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Crash modification factors for adaptive traffic signal control: An Empirical Bayes before-after study

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ABSTRACT

Adaptive traffic signal control (ATSC) is a novel traffic management system that is often deployed at high-volume intersections in order to mitigate traffic congestion and improve travel time reliability. While past studies have demonstrated its operational effectiveness, relatively few have focused on safety performance. Those that have tend to suffer from limitations including small sample sizes, insufficient study designs, or the lack of consideration of potential temporal and corridor effects after ATSC installation. Furthermore, results from previous studies are mixed: while many studies point to a safety improvement, more recent studies seem to indicate that ATSC systems might increase crash frequency. In light of this, a comprehensive Empirical Bayes (EB) before-after observational study was conducted using ATSC data collected throughout Pennsylvania. Crash modification factors (CMFs) were estimated based on the following different case scenarios: crash severity levels and crash types (total, fatal and injury, rear-end, and angle crashes); intersection locations (all intersections and intersections along corridors only); and, intersection configurations (3-leg and 4-leg). Temporal trends for intersection-level CMFs were examined using annual crash data in the after period. Corridor-level CMFs were also developed to quantify changes in safety performance along corridors with ATSC installed. The results suggest that ATSC is associated with a nominal increase in total and angle crashes, and an expected decrease in fatal plus injury crashes and rear-end crashes. However, the results were not statistically significant. The safety effect estimates are similar when considering intersection locations and configurations. In addition, the temporal trend analysis indicates that the safety effectiveness does not vary annually in the after period, suggesting no obvious novelty effect associated with ATSC. Finally, the magnitude of the corridor-level CMFs are slightly lower than the intersection-level CMFs, except for rear-end crashes.

1. Introduction

Adaptive traffic signal control (ATSC) is a traffic management technology system that mitigates traffic congestion, optimizes network performance, and reduces fuel consumption along signalized arterial corridors. ATSC systems dynamically modify signal green times and cycle lengths based on real-time traffic volume data collected from onsite detectors. Past studies have shown that ATSC can effectively improve operational performance of selected intersections and corridors by reducing the number of stops and associated travel delays (Hicks and Carter, 2000; Peters et al., 2008; Khattak et al., 2018a, b).

Unfortunately, the safety impact of ATSC is not yet clear. Among early ATSC deployments, Hicks and Carter (2000) assumed that rear-end crash frequency was expected to decrease due to a reduction in the number of stops along corridors. Subsequently, considerable effort was made to figure out the relationship between ATSC installation and its safety effectiveness, either using field data (Dutta et al., 2010; Lodes and Benekohal, 2013; Ma et al., 2016; Khattak et al., 2018a, b; Fink et al., 2016; Khattak et al., 2019) or traffic simulation studies (Stevanovic et al., 2011; Sabra et al., 2010, 2013; Stevanovic et al., 2013). From an empirical point of view, for example, Dutta et al. (2010) examined data from several counties in Michigan before and after the installation of the Sydney Coordinated Adaptive Traffic System (SCATS) and identified a shift in crash severity levels from the more severe end of the KABCO scale (i.e., levels A and B) towards the non-severe crash outcomes on the same scale (i.e., level C). Lodes and Benekohal (2013) surveyed three sites with ATSC and concluded that all sites experienced a reduction in crash frequency.

More recent studies have developed CMFs that have been included within the FHWA CMF Clearinghouse. A summary of these are provided in Table 1. Ma et al. (Ma et al., 2016) systematically investigated the safety impact of ATSC using Virginia data and reported a statistically

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Table 1
Summary of CMFs for ATSC included in the CMF Clearinghouse.

CMF estimate	Standard error	Crash Type	Crash severity	Intersection type	Study
0.83	0.05	All	KABCO	3-leg,4-leg	Ma et al (2016)
0.92	0.08	All	KABC	3-leg,4-leg	Ma et al (2016)
0.79	0.05	All	KABCO	4-leg	Ma et al (2016)
0.92	0.09	All	KABC	4-leg	Ma et al (2016)
0.996	0.13	All	KABCO	3-leg	Ma et al (2016)
0.87	0.19	All	KABC	3-leg	Ma et al (2016)
0.807	0.009	Angle	KABCO	Not specified	Fink et al (2016)
0.87	0.058	MV	KABCO	3-leg,4-leg	Khattak et al (2018b)
0.64	0.063	MV	KABC	3-leg,4-leg	Khattak et al (2018)
0.89	0.10	MV	KABCO	3-leg,4-leg	Khattak et al (2018)
0.6	0.13	MV	KABC	3-leg,4-leg	Khattak et al (2018)
0.86	0.06	MV	KABCO	3-leg,4-leg	Khattak et al (2018)
0.66	0.05	MV	KABC	3-leg,4-leg	Khattak et al (2018)
0.77	0.057	MV	KABCO	4-leg	Khattak et al (2018)
0.6	0.056	MV	KABC	4-leg	Khattak et al (2018)
0.78	0.107	MV	KABCO	3-leg	Khattak et al (2018)
0.45	0.035	MV	KABC	3-leg	Khattak et al (2018)
0.67	0.11	MV	KABCO	4-leg	Khattak et al (2018)
0.50	0.09	MV	KABC	4-leg	Khattak et al (2018)
1.04	0.20	MV	KABCO	3-leg	Khattak et al (2018)
0.6	0.21	MV	KABC	3-leg	Khattak et al (2018)
0.79	0.09	MV	KABCO	4-leg	Khattak et al (2018)
0.82	0.08	MV	KABC	4-leg	Khattak et al (2018)
0.20	0.107	MV	KABCO	3-leg	Khattak et al (2018)
0.22	0.107	MV	KABC	3-leg	Khattak et al (2018)
0.96	0.15	All	KABCO	3-leg,4-leg	Osario and Benekohal (2019)
0.67	0.22	All	KABC	3-leg,4-leg	Osario and Benekohal (2019)
1.04	0.18	All	O	3-leg,4-leg	Osario and Benekohal (2019)
1.00	0.16	All	KABCO	4-leg	Osario and Benekohal (2019)
0.67	0.23	All	KABC	4-leg	Osario and Benekohal (2019)
1.09	0.20	All	O	4-leg	Osario and Benekohal (2019)
0.68	0.29	All	KB	3-leg,4-leg	Osario and Benekohal (2019)
0.87	0.41	All	B	3-leg,4-leg	Osario and Benekohal (2019)

MV – Multi-vehicle crashes.
KABCO – Fatal (K); Incapacitating Injury (A); Non-Incapacitating Injury (B); Possible Injury (C); Property-damage Only (O).

significant reduction in total crashes of 17 percent using the Empirical Bayes (EB) before-after study design. Similarly, (b) estimated various CMFs of ATSC based on different conditions (e.g., crash severity levels, ATSC algorithms, and intersection configurations). The results indicated aggregated CMF values of 0.87 and 0.64 for total and fatal plus injury crashes, respectively, after ATSC installation. Fink et al. (2016) analyzed the SCATS-based system from Michigan, developing negative binomial regression models and multinomial logit models to estimate the safety effects on crash frequency and crash severity, respectively. The models indicated that ATSC was associated with fewer angle crashes and non-serious injuries. Khattak et al. (2019) examined the relationship between crash severity levels and ATSC installation using a random parameters ordered probit model and identified a reduction in the probability of non-fatal crashes when deploying ATSC. While most past studies have found that ATSC is associated with fewer crashes, there are several crash modification factors (CMF) reported in the recent literature that exceed 1.0 for this treatment. For example, Osario and Benekohal (2019) reported CMFs of 1.09 for total crashes at four-leg signalized intersections and 1.04 for total crashes at three- and four-leg signalized intersections in Illinois. In addition, (b) reported a CMF of 1.04 for multi-vehicle collisions at urban/suburban intersections in a study of select intersections in Pennsylvania (Pittsburgh and Philadelphia regions). These recent findings that ATSC might deteriorate safety performance suggests that the safety impacts of ATSC needs another, more comprehensive look.

In addition to observational studies, other researchers have considered simulation models to evaluate the safety effectiveness of ATSC (Stevanovic et al., 2011; Sabra et al., 2010, 2013; Stevanovic et al., 2013). For example, Stevanovic et al. (2011) incorporated field data from Utah into a microsimulation modeling framework using VISSIM and the Federal Highway Administration (FHWA)'s Surrogate Safety Assessment Model (SSAM). The simulation results suggested a reduction in rear-end and total conflicts, as well as an expected increase in angle and lane-changing conflicts. Others (Sabra et al., 2010, 2013; Stevanovic et al., 2013) identified tradeoffs between safety impacts and operational efficiency using similar simulation evaluation techniques. The results of these studies confirmed the existence of an inverse relationship between safety and efficiency (i.e., more conflicts leads to lower operational efficiency), revealing a strong relationship between number of conflicts and efficiency metrics, such as cycle length, length of each split, left-turn phasing and phase sequence. However, a drawback of these studies was that they were not validated using observed crash outcomes.

Although previous studies have demonstrated an association between crash frequency or severity outcomes and ATSC installation, the findings are not consistent: while most studies find a safety improvement, more recent studies have found ATSC systems deteriorate safety performance. In many safety evaluations, the results were not statistically significant. The small sample sizes of these studies make it difficult to tell if this is due to the limited data available or if the CMFs are similar to 1.0. In addition, it is not practical to infer crash frequency or severity changes using simulation methods. In addition to the evaluation methodology limitations, past studies contained fairly short analysis periods after ATSC installations (Lodes and Benekohal, 2013; Ma et al., 2016), few study sites (Lodes and Benekohal, 2013; Ma et al., 2016; Khattak et al., 2018b), potentially biased approaches (e.g., direct comparison or cross-sectional models) to evaluate safety benefits of ATSC (Lodes and Benekohal, 2013; Fink et al., 2016), and use of calibrated SPFs as opposed to locally developed SPFs for the analysis (Khattak et al., 2018b). Additionally, no previous study addressed temporal trends associated with ATSC after installation. Because ATSC systems modify signal timing and phasing plans in response to real-time traffic patterns, it seems plausible that the safety performance at signalized intersections with this technology may change over time. This study attempts to address this potential novelty effect.

In addition to the intersection-level effects of ATSC, corridor-level effects have not been investigated in detail. Sacchi et al. (2016) suggested considering spatial effects and clustering intersections when evaluating safety benefits since signalized intersections equipped with ATSC along a corridor are not independent sites. Ma et al. (2016) briefly explored corridor-level safety effects, but the results were developed based on individual corridors, rather than a collection of corridor sets, making it difficult to generalize the results.

In light of these issues, the objective of this paper is to comprehensively estimate CMFs using a relatively large sample of intersections from Pennsylvania. The safety effects of ATSC systems is estimated using the EB before-after framework. Different conditions are considered, including the following: crash severity levels and crash types (total, fatal and injury, rear-end, and angle crashes), intersection- versus corridor-level locations, and intersection configurations (3-leg and 4-leg). The temporal effect of ATSC is also evaluated annually to determine if there is a novelty effect associated with the traffic control strategy.

The remainder of this paper is organized into several subsequent sections. The second section describes the methodology used in this study. It is followed by a description of the data used in the research. The fourth section summarizes the estimation results. The final section of the paper offers from conclusion from the evaluation and identifies potential directions for future work.

2. Methodology

The objective of this research was to estimate CMFs for the ATSC system under different scenarios. The EB before-after approach that was applied to estimate both intersection- and corridor-level CMFs is described below.

2.1. Empirical Bayes before-after study methodology

The EB before-after approach (Hauer, 1997) was selected to develop CMFs to describe the expected change in crash frequency at signalized intersections with adaptive traffic signal control system installations. This method is widely accepted as the state-of-the-art in observational before-after studies of crash data (Hauer, 1997; Gross et al., 2010). The proposed EB analysis properly accounts for statistical factors such as: regression-to-the-mean, differences in traffic volume, and crash trends (time series effects) between the periods before and after adaptive traffic signals were installed. The EB approach is comprised of three basic steps, each defined as follows:

Step 1: Develop safety performance functions to predict what the safety performance of intersections or corridors with adaptive traffic signal installations would have been had the adaptive traffic signal not been implemented.

Step 2: Estimate what the actual (reported) safety performance should be for treatment sites (i.e., intersections or corridors where adaptive signals were installed) in the after period if adaptive traffic signals were not installed.

Step 3: Compare the predicted and reported safety performance to determine the safety effect of adaptive traffic signals.

Each of these steps is described in more detail below.

2.1.1. Step 1 – prediction of safety performance

In this step, a reference group is used to account for the effects of traffic volume changes and temporal effects on safety due to the variation in weather, demographics, and crash reporting. This is done through the calibration and application of safety performance functions (SPFs), which relate the frequency of different crash types and severities to traffic volumes and other relevant factors for a reference group of sites. This enables the simultaneous accounting for temporal and possible regression-to-the-mean effects, as well as those related to changes in traffic volume.

Negative binomial count regression models were used to estimate all intersection- and corridor-levels SPFs in this study. The negative binomial regression model was a logical choice to estimate the expected number of crashes per year at these locations because it accounts for overdispersion common in crash data. The general functional form of the negative binomial regression model is:

$$ln\lambda_i = \beta X_i + \varepsilon_i \tag{1}$$

where λ_i = expected number of crashes at location i; β = vector of estimable regression parameters; X_i = vector of geometric design, traffic volume, and other site-specific data for location i; and, ε_i = gamma-distributed error term.

The mean-variance relationship for the negative binomial distribution is:

$$Var(\lambda_i) = E(\lambda_i)[1 + \alpha E(\lambda_i)] \tag{2}$$

where $\mathrm{Var}(\lambda_i)$ = variance of reported crashes y occurring at location i; $E(\lambda_i)$ = expected crash frequency at location i; and, α = overdispersion parameter.

Eq. (3) shows the general form of the SPF that was estimated for intersections, as an example. This form is consistent with Eq. (1).

$$N_{i,SPF} = AADT\ Major^{\beta_{AADT\ Major}} \times AADT\ Minor^{\beta_{AADT\ Minor}} \times \exp(\beta_0 + \sum x_{ij}\beta_j) \tag{3}$$

where $N_{i,SPF}$ = predicted crash frequency for intersection i using an SPF created from the reference group [crashes/year]; $\beta_{AADT\ Major}$ = estimated coefficient for traffic volume on major road approach; $\beta_{AADT\ Minor}$ = estimated coefficient for traffic volume on minor road approach; and, β_j = estimated coefficient for other variables x_{ij} that describe intersection i.

2.1.2. Step 2 – before-after analysis with Empirical Bayes

An Empirical Bayes adjustment was applied to SPF predictions obtained from Eq. (3) to incorporate reported crash frequency in the prediction of crash frequency at each location. This EB adjustment is shown in Eq. (4) (Hauer, 1997).

$$N_{i,EB} = w_i \times N_{i,SPF} + (1 - w_i) \times N_{i,obs} \tag{4}$$

where $N_{i,EB}$ = predicted crash frequency at location i based on EB adjustment [crashes/year]; w_i = adjustment weight for predicted crash frequency at location i ; $N_{i,SPF}$ = predicted crash frequency at location i based on the SPF (e.g., Eq. (3)) [crashes/year]; and, $N_{i,obs}$ = reported or observed crash frequency at location i [crashes/year].

The weight (w_i) used for the EB adjustment for any location i is derived using Eq. (5) (Hauer, 1997).

$$w_i = \frac{1}{1 + \alpha \times \sum_{all\ study\ years} N_{i,SPF}} \tag{5}$$

Thus, Eqs. (3)–(5) were used to determine N_{EB}^{Before} for the treatment sites in the before period by applying the SPFs generated in Step 1.

The SPF was used to calculate the predicted crash frequency using the SPF, N_{SPF}^{After}, for all treated intersections in the after period. Finally, the EB adjusted expected crash frequency in the after period, N_{EB}^{After}, was calculated using Eq. (6) and the adjustment factor, r, from Eq. (7).

$$N_{EB}^{After} = N_{EB}^{Before} \times r \tag{6}$$

$$r = \frac{\sum_{after\ years} N_{SPF}^{After}}{\sum_{before\ years} N_{SPF}^{Before}} \tag{7}$$

where r = adjustment factor for differences in duration and traffic volume between before and after periods; and, N_{EB}^{After} = EB adjusted crash frequency predicted during the after period.

Table 2
Summary of ATSC intersections by PennDOT engineering district and region.

District	County	Number of intersections with ATSC
2	Centre	2
2	Clearfield	4
4	Luzerne	15
5	Lehigh	6
6	Bucks	58
6	Chester	19
6	Delaware	15
6	Montgomery	67
8	Cumberland	36
8	Dauphin	28
8	Lancaster	21
8	Lebanon	10
8	York	27
10	Butler	2
11	Allegheny	21
12	Westmoreland	11

This EB adjusted value obtained from Eq. (6) provides the expected crash frequency if no treatment was applied. This expected crash frequency was then compared with the reported crash frequency after the treatment was applied to assess the safety effects of the treatment.

2.1.3. Step 3 – compare predicted and actual safety performance

An unbiased estimate of the safety effect (θ) of the treatment or countermeasure is obtained using Eqs. (8) and (9).

$$\theta = \frac{N_{observed}^{After}}{N_{EB}^{After}\left[1 + \frac{Var(N_{EB}^{After})}{N_{EB}^{After^2}}\right]} \tag{8}$$

$$Var(N_{EB}^{After}) = \sum_{all\ sites} r^2(1-w)N_{EB}^{After} \tag{9}$$

where θ = unbiased estimate of safety effect of the countermeasure; and, $N_{observed}^{After}$ = reported or observed crashes at the intersection during the after period.

Finally, the standard error associated with this safety effect estimate was computed using Eqs. (10) and (11).

$$Std\ Error(\theta) = \sqrt{\theta^2\left[\frac{\left(\frac{Var(N_{observed}^{After})}{N_{observed}^{After^2}}\right) + \left(\frac{Var(N_{EB}^{After})}{N_{EB}^{After^2}}\right)}{\left(1 + \frac{Var(N_{EB}^{After})}{N_{EB}^{After^2}}\right)^2}\right]} \tag{10}$$

$$Var(N_{observed}^{After}) = \sum_{all\ sites} N_{observed}^{After} \tag{11}$$

2.2. Intersection-level and corridor-level CMF estimation

As discussed in the previous section, intersection- and corridor-level CMFs were developed in the present study. Intersection CMFs were obtained using the methodology outlined above, where each individual intersection was considered as an observation with a unique before and after period. The before period consisted of the five years prior to when each intersection was converted from traditional to adaptive operation, while the after period consisted of all years after the year the intersection was converted to adaptive operation, up to and including 2018. To obtain the corridor-level CMFs, each individual adaptive corridor was treated as a unique observation in the EB before-after process, as in Gross et al. (2018). Predicted crash frequencies from SPFs and observed crashes were obtained for individual intersections and segments making up the corridors, and these were aggregated into overall predicted and observed values for the corridor when applying the EB procedure. For the corridors, the before period consisted of the five years prior to when the first intersection along the corridor was converted from traditional to adaptive operation, while the after period consisted of all years after the last intersection was converted to adaptive operation, up to and including 2018.

3. Data

This section describes the datasets that were used in the study, including intersection and corridor data. All study sites are located in Pennsylvania, at intersections in urban/suburban areas. Four different crash metrics were examined at both the intersection- and corridor-levels: total crashes, fatal and injury crashes, rear-end crashes, and angle crashes.

3.1. Intersection data

The intersections included in this study were determined based on their traffic volume availability on the major and minor street approaches, current ATSC system status, and the duration of years in the after period through the year 2018. In total, there were 342 unique intersections with ATSC in the final dataset, including 1710 intersection-year observations in the before period and 1107 intersection-year observations in the after period. Table 2 provides a summary of the intersections included in this study by PennDOT engineering district and county, while Table 3 provides a summary of these intersections by ATSC installation date. Note that the date of installation for the ATSC systems ranged between 2010 and 2017. The end of the before period and the start of the after period were determined based on the system installation year at individual intersections. Five full years of data in the before period and at least one full year of data in the after period were required for the intersection to be included in the evaluation. The year in which the ATSC system was installed was not included in the evaluation.

Crash data were obtained from the Pennsylvania Department of Transportation (PennDOT) public crash database. Crashes reported within 250 ft. of the intersection configuration (Garber and Rivera, 2010; Donnell et al., 2014, 2016; Donnell et al., 2019) were considered as intersection crashes in this study. The roadway data that were used in SPF prediction (Donnell et al., 2014, 2016; Donnell et al., 2019), such as traffic volume and roadway and roadside characteristics, were collected from PennDOT's Roadway Management System (RMS) database, and supplemented with PennDOT's local road counting program, PennDOT's Traffic Information Repository (TIRe), and manual data collection using PennDOT's online video photolog system and Google Earth. The annual summary statistics of these intersections in the before and after periods are shown in Table 4. Only traffic volume and crash counts are shown in Table 2 since they are the only variables that varied over the analysis years. In addition to the electronic and supplemental

Table 3
Summary of ATSC intersections by installation year.

ATSC installation year	Number of years in the after period	Number of intersections	Total number of crashes in the before period	Total number of crashes in the after period
2010	8	3	42	82
2011	7	27	556	821
2012	6	29	285	551
2013	5	22	267	351
2014	4	20	311	285
2015	3	89	1998	1151
2016	2	111	1889	815
2017	1	41	1029	203

Table 4
Annual Summary of Crash Statistics for ATSC Intersections.

Variable	Mean	Standard Deviation	Minimum	Maximum
Before Period				
Total crashes per year	3.73	3.42	0	20
Fatal and injury crashes per year	1.94	2.09	0	15
Rear-end crashes per year	1.55	1.87	0	12
Angle crashes per year	1.48	1.94	0	17
AADT on major approach	23,978	10,821	5,969	63,782
AADT on minor approach	7,258	5,605	47	37,640
After Period				
Total crashes per year	3.85	3.23	0	20
Fatal and injury crashes per year	1.91	1.95	0	13
Rear-end crashes per year	1.42	1.78	0	15
Angle crashes per year	1.68	1.97	0	15
AADT on major approach	23,080	11,070	3,706	66,387
AADT on minor approach	7,321	5,603	111	34,716

data collected for the evaluation, traffic signal permit plans were also reviewed to confirm that no other infrastructure improvements were completed when implementing the adaptive traffic signals.

3.2. Corridor data

The corridor data included in the study were selected according to the traffic volume availability on the major approach (i.e., the corridor itself), current ATSC system status, number of consecutive adaptive signal-controlled intersections along the corridor, and the duration of years in the after period through the year 2018. In this study, to be identified as an ATSC corridor unit, there must be at least three adaptive signal-controlled intersections along the corridor without any significant change in the roadway cross-section characteristics. The end of the before period and the start of after period in the corridor data were determined by the first and last system installation year of each identified corridor unit. Similar to the intersection data, five years in the before period and at least one year in the after period were required for the corridor to be included in the evaluation. In total, there were 696 segment elements in the final dataset, consisting of 46 corridors based on unique state route IDs, including 3480 segment-year observations in the before period and 1916 segment-year observations in the after period. The summary of the number of corridors available for analysis by installation dates for ATSC along the corridor is provided in Table 5.

Crash data and roadway data in the corridor dataset were collected from the same data sources as described in the intersection data section. The annual summary statistics of these segments, aggregated into corridors in the before and after periods, are shown in Table 6.

4. Results

This section summarizes the safety effectiveness of the ATSC system using the EB before-after methodology described in Section 2. Intersection-level and corridor-level CMFs were estimated for different crash severity levels and crash types. CMFs for various intersection locations (i.e., intersections along an adaptive corridor vs. all intersections) and intersection configurations (i.e., 3-leg vs. 4-leg) were also estimated. In addition, a temporal trend analysis was conducted using individual year data in the after period (i.e., year 1 only vs. year 2 only vs. year 3 only) to verify the stability of the CMFs and to identify potential novelty effects associated with the ATSC system. Note that before developing CMFs, existing Pennsylvania statewide and regional SPFs were updated using reference group data (i.e., dataset without intersections/segments in the current study) to provide an unbiased estimate of the expected crash frequency at intersections without ATSC. A summary of example SPFs that were applied to develop intersection-level CMFs is provided in Table 7. The functional forms were the same as those produced in previous research projects. The full descriptions and details of these SPFs can be found in several research project reports (Donnell et al., 2014, 2016; Donnell et al., 2019).

Note that data from three different ATSC system types were considered in this study. Individual CMFs were estimated for the individual systems; however, two systems had very few observations and the CMFs have a very large standard error as a result. The 95 % confidence intervals for all CMFs exhibit considerable overlap and two systems had nearly identical CMF estimates. For these reasons, all intersections were aggregated together for the purposes of CMF estimation for the remainder of this paper. However, a review of the individual systems revealed that they all behaved very similarly in terms of general detection technologies and control logic. Specifically, all utilize real-time data collection from cameras and/or in-pavement detections to change phasing plans, green splits, offsets and/or and cycle lengths based on observed queue lengths and vehicle delays. Details on the algorithms used to optimize these parameters were not readily available since the systems were all commercial systems and that information is considered proprietary. However, several differences were noted from the review. These include: 1) one system uses aggregated information to priortize minor phases, while providing green waves on the arterial, by changing signal phasing and timing plans, offsets and cycle lengths; 2) one system uses high-resolution data to select green splits and offsets while considering delays and number of stops along the arterial; and, 3) one system is a low-cost strategy that changes phase splits and offsets.

Table 6
Annual Summary Statistics of ATSC Corridor Segment Data.

Variable	Mean	Standard Deviation	Minimum	Maximum
Before Period				
Total crashes per year	3.49	4.15	0	32
Fatal and injury crashes per year	1.75	2.35	0	22
Rear-end crashes per year	1.55	2.21	0	24
Angle crashes per year	1.18	2.09	0	26
AADT	14,178	5,402	1,812	32,811
After Period				
Total crashes per year	3.62	3.97	0	36
Fatal and injury crashes per year	1.74	2.19	0	17
Rear-end crashes per year	1.49	2.07	0	21
Angle crashes per year	1.33	2.15	0	23
AADT	13,841	5,729	3,073	35,104

Table 5
Summary of ATSC corridors by installation year.

ATSC installation year	Number of years in the after period	Corridor Number	Total number of crashes in the before period	Total number of crashes in the after period
2017	1	8	2193	464
2016	2	13	3105	1240
2015	3	10	3061	1844
2014	4	6	755	748
2013 or prior	5+	9	1438	1634

Table 7
Intersection-Level SPFs.

Three-leg Intersection on Urban Arterial

MajorAADT/ MinorAADT = major/minor road average annual daily traffic (veh/day).
ELTMaj = indicator variable for exclusive left-turn lane on the major street approach (1 = present; 0 otherwise).
ELTMin = indicator variable for exclusive left-turn lane on the minor street approach (1 = present; 0 otherwise).
ERTMaj = indicator variable for exclusive right-turn lane on the major street approach (1 = present; 0 otherwise).
ERTMin = indicator variable for exclusive right-turn lane on the minor street approach (1 = present; 0 otherwise).
MajPSL30_35 = indicator for posted speed limit of 30 or 35 mph on major road (1 = present; 0 otherwise).
MajPSL40_45 = indicator for posted speed limit of 40 or 45 mph on major road (1 = present; 0 otherwise).
MajPSL50_55 = indicator for posted speed limit of 50 or 55 mph on major road (1 = present; 0 otherwise).
MajPSL40p = indicator for posted speed limit of 40 mph or more on major road (1 = present; 0 otherwise).
MinPSL35p = indicator for posted speed limit of 35 mph or more on minor road (1 = present; 0 otherwise).

4.1. Intersection-level CMFs

4.1.1. CMFs estimated using all observations

The EB before-after study was conducted on 342 unique intersections to evaluate intersection-level safety effectiveness of the ATSC system. CMFs were developed for total, fatal and injury, rear-end, and angle crashes, based on the following categories: all intersections in the study, including those along corridors and those that are isolated (Table 8), intersections only along adaptive corridors (Table 9), and intersection configuration (Table 10). Note that isolated intersections (i.e., intersections not along identified corridors) were not used to produce location-specific CMFs due to insufficient sample size.

Table 8 shows the safety effectiveness of the ATSC system on all intersections in the study. The results indicate that the installation of ATSC systems only had a statistically significant impact on total and angle crashes at a 95th-percentile confidence level. The total crash frequency is expected to increase by 7.8 percent, while the angle crash frequency is expected to increase by 14.2 percent. Meanwhile, fatal and injury crashes are expected to decrease by 0.5 percent, and rear-end crash frequency was expected to decrease by 1.0 percent. The fatal and injury and angle crash frequency CMFs were not statistically significant.

When evaluating the CMFs of intersections along adaptive corridors only, as shown in Table 9, the results reveal a similar pattern relative to the intersection only CMFs. The total and angle crashes are associated with an increase in the expected number of crashes after ATSC at intersections along corridors, while fatal and injury and rear-end crashes are expected to decrease after deployment of ATSC systems along corridors. The total and angle crash CMFs are statistically significant while the fatal and injury and rear-end crash CMFs are not statistically significant at the 95th-percentile confidence interval.

Table 8
Intersection-Level CMFs, All Intersections.

Crash Severity / Crash Type	CMF	Standard Error	Reported in After Period	EB Estimate in After Period
Total crashes	1.078**	0.022	4,259	3,949.19
Fatal and injury crashes	0.995	0.029	2,111	2,121.41
Rear-end crashes	0.990	0.032	1,574	1,588.59
Angle crashes	1.142**	0.037	1,862	1,629.23

** Statistically significant at the 95th-percentile confidence level.

Table 9
Intersection-Level CMFs, Intersections Along Corridors.

Crash Severity / Crash Type	CMF	Standard Error	Reported in After Period	EB Estimate in After Period
Total crashes	1.071**	0.024	3,819	3,563.47
Fatal and injury crashes	0.998	0.031	1,906	1,909.59
Rear-end crashes	0.986	0.033	1,411	1,430.92
Angle crashes	1.127**	0.038	1,673	1,483.05

** Statistically significant at the 95th-percentile confidence level.

The safety effects of ATSC are also examined based on different intersection configurations, as shown in Table 10. The results are generally consistent with the CMFs shown in Tables 7 and 8, although there are some variations between 3- and 4-leg intersections. The CMFs for 3-leg intersections are smaller than the 4-leg intersection CMFs for total, fatal and injury, and angle crashes. The 3-leg intersection CMFs for fatal and injury, rear-end and angle crashes are all less than 1.0 – the fatal and injury CMF is statistically significant at the 95th-percentile confidence level. The 4-leg CMFs for total, fatal and injury, and angle crashes all exceed 1.0 – the total and angle crash CMFs are both statistically significant at the 95th-percentile confidence interval.

4.1.2. CMFs estimated only using observations with 3 or more years of crash data

The CMFs in Section 4.1.1 were estimated using all intersection data available for CMF development. However, this includes 41 intersections with only one year of crash data after the ATSC system was implemented and 111 intersections with only two years of crash data after the ATSC system was implemented. In this section, the EB before-after methodology was repeated after removing these observations to estimate the most robust CMFs possible and examine if including these observations would bias the CMF estimates. The results are provided in Table 11. The results are nearly identical with those provided in Table 8. The CMF estimate for total crash frequency changes from a statistically significant value of 1.078 to a statistically significant value of 1.097 when the abbreviated after-period observations are removed. The CMF for angle crash frequency changes from a statistically significant value of 1.142 to a statistically significant value of 1.148 when the short time period observations are removed. CMF estimates for fatal and injury and rear-end crashes remain not statistically significant in both cases. These results suggest that CMFs estimated in Section 4.1.1 are robust, even though they include some observations that do not have 3 or more years of crash data.

4.2. Temporal trends of intersection-level CMFs

The previous section described the overall safety performance of the ATSC system over the entire analysis period. An objective of the present study was to assess novelty effects associated with the ATSC system, and identify possible temporal trends of intersection-level CMFs. The evaluation was conducted using annual crash data over three years in the after period (i.e., year 1 data after installation, year 2 data after installation, and year 3 data after installation) following the same procedure as shown in Section 4.1. The results are summarized in Tables 12 through 14 . The standard errors of the CMFs are provided in parentheses. Note that "All Years" in Table 12 are the same CMFs shown for all intersections in Table 8.

The results in Tables 12 through 14 suggest similar patterns when comparing CMFs for each individual year and those developed when aggregating the after period data. The results in Table 12 indicate that the ATSC system is associated with a modest increase in the expected number of total and angle crashes, and a slight decrease in the expected number of fatal and injury and rear-end crashes at all intersections included in the study. Similar results were found along corridors

Table 10
Intersection-Level CMFs by Configuration.

Configuration	Crash Severity / Crash Type	CMF	Standard Error	Reported in After Period	EB Estimate in After Period
3-leg	Total crashes	1.011	0.046	809	799.82
	Fatal and injury crashes	0.843**	0.055	364	431.22
	Rear-end crashes	0.991	0.072	302	304.22
	Angle crashes	0.994	0.070	323	324.40
4-leg	Total crashes	1.091**	0.026	3,385	3,100.66
	Fatal and injury crashes	1.030	0.035	1,717	1,666.39
	Rear-end crashes	0.987	0.036	1,250	1,265.68
	Angle crashes	1.175**	0.043	1,506	1,281.31

** Statistically significant at the 95th-percentile confidence level.

Table 11
CMFs for Sites with At Least Three Years of After Period Data.

Crash Severity / Crash Type	CMF	Standard Error	Reported in After Period	EB Estimate in After Period
Total crashes	1.097**	0.028	3241	2953.81
Fatal and injury crashes	0.998	0.036	1626	1627.96
Rear-end crashes	1.031	0.042	1130	1094.91
Angle crashes	1.148**	0.044	1473	1281.77

** Statistically significant at the 95th-percentile confidence level.

Table 12
Temporal Trends of Intersection-Level CMFs, All Intersections.

Crash Severity / Crash Type	Year 1	Year 2	Year 3	All Years
Total crashes	1.053 (0.029)*	1.060 (0.032)*	1.012 (0.039)	1.078 (0.022)**
Fatal and injury crashes	0.996 (0.039)	0.988 (0.042)	0.940 (0.050)	0.995 (0.029)
Rear-end crashes	0.972 (0.043)	0.934 (0.046)	0.954 (0.062)	0.990 (0.032)
Angle crashes	1.129 (0.048)**	1.136 (0.051)**	1.079 (0.060)	1.142 (0.037)**

** Statistically significant at the 95th-percentile confidence level.
* Statistically significant at the 90th-percentile confidence level.

Table 13
Temporal Trends of Intersection-Level CMFs, Intersections Along Corridors.

Crash Severity / Crash Type	Year 1	Year 2	Year 3	All Years
Total crashes	1.047 (0.031)	1.051 (0.033)	1.010 (0.040)	1.071 (0.024)**
Fatal and injury crashes	0.987 (0.041)	1.008 (0.045)	0.955 (0.053)	0.998 (0.031)
Rear-end crashes	0.977 (0.045)	0.931 (0.048)	0.964 (0.065)	0.986 (0.033)
Angle crashes	1.120 (0.050)**	1.109 (0.053)**	1.066 (0.062)	1.127 (0.038)**

** Statistically significant at the 95th-percentile confidence level.

(Table 13) and for different intersection configurations (Table 14). There does not appear to be a trend over time in the disaggregate analyses, suggesting that there is not a novelty affect associated with the ATSC system.

4.3. Corridor-level CMFs

ATSC systems are usually installed at consecutive intersections along corridors to maximize capacity and minimize delay on the major street. Under such conditions, it is possible that the safety performance along the corridor may differ from that at individual intersections. To test this assumption, corridor-level CMFs were developed using the EB before-after study on 46 corridors. Similar to the intersection-level analysis, CMFs were developed for total, fatal and injury, rear-end, and angle crashes. The results are shown in Table 15.

Table 14
Temporal Trends of Intersection-Level CMFs by Configuration.

Configuration	Crash Severity / Crash Type	Year 1	Year 2	Year 3	All Years
3-leg	Total crashes	1.009 (0.064)	1.048 (0.069)	0.996 (0.080)	1.011 (0.046)
	Fatal and injury crashes	0.888 (0.083)	0.889 (0.086)	0.866 (0.101)	0.843 (0.055)**
	Rear-end crashes	1.110 (0.108)	0.925 (0.104)	1.077 (0.143)	0.991 (0.072)
	Angle crashes	0.894 (0.095)	1.028 (0.107)	0.939 (0.117)	0.994 (0.070)
4-leg	Total crashes	1.053 (0.033)*	1.061 (0.036)*	1.020 (0.045)	1.091 (0.026)**
	Fatal and injury crashes	1.006 (0.044)	1.020 (0.049)	0.959 (0.058)	1.030 (0.035)
	Rear-end crashes	0.922 (0.046)	0.942 (0.052)	0.932 (0.069)	0.987 (0.036)
	Angle crashes	1.185 (0.055)**	1.152 (0.059)**	1.114 (0.071)	1.175 (0.043)**

** Statistically significant at the 95th-percentile confidence level.
* Statistically significant at the 90th-percentile confidence level.

Table 15
Corridor-Level CMFs.

Crash Severity / Crash Type	CMF	Standard Error	Reported in After Period	EB Estimate in After Period
Total crashes	1.060**	0.017	5,930	5,595.25
Fatal and injury crashes	0.993	0.023	2,888	2,908.79
Rear-end crashes	1.055**	0.025	2,504	2,372.38
Angle crashes	1.100**	0.030	2,176	1,977.14

** Statistically significant at the 95th-percentile confidence level.

Table 15 indicates that ATSC is associated with a statistically significant increase in the expected number of total, rear-end, and angle crashes. The magnitude of increase is 6 percent, 5.5 percent, and 10 percent, respectively. The fatal and injury CMF is slightly lower than 1.0. The results of the corridor-level analysis are similar to the intersection-level CMFs shown in Table 8.

5. Conclusions

In this paper, the safety effectiveness of ATSC systems on intersection- and corridor-level crashes in Pennsylvania was investigated using the EB before-after approach. The methodology was applied to different crash severity levels and crash types (i.e., total crashes, fatal and injury crashes, rear-end total crashes, and angle total crashes), intersection locations (i.e., intersections along corridors) and intersection configurations (i.e., 3-leg and 4-leg intersections). Additionally, possible temporal trends of the ATSC system were examined at the intersection-level.

When considering all intersections in the sample, the results show that ATSC tends to increase total crashes and angle crashes, while it is associated with a slight decrease in fatal plus injury crashes and rear-end crashes. The results appear consistent with recent research in Illinois (Osario and Benekohal, 2019), which reported an expected increase in total crashes at four-leg signalized intersections, as well as an expected increase in total crashes at three- and four-leg intersections combined after ATSC deployment. Simulation studies (Stevanovic et al., 2011) found that ATSC was associated with an increase in angle conflicts, but an expected decrease in total and rear-end conflicts. Although simulation studies have not be validated using reported crash data, the results of the present study are generally consistent with the conflict analysis, with the notable exception related to total crashes. The temporal trend analysis at the intersection-level indicates a relatively stable safety effect when disaggregating the CMF annually. The corridor-level CMFs follow similar trends as the intersection-level analysis, when considering all intersections in the study. ATSC is associated with an increase in total crash frequency, decrease in fatal and injury crashes, and an increase in rear-end and angle crashes.

When disaggregating the data based on the intersection configuration, ATSC was associated with a statistically significant, expected decrease in fatal and injury crashes at 3-leg intersections. While not statistically significant, ATSC was associated with an expected decrease in rear-end and angle crashes at 3-leg intersections. ASTC was associated with a statistically significant, expected increase in total and angle crashes at 4-leg intersections.

Future research is recommended to consider additional ATSC corridors, crash types and data from other states. In addition, there are several different ATSC systems currently in use, all having different logic. Future safety studies should determine if there is an association between the signal logic and safety performance.

Disclaimer

The contents of this paper reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration or the Commonwealth of Pennsylvania at the time of publication. This paper does not constitute a standard, specification or regulation.

CRediT authorship contribution statement

Houjun Tang: Conceptualization, Methodology, Data curation. **Vikash V. Gayah:** Conceptualization, Methodology, Data curation. **Eric T. Donnell:** Conceptualization, Methodology, Data curation.

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Appendix A. Supplementary data

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