TECHBRIEF

Safety Evaluation of Flashing Yellow Arrows at Signalized Intersections

FHWA Publication No.: FHWA-HRT-19-035

FHWA Contact: Roya Amjadi, HRDS-20, ORCID: 0000-0001-7672-8485, (202) 493-3383, roya.amjadi@dot.gov

This document is a technical summary of the Federal Highway Administration report *Safety Evaluation of Flashing Yellow Arrows at Signalized Intersections* (FHWA-HRT-19-036).[1]

OBJECTIVE

The Federal Highway Administration (FHWA) established the Development of Crash Modification Factors (DCMF) Program in 2012 to address highway safety research needs for evaluating new and innovative safety strategies (improvements) by developing reliable quantitative estimates of their effectiveness at reducing crashes. The ultimate goal of the DCMF Program is to save lives by identifying new safety strategies that effectively reduce crashes and promoting those strategies for nationwide implementation by providing measures of their safety effectiveness and benefit–cost (B/C) ratios through research. State transportation departments and other transportation agencies need to have objective measures for safety effectiveness and B/C ratios before investing in broad applications of new strategies for safety improvements. Forty State transportation departments provided technical feedback on safety improvements to the DCMF Program and implemented new safety improvements to facilitate evaluations. These States are members of the Evaluation of Low-Cost Safety Improvements Pooled Fund Study, which functions under the DCMF Program.

This study investigated the safety effectiveness of the flashing yellow arrow (FYA) treatment at signalized intersections. One objective of this strategy was to reduce the frequency of left-turn (LT) crashes, especially those that involve a collision between left turns and vehicles traveling straight through from the opposite direction (also called left-turn opposite through (LTOT) crashes). Many studies have explored the safety effectiveness of FYAs. However, most of them only used data from one State, and the studies that used data from multiple States had limited samples of intersections.[1] It is clear that an evaluation with a large sample of sites from multiple States would provide useful information to practitioners on the effectiveness of this treatment under different circumstances.

INTRODUCTION

An FYA for permissive left-turn movements at signalized intersections helps drivers who are turning left on a permissive circular green signal avoid confusion. The concern is that drivers turning left on a permissive circular green signal might mistake that signal as implying that the left turn has the right-of-way over opposing traffic, especially under some geometric conditions.

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

https://highways.dot.gov/research

FHWA maintains a Web page devoted to providing information on FYAs.[(2)] This information includes a citation from the National Cooperative Highway Research Program (NCHRP) Report 493, *Evaluation of Traffic Signal Displays for Protected/Permissive Left-Turn Control*, that indicates that FYAs are the best alternative to a circular green signal for a permissive signal for a left-turn movement.[(3)] The authors of the NCHRP report performed a variety of investigations, including engineering analyses, static and video-based driver comprehension studies, field implementation, video conflict studies, and crash analyses. Their research resulted in the following key findings:[(3)]

- The FYA is the best overall alternative to the circular green signal as the permissive signal display for a left-turn movement.
- Left-turn drivers had a high level of understanding and correct response to FYAs.
- An FYA display in a separate signal face for the left-turn movement offers more versatility in field application. It is capable of operating in any of the various modes of left-turn time-of-day (TOD) operations and is easy to program to avoid the "yellow trap" associated with some permissive turns at the end of the circular green signal.

Previous studies have generally shown that the FYA treatment is associated with a reduction in LT crashes as long as the before-period phasing is not a protected left turn.[(4–9)] The magnitude of the effect of FYA on crashes varies for many reasons: (1) the methodology used for the evaluation, (2) the definition of target crashes, (3) the phasing in the before period, and (4) the States used in the evaluation. Typically, signal phasing before FYA was either permissive or protected-permissive left turn (PPLT). The previous studies showed that results of the FYA after replacing permissive or PPLT phasing ranged from a 50-percent reduction in LT target crashes to a less than 20-percent reduction. On the other hand, the increase in LT crashes after replacing PPLT phasing ranged from about 120 percent to more than 300 percent.

DATA AND METHODOLOGY

This research examined the safety impacts of FYAs using data from sites in Oklahoma, Oregon, Nevada, and North Carolina.[1] The primary target crash types were LT and LTOT crashes. However, changes in signal phasing are sometimes accompanied by changes in signal timing, altering the green time available for through movements. This alteration could affect the propensity for rear-end (RE) and angle (ANG) crashes. Because of this, the evaluation included the following intersection crash types:

- Total crashes.
- Injury and fatal (KABC) crashes.
- RE crashes.
- ANG crashes.
- LT crashes.
- LTOT crashes.

The evaluation included 307 treated sites and 438 untreated reference sites from the 4 States. Based on the before–after left-turn phasing schemes and the number of legs at the intersection, the sites were divided into seven treatment groups (table 1).

The evaluation used an empirical Bayes (EB) methodology for observational before–after studies.[(10)] To conduct the EB before–after analysis, the project team estimated safety performance functions (SPFs) for the six crash types through generalized linear modeling assuming a negative binomial error

Table 1. Treatment categories.

Category	Phasing Before FYA	Phasing After FYA	Number of Legs	Number of Sites
1	Traditional PPLT	FYA PPLT on one road	3	40
2	Traditional PPLT	FYA PPLT on one road	4	136
3	Traditional PPLT	FYA PPLT on both roads	4	64
4	Permissive or traditional PPLT	FYA permissive on one road	4	25
5	Permissive	FYA permissive on one road	4	12
6	At least one protected phase	FYA PPLT without TOD operations	4	18
7	At least one protected phase	FYA PPLT with TOD operations	4	12

[1]All data were unpublished and obtained directly from the respective agency staff.

distribution. This method is consistent with the research in developing these models. The full report contains a detailed explanation of the methodology and the development of SPFs, including a description of how the safety effects for the different crash types were estimated.[1]

RESULTS

The results of the analysis are presented according to the category of the treatment implementation. For each category, the effect of the FYA was calculated as a crash modification factor (CMF), which is a multiplicative factor that shows the increase or decrease associated with the treatment effect.

Results by Treatment Category

Table 2 through table 8 provide the treatment category, the number of intersection legs, the number of sites (intersections), the crash type, the observed number of crashes in the after period, the estimate of the expected number of crashes in the after period without treatment, and the estimated CMF and its standard error (SE) for all crash types considered.

For categories 2 and 3, the after-period phasing was an FYA PPLT on one or more roads. For these two treatment categories, LT crashes and LTOT crashes decreased between 25 and 50 percent, KABC crashes decreased about 20 percent, and total crashes decreased between 10 and 20 percent. Category 1 is similar to categories 2 and 3 in that it also had FYA PPLT after-period phasing, but it consisted of three-legged intersections. In this category, the reduction of LT crashes was not statistically significant, but the reduction of total and KABC crashes was statistically significant.

For categories 4 and 5, the after period was an FYA permissive phase. The results for these two categories were quite similar: there were statistically significant reductions in KABC, LT, and LTOT crashes.

Not surprisingly, LT crashes increased in categories 6 and 7 where FYA PPLT replaced protected phasing in at least one of the approaches with or without TOD

Table 2. CMFs for category 1 (40 sites; 3-legged intersections).

Crash Type	Actual After Period Crashes	Expected After Period Crashes	CMF	SE of CMF
Total	363	427.2	0.849*	0.053
KABC	129	162.7	0.791*	0.080
RE	148	169.4	0.871	0.084
ANG	49	63.5	0.768	0.122
LT	80	99.0	0.804	0.106
LTOT	60	70.4	0.846	0.131

*CMFs statistically different from 1.0 at the 95-percent confidence level.
Note: LTOT crash counts were not available in Nevada. For LTOT crashes, 37 sites were used.

Table 3. CMFs for category 2 (136 sites; 4-legged intersections).

Crash Type	Actual After Period Crashes	Expected After Period Crashes	CMF	SE of CMF
Total	1,951	2,194.8	0.889*	0.027
KABC	722	900.3	0.801*	0.038
RE	753	851.4	0.884*	0.042
ANG	486	505.4	0.960	0.054
LT	413	552.9	0.746*	0.047
LTOT	200	324.1	0.615*	0.055

*CMFs statistically different from 1.0 at the 95-percent confidence level.
Note: LTOT crash counts were not available in Nevada. For LTOT crashes, 37 sites were used.

Table 4. CMFs for category 3 (64 sites; 4-legged intersections).

Crash Type	Actual After Period Crashes	Expected After Period Crashes	CMF	SE of CMF
Total	750	916.4	0.818*	0.036
KABC	286	365.3	0.782*	0.055
RE	306	338.6	0.902	0.066
ANG	207	233.7	0.885	0.068
LT	185	296.2	0.624*	0.053
LTOT	75	147.6	0.507*	0.064

*CMFs statistically different from 1.0 at the 95-percent confidence level.
Note: LTOT crash counts were not available in Nevada. For LTOT crashes, 37 sites were used.

Table 5. CMFs for category 4 (25 sites; 4-legged intersections).

Crash Type	Actual After Period Crashes	Expected After Period Crashes	CMF	SE of CMF
Total	409	410.0	0.997	0.058
KABC	124	153.1	0.808*	0.082
RE	159	157.9	1.005	0.093
ANG	94	90.9	1.030	0.123
LT	55	75.1	0.729*	0.109
LTOT	39	52.9	0.733*	0.130

*CMFs statistically different from 1.0 at the 95-percent confidence level.

Table 6. CMFs for category 5 (12 sites; 4-legged intersections).

Crash Type	Actual After Period Crashes	Expected After Period Crashes	CMF	SE of CMF
Total	192	209.3	0.915	0.078
KABC	74	93.6	0.787*	0.104
RE	84	68.0	1.227	0.165
ANG	23	30.2	0.753	0.173
LT	42	68.2	0.612*	0.105
LTOT	30	54.3	0.548*	0.111

*CMFs statistically different from 1.0 at the 95-percent confidence level.

operations. Agencies typically make this change to improve capacity (not safety) by allowing more time for through movements, but the implications on safety are important to recognize.

Overall, the results of the aggregate analysis are similar to the results from previous research.[4–9] FYA implementation generally leads to a reduction in LT crashes as long as the change is not from a fully protected left-turn phase.

Crash Modification Functions

The project team estimated crash modification functions (CMFunctions) to investigate the effect of site characteristics on the effectiveness of a particular treatment. They were only able to estimate useful CMFunctions for category 2, the most common category. While the methodology used for estimating CMFunctions is available in the full report, this TechBrief only reports the resulting CMFunction for LTOT crashes.[1]

Table 7. CMFs for category 6 (18 sites; 4-legged intersections).

Crash Type	Actual After Period Crashes	Expected After Period Crashes	CMF	SE of CMF
Total	378	359.1	1.051	0.065
KABC	120	118.3	1.011	0.110
RE	152	164.0	0.925	0.087
ANG	57	55.8	1.014	0.159
LT	82	52.5	1.551*	0.219
LTOT	71	36.8	1.910*	0.299

*CMFs statistically different from 1.0 at the 95-percent confidence level.

Table 8. CMFs for category 7 (12 sites; 4-legged intersections).

Crash Type	Actual After Period Crashes	Expected After Period Crashes	CMF	SE of CMF
Total	518	531.6	0.974	0.050
KABC	178	163.1	1.089	0.095
RE	227	250.9	0.903	0.068
ANG	96	81.8	1.169	0.141
LT	44	34.4	1.267	0.226
LTOT	30	25.7	1.151	0.242

Obtaining the CMFunction for LTOT crashes for treatment category 2 is shown in figure 1.

Figure 1. Equation. CMFunction for LTOT crashes.

$$CMF = 0.694 \times (Exp\ bef\ per\ year)^{-0.2626}$$

Where *Exp bef per year* is the EB expected LTOT crashes per year at the intersection level in the before period.

ECONOMIC ANALYSIS

The project team undertook an economic analysis for treatment categories 1 through 5. Treatment categories 6 and 7 represent a phasing change (from protected to FYA PPLT) that was not implemented for safety reasons. As a result, they were not included in the economic analysis.

For the benefit calculations, the project team used the CMF results to calculate the decrease in crashes and monetized this benefit according to national estimates of crash costs. Using FHWA mean comprehensive crash costs from 2001, the team disaggregated these costs by crash severity and used location type as a base.[11] The unit costs for KABC crashes and property-damage-only (PDO) crashes in urban areas were (in 2001 U.S. dollars (USD)) $91,917 and $7,068, respectively. These costs were updated to 2015 USD by applying the ratio of the U.S. Department of Transportation's 2015 value of a statistical life of $9.4 million to the 2001 value of $3.8 million.[12] Applying this ratio of 2.47 to the unit costs resulted in an aggregate 2015 unit cost of $227,744 for KABC crashes and $17,513 for PDO crashes. A sensitivity analysis was conducted based on these unit costs, which led to a minimum and maximum for the benefit values and for the B/C ratio.

For treatment costs, the project team used a recent study in Illinois that assumed the installation cost to be $6,000 per approach leg.[9] This information was used to estimate the annual cost assuming a discount rate of 0.07 (i.e., 7 percent) and an expected service life of 10 yr. Further details about the economic analysis are available in the full report.[1] Table 9 provides the results from the economic analysis.

SUMMARY AND CONCLUSIONS

The objective of this study was to undertake a rigorous before–after evaluation of the safety effectiveness of

FYAs at signalized intersections. The study used data from four States—Nevada, North Carolina, Oklahoma, and Oregon—to examine the effects for specific crash types, including total, KABC, RE, ANG, LT, and LTOT crashes. The evaluation included 307 treated sites and 438 reference sites.

Treatment Categories

Based on the before–after left-turn phasing schemes and the number of legs at the intersection, the sites were divided into seven treatment groups, as shown in table 1.

CMFs

Table 10 shows the statistically significant CMFs (at the 95-percent confidence level) for the treatment categories for six crash types (there were no statistically significant results for category 7). The first five categories involved permissive or PPLT phasing in the before period. Intersections in these five treatment categories experienced a reduction in the primary target crashes under consideration: LT and LTOT crashes at the intersection level. The reduction ranged from 15 to 50 percent depending on the treatment category.

Table 9. Results of economic analysis.

Treatment Category	KABC Crash Reduction*	PDO Crash Reduction*	Economic Benefits from Crash Reduction*	Annualized Treatment Cost*	B/C Ratio Mean	B/C Ratio Min	B/C Ratio Max
1	0.30	0.27	$ 72,010	$854	84:1	46:1	116:1
2	0.50	0.18	$ 117,626	$1,709	69:1	38:1	95:1
3	0.78	0.85	$ 191,990	$3,417	56:1	31:1	78:1
4	1.16	−1.12	$ 245,410	$1,709	144:1	79:1	198:1
5	0.68	−0.08	$ 152,535	$1,709	89:1	49:1	123:1

*Per intersection per year.
Min = minimum; Max = maximum.

Table 10. Recommended CMFs.

Crash Type	Category 1	Category 2	Category 3	Category 4	Category 5	Category 6
Total	0.849	0.889	0.818	—	—	—
KABC	0.791	0.801	0.782	0.808	0.787	—
RE	—	0.884	—	—	—	—
ANG	—	—	—	—	—	—
LT	—	0.746	0.624	0.729	0.612	1.551
LTOT	—	0.615	0.507	0.733	0.548	1.910

—No data.

Table 11. B/C ratios.

Treatment Category	B/C Ratio Mean	B/C Ratio Min	B/C Ratio Max
1	84:1	46:1	116:1
2	69:1	38:1	95:1
3	56:1	31:1	78:1
4	144:1	79:1	198:1
5	89:1	49:1	123:1

Min = minimum; Max = maximum.

Intersections in categories 6 and 7 had at least one protected left-turn phase in the before period. Consistent with results from previous studies, these intersections experienced an increase in LT and LTOT crashes.[4–9] Agencies typically use categories 6 and 7 for capacity improvements rather than safety, but the implications for safety are important.

The project team estimated CMFunctions using data from treatment category 2; this calculation showed that the CMF was a function of expected crashes in the before period. The project team conducted an economic analysis on the effect of FYAs. Table 11 shows the B/C ratios for treatment categories 1 through 5. The mean B/C ratios ranged from 56:1 to 144:1.

According to the results of this study, crashes decrease when FYA signal phasing replaces a permissive or PPLT signal. The FYA treatment has a positive benefit, especially for total crashes, KABC crashes, and crashes related to left-turn movements.

REFERENCES

1. Srinivasan, R., Lan, B., Carter, D., Smith, S., and Signor, K. (2019). *Safety Evaluation of Flashing Yellow Arrows at Signalized Intersections*, Report No. FHWA-HRT-19-036, Federal Highway Administration, Washington, DC.

2. Federal Highway Administration. (2006). "Interim Approval for Optional Use of Flashing Yellow Arrow for Permissive Left Turns (IA-10)." *Manual on Uniform Traffic Control Devices*, Federal Highway Administration, Washington, DC. Available online: http://mutcd.fhwa.dot.gov/resources/interim_approval/ia_10_flashyellarrow.htm, last accessed February 16, 2018.

3. Brehmer, C.R., Kacir, K.C., Noyce, D.A., and Manser, M.P. (2003). *Evaluation of Traffic Signal Displays for Protected/Permissive Left-Turn Control*, NCHRP Report 493, National Cooperative Highway Research Program, Washington, DC. Available online: https://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_493.pdf, last accessed April 3, 2019.

4. Noyce, D.A., Bergh, C.R., and Chapman J.R. (2007). *Evaluation of the Flashing Yellow Arrow Permissive-Only Left-Turn Indication Field Implementation*, National Cooperative Highway Research Program Project 20-7/Task 222 (Web Only Document 123), National Cooperative Highway Research Program, Washington, DC. Available online: http://www.trb.org/Publications/Blurbs/159759.aspx, last accessed April 3, 2019.

5. Perez, R.A. (2010). *Safety Implications of Conversions to Flashing Yellow Arrow Indications*, Federal Way, WA. Available online: https://www.westernite.org/Sections/washington/newsletters/Safety_Redux_2009_Rick_Perez.pdf, last accessed April 3, 2019.

6. Srinivasan, R., Baek, J., Smith, S., Sundstrom, C., Carter, D., Lyon, C., Persaud, B., et al. (2011). *Evaluation of Safety Strategies at Signalized Intersections, Appendix E: Evaluation of Flashing Yellow Arrow for Permissive Left Turn Movements at Signalized Intersections*, NCHRP Report 705, National Cooperative Highway Research Program, Washington, DC.

7. Pulugurtha, S.S. and Khader, K.S.C. (2014). "Assessing the Effect of Introducing a Permitted Phase Through the Use of Flashing Yellow Arrow Signal for Left-Turning Vehicles." *International Journal of Injury Control and Safety Promotion*, *21*(4), pp. 338–347, Taylor and Francis, Abingdon, UK.

8. Simpson, C.L. and Troy, S.A. (2015). "Safety Effectiveness of Flashing Yellow Arrow: Evaluation of 222 Signalized Intersections in North Carolina." *Transportation Research Record*, *2492*, pp. 46–56, Transportation Research Board, Washington, DC.

9. Schattler, K.L., Anderson, E., and Hanson, T. (2016). *Safety Evaluation of Flashing Yellow Arrows for Protected/Permissive Left-Turn Control*, Report No. FHWA-ICT-16-010, Illinois Center of Transportation, Springfield, IL.

10. Hauer, E. (1997). *Observational Before-After Studies in Road Safety*, Pergamon Press, Oxford, UK.

11. Council, F., Zaloshnja, E., Miller, T., and Persaud, B. (2005). *Crash Cost Estimates by Maximum Police-Reported Injury Severity Within Selected Crash Geometries*, Report No. FHWA-HRT-05-051, Federal Highway Administration, Washington, DC.

12. U.S. Department of Transportation. (2015). *Guidance on Treatment of the Value of a Statistical Life (VSL) in U.S. Department of Transportation Analyses—2015 Adjustment*, Memorandum, U.S. Department of Transportation, Washington, DC. Available online: https://cms.dot.gov/sites/dot.gov/files/docs/VSL2015_0.pdf, last accessed May 10, 2016.

Researchers—Raghavan Srinivasan (ORCID: 0000-0002-3097-5154), Bo Lan (ORCID: 0000-0002-7998-7252), Daniel Carter (ORCID: 0000-0001-6572-6548), Sarah Smith, and Kari Signor were the main researchers of this study. The Contracting Officer's Representative and Task Manager was Roya Amjadi (HRDS-20, ORCID: 0000-0001-7672-8485) of the FHWA Office of Safety Research and Development. This study was performed by VHB under contract DTFH61-13-D-00001.

Distribution—This TechBrief is being distributed according to a standard distribution. Direct distribution is being made to the FHWA divisions and Resource Center.

Availability—This TechBrief may be obtained from the FHWA Product Distribution Center by email to report.center@dot.gov, fax to (814) 239-2156, phone to (814) 239-1160, or online at https://highways.dot.gov/research.

Key Words—Flashing yellow arrow, phasing, low-cost safety improvements, safety evaluations, empirical Bayesian, left turn, left-turn opposite direction, crash modification factor, crash modification function, intersection.

JUNE 2020

FHWA-HRT-19-035
HRDS-20/06-20(300)E