Research Need Literature Review

**Topic:** NS #583 – Driver Comprehension of Flashing Yellow Arrows  
**Date:** 5 July 2019  
**Prepared for:** Brent Rusco, Victor Lund  
**Prepared by:** Race MoChridhe  
**Resources searched:** TRID, RiP, Internet, Library Catalog

**Summary:** Within the last five years alone, a wealth of research on flashing yellow arrow comprehension and safety impacts has been produced nationally. Included in the studies below are multiple projects that specifically examined the role of ancillary signage, light arrangements, and transition timings. What is more, most of this research has been published within the last eighteen months. Until modified practices based on this most recent round of work on the topic have accumulated more time in service to provide useful data, it is difficult to foresee openings for distinctive contributions to the literature in this area.

**Results**  
(in order of relevance)

<table>
<thead>
<tr>
<th>Title</th>
<th>Safety effects of protected and protected/permissive left-turn phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td>University of Utah, UDOT</td>
</tr>
<tr>
<td>Abstract</td>
<td>This study evaluated the approach-level safety performance of left-turn phases including permissive, protected-permissive (PPLT), and protected indications, and the more recent flashing yellow arrow (FYA). Extensive data collection efforts included identification of suitable locations changing from a traditional to a FYA phase, exact date of such change, long-term high-resolution datasets of left-turn and opposing volumes, and manual verification of crashes to correct travel directions and crash assignments to specific approaches. Analysis in terms of yearly crash rates using Safety Performance Functions (SPFs) and the empirical Bayes before-after method showed overall similar performance of the FYA indication compared to a permissive phase (the exact magnitude of this CMF was found dependent on the range of values in the sample) and higher crash rates with the FYA indication compared to a PPLT phase (0.28 crashes per approach per year for the average approach in terms of conflicting volumes, and a CMF of 1.33 ± 0.12). As expected, crashes for protected phases did not show valid systematic trends since crash events are not a result of permissive movements but rather due to traffic violations and unexpected events. A time-of-day analysis of crashes revealed higher-than-expected concentration of crashes in the hours preceding afternoon peaks (2pm-4pm), pointing at opportunities to reduce crashes during these periods perhaps by extending operational strategies from</td>
</tr>
</tbody>
</table>
peak hours into the off-peak hours whenever possible. Furthermore, a new metric to estimate risk of left-turn crashes using high-resolution data (5-minute counts) is introduced to monitor in real time the intra-day risk fluctuations and help fine-tune signal timing and phasing.

Date 2018

Title Safety and operations guidance for using time-of-day protected-permissive left-turn phasing using flashing yellow arrows

Source Virginia Transportation Research Council, VDOT, FHA


Abstract Selection of the left-turn phasing mode is a significant decision for the safe and efficient movement of left-turning traffic at signalized intersections. Because of different safety and operational effects associated with the signal left-turn mode, the two must be evaluated concurrently and be balanced based on capacity and crash potential when protected-only, permissive-only, and protected-permissive left-turn (PPLT) phasing modes are compared. The choice between left-turn phasing modes can be made on a time-of-day basis so that changing traffic conditions are accommodated appropriately. The purpose of this study was to define guidance that field traffic engineers can use to select the appropriate left-turn mode based on prevailing traffic conditions by time of day. In particular, guidance on the use of PPLT or permissive-only with flashing yellow arrows (FYAs) to indicate permissive movements was of interest to the Virginia Department of Transportation (VDOT). Prior to the development of time-of-day guidance, the overall safety effects of converting between left-turn phase modes and indications (or displays) needed to be explored. The study examined the impact of converting from a circular “green ball” display for the permissive portion of PPLT phasing to the FYA signal indication and converting from protected-only phasing to PPLT with FYA. To quantify these conversions, a before-after evaluation of signal conversions was performed using standard Bayesian methods to develop crash modification factors from field data for 28 intersections in Virginia. For these intersections, the expected crash reduction after conversion from PPLT to PPLT-FYA was estimated as 12 percent (total crashes), 14 percent (fatal and injury crashes), and 30 percent (angle crashes), which was consistent with results from previous studies. In evaluating different left-turn phasing modes on a time-of-day basis, crash risk, left-turn conflicts, and capacity prediction models for permissive-only and PPLT modes were developed using simulation data. A total of 750 unique scenarios based on different combinations of intersection characteristics, traffic signal parameters, and traffic volumes were simulated in VISSIM, and trajectory files were processed using Surrogate Safety Assessment Model software to determine the number of conflicts per scenario. Based on the outputs of the simulation models, prediction models for determining left-turn capacities and the expected number of left-turn conflicts per hour per 100 left-turning vehicles were created using multiple linear regression. A final model predicting the average crash risk per hour based on the predicted number of conflicts was developed. The three models created were incorporated into a single spreadsheet tool that can be used by VDOT engineers in determining phasing mode on a time-of-day basis.

Date 2018
Title Improving the safety of left-turn operations at signalized intersections for high-risk

Source National Institute for Advanced Transportation Technology, Pacific Northwest Transportation Consortium, DOT

URL http://hdl.handle.net/1773/43489

Abstract A total of 1,062 left-turn related crashes at signalized intersections in Idaho (2006-2015) were analyzed to document the underlying factors that affect left-turn crashes and to identify crash types that prevail among different driver groups. Comparative analysis was conducted to compare the characteristics of intersections at which frequent crashes occurred and those at which few crashes occurred to identify intersection design and control elements that might have contributed to left-turn crashes. The research results showed that no significant difference in left-turn crashes between intersections that used a flashing yellow arrow and intersections that used a doghouse left-turn signal display. The study results suggested that there is a need for more emphasis on left-turn permissive operations at signalized intersections in teen driver education programs, as teen drivers represent the most vulnerable group. Protected-only left-turn operations at signalized intersections on routes and in neighborhoods with greater numbers of mature drivers can eliminate significant portion of mature drivers’ left-turn related crashes. Protected-only left-turn operations at signalized intersections during inclement weather conditions can eliminate a significant portion of the 8 percent of the crashes that occur during inclement weather.

Date 2018

Title A field and simulator evaluation of all-red clearance intervals for use in left-turn applications

Source University of Iowa, University of Massachusetts Amherst, University of Wisconsin Madison

URL http://safersim.nads-sc.uiowa.edu/final_reports/UWI%201%20Y3%20report.pdf

Abstract As the implementation of the novel flashing yellow arrow (FYA) traffic control device advances throughout the country, agencies continually seek ways to improve intersection operations and safety, especially on left turns. For example, permissive left-turn intervals have been communicated to drivers using several traffic signal indications; however, most frequently these phases are represented using the circular green ball and, more recently, the FYA. Previous research in this area found that the FYA indication produced the most effective communication of permissive left-turns. As a result of the research findings, the FYA was included in the 2009 edition of the Manual on Uniform Traffic Control Devices. In recent years, agencies across the country have embraced the implementation of the FYA for permissive left-turns. However, a lack of national guidance remains on how to define the change and clearance intervals for transitioning between protected and permissive left turns. Complicating the matter is the connection between traditional signal phasing/design and human
factors. Research on driver comprehension and real-world operations of the transition between protected and permissive left turns will allow evaluation not only of current conditions, but also of experimental and future conditions. This report presents findings from a static survey that studied the expectation of drivers after a signal indication is presented. This report also presents the results of a novel exploratory approach that allows the use of vehicle trajectory data to gain an insight into driver behavior during the transition between a protected left-turn movement and a permissive one. Research findings will provide a foundation for narrowing the scope and identifying elements that should be considered during a driving simulator evaluation.

Date 2018

Title Safety and operations assessment of various left-turn phasing strategies
Source Washington State University Pullman, WDOT, Pacific Northwest Transportation Consortium, DOT
URL http://hdl.handle.net/1773/43581
Abstract This research evaluated the safety and operational impacts of different left turn movement treatments at signalized intersections. The project (1) compared the safety and operational impacts of protected-only left-turn (POLT) phasing with those of protected-permissive left-turn (PPLT) phasing with a flashing yellow arrow (FYA) indication, (2) compared the safety and operational impacts of doghouse displays with those of four-section vertical displays for PPLT with an FYA, and (3) identified whether time-of-day (TOD) variable left-turn control mode with an FYA produces confusion among left-turning drivers. The literature showed that converting a POLT to a PPLT control mode is associated with an increase in crash rates while reducing intersection delay. Previous research has recommended selecting the control mode on the basis of traffic volumes, speed limit, sight distance, number of lanes, and crash history. Previous research has shown that doghouse displays are associated with larger crash modification factors, more confusion among drivers, and higher delays than a four-section vertical display with an FYA. The results of our driver comprehension survey showed that half of the drivers who had encountered intersections with a left-turn control mode variable by TOD felt confused by that phasing strategy. On the other hand, the simulation-based analysis showed that changing the left-turn control mode by TOD yields more efficient traffic operations and lower average delays.

Date 2018

Title Crash modification factors for the flashing yellow arrow treatment at signalized intersections
Source Transportation Research Record 2672(30): 142-52
URL http://dx.doi.org/10.1177/0361198118788192
Abstract This paper presents the results of an evaluation of the flashing yellow arrow (FYA) treatment using data from signalized intersections in Nevada, North Carolina, Oklahoma, and Oregon. The evaluation method was an empirical Bayes before–
after analysis. The treatments were divided into seven categories depending on the phasing system in the before period (permissive, protected–permissive, or protected), phasing system in the after period (FYA permissive or FYA protected–permissive), the number of roads where the FYA was implemented (one road or both roads), and the number of legs at the intersections (three or four). The first five treatment categories involved permissive or protected–permissive phasing in the before period. Intersections in these five treatment categories experienced a reduction in the primary target crashes under consideration: left turn crashes and left turn with opposing through crashes. The reduction ranged from 15% to 50%, depending on the treatment category. Intersections that had at least one protected left turn phase in the before period and had FYA protected–permissive left turn phase in the after period experienced an increase in left turn crashes and left turn with opposing through crashes, indicating that replacing a fully protected left turn with FYA will likely cause an increase in left turn crashes.

Date 2018

Title Safety effects of flashing yellow arrows used in protected permitted phasing: comparison of full bayes and empirical bayes results
Source Transportation Research Record 2672(21): 20-9
URL http://dx.doi.org/10.1177/0361198118794289
Abstract Using the flashing yellow arrow (FYA) signal indication for the permissive portion of protected-permissive left-turn (PPLT) phasing has become an increasingly popular treatment for left-turn signals as drivers are believed to understand the FYA better than the traditional circular green indication. A before-and-after safety evaluation of deploying FYA at PPLT signals at 28 intersections in Virginia was conducted. Each of the study intersections had FYA for the permitted portion of the phase on at least one left-turn approach. The focus was on left-turns that operated in the protected-permissive mode (with circular green indication for the permissive portion) before being converted to PPLT operations with the FYA indication for the permissive portion (PPLT-FYA). Crash records from before and after the activation of FYA were compared using both the full Bayes and empirical Bayes approaches. The results indicate that using the FYA signal indication instead of the circular green indication had a statistically significant effect in reducing overall frequency and severity of crashes. For the intersections studied in this research, total crashes reduced by 12% following conversion from PPLT to PPLT–FYA. The results also indicated that the full Bayes approach to safety effectiveness evaluation can, at a minimum, provide similar results to the well-established empirical Bayes approach. The 95% credible intervals for the expected crash reduction rates estimated with the full Bayes method were generally narrow, suggesting a good degree of confidence in the estimates.

Date 2018

Title Approach-level safety comparison of permissive-protected and protected left turn phasing to flashing yellow arrows
Source Transportation Research Board 97th Annual Meeting
Abstract Since the introduction of flashing yellow arrow (FYA) indications in the MUTCD, transportation agencies have increasingly adopted this alternative to improve left-turn operations. However, it has not been until recently that agencies have accumulated enough data (both temporally and spatially) to conduct safety evaluations of FYA implementations for specific types of “before” left-turn phasing. Most past studies have focused on intersection-level crash analyses given the difficulties to obtain reliable crash data at the level of a single approach where the direction of travel, particularly for left turn movements, should be individually verified. This study aims at bridging research gaps by estimating the change in target (left-turn related) crash frequencies, specifically for approaches converted from a permissive-protected or a protected only left turn operation to a permissive-protected FYA indication. Safety performance functions for permissive-protected, protected only, and the FYA approaches are estimated. In addition, crash modification factors for converting permissive-protected to FYA, and for converting protected-only to FYA are presented. Results from this approach-level analysis support some of the findings from previous studies conducted at intersection-level.

Date 2018

Title Safety performance of flashing yellow arrow for protected-permissive left-turn signal control in central Illinois

Source Transportation Research Record (2636): 32-42

URL http://dx.doi.org/10.3141/2636-05

based on original report here: https://apps.ict.illinois.edu/projects/getfile.asp?id=4814

Abstract In 2010, the Illinois Department of Transportation began implementing the flashing yellow arrow (FYA) at intersections operating with protected–permissive left-turn (PPLT) control. Research was conducted to evaluate the safety-effectiveness of FYAs at 86 intersections and 164 approaches in central Illinois. The effectiveness evaluation was performed with 3 years of before-and-after FYA installation crash data and the empirical Bayes method. In the before condition, the left-turn signals operated with a circular green display indicating the permissive interval of PPLT control using a five-section signal head. In the after condition, the FYA replaced the circular green display for the permissive interval of PPLT with a four-section signal head. Supplemental traffic signs were mounted on the mast arm adjacent to the left-turn signal at over half of the FYA installations. The results of the comprehensive safety evaluation of the FYA for PPLT control are presented. Analyses were also performed to assess the effects of the FYA supplemental signs and the effects of the FYA overall on two subsets of at-fault drivers: older drivers (age 65+) and younger drivers (age 16 to 21). The resulting mean crash modification factors for the targeted crash types ranged from 0.589 to 0.714. The findings of this research support the continued use of FYAs for PPLT control to improve safety at signalized intersections in central Illinois.

Date 2017
Title  Improving the safety left-turn operations at signalized intersections for high-risk

Source  Pacific Northwest Transportation Consortium, DOT, University of Idaho Moscow


Abstract  Intersections pose a particular safety problem for many drivers. Navigating through intersections requires the ability to make rapid decisions, react quickly, and accurately judge speed and distance. As these abilities can deteriorate through aging, distraction, or impairments. Several driver groups, such as mature drivers, young drivers, and impaired and distracted drivers face more difficulties at signalized intersections and are more likely to be involved in a fatal crash at these locations. The primary objective of this research is to investigate signalized intersection design and operation alternatives that have the potential of improving the safety of signalized intersection operations for all users. Idaho crash data along with the geometric, control, and operational characteristics of different signalized intersections in Idaho will be used to assess the potential crash reduction benefits of different measures and intersection treatments. This research effort will result in data-driver guidelines to assist Idaho Transportation Department (ITD) in identifying and prioritizing measures to improve the safety at different signalized intersections in Idaho. This research is divided into three main focus areas. The first focus area is left-turn treatment at signalized intersection approaches (permitted, protected, and permitted and protected operations). The analysis will also examine the safety impact of using flashing yellow arrow in permitted left turn operations at intersections in Idaho. The second focus area is advance warning flashing signals at high speed intersections. The third focus area is nighttime flashing operation. Three different driver groups will be considered in this project: mature drivers, young drivers, and impaired and distracted drivers. Current fatality and injury rates at intersections as well as the underlying factors which affect the level of these rates will be examined and discussed. Furthermore, the crash types which prevail among different driver groups will be analyzed and documented. The research tasks also involve a conducting a comparative analysis between intersections at which frequent crashes occur and those at which few crashes occur to identify intersection design and control elements that might have contributed to such reduction in crashes. The objectives of this research project are: (1) describe and document the characteristics of signalized intersection based on Idaho’s crash experience, (2) analyze different factors that may influence crash rates at signalized intersections in Idaho, and (3) identify intersection design and control measures that can be implemented to reduce crash rates at signalized intersections in Idaho. The research will focus on three signalized intersections operational areas: (1) left-turn treatment (2) advance warning flashing signals at high speed intersections, and (3) nighttime flashing operations. Measures to improve the safety for three different high-risk driver groups: mature drivers, young drivers, and impaired drivers will be considered for this study.

Date  2016

Title  Evaluation of flashing yellow arrow traffic signals in Indiana
Source  Purdue University, IDOT, FHA
URL  http://dx.doi.org/10.5703/1288284315530

Abstract  The evaluation of flashing yellow arrow signals for widespread implementation was evaluated. Through the collection of field driver performance data, survey data, crash data, at two test sites in the state, it was concluded that this is a worthwhile practice to be considered for a larger scale deployment. The return on investment includes both increased safety, and improved mobility. Given Indiana’s widespread usage of span and catenary signal supports, installation could be simplified to place a larger four section flashing yellow head in a horizontal orientation while leaving adjacent through lane three section signal heads in a vertical alignment, and not decrease the standard of care provided to the public, given proper engineering judgment.

Date  2015

Title  Safety effects of traffic signing for left turn flashing yellow arrow signals
Source  Accident Analysis and Prevention 75(0): 252-63
URL  http://dx.doi.org/10.1016/j.aap.2014.11.010

Abstract  In 2010, the left turn flashing yellow arrow (FYA) signal displays were installed at signalized intersections on state routes in the Peoria, Illinois, area. Supplemental traffic signs with text “Left Turn Yield on Flashing Yellow Arrow” were mounted on the mast arm adjacent to the left turn signal at over half of the FYA installations. The purpose of this paper is to present the results of the effectiveness evaluation of the FYA supplemental sign on safety. Analyses are presented on the effects of the FYA supplemental sign for all drivers and a subset of drivers age 65 and older. A crash-based comparison of 164 FYA approaches including 90 approaches with the sign and 74 approaches without the sign showed greater crash reductions when the supplemental FYA sign was present. The results also showed that crashes involving drivers age 65 and older did not experience the same magnitudes of crash reductions as compared to all drivers. The findings of this research indicate that supplemental FYA signs may help in improving safety for left-turning vehicles during the permissive interval. Thus, it is recommended that supplemental signs be used when initially implementing the FYA, and that effort to educate the driving public on new traffic control be made to further improve safety at signalized intersections.

Date  2015

Title  Safety effectiveness of flashing yellow arrow: evaluation of 222 signalized intersections in North Carolina
Source  Transportation Research Record (2492): 46-56
URL  http://dx.doi.org/10.3141/2492-05
Abstract  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.

Date 2015

Title  Assessing the effect of introducing a permitted phase through the use of flashing yellow arrow signal for left-turning vehicles


URL  http://dx.doi.org/10.1080/17457300.2013.831906

Abstract  This paper evaluates the direct and indirect effects of introducing a permitted phase, through the use of flashing yellow arrow (FYA) signal for left-turning vehicles, in reducing crashes at intersections. Data for 18 study intersections in the city of Charlotte, NC, USA were used to conduct a before–after comparison study through the use of Empirical Bayes (EB) method and examine the effects. The estimated number of left-turn crashes, had the FYA signal not been installed, was compared to the actual number of left-turn crashes to assess the direct effect, while the estimated total number of crashes, had the FYA signal not been installed, was compared to the actual total number of crashes to assess the indirect effect. Only left-turn crashes along a selected FYA leg were used to examine the direct effect as the number of legs (approaches) with the FYA signal varied between the selected study intersections. The results obtained indicate that the FYA signal helps reduce the left-turn crashes (direct effect). It does not lead to any negative consequences. Instead, the FYA signal has the potential to indirectly lower the total number of crashes (indirect effect) and contribute to improved safety at intersections.

Date 2014
Evaluation of the flashing yellow arrow (FYA) permissive left-turn in shared yellow signal sections

The objective of this research was to analyze driver behavior and comprehension related to the flashing yellow arrow (FYA) permissive left-turn indication when added to three- and five-section traffic signal displays. FYA indications were evaluated bimodally with both the green arrow (GA) and yellow area (YA) indications and compared with the recommended four-section vertical all arrow signal display. Findings from a computer-based static study showed no significant differences in driver comprehension when the FYA indication was presented bimodally in the bottom section or middle section of a three-section vertical signal display. However, driver comprehension was significantly lower when the FYA indication was added bimodally to the five-section cluster signal display with a simultaneous thru movement indication illuminated. Results of a full-scale driving simulator evaluation showed no significant differences in driver performance or vehicle operation between the evaluated traffic signal display combinations. Driver eye tracking data showed that participants spent considerably more time looking at opposing traffic than at the combination of FYA and thru movement indications. Research results support the recommendation that the FYA permissive left-turn indication can be effectively implemented bimodally with the YA indication in a three-section vertical signal display, but not bimodally with the GA or in any five-section cluster signal display.

Three- or four-section displays for permissive left turns? Some evidence from a simulator-based analysis of driver performance

Many jurisdictions are using the flashing yellow arrow (FYA) to control protected and permissive left turns. For cost and other reasons, some jurisdictions have or are considering implementing FYA with a three-section vertical head, displaying the flashing yellow indication in the same signal face as the protected green arrow. The current Manual on Uniform Traffic Control Devices permits the operation of a three-section vertical head only for permissive turns in locations where heights are restricted. This paper summarizes a comparison of driver performance with three- and four-section FYA signal configurations gathered in a high-fidelity, motion-based driving simulator with mobile eye-tracking equipment. The experiment controlled for the effects of the opposing traffic, the presence and walking direction of pedestrians, and the signal head arrangement. A 24-intersection simulated environment was created, and 27 subjects completed the course, producing 620 permissive left-turn maneuvers for further analysis. Driver performance was measured from the (a) average total eye glance durations at specific areas of interest and (b) the position of the pedestrian in the crosswalk.
when the driver initiated the left turn. No statistically significant differences between the average fixation duration when the FYA was presented with a three- or four-section signal head were identified. The pedestrian’s position in the crosswalk when the driver began the left turn was not statistically significantly different for three of the four pedestrian walking directions presented. Overall, measurable driver performance does not seem to be sensitive to the vertical positioning of the FYA display in the permissive interval.

Date 2014

Title Safety and operational impacts of optional flashing yellow arrow delay
Source Transportation Research Record (2463): 26-34
URL http://dx.doi.org/10.3141/2463-04

Abstract Considerable debate exists over whether to delay the start of the flashing yellow arrow (FYA) signal indication (e.g., with a red arrow signal indication) during the transition from a protected movement to a permissive movement in a leading left protected–permissive left turn. The 2009 Manual on Uniform Traffic Control Devices is silent on this topic. This paper reviews the state of the practice on the use of the optional FYA delay through a literature review, a survey of state departments of transportation, and consultations with practitioners and national experts. A simulation study was also used to assess the potential impacts of the optional FYA delay on traffic safety and operations. The state-of-the-practice review indicated some preference for the use of the red arrow signal indication because of the perceived safety benefit. For example, 71% of the responding state departments of transportation that use the FYA also delayed the start of the FYA. The simulation analysis showed significant safety benefits in a delay to the start of the FYA signal indication for all scenarios except the scenario with a low opposing through traffic volume, with no significant negative impacts on average delay, average queue length, or average stopped delay for either left-turning traffic or the intersection as a whole being found.

Date 2014