Estimation of the Safety Effects of an Adaptive Traffic Signal Control System

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ABSTRACT

Adaptive traffic signal control (ATSC) is a traffic management strategy in which traffic signal timings change, or adapt, based on observed traffic demand. While ATSC can improve mobility, it also has the potential to reduce crashes since mainline stops are reduced. This paper aims to evaluate the safety effectiveness of ATSC using the Empirical Bayes method. This analysis examines 47 urban or suburban intersections where ATSC was deployed in Virginia using 235 site-years of before data and 66 site-years of after data. Installing ATSC was found to produce a crash modification factor (CMF) for total intersection crashes of 0.83 with a standard error of 0.05. This CMF was statistically significant at a 95 percent confidence level. Fatal and injury crashes did not change by a statistically significant amount. Analyses of ATSC safety effects on crash type proportion, by traffic volume level, and by operational improvement magnitude were also performed. All crash types were found to be reduced, but safety benefits vary from corridor to corridor and at different volume levels. It was concluded that ATSC installation can potentially reduce both total and FI crashes at highway intersections, and public agencies should consider both its safety and mobility benefits when justifying ATSC projects.
INTRODUCTION

Adaptive traffic signal control (ATSC, also called Adaptive Signal Control Technology) is a traffic management strategy in which traffic signal timings change, or adapt, based on observed traffic demand. These systems utilize increased detection to continually collect data on observed demand, and signal timings are then re-optimized based on current data. Thus, these systems are often not bound by fixed cycle lengths or phase orders, and have the capability of responding to variations in traffic flow created by incidents, special events, seasonal traffic changes, or growth in traffic over time. ATSC has been widely deployed in recent years to enhance the efficiency of transportation systems. There is also a long history of evaluating ATSC, both using field data and microscopic simulations, primarily to examine the operational effects of these systems. Studies have shown that ATSC improved operational performance over conventional actuated signal control in terms of common metrics of traffic efficiency, such as delays, stops or travel times (NRC, 2010).

It has been hypothesized that improved operational efficiency should produce corresponding safety improvements once ATSC is installed. According to the National Cooperative Highway Research Program (NCHRP) Synthesis 403, ATSC can reduce the likelihood of crashes at intersections “through decreases of some efficiency-related performance measures, which highly correlate with some safety metrics (for example, a decrease in the number of stops reduces the chance of rear-end crashes).”

Very few studies, however, have produced quantitative evaluations of the safety benefits of ATSC. Past studies have either relied on limited empirical before and after data or used simulation technology to evaluate safety surrogate effects. When empirical investigations have been conducted, they have often only provided high level summary data and limited statistical analysis. To date, no crash modification factors (CMFs) for adaptive signal control have been generated.

LITERATURE REVIEW

Very few studies have evaluated ATSC using field data. Hicks and Carter (2000) found that ATSC reduced the number of stops by 28% to 41%, and hypothesized that the reduction in stops may lead to a reduced chance of rear-end crashes. Anzek et al. (2005) investigated the impact of converting operations at a signalized intersection from pre-timed phasing to a simple adaptive traffic control, similar to actuated control, and observed a 35 percent reduction in number of crashes after the conversion. However, this study was based on only a one-year before and after period at a single intersection. Dutta et al. (2010) applied data from an ATSC test bed in Oakland County, Michigan, to analyze the safety benefits of the Sydney Coordinated Adaptive Traffic System (SCATS). They observed a shift in the severity of crashes from Type A (incapacitating injury, permanent injury) and Type B (non-incapacitating injury, temporary injury) to Type C (possible injury, slight bruises and cuts). However, the reductions were not statistically significant at the 95% confidence level. Midenet at al. (2011) investigated exposure to lateral collisions at signalized intersections for two traffic control strategies, a real-time
adaptive traffic control strategy CRONOS and a traditional vehicle-actuated timing plan strategy. The results of case studies of an isolated intersection in Paris showed that CRONOS reduced the total exposure to lateral collisions under peak hour traffic conditions by roughly 5 min/h.

Several studies have also used microscopic simulation to evaluate the safety effects of ATSC, typically through the use of surrogate safety measures. Stevanovic (2011) used a micro-simulation model connected to SCATS to generate vehicular trajectories which were fed into a Surrogate Safety Assessment Model (Gettman et al., 2003, 2008). The results showed that ATSC simulation generated less rear-end and total conflicts but more crossing and lane changing conflicts than traditional control. However, the simulated conflicts and field crashes did not correlate well. Sabra (2010, 2013) developed a crash prediction method (safety performance function) using neural networks with field data from ATSC and actuated signals. After training the network with approximately 150 signal timing scenarios, Sabra’s crash prediction method produced an average traffic conflict prediction error for ATSC cases not used for training of 17%. These studies found that it is difficult to accurately estimate field crash data using a simulation approach. In addition to the underlying uncertainty in relating crash surrogates to crash frequency, many commercially available ATSC systems cannot be easily simulated using commercially available microsimulation packages. ATSC vendors often are reluctant to make information on how their system works publicly available, which further limits the ability to evaluate ATSC through microsimulation.

In summary, potential crash reduction benefits of ATSC have not been clearly defined. Simulation-based safety evaluations are often limited by incomplete models of the adaptive signal performance, and current empirical studies usually suffer from limited data and rely on naive before and after evaluations. There is a need for more rigorous examination of ATSC safety effects, by utilizing increasingly available data and more robust evaluation techniques.

**METHODOLOGY**

An observational before-after study utilizing the Empirical Bayes (EB) approach recommended by the first edition of Highway Safety Manual (HSM) was conducted to examine the safety impact of adaptive traffic signal control at urban intersections. The EB method is able to account for regression-to-the mean effects, as well as traffic volume and other roadway and traffic control characteristics, by combining safety performance function (SPF) estimates with the observed crash counts (Hauer, 1997).

Field before/after data from 10 corridors containing 47 intersections with ATSC in the state of Virginia were investigated. The same ATSC vendor was used at each of these sites. Each intersection was considered as a separate site and crash data within a 250 foot radius of each intersection was used in the evaluation. Each of the tasks performed to conduct the EB analysis is described below.
Field data were collected from a total of 47 intersections along ten corridors where the ATSC system was installed. Table 1 shows the sites, the number of ATSC intersections evaluated, the system activation date, and the durations of the before and after periods. In total, 235 site-years of before data and 66 site-years of after data were utilized in this analysis. All sites previously were operated using actuated signals with time-of-day plans.

**TABLE 1 Virginia ATSC Installations Used in This Paper**

<table>
<thead>
<tr>
<th>Corridor Name</th>
<th>No. of ATSC Intersections used</th>
<th>Active Date</th>
<th>Before Period</th>
<th>After Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>US 11, Winchester, VA</td>
<td>5</td>
<td>8/15/11</td>
<td>8/1/06 - 7/31/11</td>
<td>5 Yrs</td>
</tr>
<tr>
<td>US 17/50/522, Winchester , VA</td>
<td>3</td>
<td>4/3/12</td>
<td>4/1/07 - 3/31/12</td>
<td>5 Yrs</td>
</tr>
<tr>
<td>SR 7, Winchester, VA</td>
<td>6</td>
<td>5/7/12</td>
<td>5/1/07 - 4/30/12</td>
<td>5 Yrs</td>
</tr>
<tr>
<td>SR 277, Stephen’s City, VA</td>
<td>5</td>
<td>4/17/12</td>
<td>4/1/07 - 3/31/12</td>
<td>5 Yrs</td>
</tr>
<tr>
<td>US 250, Staunton, VA</td>
<td>3</td>
<td>7/10/12</td>
<td>7/1/07 - 6/30/12</td>
<td>5 Yrs</td>
</tr>
<tr>
<td>US 17, York County, VA</td>
<td>8</td>
<td>6/19/12</td>
<td>6/1/07 - 5/31/12</td>
<td>5 Yrs</td>
</tr>
<tr>
<td>SR 419, Salem, VA</td>
<td>5</td>
<td>11/13/12</td>
<td>11/1/07 - 10/30/12</td>
<td>5 Yrs</td>
</tr>
<tr>
<td>US 50, Winchester, VA</td>
<td>2</td>
<td>11/6/12</td>
<td>11/1/07 - 10/30/12</td>
<td>5 Yrs</td>
</tr>
<tr>
<td>US 29, Warrenton, VA</td>
<td>4</td>
<td>5/17/11</td>
<td>5/1/06 - 4/30/11</td>
<td>5 Yrs</td>
</tr>
<tr>
<td>US 250, Charlottesville, VA</td>
<td>6</td>
<td>9/20/11</td>
<td>9/1/06 - 8/31/11</td>
<td>5 Yrs</td>
</tr>
</tbody>
</table>

Major and minor road Annual Average Daily Traffic (AADT) data were collected from VDOT Traffic Monitoring System (TMS) and crash data were collected from VDOT Roadway Network System (RNS). Both total crashes and fatal plus injury (FI) crashes were examined. All crashes reported within 250 feet of an intersection are considered as intersection crashes in this analysis. All other crashes were categorized as segment crashes, and were not examined in this analysis. Intersection characteristics, such as number of legs, presence of turn bays, and signal phasing data were also collected. It is worth noting that there were additional intersection sites with ATSC installed in Virginia, but they were missing minor road AADT data, so they were not included in the analysis. Sites with missing minor road AADTs were often entrances to shopping centers or similar roads.

Some descriptive statistics of the data set used in this paper are shown in Table 2. There were a total of 1747 crashes (including 626 FI crashes) during the before period and 393 crashes (including 150 FI crashes) during the after period. The proportion of FI crashes in...
all crashes increased slightly from 35.83% in the before period to 38.17% in the after period. The average of AADT for both major and minor approaches are similar in the before and after periods.

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Variable</th>
<th>Annual Mean</th>
<th>Annual Minimum</th>
<th>Annual Maximum</th>
<th>Std. Deviation</th>
<th>Sum over Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before ATSC Installation</td>
<td>Total crashes</td>
<td>6.35</td>
<td>1</td>
<td>25.6</td>
<td>4.89</td>
<td>1747</td>
</tr>
<tr>
<td></td>
<td>FI crashes</td>
<td>2.66</td>
<td>0</td>
<td>7.2</td>
<td>1.71</td>
<td>626</td>
</tr>
<tr>
<td></td>
<td>AADT (major)</td>
<td>24306</td>
<td>6961</td>
<td>50329</td>
<td>12525</td>
<td>6684039</td>
</tr>
<tr>
<td></td>
<td>AADT (minor)</td>
<td>5046</td>
<td>386</td>
<td>20067</td>
<td>4529</td>
<td>1387656</td>
</tr>
<tr>
<td>After ATSC Installation</td>
<td>Total crashes</td>
<td>5.95</td>
<td>0</td>
<td>15</td>
<td>3.78</td>
<td>393</td>
</tr>
<tr>
<td></td>
<td>FI crashes</td>
<td>2.27</td>
<td>0</td>
<td>10</td>
<td>2.15</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>AADT (major)</td>
<td>24470</td>
<td>6667</td>
<td>49384</td>
<td>12640</td>
<td>1862303</td>
</tr>
<tr>
<td></td>
<td>AADT (minor)</td>
<td>4944</td>
<td>387</td>
<td>19010</td>
<td>4361</td>
<td>360057</td>
</tr>
</tbody>
</table>

**Analysis Preparation**

*Virginia Safety Performance Functions (SPF) for Urban Intersections*

Although the Highway Safety Manual (AASHTO, 2010) presents several SPFs for intersections, these were developed using national data from selected states. The HSM recommends that each state should develop its own SPFs based on local crash and traffic data, as the SPFs based on national data (a collection of states) may not adequately represent the crash characteristics in all states. A past study developed SPFs for intersections in Virginia using AADT as the most significant predictor, similar to SPFs suggested by Highway Safety Manual (Garber and Rivera, 2010). The SPFs were developed for both total crashes and combined fatal plus injury crashes through generalized linear modeling using a negative binomial distribution. Models were also developed for urban and rural intersections separately, as well as for the different regions of the state (Northern, Western, and Eastern regions) (Garber & Rivera, 2010). Regions were defined based on perceived differences in driving behavior and topography, and subsequently went through a pruning process to remove and consolidate models. Table 3 shows the recommended SPFs for signalized intersections in Virginia.
### TABLE 3 Virginia SPFs for urban signalized intersections (Garber & Rivera, 2010)

<table>
<thead>
<tr>
<th>Site</th>
<th>Virginia SPF models to be used for Urban Intersection</th>
<th>Dispersion Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban 4-Legged Signalized</td>
<td>Northern Total ( \exp(-7.6234 \cdot \text{MajADT}^{0.6742} \cdot \text{MinADT}^{0.3453}) )</td>
<td>0.6481</td>
</tr>
<tr>
<td></td>
<td>Western Total ( \exp(-12.3913 \cdot \text{MajADT}^{0.631} \cdot \text{MinADT}^{0.4567}) )</td>
<td>0.9771</td>
</tr>
<tr>
<td></td>
<td>Eastern Total ( \exp(-7.6234 \cdot \text{MajADT}^{0.6742} \cdot \text{MinADT}^{0.3453}) )</td>
<td>0.5725</td>
</tr>
<tr>
<td>Urban 4-Legged Signalized</td>
<td>Northern FI ( \exp(-8.5256 \cdot \text{MajADT}^{0.6477} \cdot \text{MinADT}^{0.3579}) )</td>
<td>0.6463</td>
</tr>
<tr>
<td></td>
<td>Western FI ( \exp(-11.4284 \cdot \text{MajADT}^{0.8662} \cdot \text{MinADT}^{0.4412}) )</td>
<td>0.7947</td>
</tr>
<tr>
<td></td>
<td>Eastern FI ( \exp(-9.9582 \cdot \text{MajADT}^{0.7484} \cdot \text{MinADT}^{0.4017}) )</td>
<td>0.5828</td>
</tr>
<tr>
<td>Urban 3-Legged Signalized</td>
<td>Northern Total ( \exp(-6.5430 \cdot \text{MajADT}^{0.6591} \cdot \text{MinADT}^{0.2119}) )</td>
<td>0.6708</td>
</tr>
<tr>
<td></td>
<td>Western Total ( \exp(-9.6143 \cdot \text{MajADT}^{0.8677} \cdot \text{MinADT}^{0.3297}) )</td>
<td>0.8647</td>
</tr>
<tr>
<td></td>
<td>Eastern Total ( \exp(-6.5430 \cdot \text{MajADT}^{0.6591} \cdot \text{MinADT}^{0.2119}) )</td>
<td>0.7576</td>
</tr>
<tr>
<td>Urban 3-Legged Signalized</td>
<td>Northern FI ( \exp(-8.4268 \cdot \text{MajADT}^{0.7147} \cdot \text{MinADT}^{0.2481}) )</td>
<td>0.7641</td>
</tr>
<tr>
<td></td>
<td>Western FI ( \exp(-11.0104 \cdot \text{MajADT}^{0.9080} \cdot \text{MinADT}^{0.3226}) )</td>
<td>1.0307</td>
</tr>
<tr>
<td></td>
<td>Eastern FI ( \exp(-8.4268 \cdot \text{MajADT}^{0.7147} \cdot \text{MinADT}^{0.2481}) )</td>
<td>0.6564</td>
</tr>
</tbody>
</table>

\( ^{A} \) Garber & Rivera (2010) divided Virginia into three different regions, Northern, Western, and Eastern, and developed region-specific SPFs.

All the sites used in this study are classified as suburban or urban signalized intersections. Several base conditions for intersections are defined in Highway Safety Manual (AASHTO, 2010) for use of national SPFs and they are also applicable to Virginia SPFs:

- No left-turn lanes
- Permissive left-turn signal phasing
- No right-turn lanes
- Right-turn on red permitted
None of the sites had red light cameras, bus stops, schools, or alcohol sales establishments near the sites. Therefore, intersection characteristic data corresponding to the other base conditions were collected, and the CMFs for each of them were obtained from Part C of HSM. The Crash Modification Factors used in the analysis are briefly described below.

**Turn Lanes**

Tables 12-24 and 12-26 in the HSM describe the CMFs for installation of left and right turn lanes, respectively, at urban or suburban arterial intersections. That information was applied to the 55 intersections studied and is summarized in Table 4.

### Table 4 CMFs for Turn Lanes on Intersection Approaches from Highway Safety Manual

<table>
<thead>
<tr>
<th>Turn Lane Type</th>
<th># of Legs</th>
<th>Number of Approaches with Turn Lanes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>One</td>
<td>Two</td>
</tr>
<tr>
<td>Left turn</td>
<td>3</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.90</td>
</tr>
<tr>
<td>Right turn</td>
<td>3</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.96</td>
</tr>
</tbody>
</table>

**Left Turn Signal Phasing**

Table 12-25 in the HSM describes CMFs for left-turn signal phasing. The CMFs shown are as follows:

- Permissive: CMF=1.00
- Protected plus permitted: CMF=0.99
- Protected: CMF = 0.94

If several approaches to a signalized intersection have left-turn phasing, the value of CMF for each approach is multiplied together.

**Right Turn on Red**

The CMF in the HSM for prohibiting right-turn-on-red on one or more approaches to a signalized intersection has been derived from a study by Clark (1983). The base condition is permitting a right-turn-on-red at all approaches to a signalized intersection.

\[
CMF = 0.98^{n_{prohib}}
\]

Where \( n_{prohib} \) = number of signalized intersection approaches for which right-turn-on-red is prohibited.
Intersection Lighting

The base condition for lighting is the absence of intersection lighting. The CMF for a lighted intersection is adapted from work of Elvik and Vaa (2004), as:

\[ CMF = 1 - 0.38 \times p_{ni} \]

Where \( p_{ni} \) = proportion of total crashes for unlighted intersections that occur at night.

While the HSM presents default values for the night time crash proportion (0.235 for both 3-leg and 4-leg signalized intersection), it encourages users to replace them with locally derived values. For this analysis, historical data from before ATSC was applied was used to CMFs for lighting.

Determination of Predicted Crashes

After the Virginia SPFs were applied to determine the base number of predicted crashes, Equation 1 was applied to determine the adjusted predicted crashed frequency that corresponds to a specific intersection’s characteristics.

\[ N_{predicted} = N_{spf} \times (CMF_{1x} \times CMF_{2x} \times ... \times CMF_{yx}) \]  

(1)

The HSM notes that caution should be used when multiplying several CMFs together, as quoted below.

"In the Part C predictive method, an SPF estimate is multiplied by a series of CMFs to adjust the estimate of crash frequency from the base condition to the specific conditions present at a site. The CMFs are multiplicative because the effects of the features they represent are presumed to be independent. However, little research exists regarding the independence of these effects, but this is a reasonable assumption based on current knowledge. The use of observed crash frequency data in the EB Method can help to compensate for bias caused by lack of independence of the CMFs. As new research is completed, future HSM editions may be able to address the independence (or lack of independence) of these effects more fully."

The fundamental assumption that the CMFs are independent of one another may or may not be true. As a result, the analysis in this paper may overestimate some safety effects if, in fact, the CMFs applied are not truly independent of one another.

Empirical Bayes Analysis and Results

Empirical Bayes method recommended by HSM was used in this study to develop a CMF for installation of ATSC. Chapter 9 of the Highway Safety Manual (AASHTO, 2010)
provides the computational procedure for implementing the Empirical Bayes before/after safety effectiveness evaluation method. The steps used to perform this analysis are briefly described below.

**Step 1:** The Virginia intersection SPFs and HSM CMFs were used to calculate predicted average crash frequency using Equation 1 for the before and after periods. The EB correction using observed data was then applied calculated the expected average crash frequency in the before period using Equation 2.

\[ N_{\text{expected, } B} = w_{i, B} N_{\text{predicted, } B} + (1 - w_{i, B}) N_{\text{observed, } B} \]  

(2)

Where the weight, \( w_{i, B} \), for each site \( i \), is determined as:

\[ w_{i, B} = \frac{1}{1 + k \sum_{\text{years}} N_{\text{predicted, } B}} \]

and:

\[ N_{\text{predicted}} = \text{Expected average crash frequency at site } i \text{ for the entire before period using the applicable SPF} \]

\[ N_{\text{observed, } B} = \text{Observed crash frequency at site } i \text{ for the entire before period} \]

\[ k = \text{Overdispersion parameter for the applicable SPF} \]

**Step 2:** Calculate adjustment factors \( r_i \) for both Total and FI crashes, to account for the differences between the before and after periods in duration and traffic volume at each site \( i \), using Equation 3. Use Equation 4 to calculate expected average crash frequency, \( N_{\text{expected, } A} \), for each site \( i \), over the entire after period in the absence of treatment.

\[ r_i = \frac{\sum_{\text{years}} N_{\text{predicted, } A}}{\sum_{\text{years}} N_{\text{predicted, } B}} \]  

(3)

\[ N_{\text{expected, } A} = N_{\text{expected, } B} \times r_i \]  

(4)

Where:

\[ N_{\text{observed, } A} = \text{Observed crash frequency at site } i \text{ for the entire after period} \]
**Step 3:** Calculate the overall effectiveness of ATSC technology, expressed as a CMF, using Equation 5. Also, calculate the standard error of the estimated CMF using Equation 6, indicating the stability of the estimated CMF.

\[
CMF = \frac{\sum_{All \ sites} N_{observed,A}}{\sum_{All \ sites} N_{expected,A}} \cdot \left[1 + \sum_{All \ sites} \left( (\eta)^2 \times N_{expected,B} \times (1 - w_i,B) \right) / \left( \sum_{All \ sites} N_{expected,A} \right)^2 \right]
\]  

(5)

Safety Effectiveness = 100 \times (1 - CMF)

(6)

\[
\sigma = \sqrt{\frac{\sum_{All \ sites} N_{observed,A}}{\sum_{All \ sites} N_{expected,A}} - \frac{1}{N_{observed,A}} + \frac{\text{Var}(\sum_{All \ sites} N_{expected,A})}{\left( \sum_{All \ sites} N_{expected,A} \right)^2}}
\]

(3)

To test the statistical significance of analysis result, the following rules are used in the Highway Safety Manual:

- If Abs[Safety Effectiveness/\(\sigma\)] < 1.7, conclude that the treatment effect is not significant at the (approximate) 90 percent confidence level.
- If Abs[Safety Effectiveness/\(\sigma\)] \(\geq\) 1.7, conclude that the treatment effect is significant at the (approximate) 90 percent confidence level.
- If Abs[Safety Effectiveness/\(\sigma\)] \(\geq\) 2.0, conclude that the treatment effect is significant at the (approximate) 95 percent confidence level.

Analysis is then conducted using the data set from 47 intersections. Results are shown in Table 5.

<table>
<thead>
<tr>
<th>TABLE 5 CMF Results and Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measures</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>CMF</td>
</tr>
<tr>
<td>Standard Error</td>
</tr>
<tr>
<td>Safety Effectiveness (%)</td>
</tr>
<tr>
<td>Safety Effectiveness / (\sigma)</td>
</tr>
</tbody>
</table>

Table 5 shows that installing ATSC technology at an urban signalized intersection can have a statistically significant effect on reducing total crashes at the 95 percent confidence level. The CMF was 0.83 with a standard error of 0.05. ATSC installation was not found to have a statistically significant effect on Fatal-and-Injury crashes. The
non-significant FI CMF seems plausible since reductions in stops along the corridor would likely have a greater impact on low-speed crashes.

The EB analysis was also conducted separately for four-leg and three-leg intersections to determine if there were differences in performance by intersection configuration. Table 6 shows that only the CMF for total crashes at four-leg intersections is significant at the 95% level. These results may be influenced by the smaller number of three-leg intersections (9 out of 47) in the data set. Future research should collect more data to determine if differences exist.

**TABLE 6 CMF Results for Three-Leg and Four-Leg Intersections**

<table>
<thead>
<tr>
<th># of Legs</th>
<th>Crash Severity</th>
<th>CMF</th>
<th>Std. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Four</td>
<td>Total Crashes</td>
<td>0.79**</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>FI Crashes</td>
<td>0.92</td>
<td>0.09</td>
</tr>
<tr>
<td>Three</td>
<td>Total Crashes</td>
<td>0.996</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>FI Crashes</td>
<td>0.87</td>
<td>0.19</td>
</tr>
</tbody>
</table>

** indicates significance at 95% level.

**Discussion**

Given the overall results on the safety effect of ATSC, several additional factors were examined to try to gather further insight into the calculated effectiveness. Changes in crash type proportions, safety effect by AADT level, and safety effectiveness by corridor relative to operational improvements experienced were all examined.

*Changes in Crash Type Proportions*

Although the previous analysis showed that ATSC was able to reduce both total and FI crashes, it was not clear whether certain crash types were disproportionately affected by ATSC. It was hypothesized that if stops are reduced at the sites, then rear end crashes may see larger declines than other crash types.

Table 7 shows that the distribution of crash types does not change much in the before and after period based on this data set. Contrary to expectations, the proportion of rear end crashes actually increased with ATSC by 6.22 and 3.71 percentage points for total and FI crashes, respectively.

There are several possible explanations as to why a proportionate decrease in rear end crashes was not observed. First, the ATSC system evaluated operates in an acyclic manner, meaning that phases could be skipped or served multiple times. This behavior may offset potential rear end decreases that created through fewer stops. Likewise, if drivers are less likely to stop along a corridor, it is possible that they may be less attentive and more likely to make an error during the times when they do need to stop. Additional investigation into crash types would appear to be warranted as more data becomes available, although based on this data it appears that significant changes in crash type proportions were not observed.
<table>
<thead>
<tr>
<th>Crash Type</th>
<th>Total Crash Before</th>
<th>FI Crash Before</th>
<th>Total Crash After</th>
<th>FI Crash After</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rear End</td>
<td>896 (51.29%)</td>
<td>319 (50.96%)</td>
<td>226 (57.51%)</td>
<td>82 (54.67%)</td>
</tr>
<tr>
<td>Angle</td>
<td>538 (30.80%)</td>
<td>202 (32.27%)</td>
<td>110 (27.99%)</td>
<td>49 (32.67%)</td>
</tr>
<tr>
<td>Sideswipe (same direction)</td>
<td>134 (7.67%)</td>
<td>26 (4.15%)</td>
<td>26 (6.62%)</td>
<td>5 (3.33%)</td>
</tr>
<tr>
<td>Sideswipe (opposite direction)</td>
<td>13 (0.74%)</td>
<td>7 (1.12%)</td>
<td>3 (0.76%)</td>
<td>2 (1.33%)</td>
</tr>
<tr>
<td>Non-collision</td>
<td>14 (0.80%)</td>
<td>9 (1.44%)</td>
<td>3 (0.76%)</td>
<td>2 (1.33%)</td>
</tr>
<tr>
<td>Other</td>
<td>152 (8.70%)</td>
<td>63 (10.06%)</td>
<td>24 (6.11%)</td>
<td>10 (6.67%)</td>
</tr>
<tr>
<td>Sum</td>
<td>1747 (100%)</td>
<td>626 (100%)</td>
<td>393(100%)</td>
<td>150 (100%)</td>
</tr>
</tbody>
</table>

**Safety Effects by AADT Level**

ATSC is typically deployed to improve mobility at sites where traffic is unreliable, relatively congested, and has changing traffic patterns. Given these attributes, it was hypothesized that ATSC could have varying effects by AADT. The average of the major road AADT across before and after periods was used to create two categories: low volume (6900<AADT<30000, 28 sites) and high volume (30000<AADT<50200, 27 sites). As shown in Table 8, the odds ratios are not significant at the 90% level at low volume sites for both total and FI crashes, while at high volume sites the odds ratios are significant at the 95% level for total crashes. This result again implies that higher volume sites are more likely to experience benefits from ATSC installation.

**TABLE 8 Odds Ratio at Different AADT Levels**

<table>
<thead>
<tr>
<th>AADT</th>
<th>Total Crashes</th>
<th>FI crashes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Odds Ratio</td>
<td>Standard Error</td>
</tr>
<tr>
<td>6900&lt;AADT&lt;30000</td>
<td>0.95</td>
<td>0.08</td>
</tr>
<tr>
<td>30000&lt;AADT&lt;50200</td>
<td>0.72***</td>
<td>0.06</td>
</tr>
</tbody>
</table>

**Significant at 95% level**

**Safety Effects by Corridor and Operational Change**

The CMFs developed using all 47 intersections also do not distinguish between sites where ATSC differed in effectiveness. First, intersections along each corridor were re-analyzed to determine a corridor-specific EB estimate. Figure 1 shows these results, with the error bars indicating a 90th percentile confidence interval. Note that the limited number of sites on a by-corridor basis has a strong influence on the width of these confidence intervals. Figure 1(a) shows the results for total crashes while 1(b) shows the results for FI crashes.
Table 9 shows the mean odds ratios relative to several measures of operational performance for each corridor. For each corridor, GPS floating car travel times were collected before and after ATSC installation during the AM peak (7-9 AM), midday (11 AM – 1 PM), and PM peak (4-6 PM). GPS position data were logged every second, and multiple probe vehicles traversed the corridors at staggered start times to collect the data.
This data was used to define the average number of stops that a probe vehicle experienced while traversing the corridor, with a stop being defined as an instance where the vehicle’s speed dropped below 5 mph. Average speeds were also examined over the entire corridor. Data before and after were compared using t-tests with an $\alpha=0.05$ for each direction of travel for each time period. In total, 9 of 11 corridors experienced improvements in stops and average speed. Only 1 corridor saw a degradation in speed and stops, and the other had a decrease in stops with a slight decrease in speed. Generally speaking, the system was able to improve operational performance, usually by a statistically significant margin, in most of the corridors evaluated.

In examining Table 9, there are no obvious correlations between the site odds ratios and the observed changes in operational performance. Correlation coefficients were calculated for the odds ratios and the changes in stops and speed, but correlations were below 0.2 in all cases. Given that rear end crashes were not disproportionately affected by ATSC, this lack of correlation between mainline operational changes and safety is perhaps not unexpected.

This lack of correlation could be attributable to several causes. First, the operational data presented was focused on the mainline, so it would not capture changes in side street delays. Second, although some sites had data from Bluetooth and private sector probe data providers, the limited floating car data set was the only information consistently available across all sites. Thus, this data may not be representative of longer term performance since it was collected at a discrete time.

**CONCLUSIONS AND FUTURE RESEARCH**

While the mobility impacts of adaptive traffic signal control (ATSC) have long been examined, its safety benefits have not been extensively studied. This paper quantitatively
evaluated the safety effectiveness of installing ATSC system using field data from Virginia. In total, 47 sites with ATSC were examined between 2006 and 2013.

Using the Empirical Bayes method, it was found that installing ATSC technology at urban signalized intersections can have a statistically significant effect on reducing total crashes at a 95 percent confidence level. The CMF was 0.83 with a standard error of 0.05, although fatal and injury crashes were not found to change significantly. Additional analysis indicates that ATSC may have larger safety effects on higher volume routes. No strong correlation was found between the system operational impact and system safety impact, however.

There are several possible avenues for further research in this area. First, this study used a single ATSC vendor for this analysis. It is possible that other ATSC vendors could produce different safety effects if their adaptive system operates in a significantly different manner. Second, this research could be extended to examine whether improved corridor performance impacts segment safety as well. Additional work on correlating operational improvements with safety changes could be conducted to determine how side street performance changes influence crash occurrence. Likewise, potential safety impacts on roadway segment crashes could also be examined.

REFERENCES


