Safety Effectiveness of Flashing Yellow Arrow

Evaluation of 222 Signalized Intersections in North Carolina

Carrie L. Simpson and Shawn A. Troy

The purpose of this project was to develop crash modification factors (CMFs) for the implementation of a flashing yellow arrow (FYA) on the basis of the specific before-and-after period conditions of a signalized intersection. Although this countermeasure has been used for years in North Carolina and other states, no published studies to date have provided CMFs for left-turn crashes specific to the treated approaches, and none has provided CMFs for the three-section FYA for permissive-only left turns. Crash data from 222 intersections in North Carolina with an FYA protected–permissive left turn (FYA-PPLT), three-section FYA permissive-only left-turn installations, or both were used to provide CMFs for five category types: Category 1 (permissive only to FYA-PPLT), Category 2 (protected only to FYA-PPLT), Category 2A (protected only to FYA-PPLT with time of day operation), Category 3 (five-section PPLT to FYA-PPLT), and Category 4 (permissive only to FYA permissive only). A before-and-after crash analysis with consideration given to increases in traffic was used to determine the safety estimates. Safety performance functions were used to account for the effect of traffic volume trends. In Categories 3 and 4, the change was exclusive to the left-turn display and not to a change in phasing. All CMF results were statistically significant for Category 3, and target and injury CMF results were statistically significant for Category 4. On the basis of the results from the study sites, a statistically significant decrease was found in target left-turn crashes and injury crashes after a site signal underwent a change from a solid green ball to an FYA for permissive left turns when phasing remained unchanged. This finding applied whether the left phasing was protected–permissive or fully permissive.

A flashing yellow arrow (FYA) is one of many options used to indicate a permissive left-turn movement. In 2003, NCHRP Report 493 assessed the safety and operational characteristics of a variety of displays to identify the "best" traffic signal display for protected–permissive left turn (PPLT) control (*1*). Photographic driver studies showed flashing indications were understood better than steady indications, while circular green indications were comprehended least by drivers, at the lowest level of not quite 50% of all PPLT displays studied. Field testing of the FYA was conducted at 15 intersections across the United States. The results of before-and-after field conflict data showed no differences attributable to a change from a circular green indication to an FYA display. On the basis of all data collected, the FYA was found to have the most versatile characteristics and to offer the highest level of safety. Report 493 recommended that the FYA be included in the *Manual on Uniform Traffic Control Devices* as an allowable alternative display to the circular green indication when used in a PPLT operation. After the publication of the report, FHWA approved additional experimental FYA sites in numerous jurisdictions.

In 2009, the *Manual on Uniform Traffic Control Devices* formally approved the FYA as the recommended configuration for PPLT and permissive left-turn displays (*2*). Section 4D.13 of the manual states that circular green indications for permissive left turns should not be located over or in front of an exclusive left-turn lane for new or reconstructed signal installations (*2*).

The FYA type used prevalently in North Carolina is the FYA-PPLT. It has four sections: a steady red arrow, a steady yellow arrow, a flashing yellow arrow, and a steady green arrow. The other type used in North Carolina is FYA for permissive-only left turns, which is used on approaches with no exclusive left-turn phase. It has three sections: a steady red arrow, a steady yellow arrow, and a flashing yellow arrow. Figure 1 provides photographs of both display types at the intersection of Timber Drive and Grovemont Road in Garner, North Carolina. The FYA also has been used in a limited number of right-turn applications in North Carolina.

LITERATURE REVIEW

Studies have analyzed the operational impacts and other effects of FYA-PPLT, but few studies have provided before-and-after crash analysis of more than a handful of sites. None of the published studies has provided a target crash modification factor (CMF) for left-turn crashes specific to the treated approaches, and none has provided CMFs for the three-section FYA permissive-only left turn. The following summary of literature published to date is specific to crash analysis studies with the FYA.

NCHRP Web-Only Document 123 documented the follow-up safety study recommended in NCHRP Report 493 (*3*). Crash data were obtained from more than 50 intersections at which FYA-PPLT was implemented in the United States. The data were categorized on the basis of conditions at the intersection before the FYA installation: PPLT, protected-only left turn, and permissive-only left turn. Although the study provided new insights into the effectiveness of

North Carolina Department of Transportation, Transportation Mobility and Safety Division, 1561 Mail Service Center, Garner, NC 27699-1561. Corresponding author: C. L. Simpson, clsimpson@ncdot.gov.

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(a) (b)

FIGURE 1 Left-turn display types: (*a*) FYA-PPLT and (*b*) FYA-permissive only.

FYA, it noted some shortcomings (i.e., limited after-period data were available at the time; evaluation was not included of known changes other than the FYA implementation). CMF results were not provided. However, the report did offer the following general conclusions:

- Safety was improved at intersections that operated with PPLT phasing before and after the field implementation of the FYA.
- Safety was not improved at intersections that operated with protected-only left-turn phasing before field implementation of the FYA-PPLT.
- No conclusions were made at intersections that operated with permissive-only left-turn phasing before implementation of the FYA-PPLT, given the minimal number of implementation sites.

A 2011 study by Pulugurtha et al. evaluated the installations of FYA-PPLT at six signalized intersections in Charlotte, North Carolina (*4*). Before-period conditions on the approaches treated with FYA were not provided. The results showed improvements in safety at five of the six study sites. They also indicated that total crashes at the treated sites in general would have increased had the FYA not been installed. The study concluded that results were needed from future evaluations of larger sample sizes that considered left-turn crashes only.

A 2012 study by Yi et al. studied crash data at intersections at which an FYA-PPLT was installed (*5*). The study included 12 intersections in Texas, which all operated with PPLT phasing in the before period, and 39 intersections from two cities in Washington State, where the before left-turn control types included protected-only, permissive-only, and PPLT. The results indicated that the overall average left-turn crash rate decreased by 2% at the study sites in all three cities involved in the study. The study compared intersection crash rates only, and CMFs were not provided.

In 2012, Srinivasan et al. published the most comprehensive before-and-after safety study of FYA-PPLT to date (*6*). The study provided CMFs for the implementation of FYA-PPLT on the basis of data from 51 urban signalized intersections in Oregon, Washington State, and North Carolina. The empirical Bayes method was applied to the North Carolina sites. It could not be applied to sites in the other states, however, although the statistical methodology combined some aspects of the empirical Bayes and the comparison group approaches. Crash data by treated approaches were not provided in North Carolina; analysis of these sites focused on intersection-level crashes. The results for all three states were combined at the intersection level and reported for total crashes and total left-turn crashes. The following CMF results were provided on the basis of the before condition at the treated sites:

- Intersections at which the converted legs had protected-only phasing in the before period (29 sites, 56 legs treated): total CMF = 1.338 and left-turn CMF = 2.242;
- Intersections at which the converted legs had either permissive or protected–permissive phasing in the before period, and at least one of the converted legs had permissive phasing (nine sites, 20 legs treated): total CMF = 0.753 and left-turn CMF = 0.635; and
- Intersections at which all of the converted legs had protected–permissive phasing in the before period (13 sites, 27 legs treated): total CMF = 0.922 and left-turn CMF = 0.806.

The results indicated a safety benefit at locations with some kind of permissive left-turn operation in the before period and a disbenefit at locations with protected-only operation in the before period. An overall CMF was not provided specifically for approaches with permissive-only left-turn operation in the before period. The study offered CMF results for FYA-PPLT under three conditions. A need was seen, however, to determine additional CMF values for the FYA treatment, especially given the wealth of data that have become available since Srinivasan et al. published their study.

PROJECT SCOPE

The purpose of this project was to develop CMFs for the implementation of FYA-PPLT, FYA-PPLT with time of day (TOD) operation, and FYA-permissive only. On the basis of earlier studies, the immense impact was recognized of before-period left-turn phasing conditions on treatment effectiveness. Data were categorized to reflect this impact. Categories 3 and 4 were of the most interest because in them the change was exclusive to the left-turn display and not to a change in phasing. The categories were as follows:

Category 1. Permissive only to FYA-PPLT,
Category 2. Protected only to FYA-PPLT,
Category 2A. Protected only to FYA-PPLT with TOD operation,
Category 3. Five-section doghouse PPLT to FYA-PPLT, and
Category 4. Permissive only to FYA-permissive only.

The measures of effectiveness included the following:

1. Total crashes;
2. Target crashes, defined as left-turn same-roadway crashes with the left-turner on an approach treated with an FYA and occurring during the TOD when the FYA is in operation; and
3. Injury crashes.

METHODOLOGY

A before-and-after crash analysis with consideration for traffic increase was used to calculate the CMFs. *Highway Safety Manual* safety performance functions (SPFs) for urban and suburban intersections were used to determine the effect of traffic volume trends on predicted crash frequency (*7*). SPFs provide an exponential form to relate volumes with expected crashes. SPFs were used to create adjustment factors that incorporated the separate effects of annual average daily traffic on the major and minor road legs into the before-and-after-periods at each site. The before-crash frequencies were multiplied by the ratio of after-SPF predictions to before-SPF predictions to obtain the expected number of after-period crashes.

The analysis did not account for selection bias or nonvolume time trends and did not address the threat of regression to the mean, which is the presumption that a site will return to its long-term mean crash frequency after an extraordinarily high or low period. Empirical Bayes before-and-after analysis, one of the techniques used to account for such potential deficiencies, was considered but not used for the study for the following reasons:

- Most sites were selected for treatment on the basis of operational concerns or other nonsafety issues. The average number of target crashes per year per intersection in the before period was small: only 1.08 crashes. On the basis of experience with urban signals in North Carolina, this number suggested that crash history was not a factor in treatment selection at many sites. Also, approximately 20% of signalized intersections in North Carolina currently used FYA or planned to do so soon. Thus it was concluded that bias from regression to the mean was not evident in the selection of the treated locations.
- The Empirical Bayes approach requires the use of a reference group of sites, similar to the treated ones but not in receipt of treatment, to account for changes in crashes unrelated to the treatment. Given the large size of the treatment group, it was decided that the compilation and analysis of an adequate reference group of similar intersections located within the vicinity of the treatment sites (but not affected by the treatment or undergoing changes in the study periods) was not feasible in the study. Also, obtaining target crashes from any potential reference group would have been a feat because it would have entailed manual review of crash reports to identify the true left-turn targets (efforts to assemble target crashes are explained later in this section).

The crash analysis was performed for each intersection with the North Carolina Traffic Records Database, which at the time of the study contained all reported crashes in the state from 1990 through November 30, 2013. The FYA installation dates varied from 2006 through 2011. Thus the period analyzed for each location varied according to the time when the treatment was installed. The before period consisted of 3 years of data, while the after period varied from 2 to 3 years at each site. The crash analyses were terminated before other known countermeasures were implemented. The data consisted of all crashes within 150 ft of the treated intersections. Injury crashes included fatal and nonfatal injury crashes combined. The current reporting threshold for crashes in North Carolina was $1,000.

Determination of target crashes required careful review of the crash data. Selected for review was every crash coded to four crash types: (*a*) left turn same roadway, (*b*) left turn different roadway, (*c*) angle, and (*d*) head on. The study's target crash type was left turn same roadway, but it was necessary to include the additional crash types in the review because 45% of target crashes comprised crashes coded as left turn different roadway, angle, and head on when a subset of the sites was tested. Had only the crashes coded as left turn same roadway been selected to determine the target group, the results might have been misleading. The selected crashes were reviewed to determine if they involved a left-turning vehicle, if the vehicle was on an approach with an FYA, and, if so, the category type on that approach. Also, if TOD operation was present, the day of the week and time of the crash were reviewed to determine whether the crash occurred at a time when an FYA was in operation.

As of late 2013, 1,625 FYAs were in design, transmitted, or installed throughout North Carolina. Figure 2 shows the process used to select the study sites. The number of sites in each group is listed in parentheses. More than 600 sites were reviewed manually for inclusion in the study. All signal files dated within a site's study time periods were scanned to determine the category type and if major changes were made beyond installation of an FYA.

The study included 222 sites with no other documented changes and with readily accessible crash data. A thorough review of signal plans was conducted to exclude sites where other treatments were implemented during the before or after period, which might have influenced the results. It was acknowledged that some changes (e.g., certain timing changes, system tweaks, law enforcement programs), which were undocumented in plans or maps, might have occurred. The decision to keep the before-and-after time periods to a maximum of 3 years might have helped to minimize the number of other changes that happened over time.

Some of the reasons to exclude certain treatment sites were the following:

- Intersection geometry changes or roadway widening,
- Offsetting left-turn lanes,
- Phasing changes (unrelated to the FYA),
- Speed limit changes,

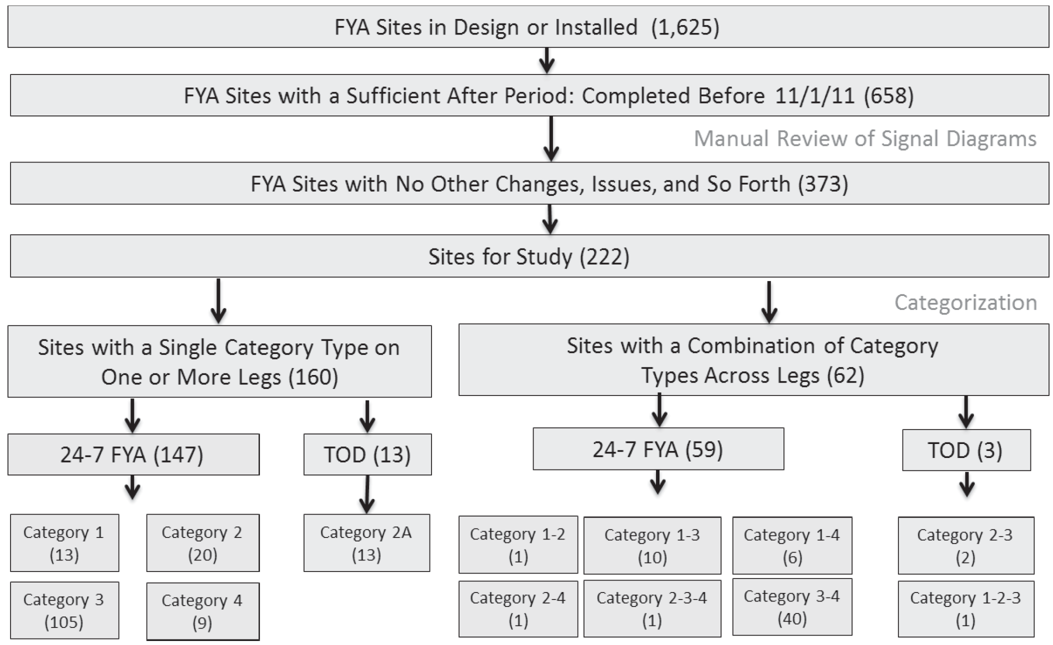


FIGURE 2 Site selection and categorization process.

- Other countermeasures implemented, and
- No signal plans found.

Sites were grouped on the basis of whether a TOD plan was in operation. If alternate phasing plans were listed on a signal plan, the local traffic engineer was contacted to determine if TOD operation was used and, if so, to obtain the time periods of operation. Most sites with TOD operation employed FYA during off-peak hours (in general, 9 p.m. to 6 a.m.) and operated fully protected the remainder of the day. Few sites in the study used TOD operation, although this option was beginning to be used more frequently. Category 2 was the only one with sites that used TOD operation, and the sample was sufficient to create Category 2A for this subgroup. The remainder of the sites in the study used an FYA 24 h/day.

Sites were further categorized on the basis of the before-and-after period conditions of each approach. Intersections with only a single category type on one or more legs were separated from intersections where combinations of category types were employed across the legs. Figure 3 displays two example intersections, Sites A and B, to illustrate site categorization. Site A has a single category type on one or more legs. This site is exclusive to Category 1 (Leg 1 is Category 1 FYA, Leg 2 is Category 1 FYA, and Legs 3 and 4 remain unchanged). Site A data were used on the intersection and the approach levels: intersection-level crashes were used to calculate a total CMF and an injury CMF for Category 1, while target left-turn crashes from Legs 1 and 2 were used to calculate a target CMF and a target injury CMF for Category 1. Site B had a combination of category types across legs. This site was a Categories 1–3 site (Leg 1 is Category 1 FYA, Leg 2 is a Category 3 FYA, and Legs 3 and 4 remain unchanged). Site B data were used on the approach level only: left-turn crashes from Leg 1 were used to calculate a target CMF and a target injury CMF for Category 1, while left-turn crashes from Leg 2 were used to calculate a target CMF and a target injury CMF for Category 3. These additional data proved helpful to support target CMF results in cases in which limited sites were available.

RESULTS

The results were provided separately by category because each type was a separate countermeasure (some change phasing as well as left-turn display) and resulted in varying crash outcomes.

Category 1. Permissive Only to FYA-PPLT

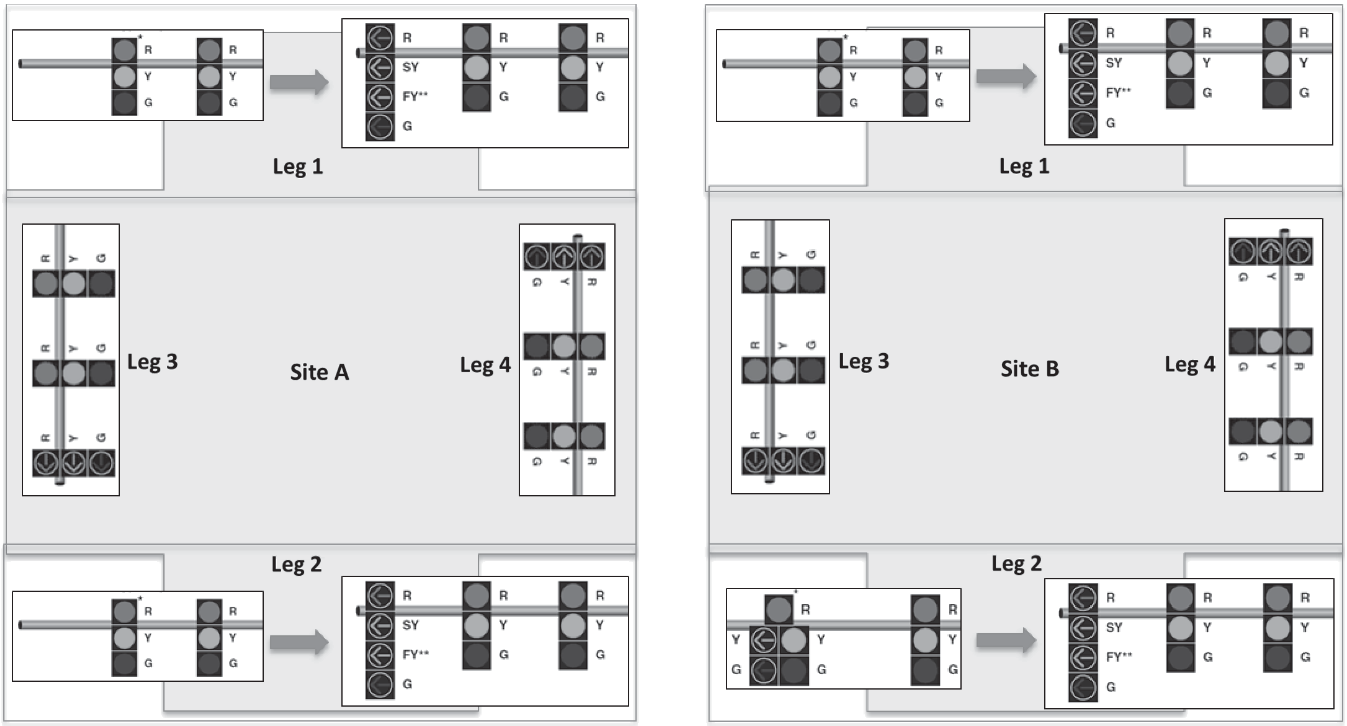
Table 1 provides summary statistics for Category 1. Summary statistics were provided for the other categories to provide a fuller picture of the types of locations included in the study, as well as any variations between categories.

Table 2 presents the results of the crash analysis for Category 1. The parameter estimates are denoted as follows:

λ = actual number of after-period crashes;
π = predicted number of after-period crashes;
CMF = ratio of what safety was with treatment to what safety would have been without treatment, used as a multiplicative factor to compute expected number of crashes after implementation of given countermeasure; and
Crash reduction factor (CRF) = estimate of percentage of reduction in crashes that might be expected after implementation of countermeasure, calculated as [(1-CMF) × 100] (*8*).

Conventional Hauer symbology and methodology were used in the countermeasure evaluation (*9*). The value after the plus-or-minus sign indicates the standard deviation of an estimated value.

Although the tables provide the results as CMF and CRF estimates, the results here are reported as the CRF estimates for ease of consumption. For the 13 intersections (20 treated legs) that exclusively received a Category 1 FYA, the results of the crash analysis yielded a 7% reduction in total crashes, a 35% reduction in total injury crashes,



(a) (b)

FIGURE 3 Site categorization at approach level (R = red; Y = yellow; G = green; SY = steady yellow; FY = flashing yellow; *shared signal face; **shall not be displayed when the signal operates in protected-only mode). [Source: Signal images from MUTCD (*2*).]

and a 26% reduction in target crashes. For the 41 treated legs that received a Category 1 FYA, the results yielded a 40% reduction in target crashes.

Category 2. Protected Only to FYA-PPLT

For Category 2, Table 3 provides summary statistics, and Table 4 presents the results of the crash analysis. For the 20 intersections (43 treated legs) that exclusively received a Category 2 FYA, the results of the crash analysis yielded a 12% increase in total crashes, a 21% increase in total injury crashes, and a 244% increase in target crashes. For the 49 treated legs that received a Category 2 FYA, the results yielded a 268% increase in target crashes.

Category 2A. Protected Only to FYA-PPLT with TOD Operation

For Category 2A, Table 5 provides summary statistics, and Table 6 presents the results of the crash analysis. As mentioned, when TOD operation was present, the day of the week and time of the crash were reviewed. Only left-turn crashes that occurred at a time when FYA was in operation were included as target crashes. Results not statistically significant at the 5% level but statistically significant at the 10% level are shown in italics. For these results, a larger sample was required to detect the same level of effect with 95% certainty.

For the 13 intersections (28 treated legs) that exclusively received a Category 2A FYA, the results of the crash analysis yielded a 10% reduction in total crashes, a 7% reduction in total injury crashes, and a 173% increase in target crashes. For the 34 treated legs that exclusively received a Category 2A FYA, the results yielded a 173% increase in target crashes.

Category 3. Five-Section PPLT to FYA-PPLT

For Category 3, Table 7 provides summary statistics, and Table 8 presents the results of the crash analysis. For the 105 intersections (193 treated legs) that exclusively received a Category 3 FYA, the results of the crash analysis yielded a 7% reduction in total crashes, a 15% reduction in total injury crashes, and a 22% reduction in target crashes. For the 254 treated legs that received a Category 3 FYA, the results yielded a 16% reduction in target crashes. All results were statistically significant at the 5% level.

Category 4. Permissive Only to FYA-Permissive Only

For Category 4, Table 9 provides summary statistics, and Table 10 presents the results of the crash analysis. For the nine intersections (14 treated legs) that exclusively received a Category 4 FYA, the results of the crash analysis yielded an 11% reduction in total crashes, a 31% reduction in total injury crashes, and a 59% reduction in target

TABLE 1 Summary Statistics for Category 1

Variable	Minimum	Maximum	Average
13 Sites Exclusive to Category 1 (20 Category 1 legs)			
Years before	3.0	3.0	3.0
Years after	2.1	3.0	2.8
Number of legs	3	4	3.8
Number of Category 1 treated legs	1	4	1.5
Number of Category 1 major road treated legs	1	2	1.2
Number of Category 1 minor road treated legs	0	2	0.3
Major road speed limit	35	45	41.2
Number of signal phases after	2[a]	8	4.5
Major road AADT before	7,000	24,000	12,300
Major road AADT after	7,800	23,000	12,900
Minor road AADT before	1,100	9,300	4,700
Minor road AADT after	1,100	9,000	4,800
Total crashes in the year before	0.7	14.0	4.8
Total crashes in the year after	0.7	12.5	4.6
Total injury crashes in the year before	0.3	6.3	1.7
Total injury crashes in the year after	0.0	3.4	1.1
Target crashes in the year before	0.0	3.3	0.8
Target crashes in the year after	0.0	1.7	0.6
Target injury crashes in the year before	0.0	2.3	0.5
Target injury crashes in the year after	0.0	1.1	0.3
17 Sites with Multiple Category Types Including at Least 1 Category and 1 Leg (21 Category 1 legs)			
Years before	3.0	3.0	3.0
Years after	2.3	3.0	2.8
Number of legs	4	4	4.0
Number of Category 1 treated legs	1	2	1.2
Number of Category 1 major road treated legs	0	1	0.7
Number of Category 1 minor road treated legs	0	2	0.5
Major road speed limit	35	55	44.1
Number of signal phases after	3	8	5.4
Major road AADT before	7,700	49,000	19,800
Major road AADT after	7,600	47,000	20,000
Minor road AADT before	600	17,000	6,400
Minor road AADT after	600	13,500	6,900
Target crashes in the year before	0.0	9.7	1.0
Target crashes in the year after	0.0	2.3	0.6
Target injury crashes in the year before	0.0	5.7	0.5
Target injury crashes in the year after	0.0	1.4	0.3

NOTE: Permissive only to FYA-PPLT. AADT = annual average daily traffic.
[a]Three-leg intersection with right turns only allowed from stem.

TABLE 2 Evaluation Results for Category 1

Crash Type	π	λ	CMF[a]	CRF (%)
13 Sites (20 Category 1 legs)				
Total	171.3 ± 12.7	161 ± 12.7	0.935 ± 0.100	6.5 ± 10.0
Total injury	61.7 ± 7.6	41 ± 6.4	**0.654** ± 0.128	34.6 ± 12.8
Target	30.2 ± 5.3	23 ± 4.8	0.738 ± 0.195	26.2 ± 19.5
Target injury	16.7 ± 3.9	12 ± 3.5	0.683 ± 0.240	31.7 ± 24.0
30 Sites (41 Category 1 legs)				
Target	84.2 ± 9.2	51 ± 7.1	**0.598** ± 0.105	40.2 ± 10.5
Target injury	41.2 ± 6.3	25 ± 5.0	**0.592** ± 0.146	40.8 ± 14.6

NOTE: Permissive only to FYA-PPLT.
[a]Boldface = statistically different from 1.0 at 5% level.

TABLE 3 Summary Statistics for Category 2

Variable	Minimum	Maximum	Average
20 Sites Exclusive to Category 2 (43 Category 2 legs)			
Years before	3.0	3.0	3.0
Years after	3.0	2.3	2.9
Number of legs	3	4	3.9
Number of Category 2 treated legs	1	4	2.2
Number of Category 2 major road treated legs	1	2	1.8
Number of Category 2 minor road treated legs	0	2	0.4
Major road speed limit	35	55	43.5
Number of signal phases after	3	8	5.5
Major road AADT before	12,000	40,500	24,300
Major road AADT after	12,000	38,000	24,800
Minor road AADT before	1,100	16,500	5,700
Minor road AADT after	900	17,000	5,800
Total crashes in the year before	2.3	18.7	6.8
Total crashes in the year after	0.7	18.0	7.5
Total injury crashes in the year before	0.3	6.3	2.4
Total injury crashes in the year after	0.0	7.1	2.9
Target crashes in the year before	0.0	6.3	0.45
Target crashes in the year after	0.0	5.7	1.6
Target injury crashes in the year before	0.0	3.0	0.2
Target injury crashes in the year after	0.0	3.0	0.9
Three Sites with Multiple Category Types Including at Least 1 Category 2 Leg (6 Category 2 legs)			
Years before	3.0	3.0	3.0
Years after	2.4	3.0	2.8
Number of legs	4	4	4.0
Number of Category 2 treated legs	2	2	2.0
Number of Category 2 major road treated legs	2	2	2.0
Number of Category 2 minor road treated legs	0	0	0.0
Major road speed limit	45	50	46.7
Number of signal phases after	5	8	6.3
Major road AADT before	9,100	49,000	25,000
Major road AADT after	10,000	47,000	25,300
Minor road AADT before	3,300	5,400	4,300
Minor road AADT after	3,100	4,900	4,200
Target crashes in the year before	0.0	0.3	0.2
Target crashes in the year after	0.4	3.7	1.6
Target injury crashes in the year before	0.0	0.0	0.0
Target injury crashes in the year after	0.3	1.3	0.7

NOTE: Protected only to FYA-PPLT.

TABLE 4 Evaluation Results for Category 2

Crash Type	π	λ	CMF[a]	CRF (%)
20 Sites (43 Category 2 legs)				
Total	390.4 ± 19.5	440 ± 21.0	1.124 ± 0.077	−12.4 ± 7.7
Total injury	139.9 ± 11.7	170 ± 13.0	1.206 ± 0.136	−20.6 ± 13.6
Target	26.1 ± 5.0	93 ± 9.6	**3.440** ± 0.727	−244.0 ± 72.7
Target injury	11.8 ± 3.4	55 ± 7.4	**4.308** ± 1.270	−330.8 ± 127.0
23 Sites (49 Category 2 legs)				
Target	28.1 ± 5.2	107 ± 10.3	**3.684** ± 0.748	−268.4 ± 74.8
Target injury	11.8 ± 3.4	61 ± 7.8	**4.778** ± 1.397	−377.8 ± 139.7

NOTE: Protected only to FYA-PPLT.
[a]Boldface = statistically different from 1.0 at 5% level.

TABLE 5 Summary Statistics for Category 2A

Variable	Minimum	Maximum	Average
13 Sites Exclusive to Category 2A (28 Category 2A legs)			
Years before	3.0	3.0	3.0
Years after	2.0	3.0	2.7
Number of legs	4	4	4.0
Number of Category 2A treated legs	1	4	2.2
Number of Category 2A major road treated legs	0	2	1.5
Number of Category 2A minor road treated legs	0	2	0.6
Major road speed limit	35	45	43.5
Number of signal phases after	4	8	7.2
Major road AADT before	19,000	41,000	30,400
Major road AADT after	19,000	40,000	29,200
Minor road AADT before	3,000	32,000	20,400
Minor road AADT after	3,000	27,000	18,600
Total crashes in the year before	1.7	60.7	20.0
Total crashes in the year after	1	43.3	17.8
Total injury crashes in the year before	1.3	17.0	6.4
Total injury crashes in the year after	0.0	13.7	5.9
Target crashes in the year before	0.0	1.0	0.2
Target crashes in the year after	0.0	2.8	0.6
Target injury crashes in the year before	0.0	1.0	0.1
Target injury crashes in the year after	0.0	2.3	0.4
Three Sites with Multiple Category Types Including at Least 1 Category 2A Leg (6 Category 2A legs)			
Years before	3.0	3.0	3.0
Years after	2.1	2.4	2.3
Number of legs	4	4	4.0
Number of Category 2A treated legs	2	2	2.0
Number of Category 2A major road treated legs	0	2	1.3
Number of Category 2A minor road treated legs	0	2	0.7
Major road speed limit	35	45	38.3
Number of signal phases after	6	8	6.7
Major road AADT before	18,500	24,000	22,000
Major road AADT after	18,000	25,000	22,700
Minor road AADT before	6,000	21,000	14,000
Minor road AADT after	5,600	20,000	13,200
Target crashes in the year before	0.0	0.0	0.0
Target crashes in the year after	0.0	0	0
Target injury crashes in the year before	0.0	0.0	0.0
Target injury crashes in the year after	0.0	0.0	0.0

NOTE: Protected only to FYA-PPLT with TOD operation.

TABLE 6 Evaluation Results for Category 2A

Crash Type	π	λ	CMF[a]	CRF (%)
13 Sites (28 Category 2A legs)				
Total	692.0 ± 25.0	624 ± 25.0	**0.901** ± 0.048	9.9 ± 4.8
Total injury	218.4 ± 14.0	203 ± 14.2	0.926 ± 0.088	7.4 ± 8.8
Target	6.4 ± 2.4	20 ± 4.5	*2.732* ± 1.053	−173.2 ± 105.3
Target injury	4.6 ± 2.1	13 ± 3.6	2.371 ± 1.043	−137.1 ± 104.3
16 Sites (34 Category 2A legs)				
Target	6.4 ± 2.4	20 ± 4.5	*2.732* ± 1.053	−173.2 ± 105.3
Target injury	4.6 ± 2.1	13 ± 3.6	2.371 ± 1.043	−137.1 ± 104.3

NOTE: Protected only to FYA-PPLT with TOD operation.
[a]Statistically different from 1.0: boldface = at 5% level; italic = at 10% level.

TABLE 7 Summary Statistics for Category 3

Variable	Minimum	Maximum	Average
105 Sites Exclusive to Category 3 (193 treated legs)			
Years before	3.0	3.0	3.0
Years after	2.1	3.0	2.9
Number of legs	3	4	3.7
Number of Category 3 treated legs	1	4	1.8
Number of Category 3 major road treated legs	0	2	1.6
Number of Category 3 minor road treated legs	0	2	0.2
Major road speed limit	20	55	43.3
Number of signal phases after	3	8	4.9
Major road AADT before	5,500	52,000	19,800
Major road AADT after	5,300	51,000	19,500
Minor road AADT before	400	26,500	6,000
Minor road AADT after	300	24,000	5,900
Total crashes in the year before	0.0	24.3	6.6
Total crashes in the year after	0.3	24.7	6.0
Total injury crashes in the year before	0.0	9.3	2.3
Total injury crashes in the year after	0.0	10.3	1.9
Target crashes in the year before	0.0	7.7	1.4
Target crashes in the year after	0.0	8.3	1.1
Target injury crashes in the year before	0.0	4.3	0.7
Target injury crashes in the year after	0.0	4.0	0.5
51 Sites with Multiple Category Types Including at Least 1 Category 3 leg (61 treated legs)			
Years before	3.0	3.0	3.0
Years after	2.2	3.0	2.9
Number of legs	4	4	4.0
Number of Category 3 treated legs	1	3	1.2
Number of Category 3 major road treated legs	0	2	1.0
Number of Category 3 minor road treated legs	0	1	0.2
Major road speed limit	20	55	42.1
Number of signal phases after	3	8	4.2
Major road AADT before	4,100	38,000	17,400
Major road AADT after	3,500	39,000	17,700
Minor road AADT before	500	17,000	5,400
Minor road AADT after	500	14,500	5,300
Target crashes in the year before	0.0	5.7	0.8
Target crashes in the year after	0.0	5.3	0.8
Target injury crashes in the year before	0.0	3.0	0.4
Target injury crashes in the year after	0.0	3.0	0.4

NOTE: Five-section PPLT to FYA-PPLT.

TABLE 8 Evaluation Results for Category 3

Crash Type	π	λ	CMF[a]	CRF (%)
105 Sites (193 treated legs)				
Total	1,964.9 ± 43.6	1,836 ± 42.8	**0.934** ± 0.030	6.6 ± 3.0
Total injury	683.4 ± 25.6	584 ± 24.2	**0.853** ± 0.048	14.7 ± 4.8
Target	417.2 ± 20.1	325 ± 18.0	**0.777** ± 0.057	22.3 ± 5.7
Target injury	220.9 ± 14.6	150 ± 12.2	**0.676** ± 0.071	32.4 ± 7.1
156 Sites (254 treated legs)				
Target	528.8 ± 22.6	444 ± 21.1	**0.838** ± 0.053	16.2 ± 5.3
Target injury	282.9 ± 16.5	212 ± 14.6	**0.747** ± 0.067	25.3 ± 6.7

NOTE: Five-section PPLT to FYA-PPLT.
[a]Boldface = statistically different from 1.0 at the 5% level.

TABLE 9 Summary Statistics for Category 4

Variable	Minimum	Maximum	Average
Nine Sites Exclusive to Category 4 (14 treated legs)			
Years before	3.0	3.0	3.0
Years after	2.0	3.0	2.7
Number of legs	3	4	3.9
Number of Category 4 treated legs	1	2	1.6
Number of Category 4 major road treated legs	1	2	1.6
Number of Category 4 minor road treated legs	0	0	0.0
Major road speed limit	35	55	48.3
Number of signal phases after	2	4	2.7
Major road AADT before	7,300	25,000	13,800
Major road AADT after	7,100	25,000	15,000
Minor road AADT before	900	13,300	5,300
Minor road AADT after	900	12,000	5,200
Total crashes in the year before	0.7	15.3	4.6
Total crashes in the year after	0.0	16.7	5.0
Total injury crashes in the year before	0.0	6.7	2.0
Total injury crashes in the year after	0.0	6.7	1.7
Target crashes in the year before	0.0	1.7	0.6
Target crashes in the year after	0.0	1.0	0.3
Target injury crashes in the year before	0.0	1.3	0.4
Target injury crashes in the year after	0.0	0.5	0.2
48 Sites with Multiple Category Types Including at Least 1 Category 4 leg (50 treated legs)			
Years before	3.0	3.0	3.0
Years after	2.2	3.0	2.8
Number of legs	4	4	4.0
Number of Category 4 treated legs	1	2	1.0
Number of Category 4 major road treated legs	0	1	0.9
Number of Category 4 minor road treated legs	0	2	0.2
Major road speed limit	20	55	41.9
Number of signal phases after	3	6	3.6
Major road AADT before	4,100	38,000	16,900
Major road AADT after	3,500	39,000	17,400
Minor road AADT before	500	13,000	5,000
Minor road AADT after	500	14,500	5,100
Target crashes in the year before	0.00	0.67	0.13
Target crashes in the year after	0.00	0.89	0.08
Target injury crashes in the year before	0.00	0.67	0.08
Target injury crashes in the year after	0.00	0.36	0.03

NOTE: Permissive only to FYA-permissive only.

TABLE 10 Evaluation Results for Category 4

Crash Type	π	λ	CMF[a]	CRF (%)
Nine Sites (14 treated legs)				
Total	140.1 ± 12.8	126 ± 11.2	0.892 ± 0.113	10.8 ± 11.3
Total injury	59.7 ± 8.4	42 ± 6.5	**0.689** ± 0.141	31.1 ± 14.1
Target	15.9 ± 4.3	7 ± 2.6	**0.410** ± 0.177	59.0 ± 17.7
Target injury	11.9 ± 3.7	4 ± 2.0	**0.306** ± 0.164	69.4 ± 16.4
57 Sites (64 treated legs)				
Target	33.1 ± 5.8	17 ± 4.1	**0.498** ± 0.145	50.2 ± 14.5
Target injury	21.9 ± 4.8	8 ± 2.8	**0.349** ± 0.139	65.1 ± 13.9

NOTE: Permissive only to FYA-permissive only.
[a]Boldface = statistically different from 1.0 at the 5% level.

crashes. For the 64 treated legs that received a Category 4 FYA, the results yielded a 50% reduction in target crashes. All results except total crashes were statistically significant at the 5% level.

CONCLUSION

The ample number of FYA sites that have been employed in North Carolina made it possible to analyze a large amount of crash data. All CMF results were statistically significant for Category 3 (Five-Section PPLT to FYA-PPLT) and target and injury CMF results were statistically significant for Category 4 (permissive only to FYA-permissive only). To find meaningful results from these two groups was a main objective of the study. On the basis of the results from the Category 3 and 4 sites, a statistically significant decrease was found in target left-turn crashes and injury crashes after the shift in use was made from a solid green ball to an FYA for permissive left turns when phasing remained unchanged. This finding applied whether the left phasing was protected–permissive or fully permissive. The Category 4 target crash results were larger than expected and might have been related to the addition of a signal head installed for the permissive left turn.

Many of the Category 1 (permissive only to FYA-PPLT), Category 2 (protected only to FYA-PPLT), and Category 2A (protected only to FYA-PPLT with TOD) results, which involved a change in left-turn phasing as well as the FYA, were not as robust, which suggested variability in performance and a need for more samples in these groups. Target crash frequency was so small at most sites (and composed such a small percentage of total crashes) that a large number of treated approaches would be necessary to determine more reliable target CMFs. It may be difficult to add many more sites to Category 2. Given the higher levels of scrutiny involved, this study rarely chose to change the left-turn mode from fully protected to protected–permissive.

In future, the safety effects of TOD operation will be investigated as more sites come online. The safety of sites that underwent a change from fully protected to FYA-PPLT only during off-peak hours (Category 2A) might not have been as degraded as sites that went from fully protected to FYA-PPLT 24-7 (Category 2). Also, there may be real benefits in the use of TOD at locations where target crashes occur at specific times of day. The left-turn signal might operate in fully protected mode only during the hours identified as peak crash frequency.

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