated only on weekdays from 5:30 to 11:00 AM in the EB direction and from 2:00 to 8:00 PM in the WB direction. After ATM activation, HSR was used dynamically in addition to the fixed time period. Figures 6 and 7 show the percentage change in travel time and travel time reliability in Years 1 and 2 compared to the pre-ATM period for HSR and non-HSR segments.

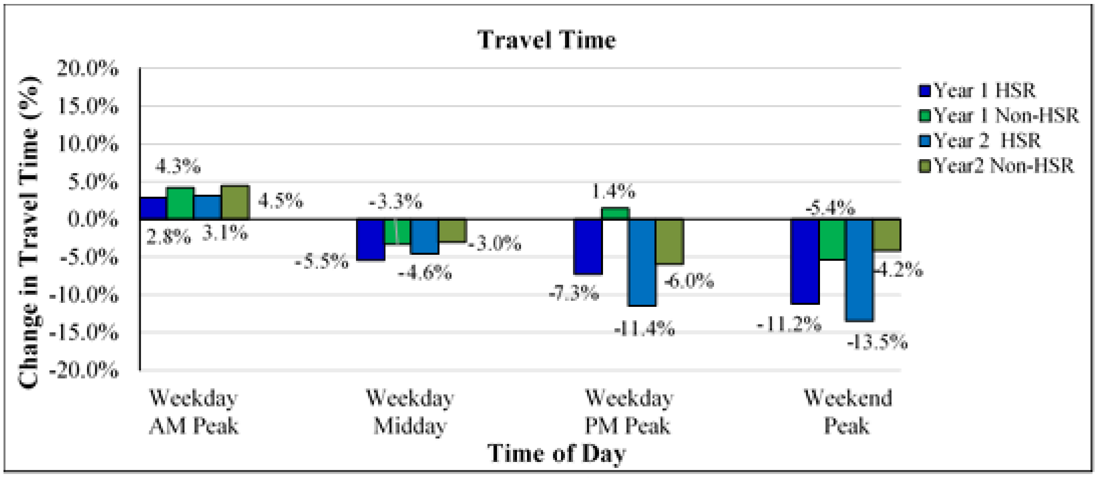
Figure 6 shows that most improvements in travel time occurred during off-peak periods on weekdays and daytime peaks on weekends in the EB direction. The weekend peak showed the most statistically significant improvement in the HSR section, where travel time was reduced by 11.20% in Year 1 and 13.50% in Year 2 compared to the pre-ATM condition. Except for the change in the weekday PM peak period for non-HSR sections, all other changes in travel time in the EB direction were statistically significant.

The change was more prominent in the WB direction, as seen in Figure 7. Travel time for almost all HSR sections improved whereas that for all non-HSR sections deteriorated in both years, with the worst time period being the PM peak. In the WB direction, the HSR segments showed the largest improvement during the weekday midday period, with travel time reductions of 12.60% in Year 1 and 15.10% in Year 2. Most of the changes in travel times were statistically significant. It should be noted that travel time did show improvements on non-HSR sections during off-peak periods in both directions, but the magnitude was much smaller compared to that of the HSR segments.

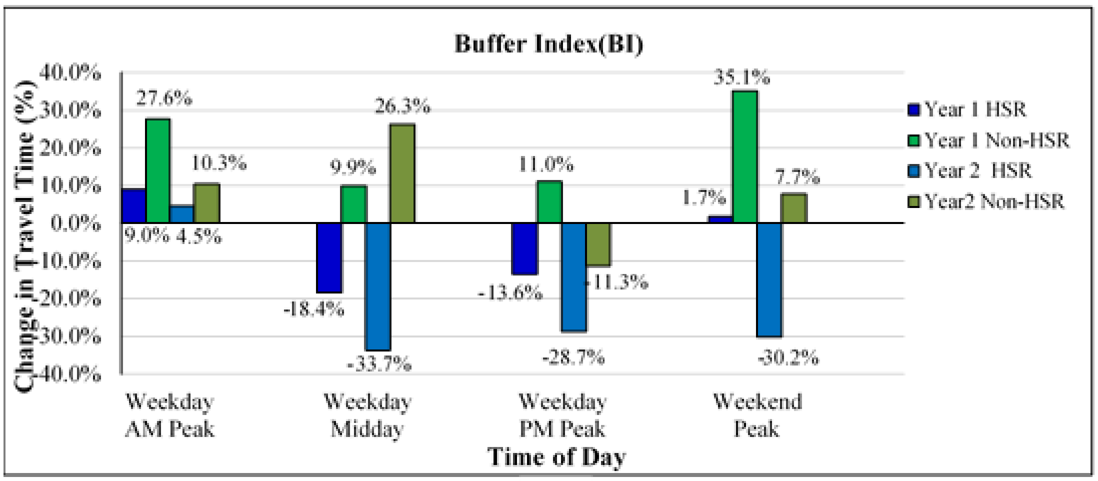
**Table 7. Weekend Before and After Changes in Average BI and PTI (Entire Corridor)**

| Time Period | Comparison | Buffer Index | | | | Planning Time Index | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Eastbound | | Westbound | | Eastbound | | Westbound | |
| | | Peak (10 AM–8 PM) | Off-peak (8 PM–10 AM) | Peak (10 AM–8 PM) | Off-peak (8 PM–10 AM) | Peak (10 AM–8 PM) | Off-peak (8 PM–10 AM) | Peak (10 AM–8 PM) | Off-peak (8 PM–10 AM) |
| October-November | Before vs. After Year 1 | -0.02 (-19.77%) | 0.002 (+6.57%) | -0.06 (-65.37%) | 0.01 (+56.58%) | -0.2 (-16.23%) | 0.02 (+1.80%) | -0.22 (-18.88%) | 0.02 (+1.40%) |
| | Before vs. After Year 2 | 0.01 (+6.64%) | 0.01 (+25.32%) | -0.03 (-26.87%) | -0.001 (-6.97%) | -0.06 (-4.73%) | 0.03 (+2.70%) | -0.11 (-26.87%) | -0.004 (-0.38%) |
| | Before vs. After Year 3 | 0.06 (+61.80%) | 0.01 (+25.65%) | -0.03 (-29.69%) | 0.01 (+45.12%) | 0.02 (+1.34%) | 0.02 (+1.67%) | -0.13 (-11.62%) | 0.01 (+0.94%) |
| December-February | Before vs. After Year 1 | -0.02 (-19.71%) | 0.002 (+8.07%) | -0.05 (-50.86%) | 0.003 (+21.77%) | -0.1 (-8.52%) | 0.01 (+1.45%) | -0.14 (-12.86%) | 0.008 (+0.92%) |
| | Before vs. After Year 2 | -0.05 (-50.05%) | 0.005 (+23.18%) | -0.05 (-52.94%) | 0.001 (+5.66%) | -0.15 (-13.61%) | 0.02 (+1.88%) | -0.15 (-13.61%) | 0.001 (+0.06%) |
| March-May | Before vs. After Year 1 | 0.012 (+15.85%) | -0.01 (-38.15%) | -0.06 (-67.24%) | -0.01 (-35.50%) | -0.13 (-10.72%) | -0.01 (-1.02%) | -0.27 (-22.22%) | -0.01 (-0.70%) |
| | Before vs. After Year 2 | 0.003 (+4.63%) | -0.01 (-19.86%) | -0.03 (-52.58%) | -0.01 (-52.58%) | -0.17 (-13.56%) | -0.01 (-0.61%) | -0.23 (-19.20%) | -0.02 (-2.01%) |
| June-August | Before vs. After Year 1 | 0.01 (+32.15%) | -0.01 (-31.24%) | -0.01 (-16.94%) | 0.001 (+11.31%) | -0.11 (-8.83%) | -0.01 (-1.04%) | -0.15 (-12.57%) | 0.004 (+0.46%) |
| | Before vs. After Year 2 | 0.01 (+19.48%) | -0.01 (-36.44%) | -0.04 (-45.90%) | 0.005 (+37.08%) | -0.19 (-15.69%) | -0.02 (-1.91%) | -0.34 (-28.55%) | -0.14 (-12.40%) |

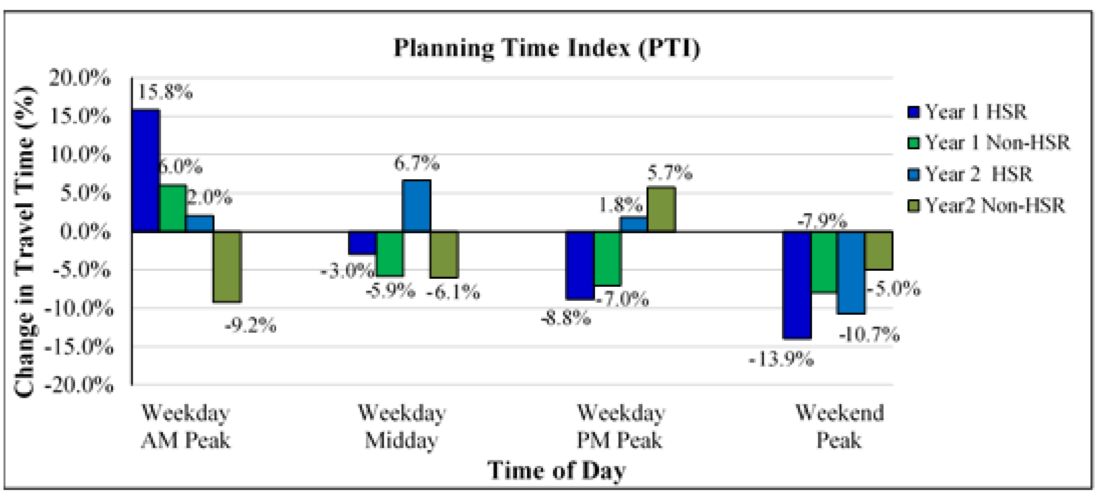
BI = buffer index; PTI = planning time index. Green cells indicate statistically significant reductions at α = 0.05. Blue cells indicate statistically significant increases at α = 0.05.




**(a)**

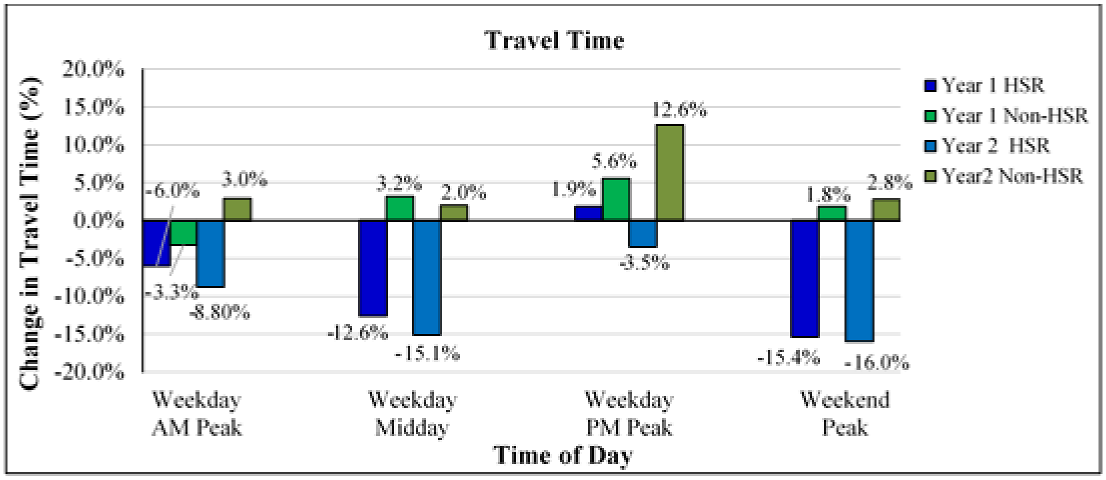



**(b)**

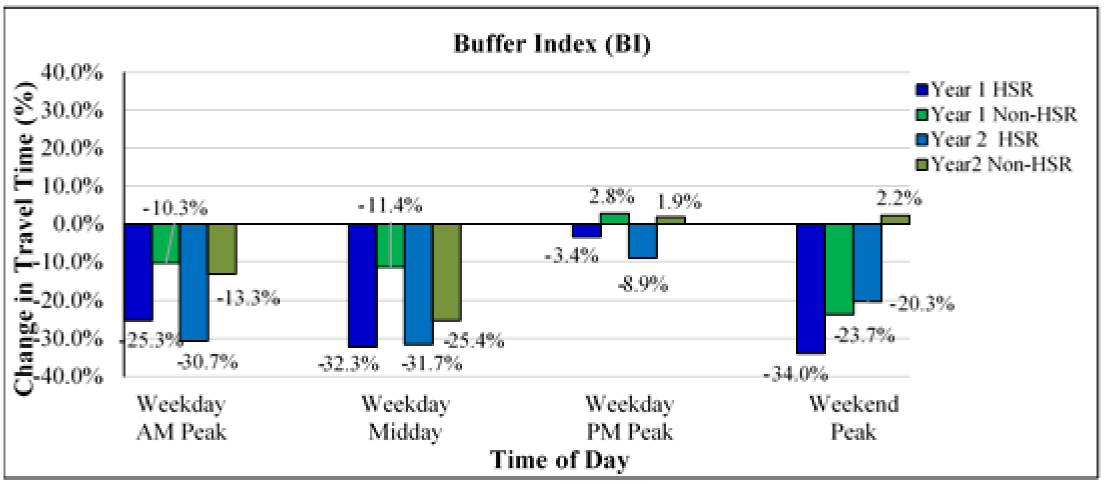



**(c)**

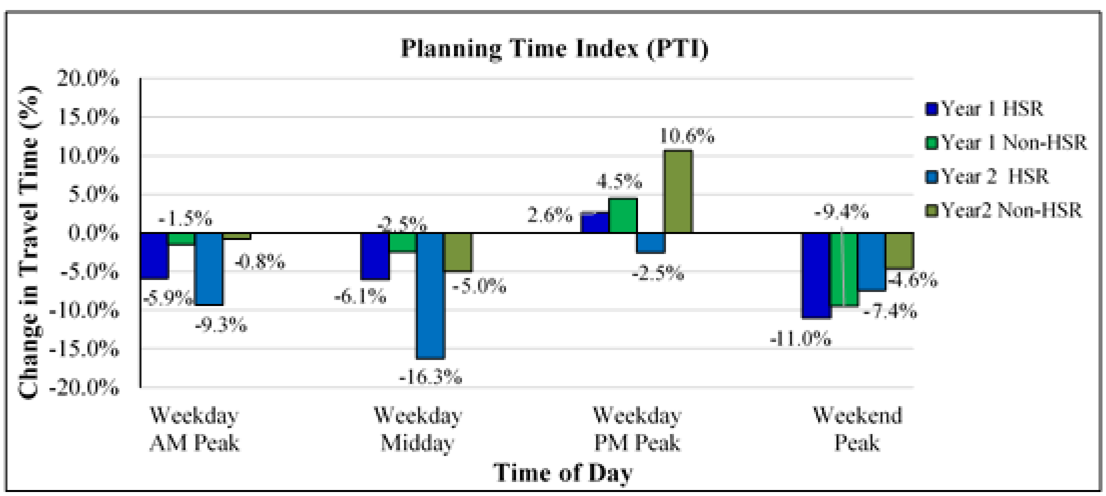
**Figure 6. Comparison Between HSR and Non-HSR Sections Eastbound: (a) Travel Time; (b) Buffer Index; and (c) Planning Time Index. HSR = hard shoulder running.**




(a)




(b)




(c)

**Figure 7. Comparison Between HSR and Non-HSR Sections Westbound: (a) Travel Time; (b) Buffer Index; and (c) Planning Time Index. HSR = hard shoulder running.**

In the WB direction, travel time reliability improved for all periods except for the PM peak. Even though improvements occurred in both the HSR and non-HSR sections, the improvements were larger for the HSR sections. In most cases, BI and PTI increased in the AM peak period in the EB direction. However, during the weekday off-peak period, BI increased for non-HSR sections and decreased for HSR sections as expected. Changes in PTI during off-peak periods in the EB direction and during weekend peak periods were mixed. In general, most of the travel time reliability results matched the findings in the average travel time analysis.

## Subsegment-Level Operational Analysis

*Average Travel Time and Travel Time Reliability Analysis*

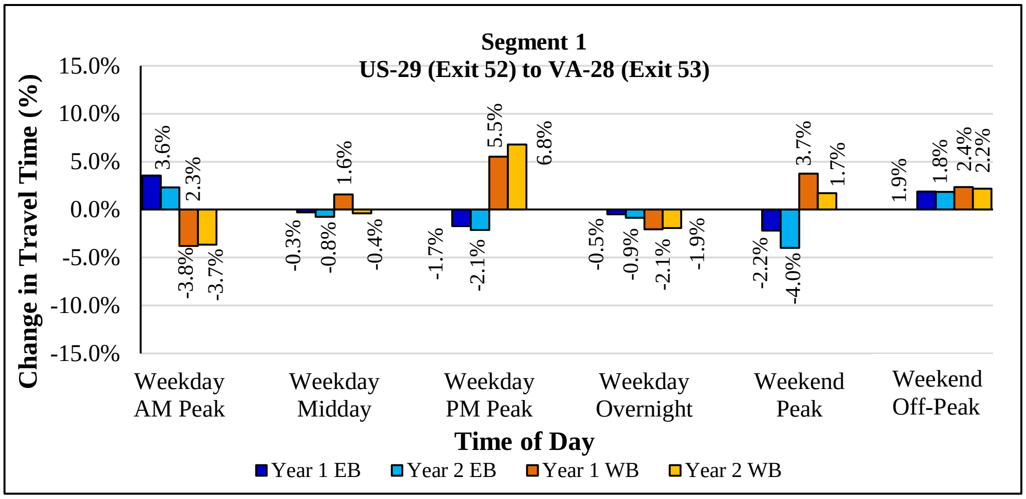
Even though a separate analysis was carried out to compare the safety and operational improvements of the HSR and non-HSR segments, it was also important to look at the operational performance of each segment in both directions to define specific areas where the ATM system performed better or worse. Both travel time and travel time reliability were evaluated. Table 8 describes the ATM components on each segment and the start and end points of each segment.

Figure 8 summarizes the changes in average travel time for Segments 1 through 3, which were all sections that had AVSLs and LUCS but not HSR. The segment-level analysis shows that some improvements in the weekday off-peak periods occurred in these segments, but the magnitude was small. Weekend off-peak periods worsened for all three segments. There were some reductions in Segments 1 and 2 in the EB direction during weekend peak periods, but the WB direction had travel time increases for all these segments. Peak periods in the peak direction continued to degrade in terms of travel time in both directions for both years.

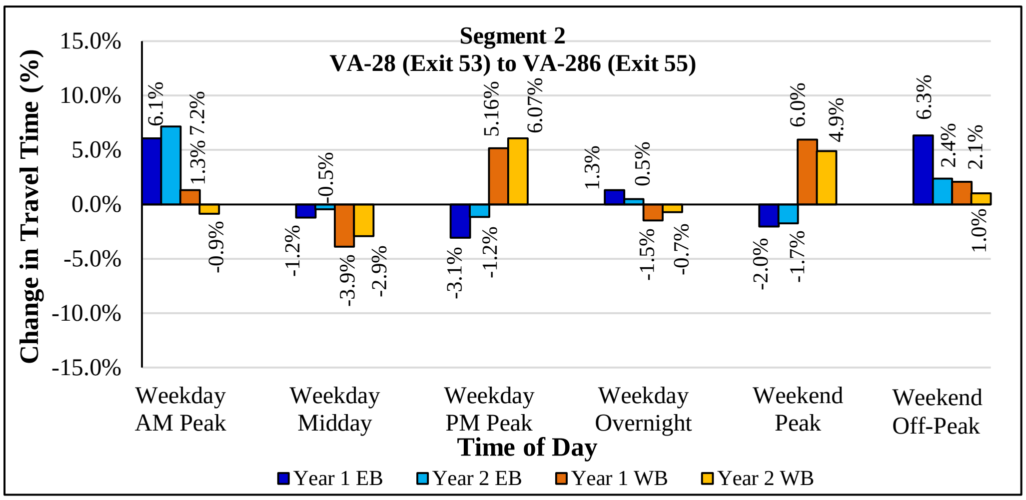
**Table 8. Description of ATM Components on I-66 Corridor by Segment**

| Segment | Location | Approx. Length (mi) | AADT (2016) | ATM Techniques | Roadway Characteristics |
|---|---|---|---|---|---|
| 1 | US-29 (Exit 52) to VA-28 (Exit 53) | 1.3 | EB: 67,000 WB: 66,000 | AVSL, LUCS | Four lanes in each direction. HOV-2 present in leftmost lane. HOV-2 operating hours are 5:30-9:30 AM EB and 3:00-7:00 PM WB. They are not dynamic. |
| 2 | VA-28 (Exit 53) to VA-286 (Exit 55) | 1.9 | EB: 80,000 WB: 81,000 | AVSL, LUCS | Four lanes in each direction. HOV-2 present in leftmost lane. HOV-2 operating hours are 5:30-9:30 AM EB and 3:00-7:00 PM WB. They are not dynamic. |
| 3 | VA-286 (Exit 55) to US-50 (Exit 57) | 2.6 | EB: 64,000 WB: 61,000 | AVSL, LUCS | Four lanes in each direction. HOV-2 present in leftmost lane. HOV-2 operating hours are 5:30-9:30 AM EB and 3:00-7:00 PM WB. They are not dynamic. |
| 4 | US-50 (Exit 57) to VA-123 (Exit 60) | 1.9 | EB: 92,000 WB: 92,000 | AVSL, LUCS, HSR | Three lanes + shoulder lane in both directions. Rightmost shoulder lane is used as travel lane during respective peak hours. Leftmost lane operates as HOV-2 lane from 5:30-9:30 AM EB and 3:00-7:00 PM WB. |
| 5 | VA-123 (Exit 60) to VA-243 (Exit 62) | 2.1 | EB: 93,000 WB: 86,000 | AVSL, LUCS, HSR | Three lanes + shoulder lane in both directions. Rightmost shoulder lane is used as travel lane during respective peak hours. Leftmost lane operates as HOV-2 lane from 5:30-9:30 AM EB and 3:00-7:00 PM WB. |
| 6 | VA-243 (Exit 62) to I-495 (Exit 64) | 3.2 | EB: 81,000 WB: 86,000 | AVSL, LUCS, HSR | Three lanes + shoulder lane in both directions. Rightmost shoulder lane is used as travel lane during respective peak hours. Leftmost lane operates as HOV-2 lane from 5:30-9:30 AM EB and 3:00-7:00 PM WB. |

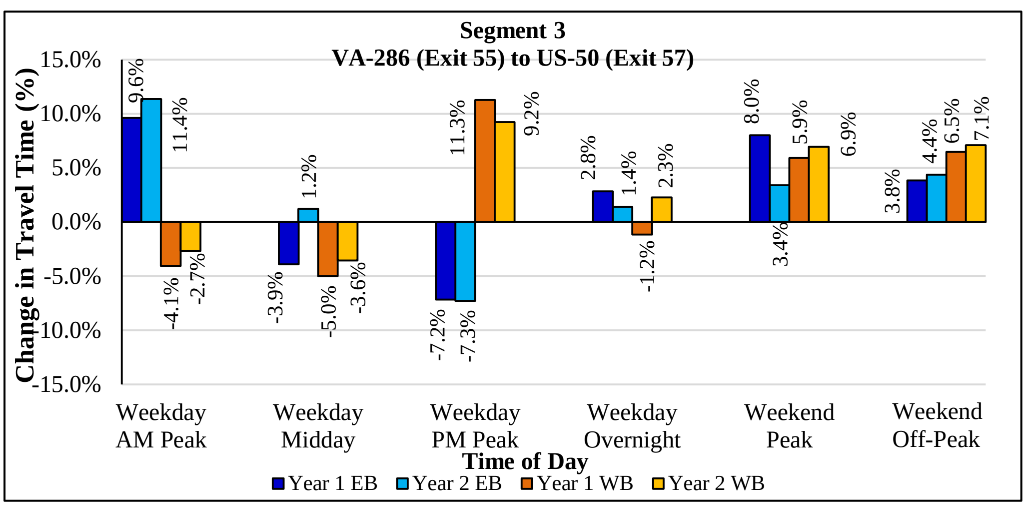
ATM = active traffic management; AADT = annual average daily traffic; EB = eastbound; WB = westbound; AVSL = advisory variable speed limit; LUCS = lane use control signal; HSR = hard should running.




**(a)**




**(b)**




**(c)**

**Figure 8. Change in Travel Time Between (a) US-29 (Exit 52) to VA-28 (Exit 53); (b) VA-28 (Exit 53) to VA-286 (Exit 55); and (c) VA-286 (Exit 55) to US-50 (Exit 57). EB = eastbound; WB = westbound.**

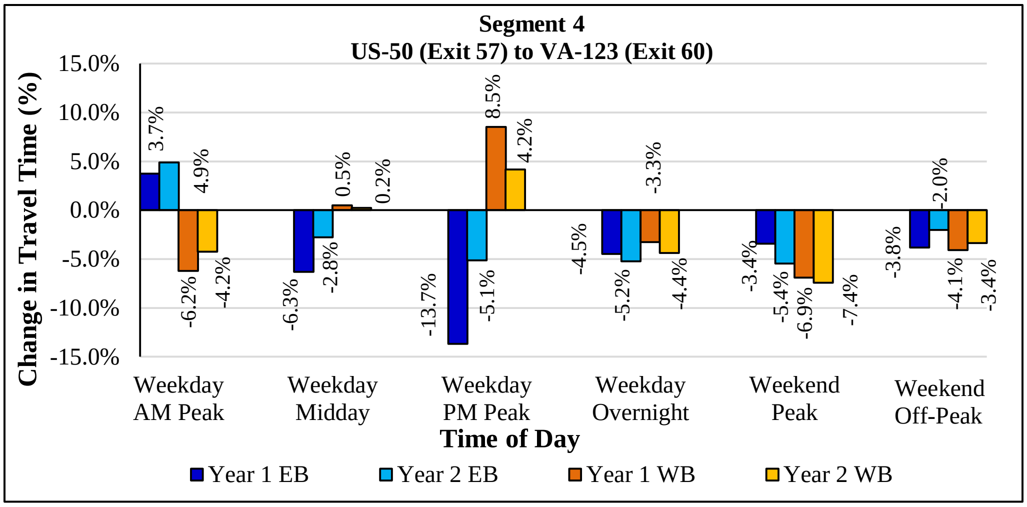
Figure 9 shows the change in travel time on Segments 4 through 6, which all had HSR in addition to LUCS and AVSL. For weekdays, the general patterns were same as for the previous segments but the reductions were larger in magnitude. Travel time during the PM peak period in the EB direction and the AM peak period in the WB direction improved significantly but deteriorated in the peak direction, as they are locations where the heaviest congestion on I-66 persists. Segments 4 through 6 showed the greatest improvements in mitigating delay over weekends in both the EB and WB directions after the implementation of ATM. Based on the average travel time analysis, this confirms that most of the improvements in traffic operations seemed to occur because of HSR. Although LUCS and AVSL may have had some incident management benefits, they did not appear to produce consistently significant reductions in average travel times.

Tables 9 and 10 summarize the change in travel time reliability. The results for changes in reliability were mixed, but travel time was more reliable in Segments 4 through 6 than in other segments.

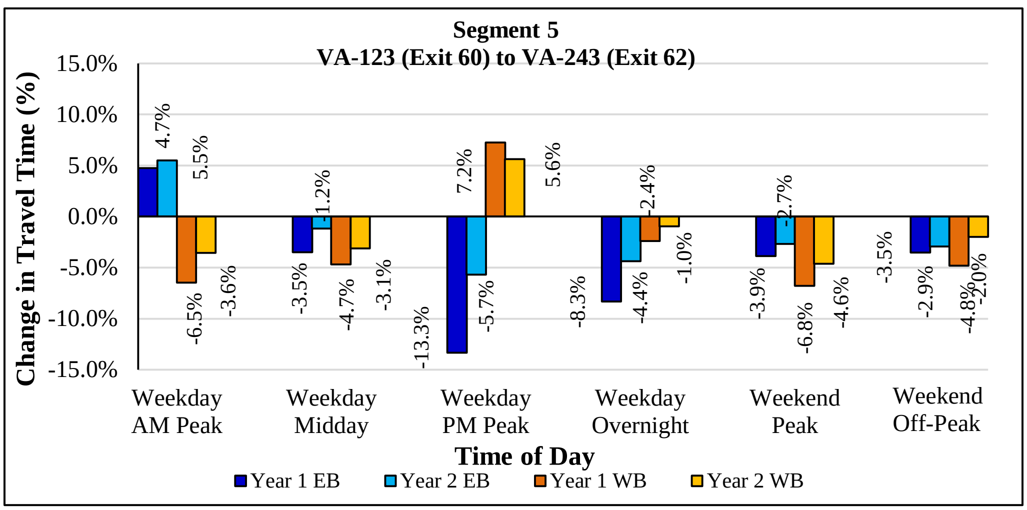
**Total Delay Analysis**

The operational analysis showed consistent reductions in delay on weekends, with more mixed results on weekdays (Table 11). The increases in delay during weekday peak periods were likely attributable to background changes in traffic volumes rather than to the ATM, however. For example, the SafeTrack projects on Metrorail caused a shift back to personal automobiles in some cases (Ali and Murray-Tuite, 2018). Given the number of external factors that influence operations on weekdays, the total delay analysis focused only on weekend days where changes in operations could be more directly attributed to the ATM system. The delays were also broken down to determine the relative impact of the HSR sections and the non-HSR segments on total delay.

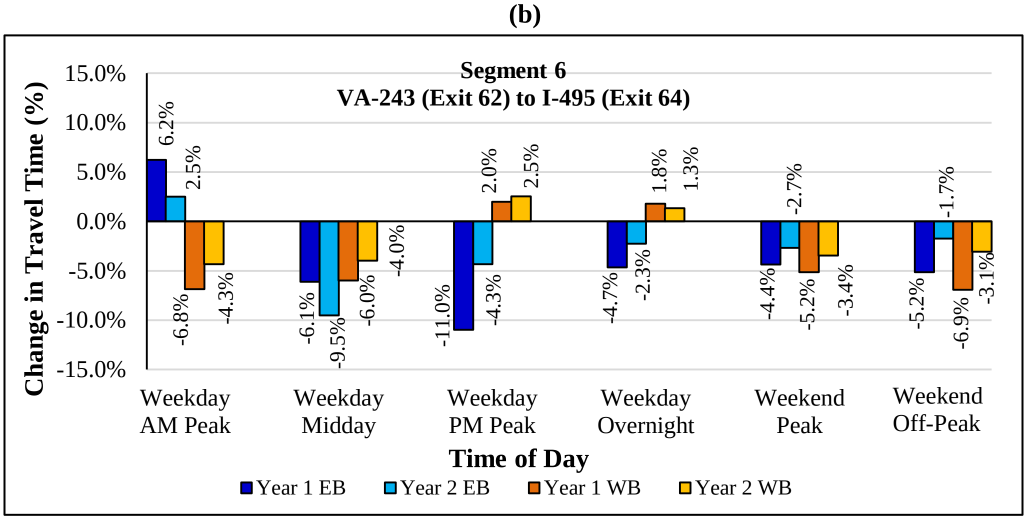
The segment-level total delay analysis shows that the segments with HSR (Segments 4 through 6) showed consistent reductions in traveler delay during weekends. The other segments with only AVSL and LUCS showed reductions in some time periods but also showed increases in delay at other times. The rate of reduction in total delay for these segments was also smaller in magnitude than for the segments with HSR. This result is consistent with all of the operational findings reported thus far and reinforces the positive effect of HSR in reducing total delay during weekends.




**(a)**




**(b)**




**(c)**

**Figure 9. Change in Travel Time Between (a) US-50 (Exit 57) to VA-123 (Exit 60); (b) VA-123 (Exit 60) to VA-243 (Exit 62); and (c) VA-243 (Exit 62) to I-495 (Exit 64). EB = eastbound; WB = westbound.**

**Table 9. Percentage Change in Buffer Index as Compared to Pre-ATM Period**

| Direction | Time Period | Segment 1 (Exit 52 to 53) | | Segment 2 (Exit 53 to 55) | | Segment 3 (Exit 55 to 57) | | Segment 4 (Exit 57 to 60) | | Segment 5 (Exit 60 to 62) | | Segment 6 (Exit 62 to 64) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Year 1 | Year 2 | Year 1 | Year 2 | Year 1 | Year 2 | Year 1 | Year 2 | Year 1 | Year 2 | Year 1 | Year 2 |
| EB | Weekday AM Peak | 8.5% | 10.9% | 3.9% | 5.4% | **-1.4%** | 3.0% | **-6.6%** | **-5.7%** | 7.4% | 5.8% | 6.4% | **-4.5%** |
| | Weekday Midday | 3.6% | 2.5% | 1.5% | 2.5% | **-4.9%** | **-3.8%** | **-27.7%** | **-15.9%** | **-14.0%** | **-20.1%** | **-6.3%** | **-7.8%** |
| | Weekday PM Peak | **-11.6%** | **-21.2%** | 22.0% | **-7.3%** | **-12.8%** | **-14.0%** | **-13.0%** | **-21.9%** | **-6.2%** | **-27.9%** | **-16.7%** | **-3.0%** |
| | Weekday Overnight | **-2.2%** | **-2.7%** | 4.7% | **-4.1%** | **-11.1%** | **-3.7%** | **-16.1%** | **-11.8%** | **-17.0%** | **-26.0%** | **-3.5%** | 5.5% |
| | Weekend Peak | 14.7% | 17.7% | **-7.9%** | **-5.4%** | **-5.7%** | **-7.1%** | 7.6% | **-5.9%** | 8.0% | 12.9% | **-24.0%** | **-11.0%** |
| | Weekend Off-peak | 5.5% | 5.0% | 5.0% | **-13.6%** | 0.7% | **-9.1%** | **-0.1%** | **-0.4%** | **-33.2%** | **-35.5%** | 5.3% | 5.2% |
| WB | Weekday AM Peak | **-5.6%** | **-12.2%** | 19.1% | **-16.4%** | 14.1% | 11.3% | 7.4% | 3.5% | **-3.1%** | **-4.4%** | **-8.7%** | **-3.8%** |
| | Weekday Midday | 2.2% | 5.2% | 6.7% | **-8.1%** | 24.0% | **-15.0%** | **-1.5%** | **-9.1%** | 1.2% | **-22.7%** | **-13.6%** | **-20.6%** |
| | Weekday PM Peak | 13.6% | -19.3% | 13.1% | **-26.3%** | 14.8% | **-17.3%** | 6.3% | **-5.4%** | 2.6% | 3.4% | **-10.6%** | **-4.7%** |
| | Weekday Overnight | **-7.8%** | **-6.8%** | **-22.1%** | **-14.1%** | **-7.2%** | **-8.4%** | **-25.6%** | **-17.9%** | **-16.2%** | 4.8% | **-24.7%** | **-16.6%** |
| | Weekend Peak | 7.4% | 6.6% | 3.8% | **-6.8%** | 2.7% | 3.5% | **-4.5%** | **-7.2%** | **-7.6%** | **-5.4%** | **-23.6%** | **-16.3%** |
| | Weekend Off-peak | **-10.5%** | **-15.2%** | 14.4% | **-5.0%** | 11.8% | 10.6% | 3.0% | **-10.3%** | **-2.0%** | **-26.5%** | **-7.9%** | 9.6% |

EB = eastbound; WB = westbound. Bold font indicates reductions in the buffer index compared to the pre-ATM period.

**Table 10. Percentage Change in Planning Time Index as Compared to Pre-ATM Period**

| Direction | Time Period | Segment 1 (Exit 52 to 53) | | Segment 2 (Exit 53 to 55) | | Segment 3 (Exit 55 to 57) | | Segment 4 (Exit 57 to 60) | | Segment 5 (Exit 60 to 62) | | Segment 6 (Exit 62 to 64) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Year 1** | **Year 2** | **Year 1** | **Year 2** | **Year 1** | **Year 2** | **Year 1** | **Year 2** | **Year 1** | **Year 2** | **Year 1** | **Year 2** |
| EB | Weekday AM Peak | 0.2% | 1.7% | **-2.4%** | 1.6% | **-6.1%** | 3.9% | **-6.3%** | **-10.7%** | **-9.8%** | **-2.1%** | 5.3% | 3.2% |
| | Weekday Midday | **-0.8%** | **-0.7%** | **-0.4%** | 1.5% | **-3.7%** | 1.5% | 0.0% | **-7.0%** | 6.8% | 5.0% | **-4.4%** | 1.4% |
| | Weekday PM Peak | **-2.5%** | 1.4% | 1.3% | 2.2% | **-21.9%** | 20.0% | **-21.5%** | **-25.1%** | **-6.5%** | **-14.0%** | **-2.2%** | **-2.2%** |
| | Weekday Overnight | **-2.1%** | **-2.2%** | 1.0% | 5.4% | **-3.1%** | 0.3% | **-13.8%** | **-16.1%** | **-3.6%** | **-2.6%** | **-1.2%** | 5.1% |
| | Weekend Peak | **-10.3%** | **-9.6%** | **-3.7%** | 2.6% | **-1.2%** | 3.8% | 4.1% | **-22.4%** | **-6.3%** | **-6.6%** | **-4.7%** | **-1.2%** |
| | Weekend Off-peak | **-3.6%** | **-2.0%** | 3.8% | 9.1% | 8.6% | 6.3% | **-4.7%** | **-4.9%** | **-7.1%** | 2.5% | **-2.8%** | **-1.4%** |
| WB | Weekday AM Peak | 0.1% | **-4.0%** | 7.0% | **-4.5%** | 3.6% | 2.4% | **-6.9%** | 0.4% | 2.1% | **-10.2%** | **-0.9%** | **-11.9%** |
| | Weekday Midday | **-0.2%** | 1.7% | 6.2% | **-4.6%** | 4.4% | 1.6% | 7.8% | **-1.6%** | 9.3% | **-5.4%** | **-19.8%** | **-18.7%** |
| | Weekday PM Peak | 15.5% | 7.8% | 16.9% | **-7.5%** | 18.0% | 13.7% | **-2.2%** | **-1.0%** | 0.9% | **-2.6%** | **-6.3%** | **-5.8%** |
| | Weekday Overnight | **-3.8%** | **-1.5%** | **-1.1%** | **-0.5%** | 0.9% | 0.1% | **-8.0%** | **-2.4%** | **-13.7%** | **-6.2%** | **-13.1%** | **-7.5%** |
| | Weekend Peak | 7.6% | 7.6% | 2.3% | **-5.5%** | 5.2% | 4.0% | 8.8% | **-3.2%** | **-3.3%** | **-11.7%** | **-16.6%** | **-21.7%** |
| | Weekend Off-peak | **-5.0%** | **-3.5%** | 1.5% | **-0.2%** | 2.5% | 1.2% | **-3.1%** | **-5.4%** | **-4.4%** | **-6.1%** | **-7.1%** | **-10.0%** |

EB = eastbound; WB = westbound. Bold font indicates reductions in planning time index compared to the pre-ATM period.

**Table 11. Total Traveler Delays Before and After ATM Implementation on Weekends by Segment**

| Direction | Segment | Total Delay (hr) | | | Change Compared to Before ATM (%) | |
|---|---|---|---|---|---|---|
| | | Before ATM | ATM Year 1 | ATM Year 2 | ATM Year 1 | ATM Year 2 |
| EB | 1 | 1460.41 | 1685.06 | 1419.95 | 15.4% | -2.8% |
| | 2 | 1516.99 | 1658.64 | 1495.40 | 9.3% | -1.4% |
| | 3 | 12719.50 | 12313.84 | 14535.55 | -3.2% | 14.3% |
| | 4 | 26746.98 | 20665.10 | 24355.22 | -22.7% | -8.9% |
| | 5 | 2465.13 | 2105.50 | 1956.67 | -14.6% | -20.6% |
| | 6 | 17419.45 | 13879.40 | 17677.32 | -20.3% | 1.5% |
| Total (EB) | | 62328.46 | 52307.54 | 61440.12 | -16.1% | -1.4% |
| WB | 1 | 65.48 | 61.34 | 73.96 | -6.3% | 12.9% |
| | 2 | 2691.21 | 2949.34 | 2529.09 | 9.6% | -6.0% |
| | 3 | 1001.21 | 1035.18 | 959.09 | 3.4% | -4.2% |
| | 4 | 1452.38 | 1000.15 | 1043.27 | -31.1% | -28.2% |
| | 5 | 35281.60 | 21982.74 | 18259.10 | -37.7% | -48.2% |
| | 6 | 63135.21 | 33556.83 | 37474.32 | -46.8% | -40.6% |
| Total (WB) | | 103627.10 | 60585.58 | 60338.83 | -41.5% | -41.8% |
| Total (Corridor) | | 165955.56 | 112893.12 | 121778.95 | **-32.0%** | **-26.6%** |

ATM = active traffic management; EB = eastbound; WB = westbound. Green font indicates reduction in total delay. Red font indicates increase in total delay.

## Safety Analysis

Table 12 summarizes the results of the empirical Bayes analysis of the safety effect of the ATM system. CMFs for total and FI crashes were calculated for all crash types, and separate CMFs were generated for multiple-vehicle crashes and rear-end crashes. In Table 12, multiple-vehicle crashes include all crashes that involved two or more vehicles, such as sideswipe crashes, angle crashes, and rear-end crashes. The rear-end crashes in Table 12 are a subset of the multiple-vehicle crashes and are broken out separately since they are often correlated with the presence of congestion. Ideally, secondary crashes that occurred in a queue caused by an incident or event would have been examined, but limited sample sizes made this impossible.

Given the results of the operational analysis, the safety effects were further broken down into HSR and non-HSR sections to determine if safety effects differed. Since operations generally improved more on the HSR sections, there was a question whether the improved flow offset any safety concerns related to the removal of the emergency shoulder for use as a travel lane. The results showed positive safety improvements when the entire corridor was examined as a whole. There was a 6% and 10% reduction in total (all severity) and FI crashes, respectively, when the entire corridor was examined. These reductions were not statistically significant, however. Multiple-vehicle crashes had a 10% and 15% reduction for total (all severity) and FI crashes, respectively, after the implementation of the ATM system. These reductions were statistically significant at a 90% confidence interval. Rear-end crashes had the largest reductions for total (all severity) and FI crashes, with reductions of nearly 11% and 17%, respectively. These reductions were also statistically significant at a 90% confidence level. The large reductions in rear-end crashes correlate well with the improved traffic flow discussed earlier.

**Table 12. Results of the Empirical Bayes Analysis for the I-66 Corridor**

| Location | Crash Type | Severity | Before Crashes/Year | After Crashes/Year | CMF | Standard Error |
|---|---|---|---|---|---|---|
| Entire corridor | All | All | 379 | 373 | 0.938 | 0.054 |
| | | FI | 122 | 114 | 0.897 | 0.092 |
| | Multiple-vehicle | All | 345 | 325 | 0.902* | 0.056 |
| | | FI | 113 | 98 | 0.854* | 0.095 |
| | Rear-end | All | 279 | 257 | 0.891* | 0.062 |
| | | FI | 97 | 80 | 0.829* | 0.101 |
| HSR sections | All | All | 204 | 161 | 0.753** | 0.065 |
| | | FI | 68 | 48 | 0.681** | 0.106 |
| | Multiple-vehicle | All | 186 | 139 | 0.711** | 0.066 |
| | | FI | 61 | 37 | 0.586** | 0.103 |
| | Rear-end | All | 154 | 111 | 0.691** | 0.071 |
| | | FI | 54 | 33 | 0.607** | 0.113 |
| Non-HSR sections | All | All | 176 | 212 | 1.152 | 0.09 |
| | | FI | 54 | 66 | 1.159 | 0.161 |
| | Multiple-vehicle | All | 159 | 186 | 1.127 | 0.094 |
| | | FI | 52 | 61 | 1.177 | 0.17 |
| | Rear-end | All | 125 | 146 | 1.141 | 0.107 |
| | | FI | 43 | 47 | 1.109 | 0.181 |

CMF = crash modification factor; FI = fatal and injury; HSR = hard shoulder running.
* Significant at 90% confidence level.
** Significant at 95% confidence level.

Much like the operational results, it appears that the safety benefits were concentrated in the sections with HSR. Locations with HSR had a reduction of nearly 25% and 32% for total (all severity) and FI, respectively, which was statistically significant at $\alpha = 0.05$. Likewise, HSR locations had a 29% and 40% reduction in total (all severity) and FI multiple-vehicle crashes, respectively, which was again statistically significant at $\alpha = 0.05$. Rear-end crashes at HSR locations had about 31% and 39% reductions in total (all severity) and FI crashes, respectively. These reductions were statistically significant at $\alpha = 0.05$. The study did not show improvement in safety at locations without HSR. This is in contrast to VSL deployments at other locations that documented safety improvements and may reflect the lack of automated speed enforcement at the I-66 site.

These safety results imply a direct correlation between safety and operational improvements. The large reductions in rear-end crashes on HSR sections would seem to be correlated with the improved flow at those locations. No statistically significant safety improvements occurred on the non-HSR sections, which also had fewer operational changes. The safety results imply that crash reductions created by improved flow more than offset any negative effects from removal of the shoulder as an emergency refuge.

One challenge that was encountered in the safety analysis was that Virginia SPFs were developed using standard freeway cross sections of six or eight lanes (Kweon and Lim, 2014). In the ATM system, the roadway cross section changes as shoulder lanes are opened or closed to travel. The safety analysis was performed using the SPF for the base number of lanes since no standard method exists in the HSM for dynamically managed facilities. This represents a potential limitation of the research and a need for future work.

## CONCLUSIONS

- *The operational analysis generally showed that the ATM produced improvements in average travel time during weekday off-peak periods and weekends, but travel time during peak periods in the peak direction of travel continued to degrade.* Prior to ATM installation, hard shoulders were already in use as a travel lane using a static time-of-day schedule, so no additional capacity was introduced by the ATM during the peak periods. These results are similar to the results of the Phase I study by Chun and Fontaine (2016).

- *Travel time reliability results were more mixed, but improvements generally occurred during midday and off-peak periods.* Again, these results were similar to those in the Phase I study (Chun and Fontaine, 2016) and show the potential benefits of using ATM to manage non-recurring congestion.

- *The safety analysis showed statistically significant reductions in multiple-vehicle and rear-ends crashes on freeway segments.* Although the overall crash reductions across the corridor were not statistically significant, there were statistically significant reductions in crash types associated with congestion. It is plausible that the improved flow created by ATM produced these secondary benefits in crash reductions. No analysis of the impact of the ATM system on interchange area crashes could be performed because of limited availability of ramp data.

- *The inclusion of dynamic HSR appeared to be responsible for most safety and operational improvements on the corridor. Limited changes occurred on the sections that had only AVSL and LUCS.* Both the operational and safety analyses showed that benefits of the ATM were accrued primarily on the segments with HSR. In this case, using AVSL for congestion mitigation appeared to have limited effects.

- *Since I-66 had static HSR prior to activation, the effects quantified in this study are conservative estimates of the effects of implementing dynamic HSR.* The dynamic use of the existing HSR system on I-66 had a positive impact on the off-peak weekday and peak weekend travel times and on overall safety. I-66 always had distinct peak period congestion and significant amounts of traffic during non-peak periods as well. AADT had an increasing trend on I-66, which indicates that traffic conditions might have worsened even further with dynamic HSR. Based on the results from I-66, it can be concluded that dynamic HSR could help mitigate congestion and improve safety on other congested Virginia interstates as well.

## RECOMMENDATIONS

1. *VDOT's Operations Division and the Regions should use the results of the I-66 ATM deployment to inform future decisions about ATM and HSR use in Virginia.* Since the I-66 ATM system was dismantled in early 2018 as a result of the Transform I-66 Outside the Beltway project, there is no opportunity to modify the existing system. The results provided in this report could be used, however, to provide ranges of benefits of proposed projects involving ATM, AVSL, or HSR that could be used to assess the viability of future projects.

# IMPLEMENTATION AND BENEFITS

## Implementation

With regard to the study recommendation, the Virginia Transportation Research Council will provide a presentation or workshop to VDOT's Operations Division and the regional operations directors on the results and findings of this study. The presentation may be a live presentation or a webinar, depending on interest from the groups. The presentation/workshop will occur by the end of 2018 and will cover the effects and lessons learned from this deployment.

## Benefits

The benefits discussed here were produced by the deployment of the I-66 ATM system, not by the implementation of the study recommendation. A planning level analysis of the benefits of the I-66 ATM system was developed by monetizing the safety and operational benefits of the system. This provided an order of magnitude estimate that could be used for future deployments, although these benefits are likely conservative for other sites given that static HSR was present before system activation on I-66.

First, the corridor-level safety benefits were estimated. Based on the empirical Bayes analysis, there were statistically significant reductions in multiple-vehicle total and FI crashes. The CMF was 0.902 for total multiple-vehicle crashes and 0.854 for FI crashes. Prior to ATM implementation, the corridor averaged 345 total crashes and 113 FI crashes per year. If these CMFs are applied, a high level estimate would be a reduction of 17.3 property damage crashes per year and 16.5 FI crashes per year across the entire corridor. Based on the current VDOT Highway Safety Improvement Program analysis spreadsheet (VDOT, 2017), the average cost of a multiple-vehicle FI crash is $70,577 and the average cost of a multiple-vehicle property damage crash is $9,651. Using these values, the planning level annual safety benefit of the ATM system was $1,331,457.

Second, the delay reduction benefits of the I-66 ATM were quantified. As noted earlier in the report, there was a trend in increased peak period congestion on I-66 although improvements occurred during off-peak periods. As noted earlier, Metrorail SafeTrack work resulted in changes in modes and travel patterns that may have mitigated some of the benefits of the ATM system during weekdays. As a result, delay reduction benefits were quantified based on the weekend delay savings shown earlier. The value of travel time delay was estimated at $17.67 per hour of person-travel based on the values used in the Texas A&M Transportation Institute Urban Mobility Scorecard (Schrank et al., 2015). To be conservative, each vehicle on I-66 was assumed to have one passenger. Overall, there was an improvement of 53,065 hours of traveler delay combined in both directions of I-66 across all weekends in Year 1 and 44,177 hours in Year 2. This translates to a total operational benefit of approximately $0.95 million in Year 1 and $0.78 million in Year 2 based on only weekend improvements. This is likely a conservative estimate of the operational benefits since weekday effects are not included.

## ACKNOWLEDGMENTS

The authors thank VDOT's Northern Regional Operations group for their continued support of this project. Specifically, the authors thank John Kornhiser and Kamal Suliman for their assistance during this project. The authors also thank the other members of the technical review panel: Lance Dougald, Ken Earnest, Sanhita Lahiri, and Ling Li.

## REFERENCES

Ali, A., and Murray-Tuite, P. Commuters' Travel Changes Due to the Washington Metropolitan Area 1 Transit Authority's MetroRail Short and Long-Term Service Disruptions. In *Transportation Research Board 97th Annual Meeting Compendium of Papers.* Transportation Research Board, Washington, DC, January 2018.

American Association of State Highway and Transportation Officials. *Highway Safety Manual.* Washington, DC, 2010.

Chun, P., and Fontaine, M.D. *Evaluation of the Impact of the I-66 Active Traffic Management System.* VTRC 17-R5. Virginia Transportation Research Council, Charlottesville, 2016.

DeGaspari, M., Jin, P.J., Wall, J., and Walton, C.M. The Effect of Active Traffic Management on Travel Time Reliability: A Case Study of I-5 in Seattle. In *Transportation Research Board 92nd Annual Meeting Compendium of Papers.* Washington, DC, January 2013.

Dutta, N., Venkatanarayana, R., and Fontaine, M.D. Examining Driver Understanding and Effectiveness of Diagonal Yellow Arrow Lane Use Control Signal Indication. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2624, 2017, pp. 38-47.

Garber, N.J., Miller, J.S., Sun, X., and Yuan, B. Safety Impacts of Differential Speed Limits for Trucks and Passenger Cars on Rural Interstate Highways: A Modified Empirical Bayes Approach. *Journal of Transportation Engineering,* Vol. 132, Issue 1, 2006, pp. 19-29.

Geistefeldt, J. Operational Experience With Temporary Hard Shoulder Running in Germany. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2490, 2012, pp. 67-73.

Goh, K.C., Currie, G. Sarvi, M., and Logan D. An Improved Methodology to Compute Crash Modification Factors: A Case Study of Bus Priority Measures in Melbourne. Presented at the 25th ARRB Conference, Perth, Australia, 2012.

Gross, F., Persaud, B., and Lyon, C. *A Guide to Developing Quality Crash Modification Factors.* FHWA-SA-10-032. Federal Highway Administration, Washington, DC, 2010.

Haghani, A., Hamedi, M., and Sadabadi, K.F. I-95 *Corridor Coalition Vehicle Probe Project.* University of Maryland, College Park, 2009.

Hauer, E. Bias-by-Selection: Overestimation of the Effectiveness of Safety Countermeasures Caused by the Process of Selection for Treatment. *Accident Analysis and Prevention*, Vol. 12, No. 2, 1980, pp. 113-117.

Hourdos, J., Abou, S., and Zitzow, S. *Effectiveness of Urban Partnership Agreement Traffic Operations Measures in the I-35W Corridor.* Intelligent Transportation Systems Institute, University of Minnesota, Minneapolis, 2013.

Hourdos, J., and Zitzow, S. *Investigation of the Impact of the I-94 ATM System on the Safety of the I-94 Commons High Crash Area.* Minnesota Department of Transportation, St. Paul, 2014.

Iteris. *I-66 Active Traffic Management Concept of Operations.* Virginia Department of Transportation, Richmond, 2011.

Kianfar, J., Edara, P., and Sun, C. Empirical Evaluation of Variable Speed Limit Systems on Freeways—A Case Study of Deployment in Missouri. Unpublished manuscript. University of Missouri-Columbia, 2010.

Kweon, Y-J., and Lim, I-K. *Development of Safety Performance Functions for Multilane Highway and Freeway Segments Maintained by the Virginia Department of Transportation.* VCTIR 14-R14. Virginia Center for Transportation Innovation and Research, Charlottesville, 2014.

Kwon, E., and Park, C. *Development of Active Traffic Management Strategies for Minnesota Freeway Corridors.* Minnesota Department of Transportation, St. Paul, 2015.

Lemke, K. Hard Shoulder Running as a Short-Term Measure to Reduce Congestion. In *4th International Symposium on Highway Geometric Design Conference Proceedings*. Valencia, Spain, 2010.

Mirshahi, M., Obenberger, J., Fuhs, C.A., Howard, C.E., Krammes, R.A., Kuhn, B.T., Mayhew, R.M., Moore, M.A., Sahebjam, K., Stone, C.J., and Yung, J.L. *Active Traffic Management: The Next Step in Congestion Management.* Federal Highway Administration, Washington, DC, 2007.

Schrank, D., Eisele, B., Lomax, T., and Bak, J. *2015 Urban Mobility Scorecard*. Texas A&M Transportation Institute and INRIX, College Station, 2015.

Virginia Department of Transportation. Business Rules and User's Information, Dashboard 3.0. 2015. http://dashboard.virginiadot.org/Help/DB%20User%20Guide.PDF. Accessed September 13, 2018.

Virginia Department of Transportation. Highway Safety Improvement Program Spreadsheet. http://www.virginiadot.org/business/FY2017-18HSP_Proposal_Form.xls. Accessed September 13, 2018.

Washington Metropolitan Area Transit Authority. SafeTrack. No date. https://www.wmata.com/service/SafeTrack.cfm. Accessed September 13, 2018.

Weikl, S., Bogenberger, K., and Bertini, R. Traffic Management Effects of Variable Speed Limit System on a German Autobahn. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2380, 2013, pp. 48-60.

# APPENDIX

## UTILIZATION RATE OF ATM COMPONENTS

**Table A-1. Hard Shoulder Running Utilization by Gantry on Weekdays**

| EB Weekday HSR Utilization | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Gantry Milepost | Average Operational Hours-Before (hr/day) | Average Operational Hours-After (hr/day) | | | | | | | | |
| | | October-November | | | December-February | | March-May | | June-August | |
| | | Year 1 | Year 2 | Year 3 | Year 1 | Year 2 | Year 1 | Year 2 | Year 1 | Year 2 |
| 58.37 | 5.5 | 10.11 | 10.74 | 12.47 | 8.4 | 7.32 | 11.74 | 12.09 | 11.54 | 13.08 |
| 58.75 | 5.5 | 7.33 | 10.74 | 8.92 | 9.45 | 7.33 | 11.31 | 11.9 | 11.59 | 9.11 |
| 59.21 | 5.5 | 10.1 | 10.77 | 12.39 | 9.28 | 7.32 | 12 | 11.91 | 11.57 | 13.1 |
| 59.98 | 5.5 | 10.15 | 10.78 | 12.48 | 9.26 | 7.32 | 10.43 | 11.87 | 11.56 | 13.1 |
| 60.62 | 5.5 | 10.19 | 10.78 | 8.15 | 9.3 | 7.31 | 9.97 | 11.93 | 11.41 | 9.16 |
| 61.09 | 5.5 | 9.93 | 10.72 | 12.43 | 9.29 | 7.29 | 10.81 | 11.95 | 11.36 | 13.09 |
| 61.55 | 5.5 | 10.01 | 10.71 | 8.33 | 9.62 | 7.57 | 10.28 | 11.62 | 11.58 | 9.27 |
| 62.03 | 5.5 | 0 | 8.98 | 12.41 | 7.61 | 7.28 | 12.32 | 11.56 | 11.56 | 13.07 |
| 62.62 | 5.5 | 0 | 10.79 | 12.42 | 7.63 | 7.29 | 12.41 | 11.59 | 11.57 | 13.09 |
| 63.16 | 5.5 | 0 | 10.79 | 8.37 | 7.63 | 7.31 | 12.01 | 11.66 | 11.55 | 9.59 |
| 63.84 | 5.5 | 0 | 7.51 | 12.44 | 7.57 | 7.31 | 11.85 | 11.89 | 11.53 | 12.95 |
| Average | 5.5 | 6.17 | 10.3 | 10.98 | 8.64 | 7.33 | 11.38 | 11.81 | 11.53 | 11.69 |
| **WB Weekday HSR Utilization** | | | | | | | | | | |
| Gantry Milepost | Average Operational Hours-Before (hr/day) | Average Operational Hours-After (hr/day) | | | | | | | | |
| | | October-November | | | December-February | | March-May | | June-August | |
| | | Year 1 | Year 2 | Year 3 | Year 1 | Year 2 | Year 1 | Year 2 | Year 1 | Year 2 |
| 59.42 | 6 | 6.87 | 9.1 | 11.18 | 6.67 | 6.77 | 10.94 | 9.98 | 9.28 | 10.92 |
| 60.01 | 6 | 7.02 | 9.08 | 11.15 | 6.66 | 6.75 | 10.93 | 11.95 | 9.26 | 10.89 |
| 60.9 | 6 | 7.01 | 9.07 | 11.23 | 6.7 | 6.75 | 10.93 | 11.99 | 9.09 | 10.92 |
| 61.27 | 6 | 7.01 | 9.05 | 11.2 | 6.67 | 6.76 | 10.93 | 12.32 | 9.08 | 10.92 |
| 61.59 | 6 | 9.25 | 9.07 | 11.21 | 6.6 | 6.75 | 10.72 | 8.98 | 9.27 | 10.91 |
| 62.08 | 6 | 6.96 | 9.02 | 11.19 | 6.05 | 6.72 | 10.67 | 12.29 | 9.23 | 10.87 |
| 62.62 | 6 | 0 | 9.02 | 7.53 | 5.45 | 6.7 | 10.63 | 9.32 | 9.18 | 10.72 |
| 63.16 | 6 | 0 | 9.05 | 11.13 | 5.48 | 6.73 | 10.88 | 12.54 | 9.15 | 10.73 |
| 63.84 | 6 | 0 | 9.03 | 11.2 | 5.54 | 6.76 | 10.95 | 12.65 | 9.28 | 10.8 |
| Average | 6 | 4.9 | 9.05 | 10.78 | 6.2 | 6.74 | 10.84 | 11.34 | 9.2 | 10.85 |

Darker colors indicate locations and time periods for which a particular component was more frequently used.

**Table A-2. Hard Shoulder Running Utilization by Gantry on Weekends**

| EB Weekend HSR Utilization | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Average Operational Hours-After (hr/day) | | | | | | | | |
| | | October-November | | | December-February | | March-May | | June-August | |
| Gantry Milepost | Average Operational Hours-Before (hr/day) | Year 1 | Year 2 | Year 3 | Year 1 | Year 2 | Year 1 | Year 2 | Year 1 | Year 2 |
| 58.37 | 0 | 7.42 | 8.63 | 8.53 | 5.7 | 4.96 | 6.56 | 6.91 | 7.48 | 9.54 |
| 58.75 | 0 | 6.32 | 8.63 | 3.62 | 6.35 | 5.12 | 6.34 | 6.94 | 7.46 | 4.28 |
| 59.21 | 0 | 7.38 | 8.68 | 8.53 | 6.35 | 4.56 | 6.87 | 6.95 | 7.48 | 9.59 |
| 59.98 | 0 | 7.19 | 8.68 | 8.45 | 6.34 | 4.98 | 6.77 | 6.95 | 7.48 | 9.69 |
| 60.62 | 0 | 7.48 | 8.68 | 3.44 | 6.43 | 4.56 | 6.95 | 7.15 | 8.14 | 3.82 |
| 61.09 | 0 | 9.57 | 8.64 | 8.46 | 6.44 | 4.83 | 8.01 | 7.15 | 7.42 | 9.68 |
| 61.55 | 0 | 7.47 | 8.64 | 3.54 | 6.43 | 4.77 | 6.95 | 6.89 | 7.48 | 5.11 |
| 62.03 | 0 | 0 | 6.88 | 8.27 | 5.09 | 4.69 | 7.55 | 7.97 | 7.48 | 9.54 |
| 62.62 | 0 | 0 | 8.61 | 8.29 | 5.09 | 4.5 | 6.59 | 6.82 | 7.47 | 9.48 |
| 63.16 | 0 | 0 | 8.61 | 4.89 | 5.11 | 5.14 | 6.56 | 7.92 | 7.47 | 4.32 |
| 63.84 | 0 | 0 | 5.08 | 8.53 | 5.06 | 4.94 | 7.53 | 7.02 | 7.49 | 9.47 |
| Average | 0 | 4.8 | 8.16 | 6.78 | 5.86 | 4.82 | 6.97 | 7.15 | 7.53 | 7.68 |
| **WB Weekend HSR Utilization** | | | | | | | | | | |
| | | Average Operational Hours-After (hr/day) | | | | | | | | |
| | | October-November | | | December-February | | March-May | | June-August | |
| Gantry Milepost | Average Operational Hours-Before (hr/day) | Year 1 | Year 2 | Year 3 | Year 1 | Year 2 | Year 1 | Year 2 | Year 1 | Year 2 |
| 59.42 | 0 | 7.14 | 7.42 | 8.7 | 5.46 | 4.09 | 6.44 | 6.66 | 6.44 | 9.22 |
| 60.01 | 0 | 7.14 | 7.41 | 8.7 | 5.47 | 4.09 | 6.74 | 6.52 | 6.44 | 9.33 |
| 60.9 | 0 | 7.14 | 7.41 | 8.7 | 5.47 | 4.08 | 6.44 | 6.7 | 6.69 | 9.32 |
| 61.27 | 0 | 7.14 | 7.43 | 8.7 | 5.47 | 4.08 | 6.45 | 6.69 | 7.36 | 9.3 |
| 61.59 | 0 | 6.33 | 7.43 | 8.7 | 5.47 | 4.09 | 6.39 | 6.65 | 6.46 | 9.21 |
| 62.08 | 0 | 7.13 | 7.43 | 8.7 | 4.95 | 4.09 | 6.19 | 7.03 | 6.44 | 9.23 |
| 62.62 | 0 | 0 | 7.43 | 6.76 | 4.29 | 4.09 | 5.86 | 6.66 | 6.65 | 9.23 |
| 63.16 | 0 | 0 | 7.43 | 8.65 | 4.29 | 4.07 | 6.06 | 7.14 | 6.71 | 9.23 |
| 63.84 | 0 | 0 | 7.42 | 8.66 | 4.29 | 4.07 | 5.78 | 7.29 | 6.44 | 9.2 |
| Average | 0 | 4.67 | 7.42 | 8.47 | 5.02 | 4.08 | 6.26 | 6.82 | 6.62 | 9.25 |

Darker colors indicate locations and time periods for which a particular component was more frequently used.

Table A-3. Lane Use Control Signal Utilization by Gantry on Weekdays (EB)

| Gantry Milepost | EB Weekday LUCS Utilization Rate (min/activation) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | October-November | | | December-February | | March-May | | June-August | |
| | Year 1 | Year 2 | Year 3 | Year 1 | Year 2 | Year 1 | Year 2 | Year 1 | Year 2 |
| 52.47 | 4.02 | 0 | 61.62 | 15.37 | 277.55 | 0 | 27.65 | 7.74 | 21.33 |
| 52.99 | 33.63 | 109.86 | 21.63 | 1.03 | 12.47 | 4.15 | 56.16 | 33.08 | 37 |
| 53.71 | 8.05 | 57.22 | 17.54 | 52.08 | 0 | 42.03 | 33.25 | 27.32 | 25 |
| 54.23 | 17.6 | 0 | 8.4 | 0 | 26.08 | 0 | 11.13 | 5.66 | 25 |
| 54.84 | 14.97 | 0 | 143.77 | 0 | 58.32 | 0 | 80.92 | 77.86 | 99 |
| 55.45 | 3.28 | 179.55 | 64.56 | 116.15 | 51.44 | 0 | 1.06 | 189.11 | 85.5 |
| 55.95 | 3.12 | 99.72 | 7.62 | 31.52 | 91.43 | 57.65 | 56.74 | 32.47 | 62.89 |
| 56.5 | 6.61 | 35.6 | 29.09 | 4.89 | 46.8 | 31.64 | 35.4 | 44.21 | 41.5 |
| 57.06 | 8.27 | 22.54 | 3.86 | 64.58 | 97.3 | 58.85 | 28.01 | 20.85 | 57.64 |
| 57.53 | 40.88 | 16.47 | 56.35 | 27.79 | 40.97 | 99.45 | 37.64 | 21.07 | 40.12 |
| 58.37 | 8.56 | 61.71 | 26.87 | 36.38 | 14.21 | 47.13 | 36.83 | 8.72 | 21.92 |
| 58.75 | 15.39 | 35.73 | 64.95 | 88.1 | 37.62 | 47.19 | 46 | 12.84 | 37.32 |
| 59.21 | 15.06 | 79.14 | 10.69 | 21.64 | 28.93 | 40.86 | 36.27 | 19.46 | 19 |
| 59.98 | 12.3 | 33.41 | 48.52 | 31.06 | 22.99 | 29.77 | 40.78 | 31.82 | 40.4 |
| 60.62 | 29.56 | 36.37 | 56.7 | 8.59 | 38.63 | 38.63 | 45.1 | 35.4 | 42.23 |
| 61.09 | 38.56 | 43.7 | 24.15 | 12.72 | 41.04 | 47.57 | 28.28 | 17.72 | 17 |
| 61.55 | 0 | 31.08 | 13.91 | 30.3 | 27.55 | 32.87 | 20.2 | 23.2 | 15.62 |
| 62.03 | 0 | 38.46 | 16.9 | 11.51 | 44.68 | 33.46 | 39.25 | 10.47 | 62.4 |
| 62.62 | 0 | 66.12 | 17.09 | 29.99 | 34.02 | 29.02 | 42.89 | 13.68 | 45.45 |
| 63.16 | 0 | 34.32 | 56.43 | 23.07 | 37.81 | 25.79 | 43.99 | 30.14 | 41.21 |
| 63.84 | 0 | 3.17 | 0 | 8.11 | 0 | 0 | 10.68 | 1.3 | 0 |
| Average | 12.37 | 46.87 | 35.74 | 29.28 | 49.04 | 31.72 | 36.11 | 31.62 | 39.88 |

Darker colors indicate locations and time periods for which a particular component was more frequently used.

Table A-4. Lane Use Control Signal Utilization by Gantry on Weekends (EB)

| Gantry Milepost | EB Weekend LUCS Utilization Rate (min/activation) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | October-November | | | December-February | | March-May | | June-August | |
| | Year 1 | Year 2 | Year 3 | Year 1 | Year 2 | Year 1 | Year 2 | Year 1 | Year 2 |
| 52.47 | 46.43 | 1 | 0 | 0 | 0 | 0 | 0 | 50.45 | 0 |
| 52.99 | 0 | 1.06 | 2.02 | 4.77 | 34.73 | 0 | 1.01 | 0 | 0 |
| 53.71 | 0 | 21.03 | 42.61 | 17.1 | 34.25 | 0 | 11.31 | 0 | 0 |
| 54.23 | 0 | 11.95 | 0 | 18.65 | 0 | 0 | 4 | 0 | 8 |
| 54.84 | 0 | 0 | 0 | 32.95 | 0 | 0 | 10.25 | 4.67 | 20.5 |
| 55.45 | 0 | 0 | 104.67 | 32.95 | 115.22 | 0 | 69.33 | 6.74 | 0 |
| 55.95 | 0 | 26.68 | 0 | 0.33 | 30.44 | 0 | 0 | 18.82 | 0 |
| 56.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 57.06 | 0 | 0 | 0 | 0 | 0 | 42.78 | 0 | 0 | 0 |
| 57.53 | 0 | 27.46 | 0 | 0 | 0 | 43.42 | 17.5 | 3.41 | 35 |
| 58.37 | 0 | 2.88 | 36.88 | 4.55 | 0 | 35.07 | 34.94 | 8.3 | 33 |
| 58.75 | 9.47 | 20.96 | 36.38 | 72.85 | 64.44 | 32.62 | 35.86 | 3.07 | 35.33 |
| 59.21 | 3.78 | 33.04 | 26.91 | 0 | 0 | 10.35 | 25.95 | 0 | 25 |
| 59.98 | 2.96 | 59.85 | 33.27 | 186.82 | 0 | 54.8 | 47.63 | 4.08 | 62 |
| 60.62 | 45 | 57.71 | 54.09 | 7.83 | 72.34 | 34.52 | 48.42 | 60.74 | 42.75 |
| 61.09 | 26.9 | 34.05 | 36.68 | 24.87 | 0 | 0.03 | 21.01 | 53.29 | 5.33 |
| 61.55 | 13.26 | 57.08 | 49.96 | 12.81 | 17.6 | 18.18 | 40.73 | 7.54 | 31.5 |
| 62.03 | 23.27 | 63.44 | 21.52 | 44.47 | 42.85 | 19.75 | 19.93 | 9.11 | 18.33 |
| 62.62 | 0 | 69.21 | 83.56 | 77.35 | 21.19 | 28.61 | 48.63 | 10.05 | 32.5 |
| 63.16 | 0 | 43.33 | 103.08 | 44.84 | 60.09 | 63.87 | 71.23 | 16.07 | 39.38 |
| 63.84 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Average | 8.15 | 25.27 | 30.08 | 27.77 | 23.48 | 18.29 | 24.18 | 12.21 | 18.51 |

Darker colors indicate locations and time periods for which a particular component was more frequently used.

**Table A-5. Lane Use Control Signal Utilization by Gantry on Weekdays (WB)**

| Gantry Milepost | WB Weekday LUCS Utilization Rate (min/activation) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | October-November | | | December-February | | March-May | | June-August | |
| | Year 1 | Year 2 | Year 3 | Year 1 | Year 2 | Year 1 | Year 2 | Year 1 | Year 2 |
| 52.47 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 52.99 | 2.93 | 37.5 | 0 | 28.82 | 0 | 0 | 28.04 | 18.58 | 4 |
| 53.71 | 0 | 0 | 0 | 42.62 | 0 | 0.77 | 13.47 | 26.94 | 13.33 |
| 54.23 | 19.86 | 105.68 | 104.41 | 35.83 | 40.57 | 23.68 | 61.53 | 17.38 | 37.17 |
| 54.84 | 29.37 | 94.4 | 61.44 | 71.56 | 57.49 | 88.83 | 54.02 | 13.63 | 43.4 |
| 55.45 | 41.63 | 83.2 | 33.09 | 24.87 | 53.72 | 44.61 | 53.15 | 23.1 | 74.25 |
| 55.95 | 15.8 | 74.11 | 0 | 10.77 | 33.18 | 81.18 | 63.47 | 52.83 | 0 |
| 56.5 | 9.57 | 76.8 | 11.01 | 31.02 | 149.38 | 77.98 | 48.81 | 20.82 | 0 |
| 57.06 | 7.6 | 33.81 | 156.82 | 118.48 | 108.33 | 61.51 | 26.11 | 18.41 | 3 |
| 57.53 | 54.17 | 72.66 | 7.97 | 0 | 93.65 | 76.14 | 53.03 | 33.4 | 3 |
| 58.37 | 36.45 | 41.69 | 10.9 | 25.01 | 10.55 | 79.05 | 29.04 | 16.39 | 2 |
| 58.75 | 0 | 17.35 | 0 | 31.37 | 8.2 | 1.35 | 21.58 | 25.8 | 80.17 |
| 59.21 | 0 | 18.1 | 0 | 13.57 | 0 | 29.46 | 17.71 | 17.33 | 8.67 |
| 59.98 | 7.97 | 1.95 | 90.31 | 87.96 | 8.9 | 66.54 | 9.94 | 17.93 | 12.89 |
| 60.62 | 45.17 | 28.51 | 50.99 | 16.87 | 62.89 | 66.16 | 22.89 | 17.27 | 45.27 |
| 61.09 | 13.42 | 17.51 | 12.54 | 88.6 | 76.91 | 151.61 | 22.83 | 28.15 | 37.67 |
| 61.55 | 14 | 40.22 | 14.62 | 50.41 | 23.95 | 58.8 | 26.93 | 13.65 | 34.54 |
| 62.03 | 141.48 | 29.42 | 11.46 | 7.46 | 25.32 | 56.45 | 23.41 | 17.41 | 34.3 |
| 62.62 | 0 | 26.39 | 55.86 | 24.09 | 25.46 | 52.95 | 19.07 | 11.75 | 23.36 |
| 63.16 | 0 | 36.89 | 25.88 | 20.87 | 53.72 | 17.65 | 23.2 | 9.5 | 23.87 |
| 63.84 | 0 | 30.58 | 62.35 | 31.5 | 47.22 | 11.3 | 22.47 | 14.36 | 34.76 |
| Average | 20.93 | 41.28 | 33.79 | 36.27 | 41.88 | 49.81 | 30.51 | 19.74 | 24.55 |

Darker colors indicate locations and time periods for which a particular component was more frequently used.

Table A-6. Lane Use Control Signal Utilization by Gantry on Weekends (WB)

| Gantry Milepost | WB Weekend LUCS Utilization Rate (min/activation) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | October-November | | | December-February | | March-May | | June-August | |
| | Year 1 | Year 2 | Year 3 | Year 1 | Year 2 | Year 1 | Year 2 | Year 1 | Year 2 |
| 52.47 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 52.99 | 0 | 0 | 0 | 13.32 | 13.1 | 25 | 8.1 | 10 | 2.89 |
| 53.71 | 0 | 0 | 3.45 | 0 | 3.64 | 0 | 0 | 0 | 0 |
| 54.23 | 4.09 | 1.62 | 14.05 | 4.54 | 3.43 | 0 | 8.27 | 9.67 | 12 |
| 54.84 | 24.71 | 36.39 | 48.2 | 41.05 | 34.53 | 54.69 | 28.03 | 0 | 15 |
| 55.45 | 68.71 | 0 | 12.12 | 93.52 | 51.16 | 0 | 53.26 | 5.53 | 13 |
| 55.95 | 26.02 | 0 | 9.49 | 0 | 9.42 | 0 | 0.5 | 7.55 | 1 |
| 56.5 | 38.88 | 156.01 | 50.77 | 0 | 5.38 | 7.08 | 0.5 | 0 | 1 |
| 57.06 | 0 | 126.32 | 50.78 | 3.25 | 4.25 | 0 | 10.12 | 12.08 | 17 |
| 57.53 | 0 | 109.33 | 34.73 | 10.92 | 0 | 9.54 | 5.46 | 0 | 0 |
| 58.37 | 0 | 13.2 | 0 | 1.18 | 0 | 0 | 3.09 | 0 | 5 |
| 58.75 | 31.37 | 0 | 0 | 13.59 | 0 | 0 | 6.8 | 10.41 | 0 |
| 59.21 | 2.73 | 0 | 45.5 | 0 | 21.22 | 1.17 | 8.33 | 10.09 | 16.67 |
| 59.98 | 23.65 | 7.65 | 167.08 | 7.49 | 10.22 | 13.54 | 15.25 | 0 | 23 |
| 60.62 | 22.13 | 44.42 | 15.27 | 0 | 50 | 50.5 | 0 | 10 | 0 |
| 61.09 | 27.3 | 27.11 | 19.16 | 0 | 19.02 | 0 | 4.12 | 57.25 | 8.25 |
| 61.55 | 29.91 | 0 | 6.01 | 73.72 | 18.02 | 0 | 44.61 | 0 | 15.5 |
| 62.03 | 7.82 | 0 | 5.5 | 92.98 | 0 | 8.97 | 47.99 | 48.9 | 3 |
| 62.62 | 17.61 | 34.19 | 5.5 | 0 | 9.5 | 33.49 | 1.5 | 0 | 3 |
| 63.16 | 8.4 | 14.34 | 0 | 0 | 0 | 9.42 | 18.83 | 8.29 | 37.67 |
| 63.84 | 45.18 | 11.17 | 21.91 | 0 | 12.05 | 9.49 | 19.17 | 6.25 | 38.33 |
| Average | 18.02 | 27.7 | 24.26 | 16.93 | 12.62 | 10.61 | 13.52 | 9.33 | 10.11 |

Darker colors indicate locations and time periods for which a particular component was more frequently used.

**Table A-7. Variable Speed Limit Utilization by Gantry on Weekdays (EB)**

| Gantry Milepost | EB Weekday AVSL Utilization Rate (hr/day) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | October-November | | | December-February | | March-May | | June-August | |
| | Year 1 | Year 2 | Year 3 | Year 1 | Year 2 | Year 1 | Year 2 | Year 1 | Year 2 |
| 52.47 | — | 3.61 | 0 | 1.59 | 3.04 | 2.9 | 1.52 | 3.46 | 3.84 |
| 52.99 | — | 3.65 | 3.71 | 1.66 | 3.01 | 3.89 | 3.36 | 3.46 | 3.82 |
| 53.71 | — | 2.2 | 2.4 | 0.71 | 1.34 | 1.85 | 1.87 | 1.62 | 1.75 |
| 54.23 | — | 1.85 | 2.06 | 0.92 | 1.07 | 2.13 | 1.56 | 1.48 | 1.57 |
| 54.84 | — | 0.34 | 0.68 | 1.01 | 2.18 | 2.23 | 1.43 | 0.57 | 0.51 |
| 55.45 | — | 0.6 | 1.01 | 1.36 | 1.46 | 3.1 | 1.23 | 0.74 | 0.79 |
| 55.95 | — | 1.36 | 1.77 | 1.36 | 1.04 | 3.1 | 1.41 | 1.25 | 1.41 |
| 56.5 | — | 2.19 | 2.35 | 1.76 | 1.69 | 4.6 | 2.02 | 2.04 | 2.06 |
| 57.06 | — | 2.87 | 3.07 | 2.71 | 2.26 | 3.42 | 2.67 | 2.72 | 2.64 |
| 57.53 | — | 4.3 | 4.4 | 2.35 | 3.12 | 4.02 | 3.76 | 4.26 | 4.32 |
| 58.37 | — | 5.16 | 4.96 | 3.76 | 3.79 | 4.41 | 4.37 | 4.92 | 4.79 |
| 58.75 | — | 5.56 | 4.96 | 5.35 | 4.14 | 4.57 | 4.55 | 4.44 | 4.66 |
| 59.21 | — | 3.53 | 3.67 | 3.38 | 2.15 | 5.57 | 2.91 | 3.63 | 3.53 |
| 59.98 | — | 4.24 | 3.53 | 3.38 | 2.6 | 5.37 | 3.06 | 4.66 | 3.44 |
| 60.62 | — | 4.61 | 3.93 | 1.97 | 2.85 | 4.08 | 3.39 | 4.91 | 3.78 |
| 61.09 | — | 2.35 | 3.6 | 1.37 | 1.42 | 2.42 | 2.51 | 2.1 | 1.55 |
| 61.55 | — | 2.02 | 1.4 | 1.42 | 0.98 | 2.18 | 1.19 | 1.46 | 1.05 |
| 62.03 | — | 3.78 | 4.06 | 1.44 | 2.46 | 2.53 | 3.26 | 3 | 3.3 |
| 62.62 | — | 5.33 | 0 | 1.5 | 3.46 | 2.98 | 1.73 | 4.51 | 4.55 |
| 63.16 | — | 6.33 | 6.25 | 0.41 | 3.84 | 1.21 | 5.04 | 4.86 | 5.11 |
| 63.84 | — | 4.11 | 6.09 | 0.46 | 3.47 | 2.03 | 4.78 | 2.16 | 4.23 |
| Average | | 3.33 | 3.04 | 1.9 | 2.45 | 3.27 | 2.74 | 2.96 | 2.99 |

Darker colors indicate locations and time periods for which a particular component was more frequently used.

Table A-8. Variable Speed Limit Utilization by Gantry on Weekends (EB)

| Gantry Milepost | EB Weekend AVSL Utilization Rate (hr/day) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | October-November | | | December-February | | March-May | | June-August | |
| | Year 1 | Year 2 | Year 3 | Year 1 | Year 2 | Year 1 | Year 2 | Year 1 | Year 2 |
| 52.47 | — | 0.38 | 0 | 0.01 | 0.2 | 0.04 | 0 | 0.13 | 0.03 |
| 52.99 | — | 0.84 | 0.97 | 0.02 | 0.22 | 0.05 | 0.49 | 0.1 | 0.05 |
| 53.71 | — | 0.88 | 0.69 | 0.02 | 0.16 | 0.03 | 0.35 | 0.15 | 0.05 |
| 54.23 | — | 0.57 | 0.47 | 0 | 0.16 | 0.02 | 0.24 | 0.14 | 0.04 |
| 54.84 | — | 0.46 | 0.11 | 0 | 0.19 | 0.02 | 0.06 | 0.16 | 0.04 |
| 55.45 | — | 0.07 | 0.05 | 0.08 | 0.19 | 0.17 | 0.07 | 0.13 | 0.11 |
| 55.95 | — | 0.04 | 0.03 | 0 | 0.08 | 0.03 | 0.02 | 0.06 | 0.04 |
| 56.5 | — | 0.2 | 0.23 | 0.23 | 0.08 | 0.81 | 0.23 | 0.16 | 0.01 |
| 57.06 | — | 0.48 | 0.66 | 0.38 | 0.18 | 1.27 | 0.52 | 0.3 | 0.09 |
| 57.53 | — | 1.58 | 2.21 | 0.45 | 0.34 | 1.22 | 1.33 | 1.17 | 0.49 |
| 58.37 | — | 2.18 | 2.6 | 0.87 | 0.52 | 1.65 | 1.73 | 1.66 | 0.61 |
| 58.75 | — | 2.63 | 2.89 | 2.36 | 0.59 | 1.79 | 2.63 | 1.71 | 0.75 |
| 59.21 | — | 1.88 | 1.95 | 0.62 | 0.44 | 1.44 | 1.29 | 1.01 | 0.64 |
| 59.98 | — | 2.52 | 2.11 | 0.55 | 0.49 | 1.62 | 1.33 | 1.36 | 0.7 |
| 60.62 | — | 3.18 | 2.48 | 0.45 | 0.58 | 1.75 | 1.46 | 1.59 | 0.8 |
| 61.09 | — | 2.06 | 2.05 | 0.49 | 0.52 | 1.97 | 1.27 | 0.93 | 0.62 |
| 61.55 | — | 2.01 | 2.04 | 0.43 | 0.54 | 1.98 | 1.23 | 0.86 | 0.66 |
| 62.03 | — | 3.35 | 3.68 | 0.47 | 1.35 | 2.33 | 2.08 | 1.82 | 1.68 |
| 62.62 | — | 4.58 | 0 | 0.61 | 1.59 | 2.66 | 0.3 | 3.63 | 2.28 |
| 63.16 | — | 5.43 | 5.21 | 0.15 | 1.63 | 0.44 | 2.68 | 4.22 | 2.75 |
| 63.84 | — | 2.93 | 4.36 | 0.2 | 1.27 | 0.73 | 2.28 | 1.12 | 2.23 |
| Average | | 1.82 | 1.66 | 0.4 | 0.54 | 1.05 | 1.03 | 1.07 | 0.7 |

Darker colors indicate locations and time periods for which a particular component was more frequently used.

**Table A-9. Variable Speed Limit Utilization by Gantry on Weekdays (WB)**

| Gantry Milepost | WB Weekday AVSL Utilization Rate (hr/day) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | October-November | | | December-February | | March-May | | June-August | |
| | Year 1 | Year 2 | Year 3 | Year 1 | Year 2 | Year 1 | Year 2 | Year 1 | Year 2 |
| 52.47 | — | 3.39 | 3.72 | 1.64 | 4.36 | 2.94 | 2.68 | 2.81 | 3.58 |
| 52.99 | — | 3.24 | 3.57 | 1.63 | 4.05 | 2.87 | 2.6 | 2.59 | 3.42 |
| 53.71 | — | 2.91 | 3.49 | 2.31 | 3.81 | 3.43 | 2.9 | 2.24 | 3.23 |
| 54.23 | — | 2.95 | 3.38 | 2.22 | 3.4 | 3.54 | 2.8 | 2.25 | 3.04 |
| 54.84 | — | 3.33 | 3.86 | 1.98 | 4.04 | 3.36 | 2.92 | 2.82 | 3.46 |
| 55.45 | — | 3.81 | 4.11 | 2.05 | 5 | 3.62 | 3.08 | 3.54 | 3.9 |
| 55.95 | — | 3.7 | 3.72 | 1.93 | 4.55 | 3.59 | 2.82 | 3.27 | 3.67 |
| 56.5 | — | 2.91 | 3.22 | 1.8 | 3.12 | 3.3 | 2.51 | 2.29 | 2.83 |
| 57.06 | — | 2.07 | 2.57 | 1.62 | 2.01 | 2.99 | 2.09 | 1.46 | 1.85 |
| 57.53 | — | 3.35 | 3.58 | 1.89 | 4.49 | 2.7 | 2.73 | 1.47 | 1.78 |
| 58.37 | — | 1.66 | 2.17 | 0.9 | 1.25 | 1.45 | 1.53 | 0.87 | 1.21 |
| 58.75 | — | 0.6 | 0.83 | 4.46 | 0.32 | 1.28 | 2.65 | 0.32 | 0.31 |
| 59.21 | — | 2.63 | 0.28 | 4.49 | 3.24 | 2.24 | 2.38 | 1.25 | 0.05 |
| 59.98 | — | 4.68 | 4.92 | 4.46 | 5.71 | 4.86 | 4.69 | 4.66 | 4.32 |
| 60.62 | — | 7.37 | 6.05 | 7.47 | 6.5 | 10.97 | 6.76 | 6.37 | 5.45 |
| 61.09 | — | 5.16 | 5.44 | 4.62 | 5.79 | 8.19 | 5.03 | 4.9 | 4.78 |
| 61.55 | — | 3.83 | 5.15 | 3.02 | 3.76 | 6.05 | 4.09 | 3.22 | 3.79 |
| 62.03 | — | 6.2 | 6.34 | 3 | 6.93 | 6.36 | 4.67 | 5.86 | 6.45 |
| 62.62 | — | 5.86 | 4.09 | 2.81 | 6.59 | 5.31 | 3.45 | 5.94 | 6.11 |
| 63.16 | — | 5.18 | 5.51 | 2.41 | 5.88 | 5.04 | 3.96 | 5.29 | 4.84 |
| 63.84 | — | 5.63 | 5.56 | 4.52 | 5.16 | 9.11 | 5.04 | 5.26 | 5.29 |
| Average | | 3.83 | 3.88 | 2.92 | 4.28 | 4.44 | 3.4 | 3.27 | 3.49 |

Darker colors indicate locations and time periods for which a particular component was more frequently used.

**Table A-10. Variable Speed Limit Utilization by Gantry on Weekends (WB)**

| Gantry Milepost | WB Weekend AVSL Utilization Rate (hr/day) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | October-November | | | December-February | | March-May | | June-August | |
| | Year 1 | Year 2 | Year 3 | Year 1 | Year 2 | Year 1 | Year 2 | Year 1 | Year 2 |
| 52.47 | — | 0 | 0.02 | 0.02 | 0.15 | 0.01 | 0.02 | 0.02 | 0.02 |
| 52.99 | — | 0 | 0.02 | 0.02 | 0.09 | 0.01 | 0.02 | 0.01 | 0.01 |
| 53.71 | — | 0.19 | 0.03 | 0.03 | 0.09 | 0.04 | 0.03 | 0.03 | 0.08 |
| 54.23 | — | 0.33 | 0.12 | 0.09 | 0.08 | 0.11 | 0.1 | 0.12 | 0.09 |
| 54.84 | — | 0.59 | 0.66 | 0.07 | 0.11 | 0.07 | 0.36 | 0.17 | 0.18 |
| 55.45 | — | 0.56 | 0.66 | 0.17 | 0.2 | 0.05 | 0.41 | 0.13 | 0.16 |
| 55.95 | — | 0.28 | 0.28 | 0.18 | 0.28 | 0.1 | 0.23 | 0.11 | 0.25 |
| 56.5 | — | 0.09 | 0.13 | 0.14 | 0.11 | 0.03 | 0.14 | 0.03 | 0.08 |
| 57.06 | — | 0 | 0.06 | 0.13 | 0.07 | 0.02 | 0.09 | 0.02 | 0.04 |
| 57.53 | — | 1.09 | 0.26 | 0.13 | 1.1 | 0.05 | 0.19 | 0.37 | 0.05 |
| 58.37 | — | 0 | 0.04 | 0 | 0.08 | 0.01 | 0.02 | 0.02 | 0.06 |
| 58.75 | — | 0 | 0 | 2.93 | 0.02 | 0.01 | 1.46 | 0.04 | 0.01 |
| 59.21 | — | 0.59 | 0.03 | 2.95 | 0.1 | 0.15 | 1.49 | 0.11 | 0 |
| 59.98 | — | 1.33 | 0.28 | 0.99 | 0.16 | 0.81 | 0.63 | 0.75 | 0.14 |
| 60.62 | — | 8.32 | 1.56 | 4.25 | 1.2 | 5.83 | 2.91 | 2.1 | 1.13 |
| 61.09 | — | 2.97 | 0.92 | 1.97 | 0.35 | 2.75 | 1.45 | 1 | 0.48 |
| 61.55 | — | 0.87 | 0.75 | 0.68 | 0.11 | 0.95 | 0.72 | 0.33 | 0.27 |
| 62.03 | — | 6.22 | 2.49 | 0.7 | 0.53 | 1.17 | 1.6 | 1.96 | 1.98 |
| 62.62 | — | 4.57 | 1.18 | 0.64 | 0.38 | 0.94 | 0.91 | 1.61 | 1.46 |
| 63.16 | — | 2.28 | 0.88 | 0.6 | 0.25 | 0.77 | 0.74 | 0.9 | 0.48 |
| 63.84 | — | 4.34 | 1.91 | 3.42 | 0.34 | 4.65 | 2.67 | 1.87 | 1.2 |
| Average | | 1.65 | 0.58 | 0.96 | 0.28 | 0.88 | 0.77 | 0.56 | 0.39 |

Darker colors indicate locations and time periods for which a particular component was more frequently used.