APPENDIX **E**

EVALUATION OF THE SAFETY EFFECTIVENESS OF URBAN SIGNAL TREATMENTS

Background

The largest obstacle in conducting before-after evaluations using state of the art empirical Bayes methods is the lack of historical data on the installation dates for treatments. Fortunately, the City of Winston-Salem, NC has very well-documented installation records for a variety of intersection treatments at both signalized and non-signalized locations. There are over 70 different individual treatments (e.g., install signal, trim trees) or combinations of treatments (e.g., move stop bar and extend centerline) in the data set, and the treatment years extend back to the 1980's. Winston-Salem DOT (W-SDOT) has consistently conducted simple before-after studies of the effects of these treatments on both total crashes and "target" crashes (e.g., angle crashes for stop-to-signal conversions). These studies usually contain three-five years of both before- and after-period crash data. The study files do not typically contain information on AADT changes across the study period.

The objective of this effort is to conduct enhanced before-after studies using empirical-Bayes methodology for a select number of these treatments. As will be detailed below, the major issue to be resolved is the lack of readily-available reference group data in Winston-Salem. There is no computerized historic file that links crashes to a specific (non-treatment) location. Nor is there a computerized listing/inventory of all signalized and unsignalized intersections in the city, nor computerized AADT information linked to intersections. Thus, to use these excellent treatment-site specific data in the enhanced EB study, it is necessary to (1) identify the subset of treatments that have a sufficient sample of before-period target crashes such that treatment effects measured will be statistically significant, (2) extract AADT data for each treatment site for the before and after periods, and (3) develop a reference group or groups of similar untreated locations in which each reference intersection contains both crash and AADT data for the before and after periods covered by the initial treatment evaluations. The text below details how the project team accomplished this.

Choice of Treatments for the Study

As noted above, the W-SDOT before-after study program covers over 70 treatments or combinations. Within a given treatment group, different intersections would have been treated in different years, and the number of sites within the treatment groups varied greatly (from 2 to 40+). Stan Polanis, Director of Transportation for Winston-Salem, sent excel files containing information on all before-after studies. For each treatment type, the file contained:

- A brief description of the treatment type
- A case number for *each* intersection in a given treatment group that provides the year the BA study was completed
- The number of before and after months for each site

- The number of total crashes in the before and after period for each site[1]
- The number of target crashes in the before and after periods for each site
- Calculated percent changes in total and target crashes per year for each site, along with changes for the entire group and statistical test results when conducted. Note that target crashes are those crashes that are being addressed by the implementation of a treatment (e.g., angle crashes).

A decision was made to attempt to limit the treatment-implementation periods to 1994 and later time periods, meaning that the before time periods might extend back to 1990-91, depending on the length of the before period studied by W-SDOT. This also means that the treatments would have been implemented in 1993 and later (with most in 1997 and later), providing us a reasonably recent study group to help ensure current vehicle and driver fleets.

To choose treatments that had adequate before-period target crash data, the project staff developed estimates of the number of expected before- period crashes required for various levels of percent reduction in order to insure 90th and 95th percentile statistical confidence (i.e., .10 and .05 levels of significance). This was done based on the procedure suggested by Hauer (1997). (*1*) These estimates are shown in Table E-1 below, and assume that the number of years in the before and after periods are equal. For example, as shown in the first row of the table, one would need 5620 target crashes in the before period to be able to detect with 95% confidence a statistically significant 5% reduction in target crashes due to the treatment. One would need less (i.e., 3935) before-period target crashes to detect the 5% reduction with 90% confidence.

Table E-1. Sample sizes of target crashes required for different expected levels of treatment effectiveness and different statistical confidence levels.

% Reduction Expected	**95% confidence**	**90% confidence**
	min. E{accidents}	min. E{accidents}
5	5620	3935
10	1279	896
15	515	361
20	261	183
25	150	105
30	93	65
35	60	42
40	40	28
45	28	19
50	19	13
55	13	9
60	9	7
65	7	5

Conversely, one can use the table to determine what percent reduction would be statistically significant given a certain number of before-period target crashes. For example, as

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[1] The crashes at each treatment site were obtained by Winston-Salem staff after reviewing hard copies of crash reports.

shown by the last two rows in the table, if one has only seven before period target crashes for a given treatment group, the treatment would have to result in a 65% (or greater) reduction for us to be able to detect a statistically significant result at the .05 significance level, or a 60% reduction to be able to detect a statistically significant result at the .10 level. Indeed, this is how this table was used. The total number of before-period target crashes for 1994 and later implementation dates within a given treatment was compared to the second and third columns to determine what percent reduction would be necessary to obtain a statistically significant result.

An initial review of all 70+ treatment groups indicated that many of the groups had far too few before-period target crashes to warrant further analysis. However, there were 11 treatment types for signalized intersections and 8 for unsignalized intersections that had sample sizes of before-period target crashes large enough to warrant more detailed sample-size analysis. These 19 treatment types are shown in Table E-2.

For each of these treatment types, using the W-SDOT excel files, the projects with 1997 and later implementation periods were identified and the before-period total and target crashes were summed. These totals are shown in the table under “Before total crashes” and “Before target crashes.” The before target crashes were then compared to the required sample sizes in Table 1 above to estimate the percent reduction would have to be found to be statistically significant at the two levels of confidence. Thus, for the first treatment (i.e., changing a permissive/protected left-turn phase to a protected phase), the 47 target crashes in the before period would allow us to detect a 38% reduction as statistically significant at the .05 level and a 34% percent reduction as significant at the .10 level. These required reductions are much smaller than what was found by the (possible biased) W-SDOT simple before/after study (i.e., a 98% reduction), providing some indication that this is a treatment worth evaluating with the EB methodology. We also tried to compare these treatments to the CRF-enhancement priorities and levels of current predictive certainty developed earlier in this project and documented in the Interim Report. For example, this top-row phasing change was rated as the 8th priority for further improvement by the State DOT survey respondents, and the existing AMF has a medium-low level of predictive certainty (Research Results Digest 299). Both these factors again strengthen the case for including this treatment in the group to be re-evaluated.

Using similar rationale, the shaded rows indicate the four treatments proposed for EB analysis.

- Change left turn phasing. This includes changes from permissive to permissive/protected and from permissive or permissive/protected to protected
- Convert from a night-time flash mode back to regular phasing
- Replace existing 8” signal heads with 12” heads
- Add double signal heads

The remainder of the signalized treatments and all of the unsignalized treatments were not chosen for re-evaluation at this point for one or more of the following reasons:

- The target crash reduction from the W-SDOT simple before-after study was below or close to the required reductions, raising questions about the available sample size (e.g., install all-red interval).

Table E-2. Details of potential treatments for EB evaluation.

Treatment	Treated Sites	Project Implement. Years Examined	Before total crashes	Before target crashes	%reduction measurable in targets with 95% conf	%reduction measurable in targets with 90% conf	W-SDOT Target crash Reduction	PRIORITY in 17-25	Level of predictive certainty
Signalized									
Change permiss/prot to protected	5	96-00	184	47	38%	34%	98%	8	ML
Change from permiss to permiss/prot or protected phase	13	95-0	437	124	27%	24%	67%	8	ML
Install all-red interval		93-95	89	38	40%	36%	1%		None
Add signal head		93-99	148	55	36%	32%	44%		ML
Convert from night-time flash back to regular phasing (angle as targets)	17	94-01	477	93	30%	27%	81%		
Add double signal head ("Dollys")		94-99	418	179	22%	20%	34%		ML
Install 12" reds	34	96-99	950	301	18%	16%	49%		ML
Install directional signs at signalized freeway ramp terminal ends on surface streets (angles)		97	167	81	32%	27%	26%		
Install additional signal head(s) to reduce rear ends		94-99	154	52	36%	32%	21%		ML
Add 2nd left turn lane		94-99	207	58	36%	32%	22%		None
Add directional signs at or before intersection to reduce SS crashes		97	98	32	44%	38%	60%		
Unsignalized									
Build/lengthen accel lane at ramp entrance on freeway		99-00	174	114	28%	25%	96%		None
Add stop bars and ~50' centerline prior to intersection		95-00	145	60	35%	32%	52%		
Convert to 4-way stop		95-01	190	131	27%	22%	85%		MH
"Stop Ahead" on pavement		93-97	58	41	40%	36%	27%		
Add/move stop bars to extended curb lines (for sight distance) and add left-side stop sign		94-00	120	71	34%	29%	20%		
Add/move stop bars to extended curb lines and extend existing CL to bars		95-01	145	61	35%	33%	24%		
Install traffic signal		95-00	335	220	22%	18%	73%	2	H
Add median to reduce angle crashes	2	98	57	43	40%	36%	90%	20	None

- Cross-referencing of the descriptive files indicated that an additional (different) treatment had been implemented at the same location during the before or after period. Omitting these sites left too small a sample size.
- The existing CRF already has a high or medium-high level of predictive certainty (e.g., convert from two-way to four-way stop control; install traffic signal), and hence was not a high priority for evaluation.
- Based on further conversations with W-SDOT, there were questions about the possibility of finding a suitable untreated reference group (e.g., add or lengthen an expressway acceleration lane at a stop-controlled ramp entrance), or the treatment was somewhat "undefined" or might not be widely applicable (e.g., add medians at stop-controlled intersections to reduce angle crashes)

Choosing one or more treatments from the unsignalized group was also considered, but dropped because of the additional data collection cost in identifying a reference group of unsignalized intersections. The currently proposed four treatments will require the development of only one reference group composed of signalized intersections. The evaluation of any of the unsignalized treatments would require the development of a new reference group of unsignalized intersections.

REVIEW OF PREVIOUS RESEARCH

This section gives a brief overview of previous research on the safety effectiveness of the four types of treatments mentioned earlier. Also discussed are the results of the simple before-after studies that Winston-Salem DOT conducted for these treatments.

Left-turn Phasing

Several studies have attempted to quantify the safety effectiveness of changes in left-turn phasing. Hauer *(2)* conducted a detailed critical review of 14 studies that were completed over a period of 24 years in several countries. Hauer (*2*) notes that the AMF for changing from permissive to protected most likely depends on the number of opposing lanes, and that most of the other evidence is insufficient and contradictory. Based on the review of these studies, Hauer (*2*) concludes that the AMF for left-turn crashes for changing to protected phasing from either permissive or permissive/protected is around 0.3 (i.e., a 70% reduction in left-turn crashes); for other crashes, the AMF is 1.0 (i.e., no effect). When changing from permissive to permissive/protected, Hauer (*2*) estimates that the AMF is around 1.0 for both left-turn crashes and other crashes (i.e., no effect).

Harwood et al. (*3*) conducted a before-after study using the EB approach to study the safety impact of adding left-turn lanes with protected or permissive/protected signal phasing. A total of 36 four-leg signalized intersections were included; 31 of these sites received a permissive/protected signal phasing while 5 received a protected signal phasing. The 31 sites with permissive/protected signal phasing system experienced a 9 percent reduction in crashes (AMF of 0.91); the five sites with protected signal phasing system experienced a 10 percent reduction in crashes (AMF of 0.90). The study report did not indicate if these results were statistically significant. The authors conclude that there is "essentially no effect of the type of signal phasing on the safety effectiveness of left-turn lanes", and "there are too few data to obtain definitive results".

More recently, Lyon et al. (*4*) used the EB approach to evaluate the impact of flashing advance green (FAG) and left-turn green arrow (LTGA) treatments on injury and fatal left-turn and left-turn side impact crashes. Priority was a leading left-turn. In some cases, some form of priority existed and in others additional minor modifications were made. A total of 35 intersections from Toronto were included; 15 sites received the FAG, while 20 received the LTGA. Left-turn crashes decreased by 16 percent in the FAG sites and 17 percent at the LTGA sites. Left-turn side impact crashes decreased by 12 percent in the FAG sites and 25 percent at the LTGA sites. All results were statistically significant at the 95 percent confidence level.

Using the same treatment data as is used in this study, Polanis (*5*) conducted a simple before-after study using data from 18 signalized intersections in Winston-Salem. In five of these sites, the left-turn phasing was changed from permissive/protected to protected, and in the remaining 13 sites, it was changed from permissive to permissive/protected or protected. For the 5 sites where the permissive/protected phase was replaced by protected phase, there was a 98 percent reduction in the target crashes (i.e., left-turn crashes); in the 13 sites where permissive phasing was replaced by permissive/protected or protected, there was a 67 percent reduction in target crashes. In this cursory analysis it was not possible to account for changes in traffic volume or possible regression-to-the-mean.

Collectively, the studies seem to indicate that changing the left-turn phasing to protected mode is associated with a reduction in left-turn crashes, although the results are not consistent, indicating the need for further research.

Convert from a Night-time Flash to Regular Phasing

Some agencies place traffic signals in a flashing mode during night-time to save electricity and reduce delay during the hours of low traffic volume. However, concerns have been raised about the safety impact of night-time flash operation. Gaberty II and Barbaresso (*6*) analyzed accident data at 59 four-leg intersections in Oakland County, Michigan, where the night-time flash mode was replaced with regular full cycle signal operation between 1980 and 1985. Results indicated a substantial reduction in angle crashes: the average annual frequency of right-angle crashes decreased from 50.5 during the before condition (with night-time flash mode) to 4.57 in the after condition (regular signal operation); a 91 percent reduction. Injury right-angle crashes decreased from 31 to 1.71, a 95 percent reduction. Similar results were obtained by Barbaresso (*7*) who found that right-angle crashes decreased from 4.942 (per year-hour) to 0.125 after the night-time flash was replaced with regular phasing operation. Both these studies did not account for possible bias due to regression-to-the-mean.

Polanis (*8*) conducted a simple before-after study based on data from 19 intersections in Winston-Salem. Night-time angle crashes decreased by 78 percent following the replacement of flashing operation with regular phasing operation.

In conclusion, the studies reviewed do seem to indicate that removing night-time flashing operation significantly reduces the number of right-angle crashes. However, since none of the studies accounted for possible bias due to regression-to-the-mean, the effects documented may be exaggerated especially if high accident sites were selected for this treatment.

Replace Existing 8” Signal Heads with 12” Heads

Most of the previous work on this topic has involved laboratory and field studies to study visibility differences for different types of signal heads (*9*). Very few have evaluated the effect of signal head size on the frequency and severity of crashes. Sayed et al. (*10*) evaluated the effect of changes in signal head size at 10 urban intersections in British Columbia. Before the change, the signals were equipped with a 300-mm (12 inches) 150-W red light; a 200-mm (8 inches) 69-W amber light, and a 200-mm 69-W green light along with a yellow back-board. The after condition consisted of a 300-mm red light, a 300-mm amber light, and a 300-mm green light, all with 150-W lamps and a yellow backboard with an additional 50-mm reflective border; the red signal heads did not seem to have been altered. The analysis methodology followed a simplistic EB procedure (as opposed to the state of the art multivariate EB) to account for regression-to-the-mean and time trend effect. The before and after periods were short (1 year before and 2 years after); however, all the treatment intersections were high volume and had a substantial number of crashes. The 10 treatment intersections experienced a total of 333 crashes in the one-year before-period and 448 crashes in the two-year after-period. The EB analysis revealed a 24 percent reduction in total crashes and a 16 percent reduction in severe crashes.

Polanis (*11*), in a simple before-after comparison, found a 47 percent reduction in right-angle crashes and a 9.9 percent reduction in total crashes following the replacement of 8 inch signal heads with 12 inch heads at 55 intersections.

Add Additional Signal Heads

Very few studies have evaluated the safety impacts of double signal heads. Forbes (*12*) reports on a study conducted by Hamilton Associates (*13*) where added signal heads was evaluated using both a cross-sectional comparison of crash rates and a before-after analysis using EB and multivariate EB. For the cross-sectional comparison of crash rates (crashes per million entering vehicles) 63 intersections were included: 48 had one signal head and 15 had two signal heads per approach. The cross-sectional study revealed that the total crash rate for 48 intersections with one signal head was 1.3, and for the 15 intersections with two signal heads, the crash rate was 1.02; a 22 percent difference.

For the before-after study, the sample size was limited to eight intersections. The number of years of before-after data was also limited to one or two years. The EB study revealed a 22 percent reduction in crashes and the multivariate EB study revealed a 28 percent reduction in crashes.

Polanis (*11*), in his simple before-after study of eight intersections in Winston-Salem found a 34 percent reduction in right-angle crashes.

DATA COLLECTION

Crash and AADT Data for Treatment Sites

Before and after crash data are available for each chosen treatment site from the W-SDOT file in our possession. However, there are no AADT data in that source file. Project team members traveled to Winston-Salem and extracted the AADTs for each treatment intersection approach for each before and after year from AADT books available at W-SDOT. These data were then added to the study file.

Development of a Reference Group

As indicated above, the second major step in this effort was the preparation of a reference group of untreated signalized that were used in the estimation of Safety Performance

Functions (SPF) for the empirical Bayes procedure. As for the treated sites, data for each reference intersection included annual crash data and annual AADT data. As noted above, there is no computerized file in Winston-Salem that links crashes to a specific intersection, and no computerized AADT data.

A number of different methods for developing a reference group were considered. The possible use of before-period crash data from chosen or not-chosen treatment sites was considered but rejected since bias due to the regression-to-the-mean phenomenon would be present. The use of computerized crash and AADT data from FHWA's HSIS system was considered, since historic data for both exist in that system back to 1987. However, this approach was rejected since (1) these HSIS locations would only be on state-system roads in Winston-Salem, which probably constitute only highest-volume roads, and (2) HSIS does not include an intersection inventory file, so all intersections would have to be manually identified and mileposts determined, which would have been a time consuming task. Charlotte, NC, data is now being captured for the HSIS system, and could possibly be used to develop a reference group SPF. However, Charlotte data are not yet in HSIS, and hence, we have not had the chance to evaluate it and ensure that there are no problems with the data. Even if Charlotte data are used, the SPF developed would have to be calibrated to Winston-Salem conditions, again requiring some manual development of a Winston-Salem crash and AADT subset.

For these reasons, it was decided that a reference group would be manually developed using crash and AADT data for Winston-Salem intersections. W-SDOT maintenance staff maintains a listing of all signalized intersections, defined by pairs of street names. Our project staff met with Stan Polanis and worked with him to choose 75 untreated intersections for the reference group. The intersections chosen were similar to the treated group in terms of traffic volume, number of legs, number of approach lanes and other characteristics.

Following choice of intersections, the project team extracted pertinent approach AADT data for the same years covered in any of the treatment before and after periods (i.e., 1990-2004) from AADT books just as described above for the treated sites. The project team then linked historic (1990-2004) crash data to each reference group intersection. These crash data were extracted from the full NC crash files retained by HSRC. (Note that these files contain all crashes in the state, unlike the HSIS files which only contain state-system crashes.) All crashes for the entire city of Winston-Salem were extracted from each annual file, and a master file covering all years was developed. Each crash record contains "on" and "toward" street names for each crash, allowing one to identify the intersection involved. The linkage to the reference-group intersections were done by manually matching the street names in each intersection pair to the sorted crash file (including possible misspellings for a given street name). We queried Mr. Polanis concerning possible street-name changes during the 1990-2004 period for the reference group sites to ensure that we captured all such changes, and after the file was built, we examined each intersection to assure that crash data were present for each year for each intersection. Finally, the descriptive information and AADT and crash data for each intersection was entered into the final analysis file. After eliminating intersections lacking in AADT or other data 60 untreated intersections were available for developing the required SPFs.

Overview of Analysis Methodology

The empirical Bayes (EB) methodology for observational before-after studies (*1*) was used for the evaluation. This methodology is rigorous in that it accomplishes the following:

- It properly accounts for regression-to-the-mean.
- It overcomes the difficulties of using crash rates in normalizing for volume differences between the before and after periods.
- It reduces the level of uncertainty in the estimates of safety effect.
- It provides a foundation for developing guidelines for estimating the likely safety consequences of contemplated strategy.
- It properly accounts for differences in crash experience and reporting practice in amalgamating data and results from diverse jurisdictions.

In the EB approach, the change in safety for a given crash type at a site is given by:

$$\lambda - \pi \qquad \text{E1)}$$

where λ is the expected number of crashes that would have occurred in the after period without strategy and π is the number of reported crashes in the after period.

In estimating λ, the effects of regression-to-the-mean and changes in traffic volume were explicitly accounted for using safety performance functions (SPFs) relating crashes of different types to traffic flow and other relevant factors for each jurisdiction *based on untreated sites*. Annual SPF multipliers are calibrated to account for the temporal effects on safety of variation in weather, demography, crash reporting and so on.

In the EB procedure, the SPF is used to first estimate the number of crashes that would be expected in each year of the before period at locations with traffic volumes and other characteristics similar to the one being analyzed. The sum of these annual SPF estimates (P) is then combined with the count of crashes (x) in the before period at a strategy site to obtain an estimate of the expected number of crashes (m) before strategy. This estimate of m is:

$$m = w_1(x) + w_2(P), \qquad \text{E2)}$$

where the weights w_1 and w_2 are estimated from the mean and variance of the SPF estimate as:

$$w_1 = \frac{kP}{kP+1} \ldots \qquad \text{E3)}$$

$$w_2 = \frac{1}{kP+1} \ldots \qquad \text{E4)}$$

where *k* is a constant for a given model and is estimated from the SPF calibration process with the use of a maximum likelihood procedure. (In that process, a negative binomial distributed error structure is assumed with *k* being the over-dispersion parameter of this distribution.)

A factor is then applied to *m* to account for the length of the after period and differences in traffic volumes between the before and after periods. This factor is the sum of the annual SPF predictions for the after period divided by *P*, the sum of these predictions for the before period. The result, after applying this factor, is an estimate of λ. The procedure also produces an estimate of the variance of λ, the expected number of crashes that would have occurred in the after period without strategy.

The estimate of λ is then summed over all sites in a strategy group of interest (to obtain λ_{sum}) and compared with the count of crashes during the after period in that group (π_{sum}). The variance of λ is also summed over all sites in the strategy group.

The Index of Effectiveness (θ) is estimated as:

$$\theta = \frac{\pi_{sum} / \lambda_{sum}}{1 + \left(Var(\lambda_{sum}) / \lambda_{sum}^2 \right)} \quad \ldots \qquad \text{E5)}$$

The standard deviation of θ is given by:

$$StDev(\theta) = \sqrt{\frac{\theta^2 \left(\frac{Var(\pi_{sum})}{\pi_{sum}^2} + \frac{Var(\lambda_{sum})}{\lambda_{sum}^2} \right)}{\left(1 + \frac{Var(\lambda_{sum})}{\lambda_{sum}^2} \right)^2}} \quad \ldots \qquad \text{E6)}$$

The percent change in crashes is in fact $100(1-\theta)$; thus a value of $\theta = 0.7$ with a standard deviation of 0.12 indicates a 30 percent reduction in crashes with a standard deviation of 12 percent.

Development of Safety Performance Functions

This section presents the safety performance functions (SPFs), which were developed for the empirical Bayes analysis. Generalized linear modeling was used to estimate model coefficients assuming a negative binomial error distribution, which is consistent with the state of the research in developing these models. The over-dispersion parameter (*k)* is estimated by an iterative process assuming a negative binomial error structure. The over-dispersion parameter relates the mean and variance of the SPF estimate. The value of *k* is such that the smaller its value, the better a model is for a given set of data.

The following safety performance function was estimated for the total number of crashes per year:

$$\text{Crashes/year} = (\text{yearly factor})*\exp[-5.3782 + 0.5236*ln(\text{majAADT}) \\ + 0.2595*ln(\text{minAADT}) - 0.3734*(4 - \text{number of legs})]$$

Efforts at estimating SPFs for individual crashes were not successful. Hence, the proportion of crashes for each crash type along with a recalibrated over-dispersion parameter was used in the EB analysis. Table E-3 shows the standard error, confidence levels, p values, and the percentage of crashes for each crash type along with their corresponding overdispersion parameter. The yearly factors for each year are shown in Table E-4.

Table E-3. Safety performance functions.

Variable	Estimate	Standard Error	Wald 95% confidence limits		Chi-square	p-value
Intercept	-5.3782	1.1388	-7.6101	-3.1460	22.30	<.0001
ln(majAADT)	0.5236	0.1079	0.3121	0.7352	23.54	<.0001
ln(minAADT)	0.2595	0.0974	0.0686	0.4503	7.10	0.0077
Number of legs =3	-0.3734	0.1619	-0.6908	-0.0560	5.32	0.0211
Number of legs = 4	0	0				
k (Over-dispersion for total crashes)	0.1774	0.0357	0.1195	0.2632		
Number of Crashes	4235					
Angle	36%; Overdispersion = 0.3571					
Night-time	13%; Overdispersion = 0.3846					
Night-time Angle	5%; Overdispersion = 0.6667					
Left-turns on Major	11%; Overdispersion = 0.4167					

Table E-4. Annual factors.

Year	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**
Yearly Factor	0.92	0.91	0.94	1.07	1.22	1.02	1.05
Year	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Yearly Factor	1.02	1.12	1.02	0.99	0.95	0.99	0.80

RESULTS

This section presents the results of the EB analysis for the five treatments discussed earlier. For each treatment, information is presented on the expected crashes in the after period based on EB, the observed crashes in the after period, and accident modification factor. Statistically significant results are also identified.

Conversion of Nighttime Flash Operation to Steady Operation

The research team was able to identify 12 intersections where nighttime (9 p.m. to 6 a.m.) flash was converted to steady operation between August 1995 and April 2002. Data were available for 518 intersection-months before the change and 516 intersection-months after the change. The target crashes for this treatment included total night-time crashes and night-time angle crashes.

Table E-5 shows the actual number of crashes in the before and after periods, the expected number of crashes based on the EB procedure, and the accident modification factor (AMF) along with the standard error. Both night-time total crashes and night-time angle crashes reduced following the change. There was about a 35% reduction in total night-time crashes and this reduction was significant at the 5% significance level. There was 34% reduction in night-time angle crashes and this was significant at the 10% significance level. These reductions are substantially lower than the reductions estimated by Polanis (*8*) based his simple before-after study, indicating that bias due to regression-to-the-mean was probably significant.

The sample size for this treatment is limited, i.e., 12 intersections. However, the total number of crashes in the before period (63) is higher than the minimum number of crashes (60) that is required to detect a 35% reduction at the 5% significance level (based on estimates from Table 1).

Table E-5. Effect of converting nighttime flash operation to steady operation.

	Nighttime angle	**All Nighttime**
EB estimate of crashes expected in the before period	26.32	41.74
Count of crashes observed in the before period	57	63
EB estimate of crashes expected in the after period without strategy	23.95	38.01
Count of crashes observed in the after period	16	25
Accident Modification Factor (Standard Error)	0.659* (0.180)	0.651** (0.145)
Note: * Statistically significant at the 10% significance level. ** Statistically significant at the 5% significance level.		

Conversion of 8-inch signal heads to 12-inch signal heads and introduction of multiple signal heads

Table E-6 shows the results for the evaluation of installing 12” signal bulbs in place of 8” signal bulbs at 26 intersections. Angle crashes were identified as the target crash type for this strategy and it appears that the strategy is effective, particularly for target crashes. There is a statistically significant decrease in angle crashes of 42 percent, and an insignificant reduction in total crashes. This is consistent with the results of the simple before-after analysis conducted by Polanis (*11*).

Based on Table E-6, the EB estimate of non-angle crashes in the after period without the strategy is 495.78 – 194.33 = 301.45, which is lower than the count of non-angle crashes in the after period (481-113 = 368). Thus, there was an increase in non-angle crashes that almost offsets the decrease in right-angle crashes. It is possible that the increased signal head size encouraged more drivers to stop at the red light and probably led to an increase in rear-end crashes. This is similar to the results obtained by Council et al. (*15*) in their evaluation of red-light cameras where an increase in rear-end crashes was detected along with a decrease in right angle crashes, because the cameras encouraged more drivers to stop at the red light.

Table E-6. Effect of replacing 8” signal heads with 12” heads.

	Right-Angle	**Total**
EB estimate of crashes expected in the before period	198.81	507.19
Count of crashes observed in the before period	243	583
EB estimate of crashes expected in the after period without strategy	194.33	495.78
Count of crashes observed in the after period	113	481
Accident Modification Factor (Standard Error)	0.58** (0.07)	0.97 (0.06)
Note: ** Statistically significant at the 5% significance level		

Since this “tradeoff” occurred, and since the severities of angle and non-angle crashes can differ, an economic analysis was conducted in order to accurately estimate the effect of this treatment on overall “crash harm”. Based on a recent report from FHWA (*16)*, the comprehensive cost per crash is $47,333 for angle crashes and $26,735 for rear-end crashes. Assuming that the overall severity of non-angle crashes is quite similar to that of rear-end crashes, the economic analysis revealed a reduction of about $11,800 per intersection-year in the overall crash harm due to this treatment.

Table E-7 shows the results for the evaluation of installing double red signals, side by side, in place of a single red bulbs at eight intersections. The results indicate a slight increase in both total and angle crashes; however, the effects are statistically insignificant. The installation of double red signals does not appear to be an effective strategy for reducing total or angle crashes.

Table E-7. Effect of replacing single red signal head with double head.

	Right-Angle	**Total**
EB estimate of crashes expected in the before period	122.96	213.65
Count of crashes observed in the before period	148	228
EB estimate of crashes expected in the after period without strategy	120.49	209.93
Count of crashes observed in the after period	128	248
Accident Modification Factor (Standard Error)	1.05 (0.13)	1.18 (0.11)

Left Turn Phasing Treatments

Three types of left-turn phasing treatments were identified. The first involved replacing a permissive left-turn phase with a permissive/protected phase at three sites. The second involved replacing a permissive left-turn phase with a fully protected phase at eight sites. The third type involved replacing a permissive/protected phase with a fully protected phase at four sites. The target crashes for these treatments were identified as those involving at least one left-turning vehicle on the treated roadway. Tables E-8 through E-11 show the AMFs for these set of treatments.

For the three sites where the permissive phase was replaced by permissive/protected phasing, there was very little change in the target as well as the total crashes (see Table E-8). However, since the sample size is small, this result of no apparent effect of this treatment cannot be taken as definitive.

For each of the other two treatment types where the left turn phase was changed to fully protected phasing (from either permissive or permissive/protected), left turn crashes were virtually eliminated, but there was very little change in total crashes (see Tables E-9 and E-10). Since the results from these two types were similar, and both involved conversion to protected phasing, the results were combined and are shown in Table E-11. Since the left-turn crashes decreased substantially, and total crashes did not, it is evident that there must have been an increase in non-left-turn crashes of the same order as the decrease in left turn crashes. This result is consistent with the AMFs proposed by Hauer (*2*) who argued that any change to protected phasing (from permissive or permissive/protected) should lead to a substantial reduction in left-turn crashes but almost no difference in total crashes. Further research is necessary to determine the specific reasons for the effect on non-left-turn crashes. However, it seems reasonable to speculate that introducing a protected left-turn phase will tend to increase mostly rear-end crashes because of the increased number of phases (and therefore dilemma zone opportunities) and the increase in queues that results from reduced green time available for all traffic not protected by the introduced phase. If this is the case, the implication is that this is still a very safety effective measure from a total harm perspective since the left turn crashes tend to be of the side impact variety and therefore more severe than rear-end crashes. The results also imply that the measure would most effective overall where there is a relatively high frequency of left turn crashes.

Table E-8. Effect of replacing permissive-only phasing with permissive-protected phasing (3 intersections).

	Left-turn on treated roadway	**All**
EB estimate of crashes expected in the before period	17.07	100.88
Count of crashes observed in the before period	27	109
EB estimate of crashes expected in the after period without strategy	17.88	104.44
Count of crashes observed in the after period	18	110
Accident Modification Factor (Standard Error)	0.978 (0.277)	1.045 (0.135)

Table E-9. Effect of replacing permissive-only phasing with protected-only phasing (8 intersections).

	Left-turn on treated roadway	**All**
EB estimate of crashes expected in the before period	47.15	244.57
Count of crashes observed in the before period	70	257
EB estimate of crashes expected in the after period without strategy	46.09	240.31
Count of crashes observed in the after period	1	235
Accident Modification Factor (Standard Error)	0.021** (0.021)	0.975 (0.085)
Note: ** Statistically significant at the 5% significance level		

Table E-10. Effect of replacing permissive-permitted phasing with protected-only phasing (4 intersections).

	Left-turn on treated roadway	**All**
EB estimate of crashes expected in the before period	25.25	122.76
Count of crashes observed in the before period	39	129
EB estimate of crashes expected in the after period without strategy	25.73	122.74
Count of crashes observed in the after period	0	126
Accident Modification Factor (Standard Error)	0.000** (0.006)	1.020 (0.123)
Note: ** Statistically significant at the 5% significance level		

Table E-11. Effect of replacing permissive-only or permissive-protected phasing with protected-only phasing (12 intersections).

	Left-turn on treated roadway	**All**
EB estimate of crashes expected in the before period	72.40	367.33
Count of crashes observed in the before period	109	386
EB estimate of crashes expected in the after period without strategy	71.82	363.05
Count of crashes observed in the after period	1	361
Accident Modification Factor (Standard Error)	0.014** (0.014)	0.992 (0.070)
Note: ** Statistically significant at the 5% significance level		

CONCLUSIONS

This study used the state of the art empirical Bayes method to evaluate the safety effectiveness of four types of engineering treatments at signalized intersections in Winston-Salem, North Carolina. In general, the results are consistent with engineering intuition and beliefs. There are also reasonable consistent with an earlier cursory evaluation of the same treatment program, although the magnitude of the effects tend to be different. The conclusions are as follows:

- Changing from permissive or permissive/protected to protected left-turn phasing resulted in a virtual elimination of left turn crashes but a compensating increase in other crashes. Further research is necessary to determine the specific reasons for the effect on non-left-turn crashes.
- Further research is necessary to determine the effect of changing from permissive to permissive/protected left turn phasing. The number of sites in this study was too small to make definitive conclusions.
- Replacing night flashing operation with regular 24-hour cycle operation can reduce the number of night-time crashes. In the sites evaluated in this study, the reduction was estimated to be around 35 percent.
- Increasing signal head size from 8 to 12 inches seems beneficial, especially for right-angle crashes. For the sites evaluated in this study, the reduction in right-angle crashes was estimated to be around 42 percent. There was an increase in other crashes, but these are likely to be of the less severe rear-end variety.
- Based on the very limited sample of sites evaluated in this study, adding a red signal head does not seem to be effective in reducing the number of crashes.

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