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Identifying the Safety Impact of Signal Coordination Projects along Urban Arterials Using a Meta-analysis Method

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Abstract: The safety impact of changes to roadway operations have been of interests in recent years with the publication of the Highway Safety Manual. One area that is in need of further study is the safety impact of traffic signal coordination projects in urban areas. Specifically, this study seeks to identify the safety benefit from traffic signal coordination projects on major arterial roadways through urban areas using a before and after study with a comparison groups approach and a meta-analysis method. The findings suggest that traffic signal coordination could decrease total crashes by 21 percent, injury crashes by 52 percent and property-damage-only crashes by 21 percent. The results can be utilized by engineering practitioners to estimate the safety benefits for projects that seek to coordinate traffic signals along an urban corridor. Because these projects can both improve the safety of roadways while improving traffic flow, the application of these findings could be broad.

Key words: Traffic safety, traffic signal optimization, traffic signal coordination, meta-data analysis, crash modification factors.

1. Introduction

Traffic signal coordination projects are frequently implemented to reduce delay, thus improving the level of service at intersections and along a corridor. These improvements are achieved through optimizing traffic signal timing at intersections and coordinating the intersections along corridors. Crashes at signalized intersections account for a significant amount of all crash types on roadways in the United States (National Highway Traffic Safety Administration, 2015). Due to the significant impact that signalized intersections have been on crash occurrence and it is important to further-understand the safety impact of traffic signal coordination projects, in addition to their operational benefits.

Several studies have been conducted looking at the different benefits of coordination projects focusing on crash type reductions, the likelihood of crash occurrence, and Crash Modification Factors (CMF). Generally, past studies have found coordination projects improve traffic safety, but inconsistent results have been reported regarding the crash reduction for specific types of crashes. Also, the findings from previous studies cannot be generalized due to the limitation of analysis methods, inadequate sample sizes, or varying conditions across states. Further, because previous research on the safety of signalized intersections has noted the relation of adjacent intersections along a corridor (Abdel-Aty & Wang, 2006), studying the impact of signal coordination is particularly important for urban corridors. However, little is known about the safety effect of implementing signal coordination along a corridor where traffic signals already exist.

This research seeks to identify the safety benefit of corridor traffic signal coordination projects in southern

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and central Illinois. First, comparison sites along several corridors were selected through a before and after study, then CMFs were developed for different types of crashes. Finally, a Meta-Data Analysis was employed to modify the CMFs by considering the impacts of data standard errors. A large sample size (number of sites and crashes) were used in the study to strength the significance of the results. The Bayesian method and Meta-Data Analysis employed in the study help to yield more stable and reliable CMF results. The results can be utilized by engineering practitioners to quantify the safety benefits for projects that seek to coordinate traffic signals along an urban corridor.

2. Literature Review

2.1 Safety Improvement

Early studies regarding the safety effect of traffic signal coordination used a naïve before and after study approach (Hauer, 1997). More-recent work has identified that the safety effect of signal improvements should not be quantified by only measuring the change in the number of crashes before and after changes. The simple before-and-after study does not consider the effect of other important factors that may influence the results. Instead, a Bayesian method is more appropriate (Grant G. Schultz, Ashley L. Dowell, Mitsura Saito, & Roundy, 2013; Ma, et al., 2016; Schultz, Dowell, Roundy, Saito, & Reese, 2014). The effect of weather, traffic patterns, and other related factors can have a significant impact on the number of crashes that occur in a given time period. Because of these variations, previous research found that a time period of one month was not statistically-stable, but three months was acceptable (Hauer, 1997). Other studies of intersection crash data have included two or five years of before data and one or two years of after data (Ma, et al., 2016; Schultz, Dowell, Roundy, Saito, & Reese, 2014).

Those studying the safety impact of signalizing intersections suggested that signalizing an intersection could increase total crashes and minor crashes, but could decrease severe crashes (Schultz, Dowell, Roundy, Saito, & Reese, 2014). Other studies recommended that neither crash modification factors (CMFs) nor safety performance functions (SPFs) should be transferred between states (Wang, Abdel-Aty, & Lee, 2016).

Others evaluated how signal timing and phasing impact safety. Improved timing can reduce red light crashes (Grembek, Li, Li, Zhang, & Zhou, 2007) and signal phasing is highly-correlated with crash rates (Kumara, Chin, & Weerakoon, 2003). Signal improvements, such as left turn phasing, could increase total crashes and minor crashes, but could decrease severe crashes (Schultz, Dowell, Roundy, Saito, & Reese, 2014).

Adaptive traffic signal control (ATSC) systems have also been evaluated for safety improvement. One study included 47 intersections along 10 corridors in Virginia. Crash data was reviewed for five years before and one or two years after implementing ATSC, depending on the site. This study predicted a CMF of 0.83 for total crashes, assuming 95 percent confidence and 0.05 standard errors. In addition, the results showed the proportion of crash types before and after remained unchanged (Ma, et al., 2016). Another study of ATSC in Illinois suggested a crash reduction; but the sample size was too small to confirm any statistical significance (Lodes & Benekohal, 2013).

Few studies specifically considered traffic signal coordination and those that did, had differing conclusions. One study found that signal coordination has a negative relation to safety. In particular, coordinated traffic signals tend to have more crashes than similar intersections without coordination. Those researchers noted that these results could be skewed because both intersection safety and signal coordination are related to congestion (Guo, Wang, & Abdel-Aty, 2010). Other investigation of crashes along one-way streets found that signal coordination could encourage red-light running behavior (Tinsdale & Hsu, 2005). On the contrary, one study evaluating six corridors and 36 intersections suggested that traffic signal coordination can improve safety. Specifically, crash severities were found to reduce when signals were offset to promote vehicles arriving towards the end of the green interval instead of during the red interval (Li & Tarko, 2011).

Overall, research is still needed to guide practitioners about the likely safety impacts of traffic signal coordination. Although some studies have identified likely impacts, research recommends that the impacts could be state-specific. Additionally, little is known about the safety effect of implementing traffic signal coordination along a corridor where traffic signals already exist.

2.2 Contributing Factors

The contributing factors to crashes at signalized intersections (Grant G. Schultz, Ashley L. Dowell, Mitsura Saito, & Roundy, 2013; AASHTO, 2010) can be broken down into three main contributing categories: human, vehicular and the roadway, with each having several factors that could influence a crash. The human factors include the drivers' judgment, skill and experience. Human factors can be greatly influenced by population characteristics; therefore, comparison sites should be taken in the same area to limit the influence of different driver behavior on roadways. The vehicle factors may include the presence or absence of safety features that can be attributed to the occurrence or severity of a crash. The last category is the roadway; including the geometrics, traffic control devices, and weather. The Federal highway Administration (FHWA) provided a list of low cost strategies to address safety issues at signalized intersections using a simple before-after study where lights were replaced, lines restriping and signage installed (Federal Highway Adminstration, 2017). The study did not address coordination of signal timing an additional low cost countermeasure that can impact the safety of intersections. It is possible that several factors from multiple categories are attributed to a crash occurrence. The study at hand will mainly focus on the human and roadway categories, where drivers make choices that result in crashes and the roadway traffic control devices influence driver behavior and traffic patterns. Other factors can be controlled in the analysis by using comparison sites, which have similar features in the same geographic area.

2.3 Crash Types

According to the National Highway Traffic Safety Administration (NHTSA) 1,423,000 crashes occurred at signalized intersection in 2015 (National Highway Traffic Safety Administration, 2015). The number can be further broken down into crash type where 5,991 fatalities, 431,000 injuries, and 987,000 property damage crashes occurred. Crashes at signalized intersections account for 25 percent of all crashes, 15 percent of fatal crashes, and 23 percent of all injury crashes on roadways in the United States annually (National Highway Traffic Safety Administration, 2015). Due to the significant impact signalized intersections have on crash occurrence it is important to further-understand the impact of traffic signal coordination projects.

The methodology (AASHTO, 2010) used in the Highway Safety Manual (HSM) regarding an intersection's functional area, included 250 feet upstream and 250 feet downstream of the crossing of two roadways. All crashes related to traffic signals within the specified areas would be in the functional area of the intersection and should be counted toward the total crashes occurring.

2.4 Crash Modification Factor Design

There is a lack of quality crash modification factors for traffic signal improvements for the purpose of estimating the impact of safety on roadways. For the purpose of developing quality CMF's, the FHWA developed a guide to assist in the development quality CMFs offering step by step instruction. The guide offers advice on methodology selection based on available data (Gross, Persuad, & Lyon, 2010).

Previous studies have developed a variety of CMFs for treatments related to intersections. For example, signalizing intersections in Florida and Ohio demonstrated CMFs of 0.785 and 1.06, respectively (Wang, Abdel-Aty, & Lee, 2016).

Crashes (Elvik & Vaa, 2004) are random events that are difficult to predict with any degree of accuracy. Extreme fluctuations are typically present in the crash data, prediction of crashes is best when using a method that will account for regression to the mean bias (RTM), such as the Empirical Bayes Method. RTM bias (AASHTO, 2010) occurs as a result of variance in the number of crashes that occur at some site after a treatment, regardless of the treatment its self. To clarify, if a change has been implemented to reduce crashes at a site there will be the treatment effect and an additional effect that influences the amount of crashes due to natural variations. The variations (Transportation Safety Council, 2009) could include traffic patterns, weather, and other factors which cause increases or decreases in the amount of crashes on roadways. The Empirical Bayes Method accounts for the RTM by using comparison sites which reflect the natural fluctuation in crashes including weather or traffic pattern changes, further isolating the true effect of some treatment. Without accounting for RTM the perceived effect of a treatment could be much greater or less than the actual effect.

Regression to the mean (RTM) (Gross, Persuad, & Lyon, 2010; Transportation Safety Council, 2009) found in crash data in the form of extreme fluctuations, further explained as an unnaturally high crash rate much above the mean for a site in one study period followed by crash rate close to or below the mean in the following period. RTM is mainly a concern in studies where there are multiple data points before and after the treatment, this study only had one data point at each site before and after the treatment. As discussed in section 4.2, the study at hand did not experience randomly high or low crash rates which would result in RTM bias and the need for a more in-depth study, such as the Empirical Bayes method.

Before-after with comparison group studies (Gross, Persuad, & Lyon, 2010) are applicable when a treatment is similar at all sites and before-after data are available. Comparison sites are needed to account for crash trends which account for the changes in crashes not caused by the treatment which might introduce error into the study. The strength of this method is that it is simple to use, and accounts for time and change in traffic volumes and other uncontrollable factors that may affect crash patterns. The weakness in this approach is that accounting for regression to the mean maybe difficult in some cases and should be tested before implementing.

An ideal comparison group (Hauer, 1997) is one that has similar characteristics as the treatment site and follows a similar crash frequency in the before period. An ideal comparison site should also come from the same area as the treatment site, for example the same city or roadway network, but far enough away to eliminate any spillover effect. The comparison site is used to calculate a comparison ratio which accounts for the natural fluctuation in crash rates what would introduce bias to the treatment site if not accounted for.

The meta-analysis method (Frank Gross, 2010) of developing CMFs combines the results of multiple studies and uses weighting system based on the standard error in the study's results. For the meta-analysis to be accurate the studies should be similar in methodology and outcome measures. This method can be used on studies of different type where a ranking method is used to estimate the accuracy of the results. Essentially the meta-analysis technique estimates the average CMF using multiple studies, considering the standard error of each with more weight given to the studies with lower standard errors.

3. Methodology

A two-sample t-test was first used to establish a basic understanding of the before and after period, without differences there would be no reason to proceed with more in-depth testing. The methodology selected for this study followed the before-after with comparison groups recommended by the FHWA (Gross, Persuad, & Lyon, 2010).

The treatment and comparison sites were grouped together and differences in the crashes per time period were tested. Crash data was potted encompassing 6 months before and after the implementation of the new signal timing plans on 6 corridors. The coordination goal was to improve traffic flow focused on minimizing delay and the number of stops on the major route. The 6-month period was selected to catch the optimal benefit of signal coordination that will dissipate as traffic patterns change. The crashes during the implementation month were excluded from the data set to allow for an adjustment period where drivers become accustom to the new timing plans. Crashes were plotted using Google Earth retaining the severity and crash type for a more in-depth analysis. The studied crashes plotted in Mount Vernon can be seen in Fig. 1.

Second, a comparison site was selected for each corridor in the same city or a neighboring city, on the same or similar roadway with the intersections having similarly characteristics. This step aimed to eliminate factors known to impact the safety of a roadway, such as driver behavior and changes in traffic volume or patterns. Table 1 lists the ADT of the coordinated route, where it is evident that locations with higher ADT's typically experience higher crash rates. To account for this effect the caparison site was selected to have the same or similar ADT, the comparison method will account for variations between treatment sites, as the ADT changes at the treatment site it also changes at the

comparison sites negating the perceived impact of crash reduction caused by lower traffic volumes. When possible the same number of sites were selected for comparison, however two cities did not have comparison sites available. Comparison sites not directly adjacent to the treatment sites were selected to prevent any spillover effect identified in the literature review, sites were selected some distance away excluding at least one signalized intersection between the treatment and comparison sites.

The next step was to collect crash data for both the treatment and comparison sites for the targeted crash types known to be related to traffic flow, keeping the crash severity and type separate. Crashes unrelated to traffic flow, such as impact with animal, were removed from the data. The target crash types for signalized intersections were identified to be rear-end, turning, angle, sideswipe, fixed object, and pedestrian/ped-cyclist. The crashes for each corridor by severity were summed and compared to the sum of the crashes at the comparison sites in both the before and after periods. Careful review of the data did not identify any differences in the crashes type (rear end, turning, etc.), road conditions (dry, wet, etc.), or lighting conditions (daylight, dark, dark and lighted); before and after signal coordination. The collected crash data was then used to identify the CMF for signal coordination projects. Equations numbered 1 to 5 were applied during the analysis.

The first step used to calculate the CMF was to determine the sample odds ratio (SOR), which is used to establish if the comparison sites are acceptably similar. When the SOR is close to one, the comparison sites are an adequate representation of the treatment sites, the confidence interval for the SOR should contain the value of one. Again, before refers to the six-month period prior to retiming traffic signals for coordination and the six-month after period begins the month after retiming. The sample odds ratio (Gross, Persuad, & Lyon, 2010) is calculated as follows:

$$SOR = \frac{\frac{(Treatment_{before} * Comparison_{after})}{(Treatment_{after} * Comparison_{before})}}{1 + \frac{1}{(Treatment_{after})} + \frac{1}{(Comparison_{before})}} \quad (1)$$

where,

SOR = the sample odds ratio

$Treatment_{before}$ = representation of the before crashes at the treatment site in the study period;

$Comparison_{before}$ = representation of the before crashes at the comparison site in the study period;

$Treatment_{after}$ = representation of the after crashes at the treatment site in the study period;

$Comparison_{after}$ = representation of the after crashes at the comparison site in the study period.

Once the comparisons sites have been tested and were acceptable, the CMF was calculated by using the comparison ratio, number of expect crashes at the treatment site, and the variance in the expected crashes at the treatment site. The comparison ratio was the control used to isolate the effect of the treatment by determining the natural fluctuation in crashes at the control sites. The number of expected crashes was the prediction of the crashes at the treatment site in the after period taking the comparison ratio into consideration. The variance estimating the possible change from the expected value was also needed to calculate the CMF. Finally, the CMF was calculated using the known before and after crashes, number of expected crashes, and variance as show in Eqs. (2)-(5) (Gross, Persuad, & Lyon, 2010).

$$CR = \frac{(N_{observed,C,A})}{(N_{observed,C,B})} \quad (2)$$

$$N_{expected,T,A} = (N_{observed,T,A}) \frac{(N_{observed,C,A})}{(N_{observed,C,B})} \quad (3)$$

$$Var(N_{expected,T.A}) = (N_{expeccted,T,A})^2 * \frac{1}{(N_{observed,T,B})} + \frac{1}{(N_{observed,C.B})} + \frac{1}{(N_{observed,C,A})} \quad (4)$$

$$CMF = \frac{\frac{(N_{observed,T,A})}{(N_{expected,T,A})}}{1 + \frac{Var(N_{expected,T,A})}{(N_{expected,T,A})^2}} \quad (5)$$

where,

CR = comparison ratio;

$N_{observed,\ C,\ B}$ = the number of observed crashes in at the comparison site in the before period;

$N_{observed,\ C,\ A}$ = the number of observed crashes in at the comparison site in the after period;

$N_{observed,\ T,\ A}$ = the number of observed crashes in at the treatment site in the after period;

$N_{expected,\ T,\ A}$ = the number of expected crashes in the after period at the treatment site;

VAR = the variance in the crash data set;

CMF = Crash modification factor (effect of signal coordination).

4. Data Analysis

Crash data for all five treatment corridors and the five corresponding comparison corridors were analyzed independently with the results compared through a Meta-Data Analysis. The corridors were all located within southern Illinois, but in four separate cities with possible differences in driver populations and weather patterns. The cities of Mt Vernon, Decatur, Edwardsville, and Columbia, Illinois were selected because they each had a recently coordinated signalized arterial corridor and at least six months of crash statistics available before and after implementing signal coordination. Comparison sites/intersections for each corridor were selected within the same city as the treatment sites. The total, injury (including all types) and PDO crash totals for the target crashes can be seen in Table 1, there were no fatal crashes included in the data set.

Table 1 Crash data and site characteristics.

US 36/IL 121, Decatur, IL					
Total crashes					
Site	Treatment	Comparison	# of intersections	ADT coordinated route	Land use
Before	7	34	4	10,316	Suburban
After	3	10			
Injury crashes					
Site	Treatment	Comparison	# of intersections	ADT coordinated route	Land use
Before	5	8	4	10,316	Suburban
After	0	1			
PDO crashes					
Site	Treatment	Comparison	# of intersections	ADT coordinated route	Land use
Before	2	26	4	10,316	Suburban
After	3	9			
IL 15, Mt Vernon, IL					
Total crashes					
Site	Treatment	Comparison	# of intersections	ADT coordinated route	Land use
Before	61	28	5	21,353	Urban
After	39	17			
Injury crashes					
Site	Treatment	Comparison	# of intersections	ADT coordinated route	Land use
Before	13	6	5	21,353	Urban
After	10	8			
PDO crashes					
Site	Treatment	Comparison	# of intersections	ADT coordinated route	Land use
Before	48	22	5	21,353	Urban
After	29	9			
IL 157, Edwardsville, IL					
Total crashes					
Site	Treatment	Comparison	# of intersections	ADT coordinated route	Land use
Before	55	43	7	11,913	Suburban
After	19	26			
Injury crashes					
Site	Treatment	Comparison	# of intersections	ADT coordinated route	Land use
Before	12	12	7	11,913	Suburban
After	6	12			
PDO crashes					
Site	Treatment	Comparison	# of intersections	ADT coordinated route	Land use
Before	43	31	7	11,913	Suburban
After	13	14			
IL 159, Edwardsville, IL					
Total crashes					
Site	Treatment	Comparison	# of intersections	ADT coordinated route	Land use
Before	41	50	4	19,500	Suburban
After	44	50			
Injury crashes					
Site	Treatment	Comparison	# of intersections	ADT coordinated route	Land use
Before	12	17	4	19,500	Suburban
After	12	11			

PDO crashes					
Site	Treatment	Comparison	# of intersections	ADT coordinated route	Land use
Before	29	33		19,500	Suburban
After	32	39			
IL 3, Columbia, IL					
Total crashes					
Site	Treatment	Comparison	# of intersections	ADT coordinated route	Land use
Before	38	45	5	25,800	Suburban
After	36	36			
Injury crashes					
Site	Treatment	Comparison	# of intersections	ADT coordinated route	Land use
Before	8	13	5	25,800	Suburban
After	13	7			
PDO crashes					
Site	Treatment	Comparison	# of intersections	ADT coordinated route	Land use
Before	30	32			
After	23	28	5	25,800	Suburban
After	7	7			

4.1 T-Testing

A two-sample t-test was first performed on the data to identified any differences between the before and after groups existed. The *p*-values for the total (p = 0.076), injury (p = 0.207), and PDO (p = 0.018) suggesting weak evidence that effects were present for total crashes, no effect for injury crashes, and strong evidence of effects on PDO crashes. These results indicated further investigation was warranted, to isolate the safety impacts of traffic signal coordination projects.

4.2 Crash Trends

To check for regression to the mean bias, a graph was created to identify if extreme fluctuation existed between before and after crashes at any one site. When crash data includes extreme fluctuation, the Empirical Bayes method should be applied. Fig. 2 shows the

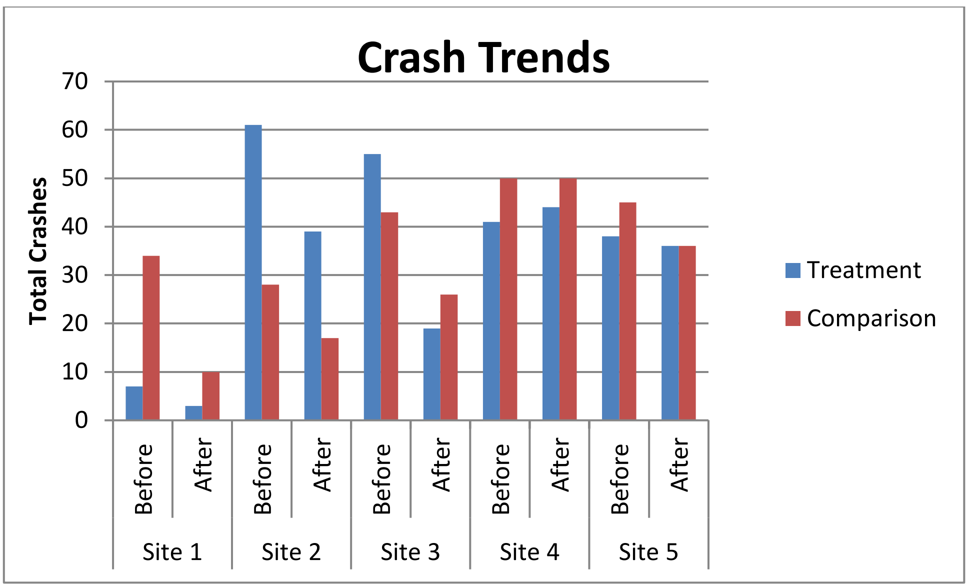

Fig. 2 Total crash trends.

total crash trends between the treatment and comparison sites in the before and after periods.

Overall total crashes decrease in the after period with the exception of one site that saw a slight increase after the treatment was applied, the increase was only by three crashes and the comparison site crashes remained constant. Given that no extreme fluctuation existed, the simpler method of before-after with comparison sites was used to account for natural fluctuation in crash frequencies not attributed to the signal timing changes such as AADT, weather and other factors know to impact crash frequencies to identify the effect of traffic signal coordination. If only a simple before and after study was conducted the perceived effect of signal timing would have been inflated caused by not adjusting for the effect of other factors impacting crash frequencies.

4.3 Before-after with Comparison Group Studies

The SOR was calculated using Eq. (1) as described in the methodology section for total, injury and PDO crashes separately, with a target value of 1.0 indicating the ideal comparison site. The SOR for the five studies was found to vary from 0.50 to 1.63 for total crash however the total crash SOR mean was determined to be 0.95 for all the corridors in these studies, injury and PDO SOR means were determined to be 0.89 and 0.84, also near one, suggesting a good comparison group. The Confidence interval (CI) was calculated with 95 percent confidence for the SOR means and found that one was included in each of the crash types SOR indicating the comparison corridors were adequate. The greater variance from 1.0 with the injury and PDO crashes was determined to be due to the lack of crashes during each six-month period. The researchers determined the low SOR was caused by low sample size that would be alleviated when combining the data in a Meta-Analysis. The SOR value for each corridor used in the calculations can be seen in Table 2.

The CR for each of the crash severities, for each study, was calculated with Eq. (4). Results indicated a much lower crash rate in the after period at the observations sites for 11 of the 15 tests. Two other results suggested CR's being equal before and after. The last two tests indicated more crashes after than before. These findings underscore the importance of using the before and after with comparison sites method. The CR values ranged from 0.22 to 1.33, indicating as much as a 78 percent reduction or 33 percent increase in crashes in the after period, depending on the corridor.

Table 2 Analysis results studies.

US36/IL121, Decatur, IL			
	Total	Injury	PDO
SOR	0.50	0.63	0.17
CR	0.29	0.22	0.35
Nexp	2.06	1.33	0.69
Var(Nexp)	1.15	1.38	0.31
CMF	1.15	0.42	2.63
SE	0.70	0.32	1.58
IL 15, Mt Vernon, IL			
	Total	Injury	PDO
SOR	0.89	1.37	0.63
CR	0.61	1.33	0.41
Nexp	37.04	17.33	19.64
Var(Nexp)	152.16	110.74	68.40
CMF	0.95	0.42	1.25
SE	0.32	0.21	0.49
IL 157, Edwardsville, IL			
	Total	Injury	PDO

SOR	1.63	1.60	1.35
CR	0.60	1.00	0.45
Nexp	33.26	12.00	19.42
Var(Nexp)	88.36	36.00	47.87
CMF	0.38	0.33	0.41
SE	5.77	3.46	4.41
IL 159, Edwardsville, IL			
	Total	Injury	PDO
SOR	0.89	0.57	1.01
CR	1.00	0.65	1.18
Nexp	41.00	7.76	34.27
Var(Nexp)	108.24	14.05	106.22
CMF	1.01	1.25	0.86
SE	0.28	0.57	0.27
IL 3, Columbia, IL			
	Total	Injury	PDO
SOR	0.80	0.29	1.06
CR	0.80	0.54	0.88
Nexp	30.40	4.31	26.25
Var(Nexp)	70.53	6.40	69.11
CMF	1.10	2.24	0.80
SE	0.33	1.08	0.27

The expected number of crashes (N_{exp}) calculated with Eq. (3) represents the number of crashes that would be expected in the after period had the treatment not been implemented. For total and PDO crash types a close prediction is seen, while a larger difference is present for injury crashes most likely due to the small number of occurrences making it difficult to accurately predict the already random event.

Using the method identified in the methodology and equation 5 the effect of the signal coordination in the form of CMFs for total, injury and PDO crashes were calculated and can be seen in Table 2. The results provide insight into the safety effect of traffic signal coordination along a corridor; however the effect differs depending on the location. Some locations indicate a decrease while others suggest a slight increase. The most significant impact was for injury type crashes, where one study found 62 percent decrease in crashes after signal coordination had been implemented.

The SE which estimates the probable range of the CMF indicates minimal fluctuation in the results of total and PDO crash types. The SE for injury crash types was much higher than considered acceptable for several of the studies, so the Meta-Analysis was employed to adjust the results based on the confidence of each study. The SE's with calculated values of less than 0.30 are within the acceptable range set by the HSM (AASHTO, 2010). Further review suggested that the some of the corridors had lower traffic volumes, fewer crashes, and thus a smaller sample size leading to weaker conclusions.

4.4 Meta-analysis

To learn more from the five studies, taking into consideration the SE of each study, the meta-analysis method was used. During this analysis, the data from all study corridors was combined. The meta-analysis method of weighting gives more weight to the CMFs that have lower standard errors, improving the accuracy of the results when combining multiply studies. Eqs. (6) and (7) show how the CMF is calculated using the weighting of studies (Frank Gross, 2010).

$$CMF = \frac{(\Sigma W_i CMF_i)}{(\Sigma W_i)} \qquad (6)$$

$$W_i = \frac{1}{(SE_i)^2} \quad (7)$$

where,

CMF_i = CMF of study i

W_i = the statistical weight assigned to each study i dependent on the standard error of each study

The standard error associated with each CMF is descriptor of the acceptability of the CMF. For example the Highway Safety Manual (AASHTO, 2010) only uses CMFs with standards of error less than 0.30, and cautions users to check the variance of the CMF before use. With the Meta-Analysis the effect of high standard error is negated by the weighting given to CMFs with low standards of error, thus improving the prediction of crashes. Each study's SE, CMF and Weight (W) can be seen in Table 3 with SE larger than the desired 0.30 highlighted in red.

The results of the Meta-Analysis can be seen in Table 4, indicating a decrease in all crash types, where all the CMFs are below 1 indicating an overall reduction in the expect crashes after implementing signal coordination along a corridor. Recall that a previous study of traffic signal coordination in Virginia found a CMF for all crashes as 0.83 (Ma, et al., 2016), suggesting that the corridors studied herein returned a similar safety benefit. Although this previous study could not conclude there were reductions in fatal or injury crashes, the methods also did not include a Meta-Analysis. Comparing the traffic volumes from this previous study suggests further benefits are possible with higher traffic volumes (Ma, et al., 2016). Together, the results from the meta-analysis indicate that after implementing traffic signal coordination in southern Illinois, the total and PDO crashes can be expected to decrease by 21 percent and Injury crashes can be expected to decrease by 52 percent.

Table 3 Meta-analysis data.

	Total			Injury			PDO		
	SE	CMF	W	SE	CMF	W	SE	CMF	W
Decatur	0.70	1.15	2.04	0.32	0.42	9.99	1.58	2.63	0.40
Mt Vernon	0.32	0.95	10.06	0.21	0.42	22.49	0.49	1.25	4.16
Edwardsville 1	0.18	0.53	31.44	0.21	0.40	23.44	0.24	0.59	17.65
Edwardsville 2	0.28	1.01	12.79	0.57	1.25	3.06	0.27	0.86	13.33
Columbia	0.33	1.10	9.19	1.08	2.24	0.85	0.27	0.80	13.28

Table 4 Meta-analysis results all studies.

Meta-analysis method		
	CMF total	0.79
5 studies	CMF injury	0.48
	CMF PDO	0.79

By combining the crash data from five corridors, the meta-analysis enabled researchers to identify a more-confident and statistically-valid estimate of the safety impacts of traffic signal coordination. Overall, these results indicate that coordinating traffic signals can reduce total, injury, and PDO crashes in Southern Illinois and similar results could be expected at similar locations.

5. Conclusions

The objective of this study was to identify the safety impact of traffic signal coordination projects for arterial corridors in urban areas. The methodology used followed the before-after with comparison groups recommended by the FHWA's "Guide to Developing Quality Crash Modification Factors" which uses similar non-treatment sites to mitigate the effect of changes in traffic patterns and other similar factors. The listed method is preferred under the study conditions specifically when a limited number of treatment sites exist. To identify additional findings from the multiple study sites, the researchers combined the results (n =

673 crashes) and used a meta-data analysis method.

The results obtained by the meta-analysis show that all crash types decreased after implementing traffic signal coordination. Specifically, the total crashes decreased by 21 percent, injury crashes by 52 percent and PDO crashes by 21 percent; an admirable amount when compared to other CMF that predict the safety of a roadway in the HSM.

The primary contribution of this study was the development of crash modification factors (CMFs) for implementing traffic signal coordination in Southern Illinois. These CMFs were 0.79 for total crashes, 0.48 for injury crashes, and 0.79 for PDO crashes. The most significant impact was found to be on the injury crashes, a common target when trying to increase the safety of a roadway. Thus, transportation engineering and safety practitioners could use these values when predicting the benefits of similar projects in this region.

Future research could include more sites to further-improve the prediction of the safety impact of traffic signal coordination projects in urban areas. The current results provide supporting evidence into the safety aspect of traffic signal coordination projects that can be expected in urban areas.

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