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Evaluating the Safety Impacts of Flashing Yellow Permissive Left-Turn Indications in Massachusetts: Approach-Level Analysis

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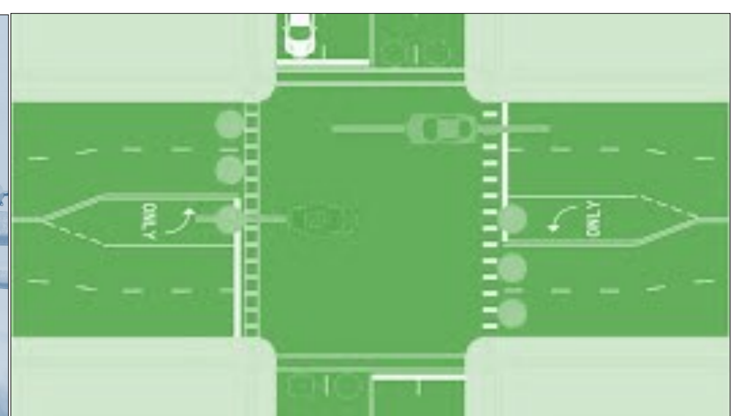

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Project Champion – James Danila – State Traffic Engineer, MassDOT

16. Abstract

Given the novelty of the Flashing Yellow Arrow (FYA) in Massachusetts, this research study provides MassDOT with a greater understanding of their impacts from an approach-level perspective. More so, this study provides the agency with a holistic overview of infrastructure and operational impacts at each of these intersections, ultimately leading to an improved understanding of future design characteristics. Approach-level analyses remain the most appropriate method to assess the true impact of the permissive indication as well as infrastructure (e.g., turn lane length, LT lane offset, etc.) and operational (e.g., clearance intervals, phase sequence, etc.) elements. This study evaluated the before and after crashes at 200 statewide FYA intersections from an approach level to better understand the safety impacts of the LT permissive FYA signal. The advancement of these crash data analytics, methodologies, and applications will continue to remain important in years to come and will increase safety by providing an increased understanding of conflict risk at signalized intersections involving FYAs.

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Evaluating the Safety Impacts of Flashing Yellow Permissive Left-Turn Indications in Massachusetts: Approach-Level Analysis

Final Report

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Disclaimer

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Executive Summary

This study of *Evaluating the Safety Impacts of Flashing Yellow Permissive Left-Turn Indications in Massachusetts; Approach-Level Analysis* was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This Program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

The uniformity of traffic control devices in the United States continues to be a critical issue in providing safety for all road users. The Flashing Yellow Arrow (FYA) has rapidly evolved in recent years for both the left- and right-turn permissive movements, with an increasing presence of the former in Massachusetts. As the FYA permissive left-turn indication becomes more prevalent across the Commonwealth, there has been an increasing need to understand these signals from both an operational and safety perspective. Following an initial research project studying FYA impacts, this extension utilized the previously developed FYA crash database to focus on understanding the intersection infrastructure and their respective impacts on traffic safety. Despite the safety contributions from the previous MassDOT FYA study, there were noticeable difficulties in assigning approach-level crashes to each of the signalized intersection. This study led to the evaluation of before and after crashes at statewide FYA intersections from the approach level to better understand the safety impacts of the LT permissive FYA signal. The advancement of these crash data analytics, methodologies, and applications continue to remain important, and improve safety by providing an increased understanding of conflict risk at signalized intersection.

This research was conducted across four main tasks in an effort to conduct an in-depth evaluation of FYA safety impacts through an approach-level analysis across Massachusetts:

Objectives:

- Develop and disseminate a survey to obtain design specs for each FYA intersection in Massachusetts.
- Stratify Approach-Level before and after crash information using the FYA and CG PPLT location database.
- Analyze the safety impacts with left-turn FYA related infrastructure (post-installation).
- Develop guidance and recommendations for left-turn FYAs based on newly identified approach-level crash data.

In an effort to utilize up-to-data FYA information, a statewide field data collection effort was initiated to inventory both operational and infrastructure information at over 300 PPLT signalized intersections. The attributes collected include: all-red clearance interval presence and timing, the application of supplementary signage at FYA signals, and the presence of conflicting pedestrian intervals. Crash data was extracted from the MassDOT IMPACT tool and cleaned to represent 2 years of before and 2 years of after data at 200 FYA intersections across Massachusetts. Crash reports were received through the RMV to include crash narratives and diagrams, and were pivotal in determining root cause. Crashes were iteratively categorized into the following:

- Approach Level: Crashes that occurred on the FYA/CG approach.
- LT-Related: crashes that occurred at an FYA/CG approach and included vehicles ‘turning left’ at the intersection.
- LTOT-Related: crashes that occurred at an FYA/CG approach, including a vehicle ‘turning left’ and including vehicles traveling straight through from the opposing direction.

The 200 FYA intersections were evaluated across four strategies: naïve before/after analysis including EPDO rating, benefit-to-cost analysis, crash modification factor using comparison groups, and infrastructure and operational safety impacts. The naïve before/after analysis emphasized the target crashes of PPLT phasing while also evaluating *injury severity* and *manner of collision* outcomes. These measures were then reported in EPDO values to assess injury-related crashes at FYA intersections and a sample of 22 CG intersections. A cost-benefit analysis was conducted to estimate the economic impacts of an PPLT FYA signal installation at the two hundred study intersections. The benefits from crash severity reduction were paired against the costs of implementation to produce a benefit-to-cost ratio (BC) of the FYA signal indication. The severe injury crashes were highlighted as fatal and injury (FI) crashes and considered to cost $441,000 per injury crash. Comparatively, the property damage only crashes (PDO) were considered to cost $16,700 per crash.

A before and after with comparison groups analysis was conducted in an effort to develop a statewide CMF for the PPLT FYA. The LT- and LTOT-related crash samples were observed in defining FYA CMFs; however, given the smaller than anticipated sample size, there were limitations in assessing the significance of these CMFs. That being said, the trends presented yield the likelihood of lower CMF values with the addition of sample site target crash data.

Lastly, the up-to-date operational and infrastructure information at all 200 FYA study intersections provided through the FYA inventory survey allowed for an essential analysis regarding their safety impacts. All-red (AR) clearance interval timing, supplementary signage, and conflicting pedestrian intervals were captured and analyzed against the FYA crash data across 2 years. The results provided regarding infrastructure and signal operations with the PPLT FYA signal were crucial in identifying strategies to improve injury severity reduction. That said, these analyses remain preliminary given their small sample size in nature.

Key Findings:

- The naïve before/after analysis yielded significant reductions in crashes for both 3-way and 4-way FYA intersections, primarily focused on the LTOT-related crash data sample.
- The LT- and LTOT-related data yielded a reduction in crashes resulting in injury and PDO, in addition to a reduction in severe crash types (head-on, angle, sideswipe).

- Significant reductions in EPDO for both the LT- and LTOT-related samples of FYA crashes (95% confidence); however, there were significant increases in EPDO for both the LT- and LTOT-related sample of CG crashes (95% confidence).
- The LT- and LTOT-related crash data samples resulted in BC ratios ranging from 18:1 to 2:1 and 21:1 to 3:1, respectively.
- The LTOT-related sample yielded significant CMFs with 95% confidence regarding severe crash type reduction (head-on, angle, sideswipe) as well as injury crash reduction; however, the total crash (including PDO) reduction remained significant at 90% confidence.
- In the infrastructure analysis, the *No All-Red* condition yielded the lowest EPDO rating, following by *Greater than 3 seconds* and *Less than 3 seconds*.
- In evaluating the presence of Supplementary Signage, the *Not Present* condition led to an EPDO rating of 17.7 per approach, while the *Present* condition led to 21.6 per approach.
- In evaluating the presence of conflicting pedestrian intervals, the *Not Present* condition yielded an EPDO rating of 19.5 per approach as compared to the *Present* condition of 24.6.

Recommendations:

- Prioritize the installation of FYAs at all PPLT locations in Massachusetts based on the crash and injury severity reductions.
- Assess the need for reliable statewide volume data to be utilized in future safety analyses.
- Investigate the application of supplementary signage, with the particular need for a larger sample size.
- Evaluate the efficacy of the FYA at permissive-only locations, as well as in right-turn applications to assess consistency with these results.

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List of Acronyms

Acronym	Expansion
AADT	Annual Average Daily Traffic
BC	Benefit-to-Cost
CG	Circular Green
CMF	Crash Modification Factor
EB	Empirical Bayes
EPDO	Equivalent Property Damage Only
FHWA	Federal Highway Administration
FYA	Flashing Yellow Arrow
GIS	Geographic Information System
HSM	Highway Safety Manual
LPI	Leading Pedestrian Interval
LT	Left-Turn
LTOT	Left-Turn-Opposing-Through
MassDOT	Massachusetts Department of Transportation
MUTCD	Manual on Uniform Traffic Control Devices
NCHRP	National Cooperative Highway Research Program
PDO	Property Damage Only
PPLT	Protected-Permissive Left-Turn
RMV	Registry of Motor Vehicles
SGA	Solid Green Arrow
SPF	Safety Performance Functions
SRA	Solid Red Arrow
SYA	Solid Yellow Arrow

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1.0 Introduction

This study of *Evaluating the Safety Impacts of Flashing Yellow Permissive Left-Turn Indications in Massachusetts: Approach-Level Analysis* was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

The uniformity of traffic control devices in the United States continues to be a critical issue in providing safety for all road users. The Flashing Yellow Arrow (FYA) was adopted into the 2009 Edition of the Manual on Traffic Control Devices (MUTCD) after the signal indication was proven to be instrumental in improving left-turn crash rates at intersections (1, 2). In the MUTCD it is stated that, the FYA allows drivers to make a left-turning movement based on several conditions; 1) they yield the right-of-way to vehicles from the opposing side of the intersections; 2) there are no pedestrians lawfully in conflicting crosswalks; and 3) there are no other vehicles in the intersection that would be in conflict with the left-turning vehicle. The FYA was primarily introduced within a 4-section configuration; however, in recent years efforts have been made to evaluate the FYA within a 3-section vertical signal as well. Figure 1 illustrates a 4-section signal example from the MUTCD with the location of the FYA in relation to existing indications prior (solid green arrow (SRA), solid yellow arrow (SYA), solid red arrow (SRA)). As the FYA permissive left-turn indication has become more prevalent across the Commonwealth, there has been an increasing need to understand these signals from both an operational and safety perspective. Following an initial research project studying FYA impacts from an intersection-level, this secondary phase utilizes the previously developed FYA crash database to focus on understanding the intersection infrastructure elements and their respective impacts on driver behavior from an approach-level analysis across Massachusetts.

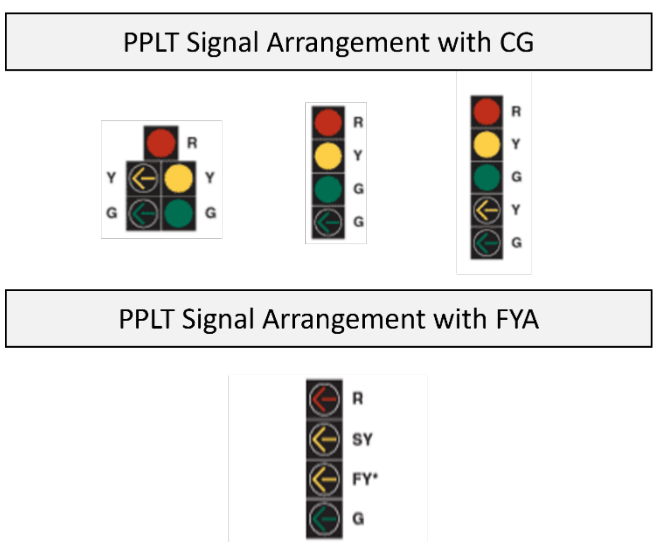

Figure 1: Typical PPLT signal phasing for left turns

An approach-level analysis remains the most accurate method to assess the true impact of the permissive indication as well as infrastructure (e.g., turn lane length, LT lane offset, etc.) and operational (e.g., clearance intervals, phase sequence, etc.) elements. Thus, this study focuses on evaluating the before/after crashes of these FYA intersections from the approach level to better understand the safety impacts of the LT permissive FYA signal. The advancement of these crash data analytics, methodologies, and applications continue to remain important, providing a better assessment of safety impacts and will improve safety through a better understanding of conflict risk at signalized intersections involving this novel traffic control device.

1.1 Background

The following section provides an up-to-date synthesis of the historical research regarding PPLT phasing and the implementation of the FYA for left turns.

1.1.1. Early Integration of the Flashing Yellow Arrow

There has been a myriad of studies conducted throughout the United States to assess the impacts that the FYA has on both crash severity/frequency and driver comprehension. These studies have revealed important statistical information in an effort to defend the installation of FYA indications for intersections with PPLT phasing.

Of the many analytical approaches utilized to evaluate experimental signal indications, driving simulation has continued prevalent in this industry. A clear-cut conclusion from the research in NCHRP 493 state that a driving simulator was valid in determining the effects of the FYA on driver behavior (1). The experiments completed in and around the NCHRP 493 breadth (3,4,5) resulted in a higher correct response rate for the FYA than the CG regarding driver action as they approach the intersection. More so, it was found that the CG was not impacted by a driver's understanding of the new FYA indication. The results from these previous studies within NCHRP 493 also concluded that there was little difference in the driver understanding of the CG and the FYA indications (2), inferring that the drivers may have less difficulty adapting to the new indication. Knodler et al. found that the driving simulator research resulted in little significant difference in driver actions based on the PPLT indication within their balanced simulator scenarios, focusing primarily between the 4-section vertical FYA and the existing CG cluster PPLT indications (5).

The integration of survey-based data collection has also been integrated into several research endeavors regarding the driver comprehension of the FYA signal indication 2, 5, 6, 7, 8). Noyce et al. and Geyer et al. both found that drivers provided higher correct response rates for the FYA than for CG permissive left-turn indications (6, 7). Additionally, Geyer et al. determined that drivers who had already observed the FYA yielded a higher correct response rate than those who had not. More so, the results from Brehmer et al. and Knodler et al. provided evidence to suggest that the CG had the lowest correct response rate out of all tested PPLT indications (2, 5), while Brehmer et al. also indicated that the FYA had a lower response time from drivers than the CG. While these aforementioned studies evaluated the driver comprehension of PPLT indications through driving simulation and survey-based data collection approaches, other recent studies also developed an approach to also identify user-friendliness with PPLT indications. Schattler et al. found that the majority of responses determined the FYA favorable over the CG indication (8). More so, results from this study found that there was a higher comprehension rate for the FYA than CG, as displayed in Figure 2.

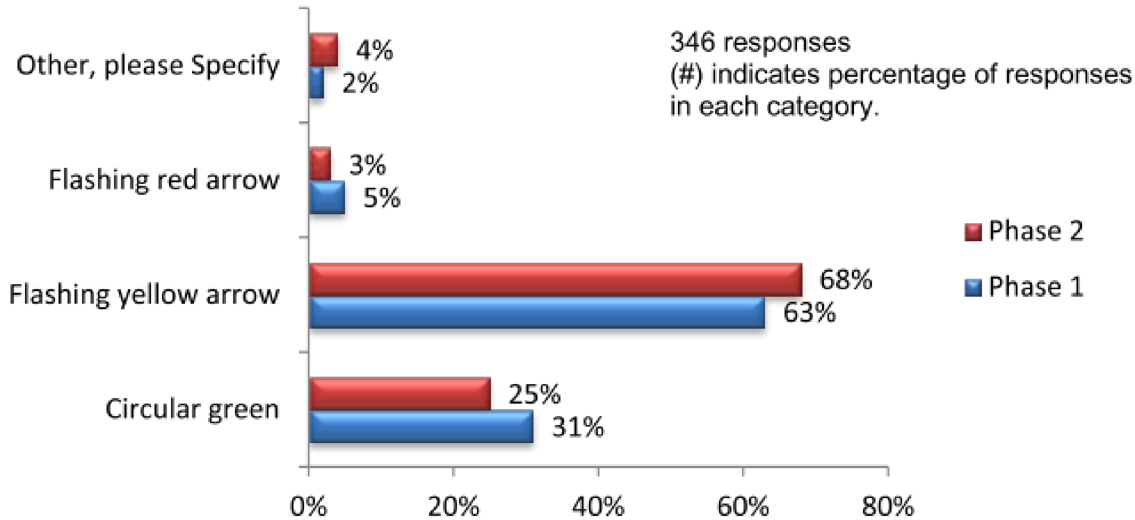

Figure 2: Survey responses to "which PPLT control sends the best message?"

1.1.2. Intersection Safety Analysis

Following the initial behavioral and comprehension studies regarding the FYA, the new PPLT signal indications were implemented in many states around the country. Given a large quantity of years with the treatment in place, many efforts were made to evaluate a before-and-after analysis. From many communities and states around the country, there has been evidence to suggest that the change from the CG PPLT indication to FYA has reduced left-turn crash rates and lowered the total number of crashes (9, 10, 11), reduced crash and severity rates (11, 12), and significantly reduced left-turn-opposing-through (LTOT) crashes (10, 11, 13). While the FYA has primarily resulted in nationwide benefits when translated with PPLT phasing, the change from protected phasing to a PPLT FYA increased total crashes (9, 12, 14, 15), increased left-turn crashes (9, 11, 14), and increased severity rates in crashes (12, 14).

While before and after studies may be conducted through an assortment of methods, many previous research endeavors were conducted under empirical bayes (EB) or full bayes (FB) models. Appiah et al. showed with the EB that the FYA led to a reduction in angle crashes (16), while Pulugurtha et al. explained that the FYA indication improved safety at a majority of intersections by comparing predicted and actual crashes at the studied intersections (17). In utilizing an EB approach, Qi et al. found that at 14 of their 17 studied intersections, the crash rates decreased after the implementation of an FYA PPLT signal (12). With the application of FB, the FYA was found to reduce the number of angle crashes, total crashes, and fatal and injury crashes significantly (16). In 2020, Srinivasan comparted CG

PPLT phasing to FYA phasing between 3 and 4-leg intersections and found that 3-leg intersections did not have a significant decrease in LT crashes, but a significant decrease in LTOT and severe injury crashes (11). More so, that collected data from Nevada, North Carolina, Oklahoma, and Oregon found that there was a significant difference in the reduction of crashes across these intersections from each state (11).

1.1.3. Approach-Level Safety Analysis

In conducting safety analyses from an intersection-level, there have been many methods of utilizing before-and-after crash data. The current study employed an “approach-level” analysis; however, given the historical approach from intersection-level a review of previous literature regarding this terminology and methods were necessary. Yuan et al. defined “approach level” by overlaying the studied intersections with shapes defining the crash as either entering, in, or exiting the intersection (18); however, these crashes were defined through reported XY coordinates. Schattler et al. defined approach level as a subset of the intersection-level crashes, while taking into consideration crash reports and narratives (10). It is important to note that only 328 total crashes were evaluated from this “approach-level” data, while also splitting the analysis between having and not having supplementary signage (10). Figure 3 presents an example of the supplementary signage as presented in the MUTCD (1) utilized at FYA approaches. From other safety analyses, Potts compared approaches based on the type of right-turn channelization that was present (19), while Himes compared the crashes of approaches of differing design geometries (20). And more recently, Asaduzzaman et al. used crashes reports to determine the left-crashes from the total crashes at an intersection-level (14). These methods utilized in Louisiana were taken into consideration in the development of this study.

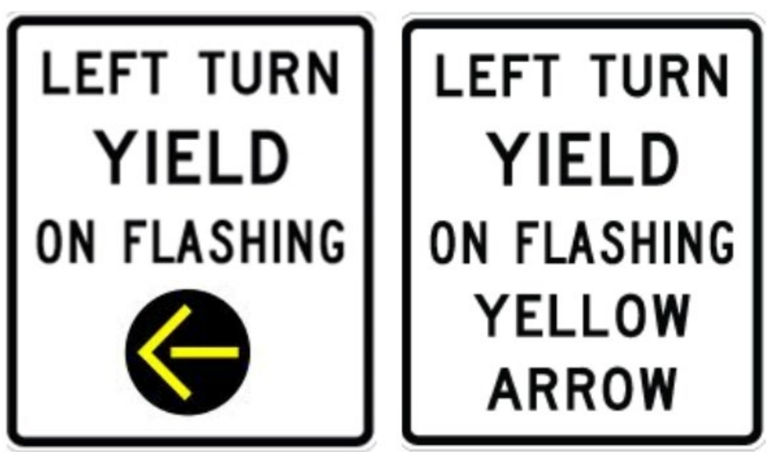

Figure 3: Supplementary signage for FYA signal

1.1.4. Intersection Operations Research

This study integrated the development and employment of a survey to collect intersection infrastructure characteristics, including operation sign phasing information. The decision to include an all-red clearance interval at signalized intersections with PPLT phasing has been highly relevant in the transportation industry in recent years. More so, the application of conflicting/concurrent pedestrian intervals with left-turning vehicles has been controversial. This section presents relevant literature on these topics and provide evidence to suggest a need in collecting and analyzing data on this across Massachusetts FYA intersections.

In 2003 Schattler et al. calculated the clearance interval for three sites and collected before-and-after video data for those sites in an effort to evaluate the benefits of the clearance interval. There were mixed results related to red-light running (RLR), but there was a significant reduction in late exiting vehicles and traffic crash rates were beginning to decrease (21). In 2004, Souleyrette et al. conducted a before-and-after analysis in Minneapolis that included intersections recently equipped with all-red clearance intervals. There was a decline in total crashes in the short term, but the crash rates returned to before levels in the long term (22). Figure 4 presents a citywide representation of the Minneapolis study, specifically noting the intersections with all-red clearance intervals. Additionally, Tainter et al. performed a static and field evaluation of drivers at several intersections equipped with PPLT with and without all-red clearance intervals where the all-red clearance was found to reduce the number of RLRs (23).

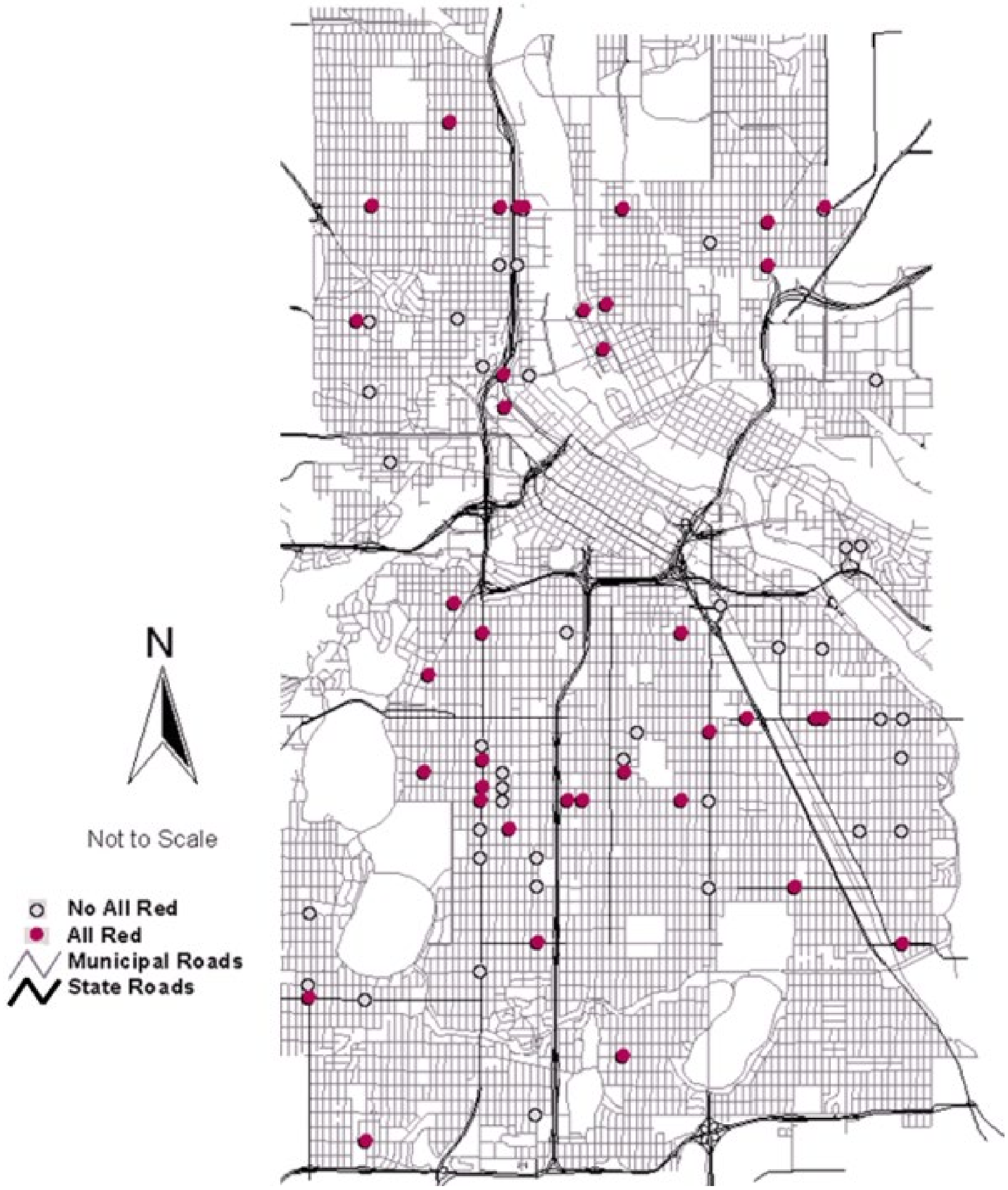

Figure 4: Study intersections that investigated the use of all-red clearance intervals in Minneapolis

Early studies regarding the all-red clearance interval led to a full FHWA report regarding the definition of when and when not to implement. In a 2009 report, FHWA stated that an all-red should be from 1- to 3-seconds due to 94.2% of red-light violations occurring within 2 seconds of the red-light signal (24). In 2012, the NCHRP Report 731 recommended that if a calculated all-red clearance interval is less than 1-second in duration, the minimum 1-second should be used (25). In 2016, an analysis conducted by Savolainen et al. from intersections in the Washington DC area explained that the all-red clearance intervals increased the likelihood of stopping only if the time to the stop bar was less than 3 seconds (26). More recently, a 2017 study by Simpson et al. conducted video data collection at several intersections in North Carolina and found that 99% of RLRs entered the intersection within 5 seconds into the red clearance interval (27). These mixed results from previous all-red clearance literature presents an emphasis on clearance interval impacts and yielded the need for data to be collected and analyzed in this research endeavor. It remains important to note that the current nationwide study, *NCHRP 03-125: Evaluation of Change and Clearance Intervals Prior to the Flashing Yellow Arrow Permissive Left-Turn Indication*, was recently completed with recommendations that should be released publicly in the near future.

As previously mentioned, the current study employed an inventory of intersection operations, which also included the concurrent pedestrian phasing in crosswalks perpendicular to the PPLT maneuver. Concurrent pedestrian phasing allows pedestrians to cross at the same time as PPLT phasing to the left-turning vehicles within the same cycle. Exclusive phasing represents the alternative, where pedestrians provided their exclusive pedestrian phase that does not conflict with vehicular movement.

Previous literature has provided evidence on the safety impacts from these two pedestrian phasing intervals. The models from Zhang et al. in 2015 explained that exclusive pedestrian phasing decreased the probability of pedestrian crashes; however, the pedestrian crashes that occurred were likely to be more severe than those that would occur during a concurrent phase (28). Tian et al. explained that when using exclusive phasing, vehicles intersection capacity was reduced and suggested that it should only be used when the total vehicle demand times were less than half of the pedestrian crossing time (29). A potential confounding reason for the application of concurrent phasing remains with the compliance of pedestrians, which was discussed in a 2018 Cape Town, South African study. This study observed a higher number of near-misses with pedestrians at exclusive phased intersections than concurrent ones (30). While these were mostly during illegal crossings and pedestrians interviewed at these locations reported that they believed the waiting time at exclusive phased intersections were “excessive” (30). Lastly, a crash report data synthesis was confused in the Perth Central Business District by Palamara in 2013, which sought differences in crash patterns between alternative pedestrian phasing. The results from this Australian study found no difference and the number of intersections with newly implemented phasing plans were too small to make any definite conclusions (31).

Many of these aforementioned studies addressed the need for protected pedestrian phasing limitations, some of which included small sample sizes and therefore suggested that “next-steps” analyze a larger sample in future work. Again, it is important to note that the topic of conflicting pedestrian phasing remains ever-changing in the transportation industry, with many researchers awaiting new guidance from the updates of nationwide manuals (i.e., MUTCD).

1.2 Objectives and Project Motivation

The Flashing Yellow Arrow (FYA) has rapidly evolved in recent years for both the left- and right-turn permissive movements, with an increasing presence of the former in Massachusetts. As previously discussed in the literature synthesis, prior research regarding before-and-after FYA safety impacts have relied primarily on intersection-level crash data, or with very sample sizes at an approach level. While these previous studies provided some insight into the overall intersection effectiveness of the FYA, there were some limitations with regards to the impact of the FYA on their respective approaches and more importantly left-turn across path crashes (e.g., LTOT). In phase 1 of this study, researchers compiled an inventory of over 350 traditional PPLT traffic signals that were set for retrofit under a statewide signal contract. The analysis was completed through intersection-level crashes and identified strong benefits from FYA implementation. That said a crucial need still remained apparent to analyze FYAs from an approach level to make certain the benefits greatly outweighed the costs. The current study employed methods to stratify crashes from over 200 intersections to better understand the true impacts from LT vehicles with FYA signal indications. This research was conducted across four main tasks in an effort to conduct an in-depth evaluation of FYA safety impacts through an approach-level analysis across Massachusetts:

Task 1 – Stratify Approach Level Before and After Crashes. Based on the FYA inventory completed in Phase 1, the research team assesses the crash information from before and after installation periods through a holistic crash report stratification process. Crash data was re-queried to obtain the "complete" crash years that were limited in phase one. The team identified a randomized sample of control intersections with PPLT phasing with Circular Green (CG) indications, and queried crash data from these intersections. An in-depth surveillance of coded fields, narratives, and collision diagrams for all FYA and sample CG intersections was completed for both the before and after installation periods. Crashes were aggregated into four main categories: intersection-level, PPLT approach level, left-turn (LT) specific crashes, and left-turn-opposing-through (LTOT) crashes.

Task 2 – Develop an Inventory Survey to Obtain Intersection Design Specifications. The research team developed an inventory based on a Qualtrics survey that was deployed in the field to obtain both operational and infrastructure information from each intersection ID (FID). The attributes that were inventoried include: application of all-red clearance intervals, conflicting pedestrian intervals, and the use of supplementary signage for FYA LT signals.

Task 3 – Analyze Safety Impacts with Left-Turn FYA, including Related Infrastructure (post-installation). The LT approach-level crash information from Task 1 was utilized to identify the safety impacts with LT FYA/CG intersections, primarily focusing on the LTOT impacts. In addition, infrastructure impacts during the post-installation phase were evaluated. Using the crash data, this research integrated a simple comparative analysis with phasing, pedestrian intervals, and supplementary signage. The post implementation crash data at intersections with FYA/CG indications should provide MassDOT with overarching safety implications of each treatment.

Task 4 – Develop Guidance and Recommendations for Left-Turn FYAs. Based on the results collected and analyzed in previous tasks, an investigation was conducted on the correlation between left-turn crash patterns and FYA implementation. In this task, the research team provided a list of recommendations for future FYA installations within Massachusetts, while taking into consideration the crash patterns identified within this study. These recommendations included a glance into the true safety benefits of the FYA, and provided a statewide crash modification factor (CMF) for their implementation at signalized intersections (both 3-way and 4-way intersections).

1.3 Organization of Report

The report is organized as follows. Chapter 1 introduces the implementation of the Flashing Yellow Arrow and its recent history, previous literature that evaluates its efficacy, research motivation, followed by a detailed list of objectives and tasks that were completed for this research project. Chapter 2 presents the research methodology, including a review of the statewide FYA infrastructure inventory that was conducted, an in-depth analysis regarding FYA and CG approaches, and a completed cost-benefit analysis. Chapter 3 presents the results from this study, Chapter 4 presents the implementation and tech transfer applicability, and Chapter 5 summarizes the overall findings of this research project, including a resulting statewide crash modification factor for FYA installations in Massachusetts.

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2.0 Research Methodology

This research study was completed across four main tasks, in an effort to conduct an approach-level analysis of FYAs across Massachusetts. First an inventory was compiled to collect FYA and CG infrastructure operational elements, including phasing and supplementary signage. Next, an in-depth before-and-after analysis was conducted by stratifying approach-level crashes at each of the studied FYA intersections as well as the control CG intersections, followed by an updated cost-benefit analysis regarding FYA benefits in Massachusetts. Lastly, these results were evaluated to output a list of recommendations and guidance moving forward in FYA implementation through Massachusetts, specifically identifying their crash reduction benefits.

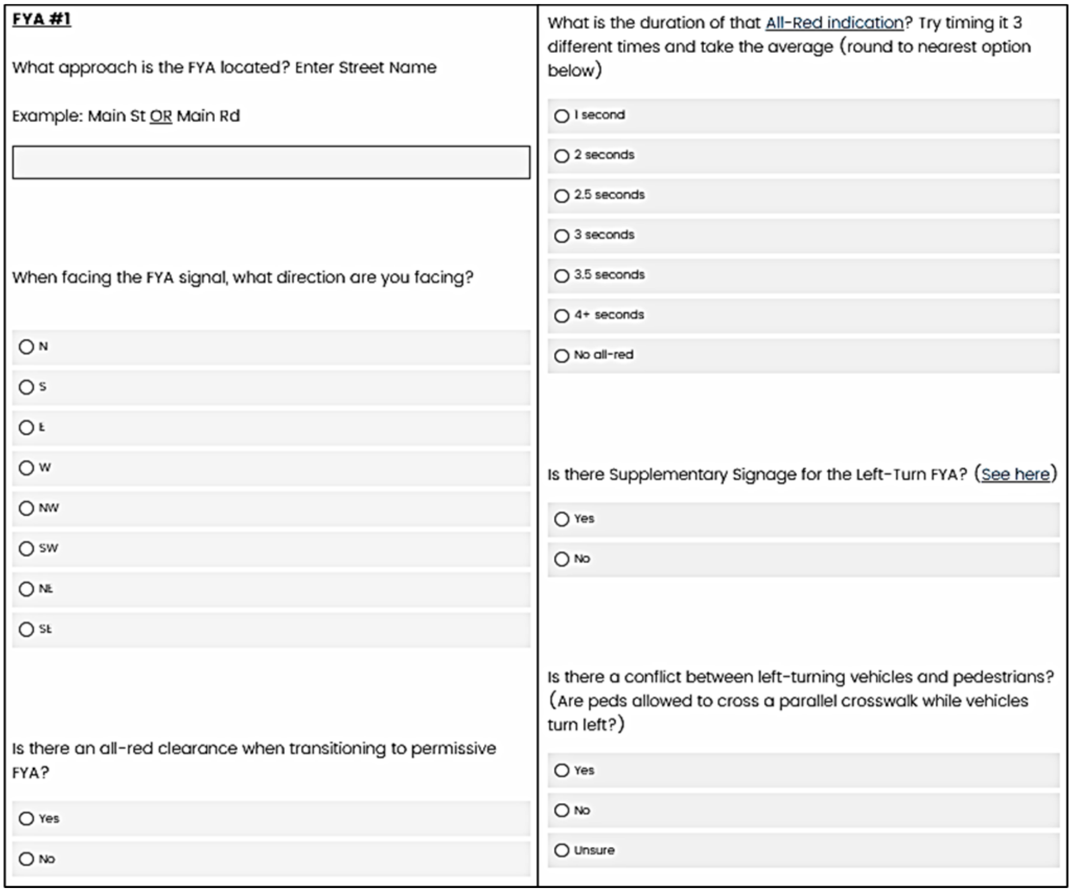
2.1 Intersection Survey Inventory

In Phase 1, the research team conducted an in-depth inventory of FYAs in Massachusetts by utilizing Google imagery data and determining the implementation window of each FYA that was retrofit by MassDOT. While identifying these windows of time, the team was able to determine a "before" installation period and an "after" implementation period for over 250 FYA intersections. In the current research endeavor, the team advanced this information by collecting operational information at over three hundred intersections throughout Massachusetts. For both FYA and CG (control) intersections, the team sought to verify the FYA/CG implementation while also confirming a list of operational and infrastructure elements at each signalized intersection.

The following section presents the steps taken to develop and initiate the intersection inventory survey throughout Massachusetts, including the information that was collected at each intersection. Also, this section includes an explanation for the operational and infrastructure elements that were collected during this process.

2.1.1. Survey Creation

An updated inventory of FYA and CG study intersections was crucial in completing the analysis of this study. In order to complete an approach-level safety analysis, there was a need to have up-to-date infrastructure information for each of the study intersections. Therefore, a plan was initiated to complete a statewide data collection effort that aimed to collect the information as exampled in Figure 5. The inventory survey may be seen in full in Appendix A, and it remains important to note that the survey was created as a short-duration survey to optimize the data collection effort while maximizing the information being collected by the research team. The survey was created in Qualtrics and was designed with survey-based logic to ensure completion of under 5 minutes per intersection.



FYA #1

What approach is the FYA located? Enter Street Name

Example: Main St OR Main Rd

When facing the FYA signal, what direction are you facing?

- N
- S
- E
- W
- NW
- SW
- NE
- SE

Is there an all-red clearance when transitioning to permissive FYA?

- Yes
- No

What is the duration of that All-Red indication? Try timing it 3 different times and take the average (round to nearest option below)

- 1 second
- 2 seconds
- 2.5 seconds
- 3 seconds
- 3.5 seconds
- 4+ seconds
- No all-red

Is there Supplementary Signage for the Left-Turn FYA? (See here)

- Yes
- No

Is there a conflict between left-turning vehicles and pedestrians? (Are peds allowed to cross a parallel crosswalk while vehicles turn left?)

- Yes
- No
- Unsure

Figure 5: Section of FYA field data collection inventory survey

2.1.2. Data Collection Effort

The investigation into PPLT phasing and their impacts on the safety of the FYA remained critical to this study; however, many other factors including infrastructure and operational elements, had potential to impact the outcomes within a signalized intersection. Therefore, the field data collection inventory survey was necessary in identifying these potential correlating factors that to be utilized in the safety analysis. Over 250 intersections were inventoried in this process, include 98 3-way FYA intersections and 159 4-way FYA intersections. It is important to note that not all of these inventoried intersections were utilized in the crash data analysis portion of this study; however, the data was collected and compiled into the FYA database regardless.

Researchers developed a strategic statewide data collection plan ranging that included 10-25 intersections inventoried per trip. In addition, data collection was outsourced to student researchers over inter-session in an effort to assist in completing the statewide data collection and providing greater opportunity to collect information from intersections in Eastern MA (furthest from the UMass Amherst campus). Figure 6 represents the information collected at each of the inventory intersections. When arriving at each intersection, the research noted the total number of approaches with FYA PPLT signals present. Then, the research began with a FYA on the major road approach (if present) and collection information regarding the street name as well as the cardinal direction in which the driver was facing at the approach. Next, the researcher collected information regarding the operational and infrastructure elements at that intersection approach, including: the presence of an all-red clearance interval (as discussed in Section 1.1.4, presence of FYA supplementary signage (Figure 3), and conflicting pedestrian intervals. This process was repeated for all remaining FYA signal approaches at a given intersection.

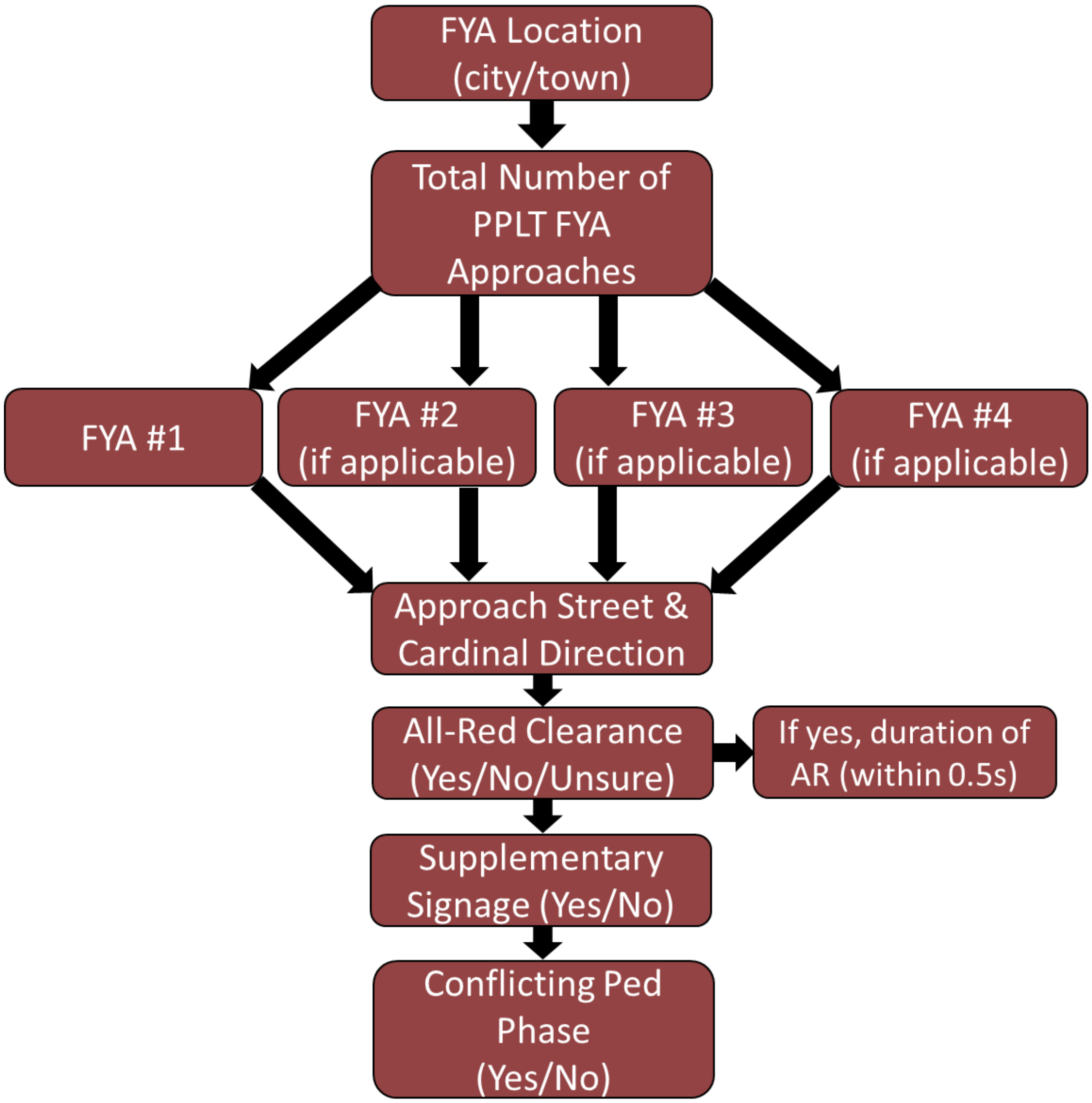


Figure 6: Information collected at each FYA intersection through inventory survey

2.1.3. Operational and Infrastructure Element Inventory

The researchers collected operational and infrastructure elements at each of the study intersections as previously mentioned. The all-red clearance intervals, if present, were collected in intervals of 0.5s ranging from 0.5-3.5s with signals of 4+ all-red clearance intervals being documented as such. It is important to note that the researcher recorded those signals at varied traffic demand conditions, and therefore certain intersection did not yield enough LT-volume to trigger the protected LT phase. This all-red clearance information was noted as “unsure” in these conditions. Figure 7 presents the signal phasing that includes the usage of the all-red clearance interval.

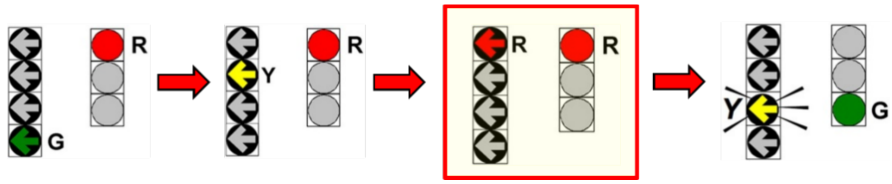


Figure 7: All-red clearance presence at FYA intersection approach

The collection of supplementary signage was conducted at each of the intersections where there was an FYA present. Figure 8 displays the typical location of the supplementary signage; however, it is important note that the signage was present on far-side post-mounted FYA signals in certain instances depending on the geometry of the intersection. The variance between these signage locations were not documented in this survey. The FYA supplementary signage was analyzed by approach; however, intersections typically utilized the signage at all approaches and therefore this was documented as “Yes” or “No” from and intersection-level for data processing purposes.

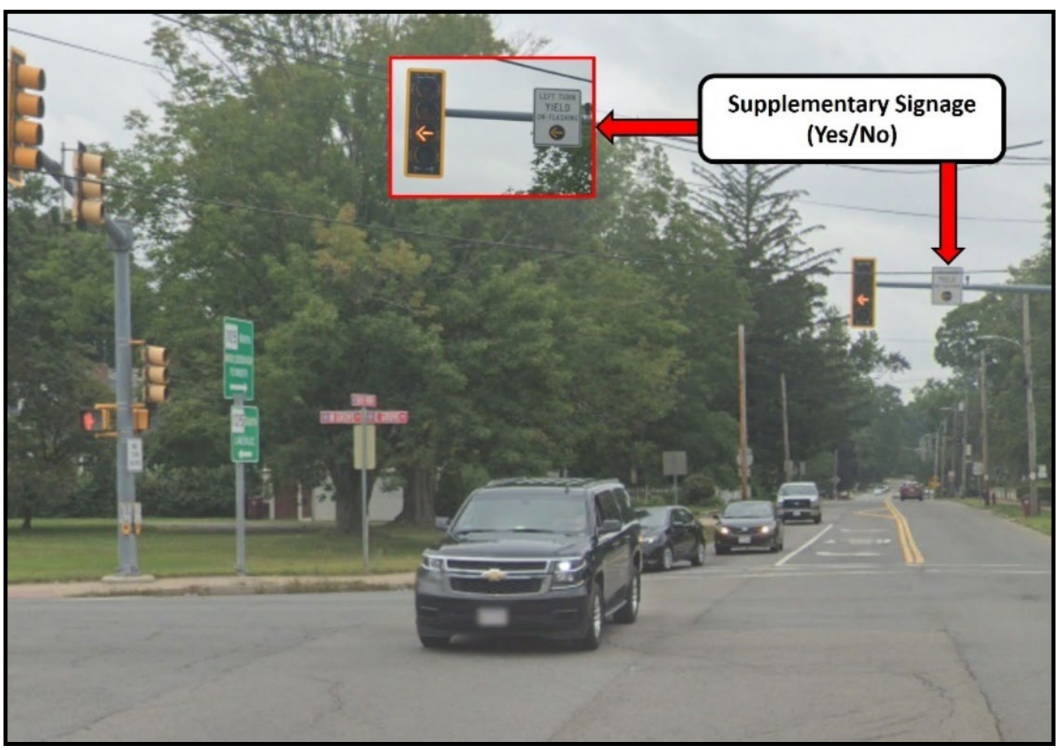


Figure 8: Supplementary signage presence at FYA intersection approach

The conflicting pedestrian phasing information was collected manually at each of the FYA approaches within an intersection via the activated pedestrian push button. If there were no pedestrian push buttons located at any given approach, the information was documented as

"No" for not present. Figure 9 displays the location of the conflicting pedestrian crosswalk. It is important to note that in this graphic, the pedestrians did not have the "WALK" sign during the FYA permissive phase at this approach. Therefore the approach was documented as not having a conflicting pedestrian interval. The researchers did not take into consideration the application of a leading pedestrian interval (LPI) in this data collection.

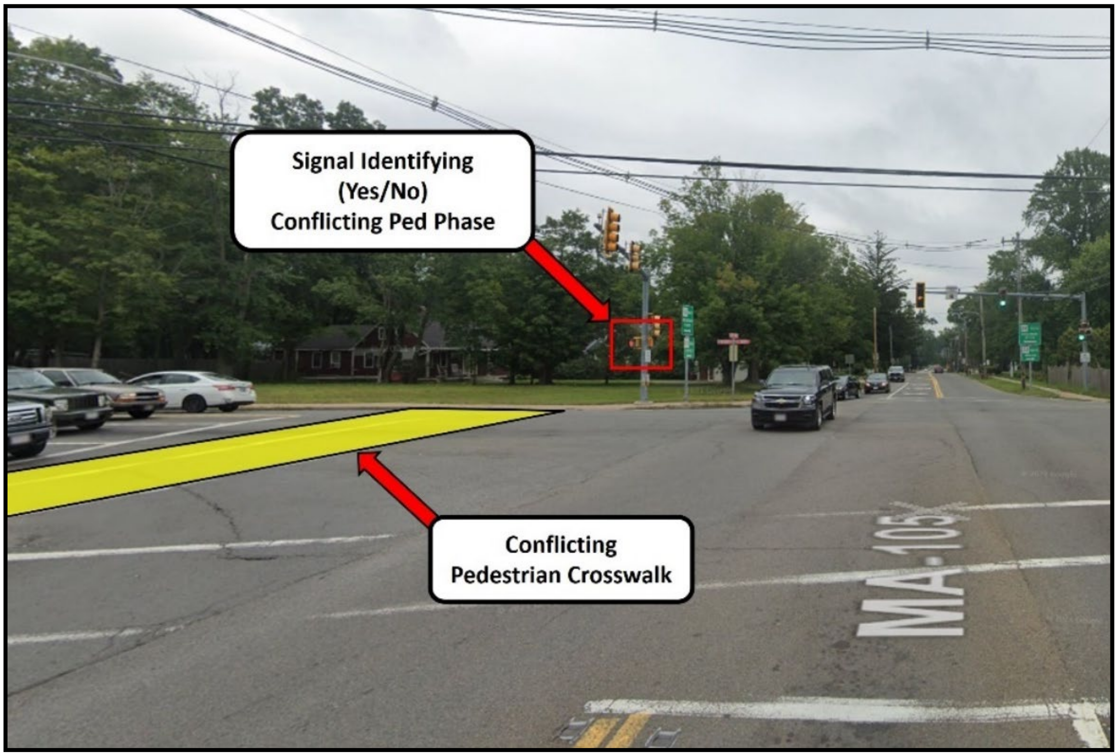


Figure 9: Conflicting pedestrian interval presence at FYA intersection approach

2.2 Crash Stratification for Approach Level

Based on the FYA inventory that was completed during Phase 1 of this research, there was a need to assess crash data for before and after installation periods of the FYA signal through a holistic crash report stratification process. The results from Phase 1 yielded strong benefits regarding the safety impacts of the FYA; however, the results relied heavily on intersection-related crashes. The previous completed work parsed data into "LT-related" and "left-turn-opposing-through" (LTOT) based on the *Manner of Collision* field within each crash data point. While this was effective at identifying the LT crash impacts within each treatment category (3-way intersection, 4-way intersection with one FYA, 4-way intersection with two-or-more FYAs), there was a limitation in identifying crashes specific to the approaches specific to an FYA signal indication. Therefore, it was necessary to conduct a follow-up analysis where the research team parsed through all crashes located at FYA intersections to identify its root cause, and develop an analysis based on FYA approach-level crashes.

The following sections explain the data collection effort that was conducted to identify and extract crashes for FYA study intersections, as well as the process of identifying a sample of control intersections with the permissive circular green (CG) indication for left turns (under comparable circumstances).

2.2.1. Crash Data Collection Effort

The MassDOT IMPACT portal was utilized for the primary extraction of crash data for this study (32). This portal provides crash files with complete crash data for each year required in this analysis, as exampled in Figure 10. Similar to Phase 1, there were two dates that were taken into consideration when identifying crash years to extract. The installation of the first FYA was in early 2013 and the completion of the statewide retrofit plan was contractually closed between 2016-2017 depending on the District. Therefore, the researchers extracted statewide crash data from 2011 through 2019. Given that the 2019 crash data was recently marked as closed by MassDOT, the crash dataset was "complete" when extracted. As an added note, 2020 crash data was avoided in this study to avoid any potential impacts from the COVID19 pandemic.

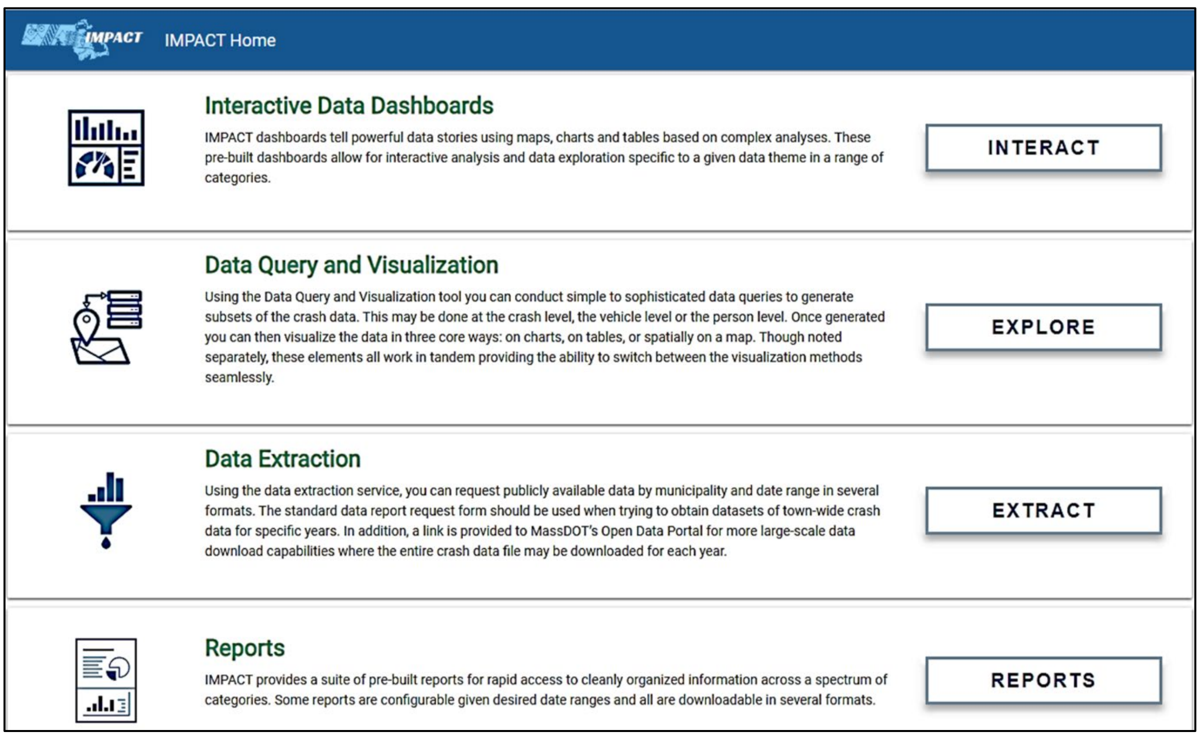


Figure 10: IMPACT crash data repository, including data extraction

Once the crash data from 2011-2019 was extracted and important into a database, the data cleaning and reduction process began. Using ArcMap GIS (33), the data was visualized across Massachusetts. A 200-ft buffer was created around each individual FYA intersection with the intent of capturing all relevant crashes. The crashes within these buffer zones were compiled as FYA intersection crashes. Utilizing data processing in R, the team began cleaning the crash data to include the appropriate before and after crash data. As completed in Phase 1, each of the intersections were marked for "before" and "after" years via Google Streetview imagery. Each of the FYA intersections were verified with their "before implementation" and "after installation" periods. As a result, two-year windows were established for each individual signalized intersection, representing the before and after study periods. As previously mentioned, the first FYA installation in early 2013 and the contract closeout dates were used as placeholders when determining the implementation windows at each intersection. Once a 2-year window for before and after were compiled, the data was imported back into GIS. Figure 11 presents an overview of all FYA and CG intersections in Massachusetts that were initially considered in this study. This study did not take into consideration volume data, which became a limitation in Phase 1 due to the lack of availability and reliability of roadway volume data.

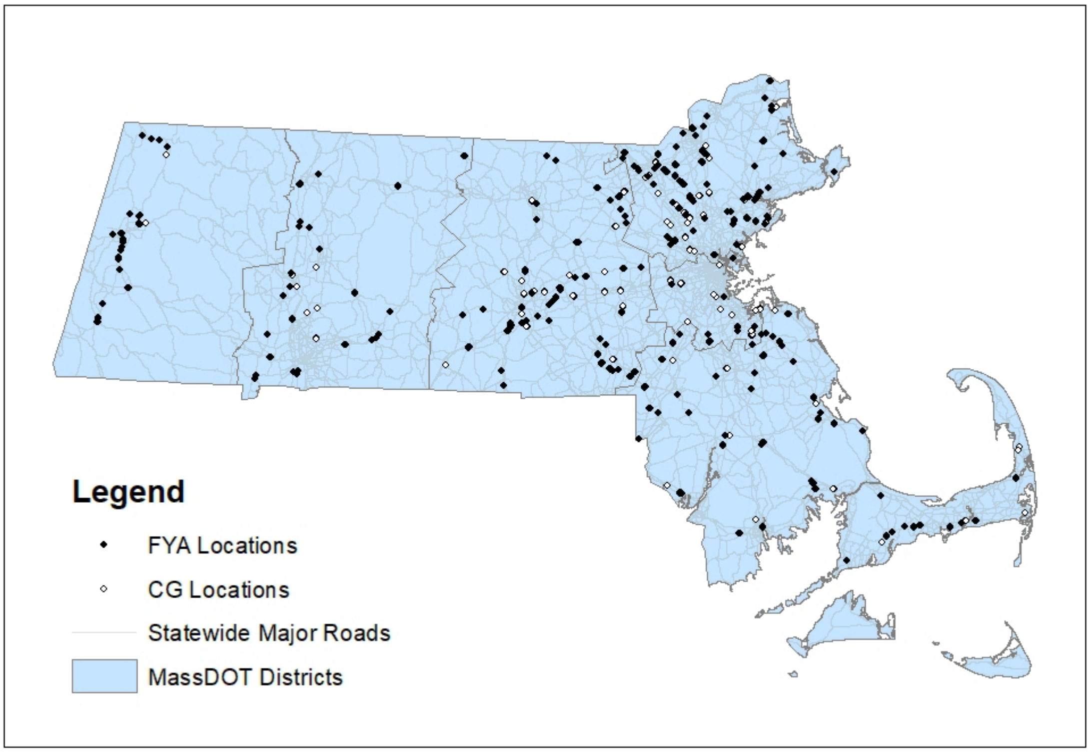


Figure 11: GIS Graphic Displaying FYA and CG Locations in Massachusetts

2.2.2. FYA Intersection Selection and Scoring

An in-depth surveillance of coded fields, narratives, and collision diagrams was completed for all FYA intersections for the before and after installation periods. The complete crash reports, including narratives and diagrams, were resourced from the RMV database. The assistance with machine learning allowed for each individual crash report to be downloaded and remove any personal identifying information (PII). In total, 4840 crash reports were retrieved and reviewed manually by the research team. A double-blind review of crash reports, narratives, and collision diagrams were reviewed and verified in an effort to identify the causal reasoning of each crash. While there were instances when the crash type and cause was clear, as displayed in Table 1, many of the other crash report fields were used to assist the researchers in identifying the location and cause of the crash to verify its proximity and relation to the FYA approach.

Table 1: Example of redacted crash narrative during "before" and "after" time periods

Before/After	Crash Narrative
Before (with CG present)	*"THE OPERATOR OF VEHICLE #1 HAD A GREEN LIGHT, AND WAS GOING STRAIGHT THROUGH THE INTERSECTION OF BEDFORD STREET AND CAMBRIDGE STREET. THE OPERATOR OF VEHICLE #2 HAD A SOLID GREEN, AND WAS TURNING LEFT FROM BEDFORD STREET ONTO CAMBRIDGE STREET. THERE IS A GREEN ARROW TO TURN LEFT, BUT THE GREEN ARROW HAD ALREADY CHANGED. THE OPERATOR OF VEHICLE #2 CRASHED INTO VEHICLE #1. NO INJURIES WERE REPORTED AT THE SCENE, AND NEITHER VEHICLE WAS TOWED."*
After (with FYA present)	*"V1 WAS TRAVELING STRAIGHT AHEAD AND HAD A SOLID GREEN TRAFFIC SIGNAL. V2 WAS IN THE TURNING LANE WITH A FLASHING YELLOW YIELD ARROW. V2 ATTEMPTED TO MAKE A LEFT-HAND TURN ACROSS 2 LANES OF ONCOMMING TRAFFIC, CUTTING OFF V1. V1 HAD THE RIGHT OF WAY AND DID NOT HAVE TIME TO STOP BEFORE STRIKING V2 IN THE REAR.OPERATOR OF V2 WAS ISSUED MASSACHUSETTS UNIFORM CITATION XX FOR FAILING TO USE CARE WHEN TURNING."*

Ultimately, crashes were aggregated into four main iterative categories: intersection-level, FYA approach level, left-turn (LT) related, and left-turn-opposing-through (LTOT) related. Figure 12 presents the iterative steps of these categories. The team determined whether the crash occurred at the approach (or approaches) through the crash narrative, collision diagram, and compared those against the cardinal directions written into the report. In the next stage of scoring, the crashes were reviewed under the category of LT-related if the crash was located at the FYA approach with at least one of the vehicles placed in the left-turn lane. Lastly, the final iteration was identified for FYA approach crashes, traveling in the left-turn lane, which resulted in a crash with an opposing through vehicle. These crashes are sometimes referred to as left-turn-across-path, or as mentioned hereafter as LTOT crashes. More so, the diagram presented in Figure 13 illustrates a prime candidate crash for LTOT where vehicle 1 traveled straight through the intersection while vehicle turned left at the approach with an FYA PPLT signal indication.

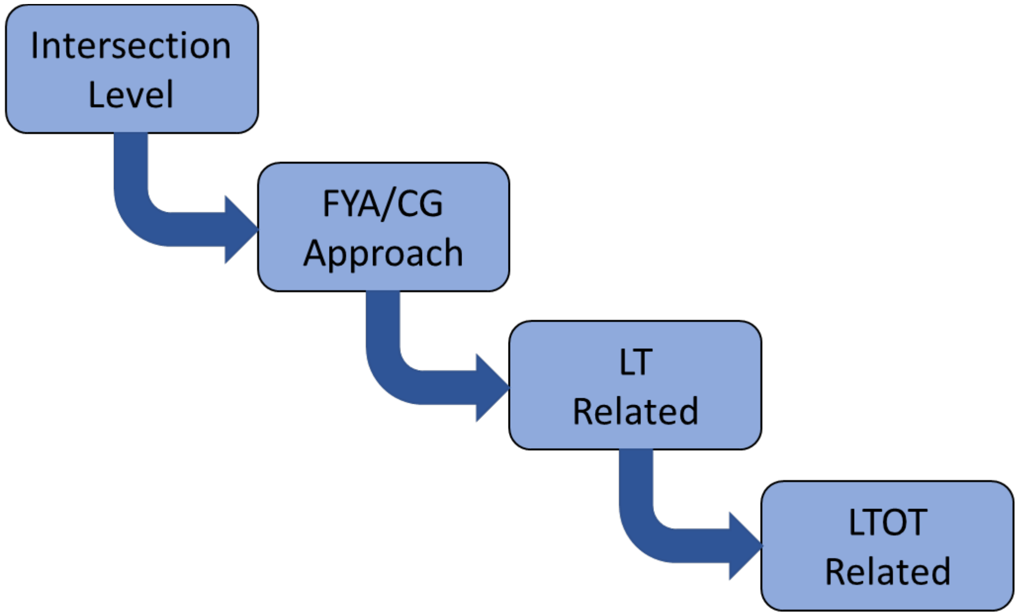


Figure 12: Crash report review iterative categories

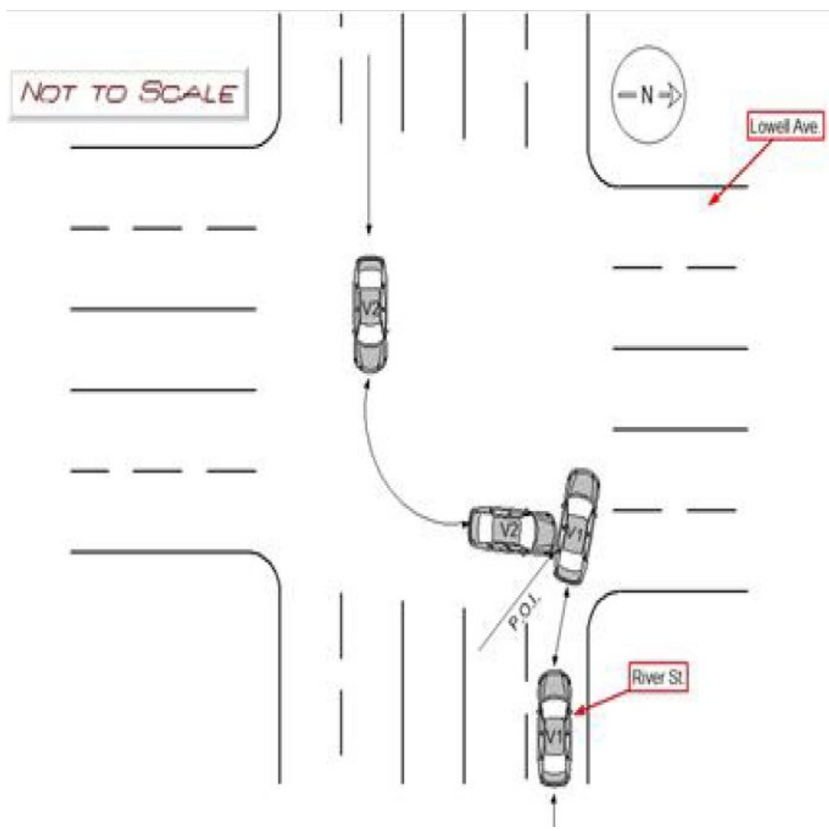


Figure 13: Example of LTOT Crash as Shown in Crash Report from FYA/CG Intersection

2.2.3. Control Intersection Selection and Scoring

The database created during Phase 1 of this study led to a list of FYA intersections, as well as a list of intersections that had not been converted to the PPLT FYA across Massachusetts. In order to conduct a before/after crash analysis, a list of control intersections was needed.

In total, there were 80 CG intersections in the inventory, with 28 of those intersections utilizing 4-section vertical signals and the remaining 52 intersections utilizing 5-section cluster signals (or commonly referred to as "doghouse"). These signal orientations were displayed in Figure 1. First, the *before* and *after* crash date ranges were determined. This was processed by using the average before and after data ranges with the 200 FYA intersections. As a result, the before range with CG intersections was between December 2012-2014 and the after range was between June 2017-2019. Crash data was extracted for all 80 CG intersections; however, the analysis conducted in this study only required a subset of this sample. Therefore, the following steps were initiated to randomly select 22 CG study intersections:

- Separate CG intersections into tiers based on number of crashes.
    - High, Med-High, Med-Low, Low
- Separate into additional tiers based on signal configuration.
    - 4-section vertical
    - 5-section cluster
- Random selection leading to 22 control intersections.

Once the CG control intersections were selected, an in-depth surveillance of coded fields, narratives, and collision diagrams was completed. The process from Section 2.2.2. was repeated with this new sample. Crash reports were extracted from the RMV database resulting in 868 crashes that occurred at the control intersections. Table 2 provides the list of control study intersections with CG PPLT indications. It is important to note that intersection type (3-way vs. 4-way) was not taken into consideration in randomly sampling control intersections given that there were minimal 3-way intersection locations in the database.

Again, crashes were reviewed via double-blind process and verified for their proximity and relationship to the CG PPLT approach. Crashes were organized into the iterative categories of intersection-level, approach level, LT-related, and LTOT-related crashes. These categorical iterations of crashes were analyzed further against the FYA treatment groups, as explained in the following sections.

Table 2: Control study intersections with CG PPLT indication

ID	City/Town	Intersection Legs	Signal Orientation*	X	Y
1	DALTON	4-way	4-section	42.47123	−73.1788
2	SOUTH HADLEY	4-way	5-section	42.23570	−72.5834
3	GRANBY	4-way	5-section	42.24658	−72.5446
4	BURLINGTON	4-way	5-section	42.51068	−71.2007
5	ACTON	4-way	4-section	42.47493	−71.4539
6	MARLBOROUGH	3-way	4-section	42.35057	−71.4930
7	HADLEY	4-way	4-section	42.35766	−72.5510
8	WORCESTER	3-way	4-section	42.29379	−71.7610
9	WORCESTER	4-way	4-section	42.29015	−71.7904
10	ARLINGTON	4-way	5-section	42.41106	−71.1817
11	BURLINGTON	3-way	4-section	42.48353	−71.1890
12	BEDFORD	4-way	5-section	42.48650	−71.2625
13	PLYMOUTH	4-way	4-section	41.94966	−70.7147
14	RAYNHAM	4-way	5-section	41.90639	−71.0394
15	SWANSEA	4-way	4-section	41.76940	−71.2649
16	EASTHAM	4-way	5-section	41.85574	−69.9872
17	WILMINGTON	4-way	5-section	42.55882	−71.1444
18	WOBURN	4-way	4-section	42.50407	−71.1309
19	WEYMOUTH	4-way	5-section	42.17949	−70.9552
20	QUINCY	3-way	5-section	42.23395	−71.0288
21	WORCESTER	3-way	5-section	42.23540	−71.7962
22	BOSTON	4-way	5-section	42.28779	−71.0940

*4-section vertical, and 5-section cluster signals

2.3 Before/After Crash Analysis for Approach Level

In order to yield a better understanding of FYA safety impacts at signalized intersections, the research team focused on analyzing before-and-after crash conditions at FYA intersections across Massachusetts. The following section explains the treatment categories that were studied (as comparatively to Phase 1), the methods of a naïve before/after crash analysis, the equivalent property damage only (EPDO) weighting factor, methods of the cost-benefit analysis from the approach level, and development of a statewide crash modification factor for FYAs.

2.3.1. Treatment Categories

The 200 FYA intersections through Massachusetts were categorized into two treatment categories in this study. As explained previously, this analysis determined crashes down to the approach level and therefore provided more holistic representation of causal crash location. Figure 14 presents the breakdown of each treatment category: 3-way intersections and 4-way intersections. It is important to note that compared to Phase 1, this analysis combined all 4-way intersections into one treatment category due to the approach-level nature of this study. This results in 80 3-way intersections and 120 4-way intersections with a total of 272 FYA approaches. A complete list of these FYA study intersections may be found in Appendix B.

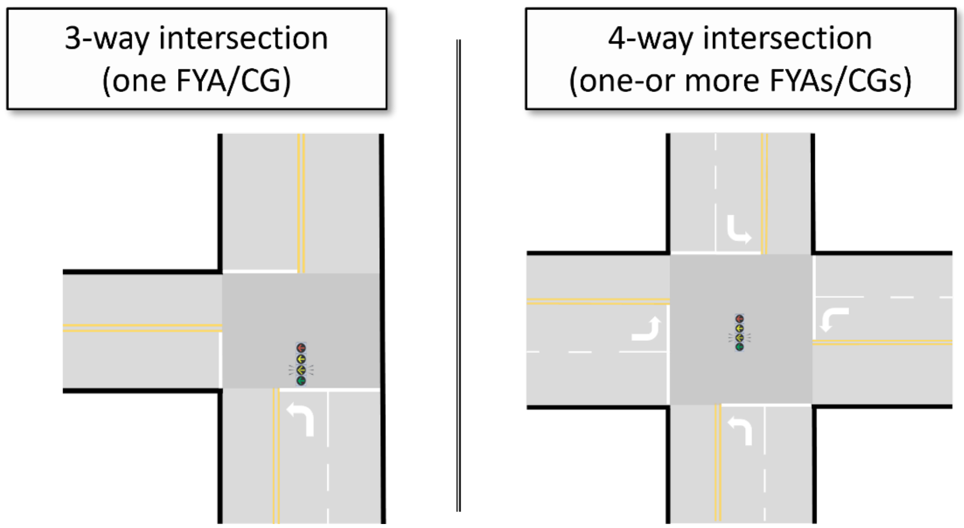


Figure 14: Three-way and 4-way FYA treatment categories

2.3.2. Naïve Before/After Analysis

A naïve before/after crash analysis was conducted for FYA approaches statewide. This analysis was primarily selected due to the uncertainty behind reliable traffic volume information from a roadway inventory perspective. As previously mentioned, Phase 1 determined that although some districts in Massachusetts provide more accurate average annual daily traffic (AADT) data than others, it limited the number of study intersections in the crash analysis. Therefore, the researchers ultimately chose a naïve before/after crash analysis that takes into consideration annual average crashes at each of the FYA approaches.

The before/after crash analysis took into consideration *injury severity*, *manner of collision*, as well as *intersection type*. The *injury severity* was broken down into injury crashes and property-damage-only crashes, as explained further in Section 2.3.3. *Manner of Collision* was separated into categories that typically lead to more severe injuries vs less severe injuries (34). Head-on, sideswipe, and angle crashes were represented in one subset of data, while rear-end crashes were compiled in another subset. It is important to note that comparatively to Phase 1, this analysis did not include "LT" and "LTOT" crash subset, as these were filtered into their own crash totals as explained in Section 2.2.2.

2.3.3. EPDO Weighting Factor

The reduction of injury severity of crashes continues to be critical concern in transportation safety, and therefore was taken into consideration in this crash analysis. Similar to Phase 1, the equivalent property damage only (EPDO) weighting factor was taken into consideration for this analysis. In an effort to remain consistent with prior MassDOT crash reporting literature (35), the before/after crashes were adjusted to report EPDO values. Essentially, this removes the "chasing fatal" crash concern, and applies a weighted value of 21 to all crash resulting in an injury. Figure 15 represents that rational regarding crash cost and percent of injury-type crashes in Massachusetts. It remains important to note that the costs designated in this chart were not utilized in the cost-benefit analysis, and only utilized in determining the EPDO weighting factor.

Crash Severity	Costs	% of all crashes in MA	Weighting Factor
Fatal Crashes	$14,482,300	0.2%	21
Incapacitating Injury Crashes	$860,700	2.0%	
Non-Incapacitating Injury Crashes	$260,800	12.0%	
Possible Injury Crashes	$165,000	16.0%	
Property Damage Only Crashes	$15,600	70.0%	1
TOTAL		100.0%	

Figure 15: Massachusetts EPDO weighting value for injury crashes

2.3.4. Cost-Benefit Analysis

The cost of FYA installation and the benefit of crash injury reduction were taken into consideration in developing the cost-benefit analysis for the FYA from an approach level. The cost of FYA installations were derived during Phase 1 of this study; however, Table 3 presents the conclusive allocated costs for implementation. These values were backed by previous FYA safety literature, MassDOT contractual information, as well as information provide from local consultants that have in-depth experience in traffic signal retrofitting and cabinet work. These costs were calculated per approach and were applied as such in the analysis.

Table 3: FYA implementation costs used in cost-benefit analysis

Installation Cost (per FYA approach)	Source
$6,000	Schattler et al. 2016 *(10)* and Srinivasan et al. 2020 *(11)*
$10,000	MassDOT Contract Estimate (lower threshold,)
$50,000	MassDOT (upper threshold) and Local Consultants Estimate

In addition to utilizing the FYA signal implementation costs, the researchers needed to determine the application of economic cost for crashes that occurred at each FYA approach during the study period. The benefits refer to the reduction in overall crash cost, meaning a reduction in the severity of injuries sustained in FYA approach crashes. As previously mentioned, crashes were analyzed by annual average per year during the before and after periods, with the primary focus on separating injury-related crashes and PDO crashes. In this case, the crashes were categorized into KABC and O, as referred to in the FHWA injury classification scale (36). Comparatively to Phase 1, the FYA approach-level analysis did not result in any fatal crashes and therefore all injury classifications were categorized together in the cost estimation. The economic costs per KABC and O were calculated based on the *Crash Costs for Highway Safety Analysis* (37) and were converted into Massachusetts dollars by utilizing the *MassDOT Safety Alternatives Analysis Guide* (38). Ultimately, these crashes were analyzed per FYA intersection type.

2.3.5. Crash Modification Factor Development

Given the novelty of the FYA, there still exists a need to apply crash modification factors (CMFs) to the PPLT signal indication, particularly with a statewide need in Massachusetts. The *MassDOT Safety Alternatives Analysis Guide* presents some of the key characteristics required to develop and assign an appropriate CMF (38). More so, the recommendation yields that MassDOT's preferred CMFs include the all-classified crashes including injury-related and property damage only combined, as well as injury-related crashes which they refer to as "Fatal and Injury" (FI). These crash categories were taken into consideration in the development of a statewide FYA CMF.

Although the MassDOT safety alternatives guide provides examples of empirical bayes in developing and assigning CMFs, there have been limitations in the reliability of applying statewide volume data. Therefore, this study employed an alternative analysis that further extended the naïve before and after analysis by including a sample of comparison groups. Prominently explained by Hauer in *Observational Before-After Studies in Road Safety*, the application of a before-and-after study with comparison groups can effectively measure the effectiveness of a treatment when compared against a group of comparison measures given the following factors remain true (39):

- The before and after periods of both the treatment and comparison groups should be similar in total years;
- A rational explanation for similar changes in factors outside of just the treatment. For instance, the change in traffic volume should be consistent across both the treatment and comparison groups;
- Sample size of crashes needs to be large enough to yield significant a CMF estimate.

More so, a CMF guide released by the Federal Highway Administration (FHWA) in 2010 provided an updated explanation for developing CMFs, and further discussed the difference between the comparison group method versus the empirical bayes method (40). This guide has been utilized in several studies nationwide in reference the strengths and limitations of both methods. For example, recently in North Carolina, researchers conducted a study regarding the time-of-day (TOD) impacts of the FYA for PPLT at signalized intersections. (41). In addition, the methods regarding comparison group analyses have been utilized in safety performance studies at both signalized and unsignalized intersections in recent years (42, 43, 44).

The development of a CMF for Massachusetts statewide FYAs was structured from the FHWA 2010 study. It remains important to note that while the Massachusetts Roadway

Inventory provides statistics on AADT for statewide roads, the results from the Phase 1 study presented limitations in these data. Therefore, it was decided that the comparison groups method would be utilized over an empirical bayes approach.

In order to effectively develop a CMF, both the treatment and comparison group must represent similar conditions. Given the list of CG control intersections provided were considered with a "future retrofit" condition, all of these intersections may be deemed of similar conditions to the treatment FYA intersections. That said, using the sample odds ratios method presented from Hauer (39), the CG and FYA intersection-level crashes were compared to verify the effectiveness of the comparison. Equation 1 presents the calculation of the sample odds ratios, which in this case resulted in a value of 0.99. Given this value and its proximity to 1.0, the comparison group was considered valid in this analysis.

$$sample\ odds\ ratios\ = \frac{\frac{(Treatment_b \cdot Comparison_a)}{(Treatment_a \cdot Comparison_b)}}{(1+\frac{1}{Treatment_a}+\frac{1}{Comparison_b})} \qquad (1)$$

where
$Treatment_b$ = total crashes for the treatment group in year x,
$Treatment_a$ = total crashes for the treatment group in year y,
$Comparison_b$ = total crashes for the comparison group in year x, and
$Comparison_a$ = total crashes for the comparison group in year y.

Ultimately, the procedure in developing a CMF for FYA was coordinated through similar methods as the before/after analysis. Each iterative crash category (intersection-level, approach level, LT-related, and LTOT-related) were evaluated based on total crashes and injury-inducing crashes (KABC). These crashes contained both 3-way and 4-way intersections and in calculating the CMF intersection type was not taken into consideration as an additional variable. Table 4 presents the level crash categories, the number of intersections per group, and the number of approaches analyzed within each group. It remains important to note that the number of intersections and approaches were reduced based on the iterative crash category. The LTOT-related crashes only occurred at 142 intersections across 197 approaches.

Table 4: CMF development including treatment and comparison intersection/approach totals

Crash Sample	Category	Treatment Group Intersections	Treatment Group Approaches	Comparison Group Intersections	Comparison Group Approaches
Intersection Level	Total crashes KABC	200	272	22	37
Approach Level	Total crashes KABC	195	265	22	37
LT Related	Total crashes KABC	159	215	19	33
LTOT Related	Total crashes KABC	142	197	19	33

The development of a CMF for each category began with a comparison ratio, which indicated the expected change in crashes without the treatment of an FYA. The $N_{expected,T,A}$, as presented in Equation 2, was calculated as the estimated number of crashes in the after period and compared against the actual treatment value in the after period.

$$N_{expected,T,A} = N_{observed,T,B}\left(\frac{N_{observed,C,A}}{N_{observed,C,B}}\right) \qquad (2)$$

where
$N_{expected,T,A}$ = expected number of crashes in after condition for the treatment group,
$N_{observed,T,B}$ = observed total crashes in before condition for the FYA treatment group,
$N_{observed,C,B}$ = observed total crashes in before condition in the CG comparison group, and
$N_{observed,C,A}$ = observed total crashes in after condition in the CG comparison group

Next, the variance of the estimate after period crashes was calculated as presented in Equation 3. It important to note that these estimates refer to that of an ideal comparison and would represent identical crash trends per year to the treatment group (42). However, as Gross et al. stated, these estimations remain valid with the understanding that they remain a conservative estimation of the CMF. In doing so, the Equation 4 and Equation 5 were applied to calculate the CMF and their respective variance values.

$$VAR(N_{expected,T,A}) = N_{expected,T,A}{}^{2}\left(\frac{1}{N_{observed,T,B}} + \frac{1}{N_{observed,C,B}} + \frac{1}{N_{observed,C,A}}\right) \qquad (3)$$

$$CMF = \frac{\left(\frac{N_{observed,T,A}}{N_{expected,T,A}}\right)}{\left(1+Var\left(\frac{N_{expected,T,A}}{N_{expected,T,A}{}^{2}}\right)\right)} \qquad (4)$$

$$Variance(CMF) = \frac{CMF^{2}\left[\left(\frac{1}{N_{expected,T,A}}\right)+Var\left(\frac{N_{expected,T,A}}{N_{expected,T,A}{}^{2}}\right)\right]}{\left[1+Var\left(\frac{N_{expected,T,A}}{N_{expected,T,A}{}^{2}}\right)\right]^{2}} \qquad (5)$$

Lastly, each of the CMFs were verified in their significance through an evaluation of standard error (as presented in Equation 6). The standard error referred to the deviation from the mean, with a smaller error providing greater certainty in the estimation of the CMF. It remains important to note that the confidence interval created by standard error was verified from a 95% and 90% significance, which was explained further in the results section.

$$Standard\ Error_{CMF} = \sqrt{Variance(CMF)} \qquad (6)$$

2.4 Operational and Infrastructure Impacts

The FYA inventory survey conducted in this study provided up-to-date information regarding the current operational and infrastructure information regarding the 200 FYA study intersections. In an effort to provide insight into the potential confounding impacts of each, the following sections discussion the brief methods utilized in assessing these factors.

2.4.1. Analysis of Supplementary Signage, All-Red Clearance, and Pedestrian Conflicts

Operational and infrastructure elements at each of the 200 FYA study intersections were evaluated during the "after" period, meaning that crashes were extracted after the implementation of the FYA at each intersection. The FYA supplementary signage was analyzed by approach; however, intersections typically utilized the signage at all approaches and therefore analysis by intersection. The all-red clearance intervals, if present, were evaluated in intervals of 0.5 s ranging from 0.5-3.5 s and 4+ s. Lastly, conflicting pedestrian intervals were evaluated based on their presence at each FYA intersection. It is important to note that this study did not take into consideration any pedestrian crashes; however, this preliminary investigation presented insight into the impacts from the signal indication on pedestrian safety impacts.

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3.0 Results

The following section presents the results from this FYA study, including the before and after crash data analysis, an approach-level cost-benefit analysis, the CMF development, and the preliminary analysis of operational and infrastructure elements at FYA approaches.

3.1 FYA Approach-Level Crash Analysis

Given the need to address approach-level crashes to identify the direct impacts of the FYA signal indication, the research team evaluated 200 study intersections across Massachusetts. Alternatively to the methods conducted in the Phase 1 study, this research evaluated intersections based on geometry rather than number of FYA signals at the intersections. As a result, 3-legged and 4-legged intersections were observed and described herein as *3-way intersection* and *4-way intersection*, respectively. Table 5 provides the breakdown of treatment sites within each category as well as the total number of crashes initially observed within each. There were 80 3-way intersections resulting in 1163 crashes, and 120 4-way intersections resulting in 2950 crashes.

Table 5: Total crashes by intersection type

Treatment Category	Description	Number of Treatment Sites	Total Number of Crashes
1	3-way intersection	80	1163
2	4-way intersection	120	2950
Total	All FYA Intersections	200	4113

The FYA approach-level before/after analysis was conducted threefold. First a comparison of treatment types was completed using each level of crash sample as explained in Figure 13, followed by an in-depth look into crash types and relative injury severity outcomes. Lastly, the FYA EPDO values were calculated and compared against the control CG intersections to highlight the percent reduction differences over the study years.

3.1.1. FYA Before/After Analysis by Crash Sample

A naïve before/after analysis was initially completed to compare the crash totals within each treatment type during each study period. Phase 1 highlighted a study regarding how the naïve before/after analysis has yielded similar effectiveness as compared to other methods such as the EB analysis (10). As previously mentioned, the results were calculated across each crash sample dataset, including intersection-level crashes, FYA approach-level crashes, LT-related crashes, and LTOT-related crashes. The explanation of these iterative samples was found in Section 2.2.2. Table 7 highlights the average annual crashes during the before and after period for each FYA treatment type, under each crash data sample. Average annual before (avg annual before) and average annual after (avg annual after) represent the average yearly crash output over the 2-years of before and 2-years of after data at each FYA intersection. The percent reduction was calculated for each of these before/after comparisons. Due to the non-normal distribution of motor vehicle crash data, a Poisson test was applied in order to determine the statistical significance of before and after average annual crashes within each category. The 90% confidence was assumed with a one-tail test to evaluate these differences, with $p<0.10$ yielding statistical significance.

Table 6: Naïve before/after analysis of FYA treatment types and crash samples

Crash Sample	Treatment Type	Avg Annual Before	Avg Annual After	% Reduction	Significant? (p-value)
Intersection Level	3-way	282.5	299	−6%	0.170
	4-way	723.5	751.5	−4%	0.851
Approach Level	3-way	92.5	92	1%	0.507
	4-way	337.5	352.5	−4%	0.794
LT Related	3-way	57.5	53.5	7%	0.304
	4-way	136	122.5	11%	0.122
LTOT Related	3-way	50	40.5	23%	**0.086***
	4-way	109	92	18%	**0.054***

Note: *90% confidence.

The results from Table 6 highlight the significance of conducting an approach-level analysis. From the intersection-level the results misconstrue the impact from FYA, given the inclusion crashes not occurring at the FYA approach. More so, the LTOT-related crash sample, representing the target crash of PPLT phasing, was essential in identifying the before and after impacts of implementing a FYA indication at signalized PPLT approaches. The iterative review of these crashes highlights the effective crash reduction at both 3-way and 4-way intersections. Both of these crash reductions were considered statistically significant at 90% confidence. That said, this does not reflect the severity of the injuries sustained in the crashes, nor the type of crashes.

3.1.2. FYA Injury Severity and Crash Type

Given the need to distinguish severity of crash outcomes, the research team conducted an analysis regarding *Injury Severity* and *Manner of Collision* to determine their crash reduction rates. The "Crash Severity Description" field was utilized to categorize the severity of each crash in the sample, including the following: fatal injury, non-fatal injury, property damage only (none injured), and not reported. It remains important to note that the intersection-level crashes included very few crashes resulting in fatal injuries; however, since there were no fatal crashes reviewed at the approach level, these were evaluated as injury-related crashes in all crash data samples. Table 7 presents the average annual before and after crashes under each iterative crash sample, focusing on four main categories: injury-related (injury), severe crash (head-on, angle, and sideswipe crashes), PDO (property-damage only crashes), and rear-end (rear-end crashes only). These categories were summarized to include both 3-way and 4-way intersections.

Table 7: Injury severity and crash type for FYA crash samples

Crash Sample	Category	Avg Annual Before	Avg Annual After	% Reduction	Significant? (p-value)
Intersection level	Injury	248.5	236.5	5%	0.225
	Severe Crash	577.5	583.5	−1%	0.404
	PDO	757.5	814	−7%	**0.023****
	Rear-End	428.5	467	−8%	**0.036****
Approach level	Injury	127	123	3%	0.383
	Severe Crash	282.5	267	6%	0.187
	PDO	302	322.5	−6%	0.132
	Rear-End	147.5	177.5	−17%	**0.011****
LT related	Injury	67	60	12%	0.216
	Severe Crash	181.5	160.5	13%	**0.057***
	PDO	126.5	116	9%	0.188
	Rear-End	12	15.5	−23%	0.228
LTOT related	Injury	58	51	14%	0.198
	Severe Crash	156.5	131	19%	**0.021****
	PDO	101	81.5	24%	**0.023****
	Rear-End	2.5	1.5	67%	0.287

Note: *90% confidence; **95% confidence.

In addition to the data presented in Table 8, this information was transcribed into visualized graphics in order to better understand the before and after crash reduction differenced. Figure 16 presents the FYA approach-level crashes per injury severity and crash type. In this iteration, reviewing crashes that only occurred on the approach with an FYA, there was still an apparent increase in both rear-end crashes and crashes resulting in PDO; however, the crash reduction trend of head-on, angle, sideswipe crashes, and the crashes resulting in injury began to increase.

Figure 17 presents the LT-related crashes per injury severity and crash type. This crash data sample iteration consisted of crashes that occurred at an FYA approach <u>and</u> included vehicles 'turning left' at the intersection. With the smaller sample of rear-end crashes there also yielded a smaller sample of crashes resulting in PDO. That said, there was a greater decrease rate of severe crashes which was reflected in the decrease of crashes resulting in injuries.

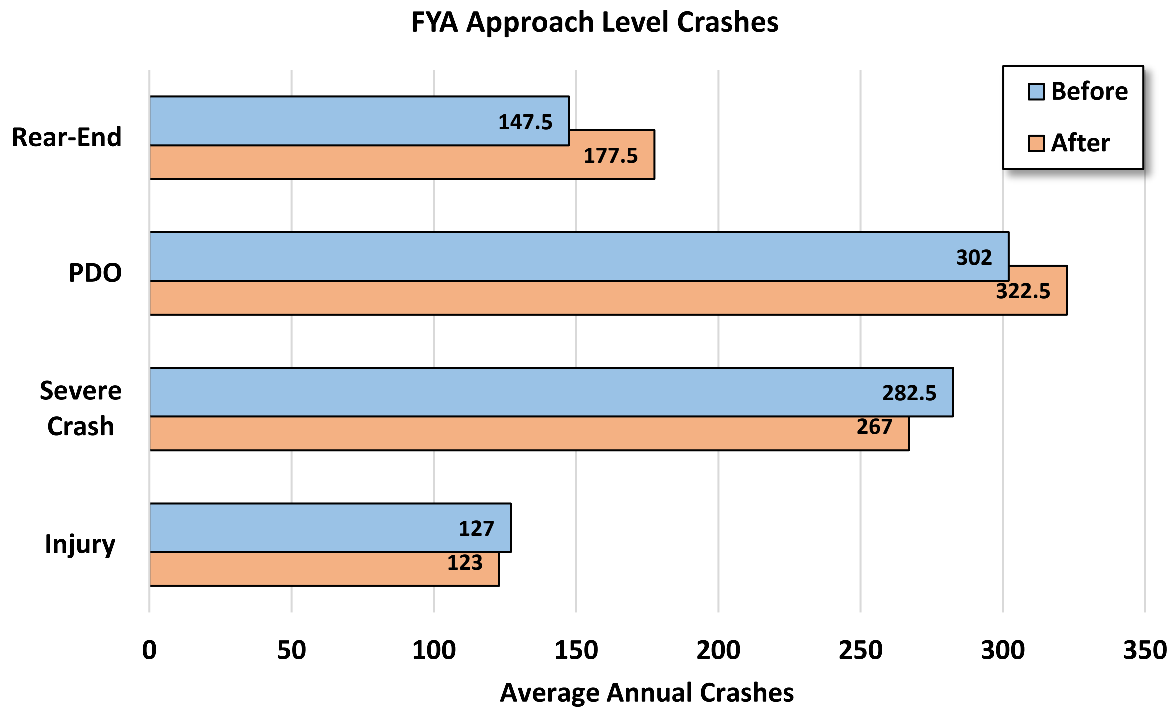

Figure 16: FYA approach-level crashes per injury severity and crash type

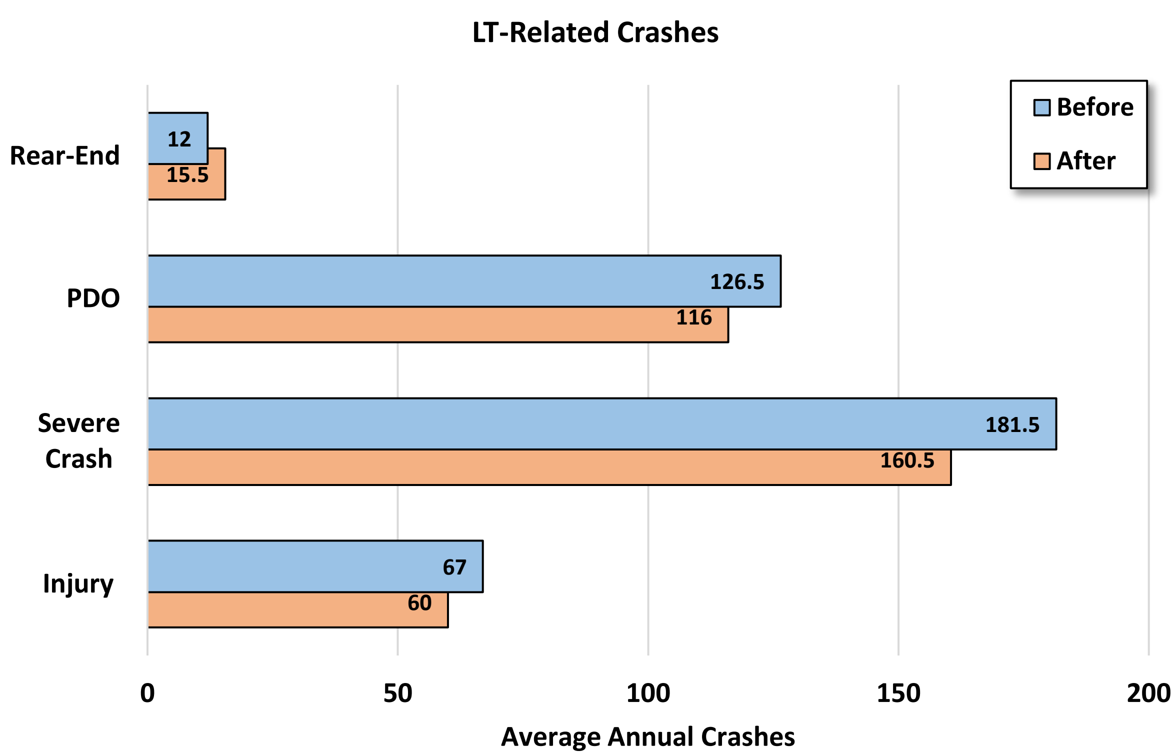

Figure 17: FYA LT-related crashes per injury severity and crash type

Figure 18 presents the LTOT-related crashes per injury severity and crash type. The final crash data sample iteration consisted of crashes that occurred at an FYA approach, including a vehicle "turning left" at the intersection, and including vehicles traveling straight through from the opposing direction. The number of rear-end crashes in this sample were minimal given that they were secondary collisions at the intersection and in most cases a results of conflicting with the primary collision vehicles. Overall, the results yielded a reduction in both crashes resulting in PDO and a significant reduction in crashes resulting in injury.

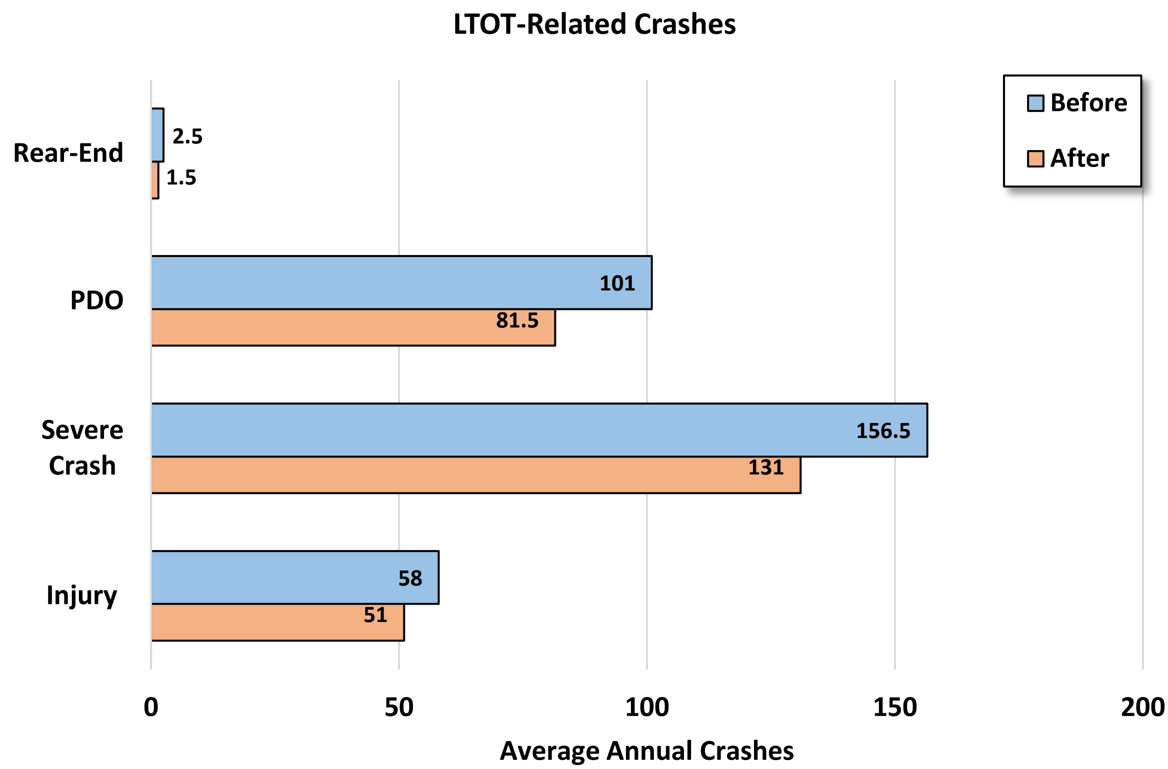

Figure 18: FYA LT-Related Crashes per Injury Severity and Crash Type

3.1.3. FYA vs CG EPDO Analysis

The naïve before/after analysis, as well as the injury severity and crash type visualizations highlighted some of the key advantages from conducting an approach-level crash study. More so, the injury severity and crash type visualizations helped develop a better understanding of the FYA safety impacts. That said, the application of equivalent property damage only (EPDO) was needed to synthesize the impacts of the FYA as compared to before conditions. As previously mentioned, the EPDO values were calculated in effort to balance the measure of injury-related crashes to not 'chase' fatal crashes in a safety analysis. Table 8 highlights the EPDO values for the FYA intersections. Here, FYA treatment types were presented separately to highlight the safety benefits of the LTOT-Related crash sample from both the 3-way and 4-way intersections.

Table 8: EPDO crashes by treatment type and crash sample for FYA intersections

Crash Sample	Treatment Type	Avg Annual Before	Avg Annual After	% Reduction	Significant? (p-value)
Intersection Level	3-way	1602.5	1839	−13%	**0.000****
	4-way	4373.5	3941.5	11%	**0.000****
Approach Level	3-way	671.5	693	−3%	0.208
	4-way	2297.5	2212.5	4%	**0.037****
LT Related	3-way	457.5	443.5	3%	0.748
	4-way	1076	932.5	15%	**0.000****
LTOT Related	3-way	430	380.5	13%	**0.008****
	4-way	889	772	15%	**0.000****

Note: **95% confidence.

In order to compare the FYA crash severity reduction holistically, an effort was made to review a sample of PPLT CG control intersections. Table 9 provides the breakdown of treatment sites within each category as well as the total number of crashes initially observed within each. There were 5 3-way intersections resulting in 83 crashes, and 17 4-way intersections resulting in 786 crashes. While the sample of 3-way intersections was small, the value accurately presents the ratio of 3-way to 4-way intersections regarding PPLT CG indications in Massachusetts. Nonetheless, in comparing EPDO values, these treatment categories were combined due to the approach-level nature of the analysis.

Table 9: CG control intersections used in developing CMF

Treatment Category	Description	Number of Treatment Sites	Total Number of Crashes
1	3-way intersection	5	83
2	4-way intersection	17	786
Total	All FYA Intersections	22	869

In a similar effort, the crashes occurring at the CG intersections were reviewed and categorized into the iterative crash samples similar to the FYA intersections. Thus, a similar comparison could be made between the average annual crash reduction between the FYA and CG. Figure 19 and Figure 20 present the comparative EPDO values for the FYA and CG, respectively. Statistical tests revealed significant reductions in EPDO for both the LT-related LTOT-related sample of FYA approach crashes (95% confidence). Alternatively, statistical tests revealed significant increases in EPDO for both the LT-related and LTOT-related sample of CG approach crashes (95% confidence).

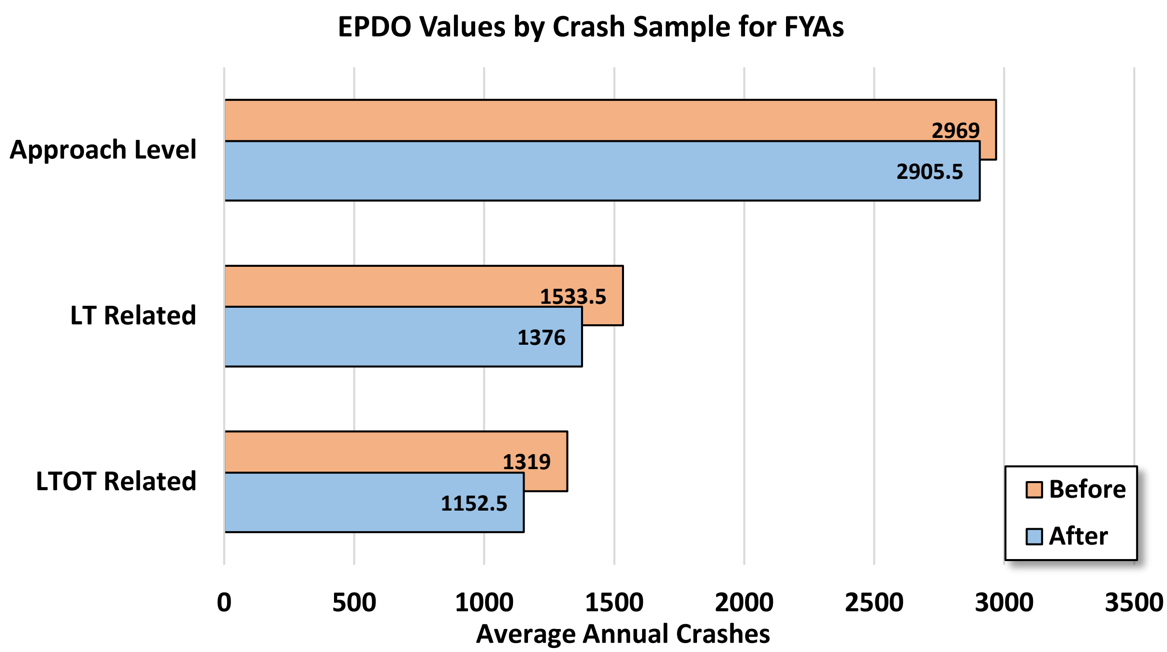

Figure 19: EPDO values by crash sample for FYAs

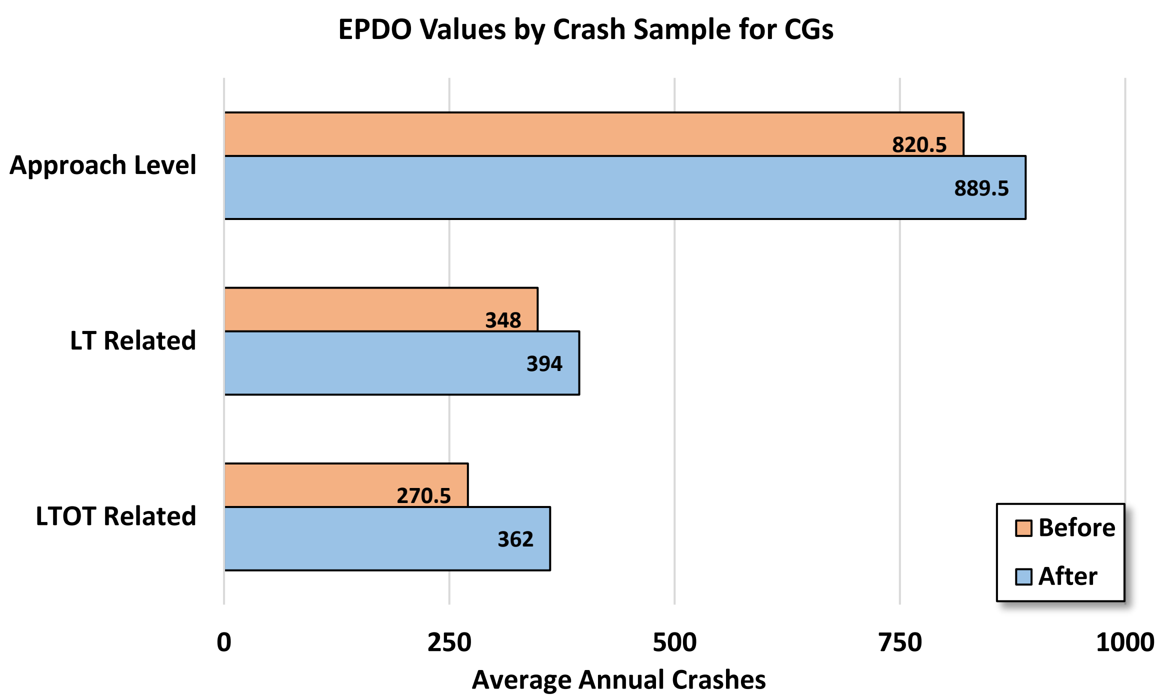

Figure 20: EPDO values by crash sample for CGs

3.2 Cost-Benefit Analysis

A cost-benefit analysis was conducted to estimate the economic impacts of an PPLT FYA signal installation at the 200 study intersections. The benefits from crash severity reduction were paired against the costs of implementation to produce a benefit-to-cost ratio (BC) of the FYA signal indication.

In order to calculate the BC ratios, the crash costs were calculated between the before and after time periods. The net benefits refer to the reduction in overall crash cost, as a rate of injury severity reduction. Given the minimal value of crashes resulting in a fatal injury, the crash costs were weighed on a KABC and O scale; meaning that fatal, serious, and minor injury crashes were calculated together against property damage only (no injury) crashes. The dollar values used to calculate the economic crash cost were converted into Massachusetts dollars (38). Table 10 presents the average annual crashes before and after FYA implementation. The severe injury crashes, as previously mentioned as KABC, were highlighted as fatal and injury (FI) crashes. FI crashes were considered to cost $441,000 per injury crash. Comparatively, the property damage only crashes were highlighted as PDO and were considered to cost $16,700 per PDO crash. As a result, the *Crash Reduction Benefits* were calculated (in Massachusetts dollars) to estimate the injury cost reclamation at both 3-way and 4-way intersections. It is important to note that the LT- and LTOT-related crash samples yielded positive crash reductions due to their overall decrease in injury severity crashes.

Table 10: Injury cost by FYA treatment type and before and after average annual crashes

Crash Sample	Treatment Category	FI (before)	PDO (before)	FI (after)	PDO (after)	Crash Reduction Benefits (MassDOT Cost)
Intersection Level	3way	66	216.5	77	222	–$4,942,850
	4way	182.5	541	159.5	592	$9,291,300
Approach Level	3way	29	62.5	30	63	–$449,350
	4way	98	239.5	93	259.5	$1,871,000
LT Related	3way	20	37.5	19.5	34	$278,950
	4way	47	89	40.5	82	$2,983,400
LTOT Related	3way	19	31	17	23.5	$1,007,250
	4way	39	70	34	58	$2,405,400

To calculate the annual expected cost of installing an FYA indication for an intersection approach, the costs as presented in Section 2.3.4. were applied to estimate the annual economic cost. The following assumptions were made to estimate these costs:

- Interest Rate: 7%
- Annual Maintenance of FYA installation: $0

- Economic expected lifespan of improvement: 20 years

These assumptions, as utilized in Phase 1 of this study, were used to derive an annualized capital recovery factor (CR),

$$CR = \frac{i(1+i)^n}{((1+i)^n - 1)} \qquad (7)$$

where
i = interest rate (7%), and
n = expected lifespan of the improvement (20 years).

Given the assumptions, a CR of 0.0944 was calculated to determine an annual treatment cost per intersection.

Table 11 displays the iterative representation of the BC ratios across each FYA crash data sample. The 3-way and 4-way intersections were summarized together in these calculations given the approach-level nature of the analysis. Comparatively to Phase 1, the FYA treatment costs were increased to reflect the increased average FYA approaches per intersection. On average, there were under 2 FYA approaches at any given 4-way intersection Massachusetts and therefore these costs were increased twofold to reflect that. Notably, this impacted the annual treatment costs that were calculated from an intersection perspective given the aforementioned cost of FYA installation. That said, annual treatment costs were calculated based on the number of intersections evaluated in that iterative crash sample. As presented in Table 11, the LT- and LTOT-related crash samples evaluated 159 and 142 FYA intersections, respectively. The LT- and LTOT-related crash data samples resulted in BC ratios ranging from 18:1 to 2:1 and 21:1 to 3:1, respectively. Given the conservative treatment cost calculations, these BC ratios yield significant benefits for the implementation of the FYA indication at PPLT signalized intersections. These results provide an impactful determination of the FYA safety benefits in Massachusetts with the emphasis on LT crashes.

Table 11: Benefit-cost ratios summarized by crash sample

Crash Sample	FYA Treatment Cost	Annualized Treatment Cost (per intersection)	Crash Reduction Benefits (MassDOT Cost)	Benefit-to-Cost Ratio (FHWA Cost)
Intersection Level *n* = 200	$12,000	$226,543	$4,348,450	19.2
	$20,000	$377,572	$4,348,450	11.5
	$100,000	$1,887,859	$4,348,450	2.3
FYA Approach Level *n* = 195	$12,000	$220,879	$1,421,650	6.4
	$20,000	$368,132	$1,421,650	3.9
	$100,000	$1,840,662	$1,421,650	0.8
LT Related *n* = 159	$12,000	$180,102	$3,262,350	18.1
	$20,000	$300,170	$3,262,350	10.9
	$100,000	$1,500,848	$3,262,350	2.2
LTOT Related *n* = 142	$12,000	$160,846	$3,412,650	21.2
	$20,000	$268,076	$3,412,650	12.7
	$100,000	$1,340,380	$3,412,650	2.5

3.4 Crash Modification Factor Development

The need for a statewide CMF for the FYA exists, given that CMFs present a benchmark for practitioners to utilize when designing to reduce the potential for crashes. Given the quantity of before and after crash years since the statewide retrofitting project to implement FYAs statewide at PPLT signalized intersections, this study developed CMFs to pinpoint safety impacts. As previously mentioned, this study employed a before and after study with comparison groups to develop CMFs. The comparison groups in this case were required to follow a set of rules, such as containing similar years of crash data, rational for external conditions at the comparison intersections (e.g., volume, geometry, etc.), and provide a sufficient sample size to yield a significant CMF estimate. In total, the sample of 22 control intersections produced an adequate sample odds ratio (as explained in Section 2.3.5).

The CMFs were developed to evaluate the impacts of before and after crash data at each of the FYA intersections as compared to those at the CG control intersections. More so, the LT- and LTOT-related crash data samples were observed in defining FYA CMFs. The following FYA crash categories were considered:

- Total Crashes – including crashes resulting in injury and PDO,
- Injury Crashes – including only crashes resulting in PDO,
- Severe Crash Types – including head-on, angle, and sideswipe crashes.

Each of the CMFs were calculated using the procedure outlined in Section 2.3.5. Table 12 presents the results for the LT- and LTOT-related crash samples including the before/after crashes within each FYA crash category. Each CMF was evaluated under confidence intervals greater than 90%. Confidence intervals (CI) measured the significance of the CMF and were calculated by multiplying the standard error by the cumulative probability factor. When the CI does not include 1.0 the CMF was considered significant; however, if the value of 1.0 was included within the CI then the CMF was considered as potentially insignificant. It remains important to note that insignificant CMFs should be dealt with caution as they may not sufficiently represent the rate of crash reduction.

Overall, the CMFs in Table 12 yield significant results across all categories within the LTOT-related crash sample and within the Injury Crash category within the LT-related crash sample. In grading CMFs, the values <1 present crash reduction, while the values >1 present crash increase. The LTOT-related sample developed significant CMFs with 95% confidence regarding severe crash type reduction (head-on, angle, sideswipe) as well as injury crash reduction; however, the total crash (including PDO) reduction remained significant at 90% confidence. Given the smaller than anticipated sample size, there were limitations in assessing the significance of these CMFs; however, the trends presented yield the likelihood of lower CMF values with the addition of sample site target crash data.

Table 12: FYA CMFs developed for LT- and LTOT-related crash samples

Crash Sample	FYA CMF Crash Category	TG Before	TG After	CG Before	CG After	Crash Modification Factor (CMF)
LT Related	Total Crashes (KABCO)	387	352	96	88	0.871
	Injury Crashes (KABC)	134	120	30	35	**0.718***
	Severe Crash Types	363	321	85	80	0.915
LTOT Related	Total Crashes (KABCO)	318	265	61	64	**0.767***
	Injury Crashes (KABC)	116	102	24	33	**0.592****
	Severe Crash Types	313	262	58	62	**0.755***

Note: *90% confidence; **95% confidence. TG = treatment group; CG = comparison group.

3.5 Preliminary Infrastructure and Operational Impacts

The up-to-date operational and infrastructure information at all 200 FYA study intersections provided through the FYA inventory survey allowed for an essential analysis. These signalized intersection components were evaluated during the "after" to evaluate their efficacy with the FYA signal indication. All-red (AR) clearance interval timing, supplementary signage, and conflicting pedestrian intervals were captured and analyzed against the FYA crash data across 2 years. The following presents a preliminary analysis of this data.

Table 13 presents the results from the all-red clearance interval evaluation. Given the varied timing utilized statewide, the intervals were separated into two categories: *less than 3 seconds* and *more than 3 seconds*. In addition, there were several intersections that did not yield enough left-turn throughput to trigger the protected phase, and as a result there were 23 intersections that were left as *unsure*. The annual average crashes and EPDO ratings were calculated across these AR timings per intersection approach. As a result, the *No All-Red* yielded the lowest EPDO rating, following by *Greater than 3 seconds* and *Less than 3 seconds*. While these results remain preliminary given their small sample size, the data has suggested that signal phasing without the all-red clearance may reduce the level of crash severity; however, if an AR should be used, an interval greater than 3 seconds remains preferred.

Table 13: All-red clearance and EPDO per FYA approach

All-Red Clearance Timing	FYA Intersections	FYA Approaches	Annual Average Crashes per Approach	Annual Average EPDO Rating per Approach
Less than 3 seconds	21	32	4.6	24.9
Greater than 3 seconds	18	32	3.9	21.7
No All-Red	138	186	3.6	18.6
Unsure	23	31	3.8	27.0

Table 14 presents the results from the supplementary signage evaluation. Here, there were a large majority of intersections that utilized the application of supplementary signage as compared to not. More so, the annual average crashes and EPDO ratings were calculated against these two conditions (*Not Present* and *Present*). As a result, the *Not Present* condition led to an EPDO rating of 17.7 per approach, while the *Present* condition led to 21.6 per approach. Given the similar annual average crashes per approach under these conditions, further investigation remains warranted to evaluate temporal impacts from signage placement.

Table 14: Supplementary signage and EPDO per FYA approach

Supplementary Signage	FYA Intersections	FYA Approaches	Annual Average Crashes per Approach	Annual Average EPDO Rating per Approach
Not Present	47	74	3.7	17.7
Present	153	207	3.8	21.6

Table 15 presents the results from the conflicting pedestrian interval evaluation. Over 150 intersections within the sample did not provide a conflicting pedestrian interval. The annual average crashes and EPDO ratings were calculated against the conditions of *Not Present, Present,* and *Unsure.* There were several intersections that did not provide sufficient information regarding conflicting pedestrian intervals or were considered complex timing intersections. As a result, the *Not Present* condition yielded a 19.5 EPDO rating as compared to the *Present* condition of 24.6. There remain safety impacts when utilizing concurrent pedestrian timing, or conflicting pedestrian intervals, and therefore the larger EPDO under the *Present* was expected.

Table 15: Conflicting pedestrian interval and EPDO per FYA approach

Conflicting Pedestrian Interval	FYA Intersections	FYA Approaches	Annual Average Crashes per Approach	Annual Average EPDO Rating per Approach
Not Present	153	215	3.6	19.5
Present	22	33	4.3	24.6
Unsure	25	33	4.0	23.7

The results provided regarding infrastructure and signal operations with the PPLT FYA signal were crucial in identifying strategies to improve injury severity reduction. That said, these analyses remain preliminary given their small sample size in nature, and future investigation remains warranted to determine quantifiable impacts.

4.0 Implementation and Technology Transfer

This research study redefined the critical nature of evaluating infrastructure and operational information at signalized infrastructure throughout the Commonwealth of Massachusetts, primarily through the lens of an FYA safety and efficacy analysis. While intersection-level safety analyses remain prevalent throughout the profession, there remains a need to siphon crash data further into an approach level to identify target crashes. With the growing number of FYAs being installed in Massachusetts, this study provided the unique insight into crash causation across all locations and identified the true net benefit of implementing the FYA for PPLT phasing.

In this research study, the FYA was evaluated from an approach level, meaning that every crash included in this study was reviewed and verified to be affiliated with the FYA signalized approach. While the research team worked diligently to manually review thousands of crash reports, a future endeavor could build on adapting machine learning technologies to assess crash reports (including narratives and diagrams) to better enhance intersection safety analyses.

There were a few limitations that were presented in this research. First and foremost, the limited sample size and statistical strength continue to challenge researchers regarding niche intersection crash data. Given the low sample size within the LT- and LTOT-related sample groups, a follow-up analysis should be considered in coming years in order to provide more inclusive representation of FYA intersection crashes. Additionally, the signalized intersection information was challenging to inventory across Massachusetts. The digitalization of traffic signal phasing plans should be made widely available to researchers in an effort to optimize infrastructure and operations-based research studies. Lastly, there was a discrepancy between 3-way and 4-way intersection results with FYAs; therefore, further analyses remain to evaluate the effects of FYAs at 3-way intersections comparatively to 4-way installations.

Given the findings of this study, which revealed encouraging benefit-to-cost ratios for LT-related crashes, a net reduction in injury severity, significant statewide CMFs for FYAs, and infrastructure assessments, there should be a methodical outreach plan to disseminate the benefits of the FYA for PPLT at signalized intersections. The results from this statewide FYA evaluation should also be applied with the implementation of FYA signals on local roadways. Thus, there remains a need to provide outreach and communications to local municipalities regarding the recommendations of FYAs to maximize safety benefits.

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5.0 Conclusions

This research endeavor sought to evaluate the safety of the flashing yellow arrow (FYA) signal indication, utilized under PPLT phasing, through an in-depth approach-level analysis. Given the novelty of the FYA in Massachusetts, this research provided MassDOT with a greater understanding of their impacts from an approach-level perspective. The study was conducted across four main tasks, with their respective results explained as follows.

A statewide field data collection effort was initiated to inventory both operational and infrastructure information at over 300 PPLT signalized intersections. The data was collected through the application of Qualtrics survey that was deployed in the field. The attributes collected include all-red clearance interval presence and timing, the application of supplementary signage at FYA signals, and the presence of conflicting pedestrian intervals. This data inventory may be utilized moving forward to continue collecting and evaluating the safety impacts of these operational and infrastructure elements.

A thorough before/after analysis was completed to evaluate the approach-level safety impacts of the FYA. Crash data was extracted utilizing the MassDOT IMPACT tool and cleaned to represent the crashes occurring at statewide FYA intersections. Crash reports were compiled from the RMV to include narratives and crash diagrams for all crashes. These were used to conduct a manual review of all FYA intersections crashes, ultimately leading to four main iterative crash sample categories: intersection-level, FYA approach level, LT-related, and LTOT-related. As a result, a total of 200 FYA intersections were selected for the analysis based on these filtering methods. The naïve before/after analysis yielded significant reductions in crashes for both 3-way and 4-way FYA intersections, primarily focused on the LTOT-related crash data sample. This represented the target crashes of PPLT phasing and was essential in identifying the before/after impacts of FYA indications. Further, *injury severity* and *manner of collision* was evaluated to assess the crash types and injury outcomes. The LT- and LTOT-related data yielded a reduction in crashes resulting in injury and PDO, in addition to a reduction in severe crash types (head-on, angle, sideswipe). Lastly, a measure of EPDO values was conducted to assess injury-related crashes. A sample of 22 CG control intersections were selected as comparison in before/after EPDO values. Statistical tests revealed significant reductions in EPDO for both the LT- and LTOT-related samples of FYA crashes (95% confidence); however, there were significant increases in EPDO for both the LT- and LTOT-related sample of CG crashes (95% confidence). As an added note, the 3-way intersections yielded a less significant outcome, and therefore 4-way intersection installations should be prioritized.

A cost-benefit analysis was conducted to estimate the economic impacts of an PPLT FYA signal installation at the two hundred study intersections. The benefits from crash severity reduction were paired against the costs of implementation to produce a benefit-to-cost ratio (BC) of the FYA signal indication. The severe injury crashes, as previously mentioned as KABC, were highlighted as fatal and injury (FI) crashes. FI crashes were considered to cost \$441,000 per injury crash. Comparatively, the property damage only crashes were highlighted as PDO and were considered to cost \$16,700 per PDO crash. The LT- and

LTOT-related crash data samples resulted in BC ratios ranging from 18:1 to 2:1 and 21:1 to 3:1, respectively. Given the conservative treatment cost calculations, these BC ratios yield significant benefits for the implementation of the FYA indication at PPLT signalized intersections. These results provide an impactful determination of the FYA safety benefits in Massachusetts with the emphasis on LT crashes.

A before and after with comparison groups analysis was conducted in an effort to develop a statewide CMF for the PPLT FYA. In total, the sample of twenty-two control intersections produced an adequate sample odds ratio (as explained in Section 2.3.5). The LT- and LTOT-related crash samples were observed in defining FYA CMFs. The LTOT-related sample established significant CMFs with 95% confidence regarding severe crash type reduction (head-on, angle, sideswipe) as well as injury crash reduction; however, the total crash (including PDO) reduction remained significant at 90% confidence. Given the smaller than anticipated sample size, there were limitations in assessing the significance of these CMFs; however, the trends presented yield the likelihood of lower CMF values with the addition of sample site target crash data.

Lastly, the up-to-date operational and infrastructure information at all 200 FYA study intersections provided through the FYA inventory survey allowed for an essential analysis regarding their safety impacts. All-red (AR) clearance interval timing, supplementary signage, and conflicting pedestrian intervals were captured and analyzed against the FYA crash data across 2 years. The *No All-Red* yielded the lowest EPDO rating, following by *Greater than 3 seconds* and *Less than 3 seconds*. While these results remain preliminary given their small sample size, the data has suggested that signal phasing without the all-red clearance may reduce the level of crash severity; however, if an AR should be used, an interval greater than 3 seconds remains preferred. In evaluating the presence of Supplementary Signage, the *Not Present* condition led to an EPDO rating of 17.7 per approach, while the *Present* condition led to 21.6 per approach. Given the similar annual average crashes per approach under these conditions, further investigation remains warranted to evaluate temporal impacts from signage placement. In evaluating the presence of conflicting pedestrian intervals, the *Not Present* condition yielded a 19.5 EPDO rating as compared to the *Present* condition of 24.6. There remain safety impacts when utilizing conflicting pedestrian intervals and therefore the larger EPDO under the *Present* condition was expected.

Future work should focus on the driver comprehension regarding the implementation of new FYA applications such as the 3-section permissive-only LT FYA signal indications, as well as the application of the protected-permissive right-turn FYA. These signal applications have started to appear across Massachusetts and require additional evaluation regarding their effectiveness and benefit. More so, the results from this study suggest further investigation into the all-red clearance interval phasing in Massachusetts regarding PPLT intersections. While research has been forthcoming regarding the national guidance on these designs, there still exists a need to assess the statewide recommendations for consistency purposes. Lastly, given the challenges of obtaining accurate and reliable volume information in Massachusetts, there continues to be a need to evaluate these infrastructure elements through more powerful statistical means. These data should prove impactful in assisting with evaluating the 3-way vs

4-way FYA installations as explained previously. Regardless, the evaluation of signalized infrastructure will continue to remain crucial and thus the inclusion of reliable crash, volume, and roadway inventory will be pivotal to assess crash reductions across Massachusetts.

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7.0 Appendices

7.1 Appendix A: Example of FYA/CG Inventory Survey (translated to text)

MassDOT Permissive Left-Turn Intersection Inventory (CG and FYA Indications)

Please follow the questions below for each Flashing Yellow Arrow (FYA) or Circular Green (CG) permissive left-turn indication that you inventory.

1) What is your name?

2) What is the FID of the intersection you are surveying? (Please double check the CG location or FYA locations files). Example: FYA-19 or CG-102

3) What town/city is the intersection located?

4) What is the configuration of the intersections?

- 3-way intersection
- 4-way intersection

5) What is the primary permissive LT indication used by left-turning vehicles at this intersection? (aka, what list does this FID come from.)

- FYA
- CG (5-section) or CG (4-section)

6a) How many approaches with a permissive left-turn FYA are located at this intersection?

- 1
- 2
- 3
- 4

6b) How many approaches with a permissive left-turn CG are located at this intersection?

- 1
- 2
- 3
- 4

7a) FYA #1:
What approach is the FYA located? Enter street name (Example: Main St <u>OR</u> Main Rd)

8a) When facing the FYA signal, what direction are you facing?

- N
- S
- E
- W
- NW
- SW
- NE
- SE

9a) Is there an all-red clearance when transitioning to permissive FYA?

- Yes
- No

10a) What is the duration of the All-Red indication? Try timing it 3 different times and take the average (round to the nearest option below)

- 1 second
- 2 seconds
- 2.5 seconds
- 3 seconds
- 3.5 seconds
- 4+ seconds
- No All-Red

11a) Is there supplementary signage for the left-turn FYA?

- Yes
- No

12a) Is there a conflict between left-turning vehicles and pedestrians? (Are pedestrians allowed to cross a parallel crosswalk while vehicles turn left?)

- Yes
- No
- Unsure

Questions 7-12 repeated for additional PPLT signals at the studied intersection

7.2 Appendix B: List of FYA Study Intersections

ID	Intersection Name	City/Town	Int. Type	X	Y	FYA App.	All-Red Clearance	Supp. Signage	Conf. Ped Phase
1	SR 2A & SR 119 (Nagog Park)	ACTON	3-way	42.5216	−71.4336	1	No	No	No
2	SR 2A & SR 119 (Great Road)	ACTON	3-way	42.4830	−71.4157	1	No	Yes	No
3	SR 159 (Main Street)	AGAWAM	3-way	42.0696	−72.6152	1	No	Yes	No
4	SR 159 (Main Street)	AGAWAM	4-way	42.0679	−72.6156	2	No	Yes	No
5	SR 159 (Main Street)	AGAWAM	4-way	42.0776	−72.6146	2	No	Yes	No
6	SR 28 (South Main Street)	ANDOVER	3-way	42.6461	−71.1334	1	No	Yes	No
7	SR 28 (Main Street)	ANDOVER	4-way	42.6494	−71.1357	1	No	Yes	No
8	US 7 & 20 (Pittsfield Road)	LENOX	4-way	42.4048	−73.2652	2	No	Yes	No
9	SR 126 (Pond Street)	ASHLAND	4-way	42.2419	−71.4313	3	No	No	No
10	SR 2A (South Main Street)	ATHOL	3-way	42.5821	−72.2552	1	No	Yes	No
11	US 1 (Washington Street)	ATTLEBORO	4-way	41.8962	−71.3704	1	No	No	No
12	SR 12 (Southbridge Street)	AUBURN	4-way	42.2064	−71.8337	4	Yes	No	No
13	SR 12 (Southbridge Street)	AUBURN	3-way	42.1951	−71.8440	1	No	Yes	No
14	SR 12 (Southbridge Street)	AUBURN	4-way	42.2042	−71.8364	2	No	No	No
15	SR 12 (Southbridge Street)	AUBURN	4-way	42.1889	−71.8489	1	No	Yes	No
16	SR 12 (Southbridge Street)	AUBURN	4-way	42.2010	−71.8395	2	No	Yes	No
17	SR 28 (Falmouth Road)	BARNSTABLE	3-way	41.6376	−70.4518	1	Yes	Yes	No

18	SR 28 (Falmouth Road)	BARNSTABLE	4-way	41.6569	−70.3499	1	Yes	Yes	No
19	SR 28 (Falmouth Road)	BARNSTABLE	4-way	41.6523	−70.3715	2	Unsure	Yes	Unsure
20	SR 28 (Falmouth Road)	BARNSTABLE	4-way	41.6523	−70.4045	2	Unsure	Yes	No
21	SR 9 (Federal Street & Sargent Street)	BELCHERTOWN	4-way	42.2893	−72.4067	1	No	Yes	No
22	SR 9 (Federal Street)	BELCHERTOWN	3-way	42.2912	−72.4091	1	Yes	Yes	No
23	SR 126 (North Main Street)	BELLINGHAM	3-way	42.0873	−71.4748	1	No	Yes	No
24	SR 126 & SR 140 (Mechanic Street)	BELLINGHAM	4-way	42.0864	−71.4741	1	No	Yes	Unsure
25	SR 140 (Mechanic Street)	BELLINGHAM	3-way	42.0816	−71.4643	1	No	No	No
26	SR 1A (Dodge Street)	BEVERLY	3-way	42.5771	−70.8906	1	No	Yes	No
27	SR 3A (Boston Road)	BILLERICA	3-way	42.5380	−71.2438	1	No	Yes	Unsure
28	SR 117 (Main Street)	BOLTON	4-way	42.4312	−71.5950	2	No	Yes	No
29	SR 37 (Washington Street)	BRAINTREE	3-way	42.2018	−71.0072	1	Yes	Yes	No
30	SR 37 (Washington Street)	BRAINTREE	3-way	42.1884	−71.0075	1	No	Yes	No
31	SR 3A (Cambridge Street)	BURLINGTON	4-way	42.5050	−71.1959	1	No	No	No
32	SR 3A (Cambridge Street)	BURLINGTON	3-way	42.5241	−71.2198	1	No	Yes	No
33	SR 4 (North Road)	CHELMSFORD	3-way	42.6312	−71.3736	1	No	Yes	No
34	SR 3A (Tyngsboro Road)	CHELMSFORD	3-way	42.6396	−71.3836	1	No	Yes	No
35	SR 110 (Chelmsford Street)	CHELMSFORD	3-way	42.6114	−71.3357	1	No	Yes	No
36	SR 129 (Billerica Road)	CHELMSFORD	3-way	42.5893	−71.3145	1	No	Yes	No

37	SR 4 (North Road)	CHELMSFORD	4-way	42.6268	−71.3691	2	No	Yes	No
38	SR 3A (Cushing Highway)	COHASSET	4-way	42.2335	−70.8220	1	Yes	Yes	No
39	Endicott Street	DANVERS	3-way	42.5488	−70.9382	1	Unsure	Yes	No
40	Endicott Street	DANVERS	4-way	42.5493	−70.9343	1	No	Yes	No
41	SR 2A & SR 119 (Great Road)	LITTLETON	4-way	42.5465	−71.4729	4	Yes	Yes	No
42	SR 114 (Andover Street)	DANVERS	3-way	42.5555	−70.9657	1	Unsure	No	No
43	SR 114 (Andover Street)	DANVERS	4-way	42.5547	−70.9640	2	No	Yes	No
44	SR 35 (High Street)	DANVERS	4-way	42.5578	−70.9284	1	No	No	No
45	SR 35 (High Street)	DANVERS	4-way	42.5583	−70.9295	1	No	No	Yes
46	SR 35 (High Street)	DANVERS	3-way	42.5585	−70.9299	1	No	Yes	Unsure
47	SR 2A (Great Road)	ACTON	4-way	42.5019	−71.4195	3	No	Yes	No
48	US 6 (State Road)	DARTMOUTH	4-way	41.6409	−71.0064	2	No	Yes	No
49	US 6 (State Road)	DARTMOUTH	3-way	41.6408	−71.0040	1	No	Yes	Yes
50	SR 5 & SR 10 (South Deerfield Bypass)	DEERFIELD	4-way	42.4826	−72.6127	2	No	Yes	Yes
51	SR 28 (Main Street)	DENNIS	4-way	41.6675	−70.1480	3	Yes	Yes	No
52	SR 10 (Northampton Street)	EASTHAMPTON	4-way	42.2812	−72.6696	1	No	Yes	No
53	SR 138 (Washington Street)	EASTON	4-way	42.0667	−71.0873	4	Yes	No	Yes
54	SR 140 (West Central Street)	FRANKLIN	3-way	42.0865	−71.4442	1	No	Yes	No
55	King Street	FRANKLIN	3-way	42.0656	−71.4003	1	No	Yes	No
56	SR 140 (E. Central Street)	FRANKLIN	4-way	42.0803	−71.3846	2	No	No	No
57	SR 2 & SR 2A (Mohawk Trail & French King Hwy)	GILL	4-way	42.6131	−72.5488	2	Yes	Yes	No
58	SR 128	GLOUCESTER	4-way	42.6196	−70.6488	2	No	Yes	Yes

59	US 7 & SR 183 (Stockbridge Road)	GREAT BARRINGTON	4-way	42.2107	−73.3455	2	No	Yes	No
60	US 7 & SR 23 (State Road)	GREAT BARRINGTON	3-way	42.2015	−73.3491	1	No	Yes	No
61	US 7 & SR 183 (Stockbridge Road)	GREAT BARRINGTON	3-way	42.2486	−73.3316	1	No	Yes	No
62	SR 2A (Mohawk Trail)	GREENFIELD	4-way	42.5855	−72.6127	2	Yes	Yes	No
63	SR 53 (Washington Street)	HANOVER	4-way	42.1494	−70.8455	1	Yes	Yes	No
64	SR 110 & SR 113 (River Street)	HAVERHILL	4-way	42.7727	−71.1163	1	No	No	No
65	SR 53 (Whiting Street)	HINGHAM	4-way	42.1827	−70.9034	2	Yes	No	No
66	SR 141 (Easthampton Road)	HOLYOKE	4-way	42.2175	−72.6374	1	No	Yes	No
67	SR 8 (Cheshire Road)	LANESBOROUGH	3-way	42.4888	−73.2028	1	No	Yes	No
68	SR 8 (Cheshire Road)	LANESBOROUGH	3-way	42.4937	−73.2018	1	No	Yes	No
69	SR 102 (Pleasant Street)	LEE	4-way	42.2952	−73.2393	2	No	Yes	No
70	US 7 & 20 (Veterans Memorial Hwy)	LENOX	3-way	42.3723	−73.2774	1	No	Yes	No
71	US 20 (Lee Road)	LENOX	3-way	42.3433	−73.2706	1	No	Yes	No
72	US 7 & 20 (Pittsfield Road)	LENOX	4-way	42.3971	−73.2698	1	No	Yes	No
73	US 20 (West Housatonic Street)	LENOX	4-way	42.3774	−73.2770	2	No	Yes	No
74	SR 13 (Main Street)	LEOMINSTER	3-way	42.5372	−71.7444	1	No	Yes	No
75	SR 12 (Central Street)	LEOMINSTER	4-way	42.4936	−71.7452	1	No	Yes	No
76	SR 2A (Marrett Road)	LEXINGTON	4-way	42.4359	−71.2346	2	No	No	No
77	SR 2A (Marrett Road)	LEXINGTON	4-way	42.4457	−71.2630	1	Yes	Yes	No

78	SR 2A (Marrett Road)	LEXINGTON	3-way	42.4343	−71.2417	1	No	Yes	No
79	Spring Street	LEXINGTON	4-way	42.4251	−71.2504	4	No	Yes	Yes
80	SR 2A (Marrett Road)	LEXINGTON	4-way	42.4447	−71.2615	1	No	Yes	Unsure
81	SR 38 (Nesmith Street)	LOWELL	4-way	42.6422	−71.2976	1	No	No	No
82	SR 107 (Highland Avenue)	LYNN	3-way	42.4875	−70.9387	1	Unsure	Yes	Unsure
83	SR 140 (Commercial Street)	MANSFIELD	4-way	42.0173	−71.2275	1	No	Yes	No
84	US 20 (West Main Street)	MARLBOROUGH	3-way	42.3396	−71.5620	1	No	No	No
85	US 20 (Boston Post Road)	MARLBOROUGH	4-way	42.3356	−71.6021	1	No	Yes	No
86	SR 28 (Falmouth Road)	MASHPEE	4-way	41.6282	−70.4725	3	Yes	Yes	Unsure
87	SR 140 (Cape Road)	MENDON	4-way	42.1029	−71.5042	1	Yes	Yes	No
88	SR 110 (Jackson Street)	METHUEN	4-way	42.7225	−71.1587	1	No	Yes	No
89	SR 113 (Pleasant Valley Street)	METHUEN	4-way	42.7411	−71.1681	1	Yes	No	Yes
90	SR 38 (Mystic Avenue)	SOMERVILLE	4-way	42.3956	−71.0891	1	No	Yes	Unsure
91	SR 110 (Merrimack Street)	METHUEN	4-way	42.7460	−71.1298	2	No	No	No
92	SR 28 (East Grove Street)	MIDDLEBOROUGH	4-way	41.8860	−70.9171	4	Yes	Yes	No
93	SR 105 (South Main Street)	MIDDLEBOROUGH	3-way	41.8837	−70.9196	1	Yes	Yes	Yes
94	SR 105 (South Main Street)	MIDDLEBOROUGH	3-way	41.8812	−70.9227	1	Yes	Yes	Yes
95	SR 140 (South Main Street)	MILFORD	4-way	42.1272	−71.5182	2	No	Yes	No
96	SR 16 (East Main Street)	MILFORD	4-way	42.1534	−71.4895	2	Yes	Yes	No
97	SR 122 (Grafton Road)	MILLBURY	3-way	42.2303	−71.7386	1	No	Yes	Yes
98	Coggeshall Street	NEW BEDFORD	4-way	41.6561	−70.9196	3	Yes	Yes	No

99	SR 113 (Storey Avenue)	NEWBURYPORT	3-way	42.8221	−70.9034	1	No	Yes	Yes
100	SR 2 (Mohawk Trail)	NORTH ADAMS	3-way	42.6984	−73.1370	1	No	Yes	No
101	SR 2 (Mohawk Trail)	NORTH ADAMS	3-way	42.7001	−73.1643	1	No	Yes	Yes
102	SR 8 (Curran Highway)	NORTH ADAMS	3-way	42.6802	−73.1065	1	No	Yes	No
103	SR 114 (Salem Turnpike)	NORTH ANDOVER	4-way	42.6733	−71.1259	2	No	Yes	No
104	SR 114 (Salem Turnpike)	NORTH ANDOVER	4-way	42.6676	−71.1180	1	No	Yes	No
105	SR 114 (Salem Turnpike)	NORTH ANDOVER	4-way	42.6749	−71.1281	2	No	No	No
106	SR 114 (Salem Turnpike)	NORTH ANDOVER	3-way	42.6763	−71.1302	1	No	No	No
107	US 1 (East Washington Street)	NORTH ATTLEBORO	4-way	41.9813	−71.3297	2	Yes	No	No
108	Robert F. Toner Boulevard	NORTH ATTLEBORO	3-way	41.9691	−71.2984	1	No	No	Unsure
109	SR 28 (Main Street)	NORTH READING	4-way	42.5891	−71.1163	2	No	Yes	Unsure
110	SR 10 (South Street)	NORTHAMPTON	3-way	42.3062	−72.6472	1	No	No	No
111	SR 5 & SR 10 (North King Street)	NORTHAMPTON	3-way	42.3416	−72.6410	1	No	Yes	Yes
112	US 20 (Southwest Cutoff)	NORTHBOROUGH	3-way	42.2813	−71.6708	1	No	Yes	No
113	US 20 (Southwest Cutoff)	NORTHBOROUGH	4-way	42.3006	−71.6573	1	No	No	No
114	US 20 (Southwest Cutoff)	NORTHBOROUGH	3-way	42.3074	−71.6576	1	No	Yes	No
115	SR 53 (Washington Street)	NORWELL	4-way	42.1721	−70.8788	1	Yes	Yes	No
116	SR 53 (Washington Street)	NORWELL	4-way	42.1595	−70.8538	1	No	Yes	No
117	SR 1A (Walpole Street)	NORWOOD	3-way	42.1798	−71.2210	1	No	No	Unsure
118	SR 6A (Cranberry Highway)	ORLEANS	4-way	41.7803	−69.9999	1	Unsure	Yes	No

119	US 20 (North Main Street)	PALMER	4-way	42.1632	−72.3434	1	No	Yes	No
120	SR 32 (Thorndike Street & Ware Road)	PALMER	4-way	42.1787	−72.3194	1	No	Yes	Yes
121	SR 32 (Thorndike Street)	PALMER	3-way	42.1689	−72.3263	1	Yes	Yes	No
122	SR 114 (Andover Street)	PEABODY	3-way	42.5439	−70.9425	1	No	Yes	No
123	Lowell Street	PEABODY	4-way	42.5490	−70.9851	1	Unsure	Yes	No
124	SR 53 (Columbia Road)	PEMBROKE	4-way	42.1040	−70.8037	1	Yes	Yes	No
125	US 20 (West Housatonic Street)	PITTSFIELD	4-way	42.4436	−73.2698	1	No	Yes	No
126	US 20 (West Housatonic Street)	PITTSFIELD	4-way	42.4396	−73.2983	1	No	Yes	No
127	SR 9 (Dalton Avenue)	PITTSFIELD	4-way	42.4689	−73.2005	1	Yes	Yes	No
128	SR 7 & 20 (South St)	PITTSFIELD	4-way	42.4166	−73.2609	2	No	No	No
129	SR 8 (Cheshire Road)	PITTSFIELD	3-way	42.4701	−73.2038	1	No	Yes	No
130	US 20 (West Housatonic Street)	PITTSFIELD	4-way	42.4432	−73.2681	1	No	Yes	No
131	SR 7 & 20 (South St)	PITTSFIELD	4-way	42.4263	−73.2597	2	No	Yes	No
132	Commerce Way	PLYMOUTH	3-way	41.9644	−70.7083	1	Yes	Yes	No
133	SR 80 (Plympton Road)	PLYMOUTH	4-way	41.9468	−70.7162	2	Yes	Yes	No
134	US 44 (Cape Highway)	RAYNHAM	3-way	41.9056	−71.0546	1	No	Yes	Unsure
135	SR 60 (Squire Road)	REVERE	4-way	42.4250	−71.0114	1	No	Yes	Unsure
136	SR 123 (Market Street)	ROCKLAND	4-way	42.1211	−70.9165	2	Yes	Yes	No
137	US 1 (Newburyport Turnpike)	ROWLEY	4-way	42.7052	−70.9091	4	No	Yes	No
138	SR 1A (Loring Avenue)	SALEM	3-way	42.5005	−70.8960	1	Unsure	Yes	Unsure

139	SR 1A (Loring Avenue)	SALEM	3-way	42.4944	−70.8937	1	Unsure	No	Unsure
140	Toll Road	SALISBURY	4-way	42.8697	−70.8829	1	No	Yes	No
141	SR 129 (Walnut Street)	SAUGUS	4-way	42.4906	−71.0187	1	Unsure	Yes	Unsure
142	Lynn Fells Parkway	SAUGUS	3-way	42.4808	−71.0232	1	Unsure	Yes	No
143	US 20 (Hartford Tpk.)	SHREWSBURY	4-way	42.2708	−71.6864	1	No	No	No
144	US 20 (Hartford Tpk.)	SHREWSBURY	4-way	42.2621	−71.6958	2	No	No	No
145	SR 10 & US 202 (College Highway)	SOUTHWICK	4-way	42.0549	−72.7701	2	No	Yes	No
146	SR 10 & US 202 (College Highway)	SOUTHWICK	3-way	42.0624	−72.7652	1	No	Yes	No
147	US 20 (Boston Post Road)	SUDBURY	4-way	42.3607	−71.4221	2	No	No	No
148	US 20 (Boston Post Road)	SUDBURY	3-way	42.3603	−71.4247	1	No	No	No
149	SR 47 (North Main St & South Main St)	SUNDERLAND	4-way	42.4664	−72.5795	2	No	No	No
150	SR 1A (Paradise Road)	SWAMPSCOTT	3-way	42.4801	−70.9045	1	No	Yes	Unsure
151	US 6 (Grand Army Highway)	SWANSEA	3-way	41.7498	−71.2165	1	No	Yes	No
152	US 6 (Grand Army Highway)	SWANSEA	3-way	41.7500	−71.2204	1	Yes	Yes	No
153	SR 38 (Main Street)	TEWKSBURY	4-way	42.5894	−71.2025	4	No	No	No
154	SR 38 (Main Street)	TEWKSBURY	4-way	42.6118	−71.2329	1	No	Yes	Yes
155	SR 38 (Main Street)	TEWKSBURY	4-way	42.6282	−71.2732	1	No	No	No
156	SR 133 (Andover Street)	TEWKSBURY	4-way	42.6428	−71.2338	2	No	Yes	No
157	SR 133 (Andover Street)	TEWKSBURY	4-way	42.6427	−71.2297	1	No	Yes	No
158	SR 38 (Main Street)	TEWKSBURY	4-way	42.5936	−71.2101	1	No	Yes	Yes
159	SR 38 (Main Street)	TEWKSBURY	3-way	42.6286	−71.2741	1	No	Yes	Unsure

160	SR 38 (Main Street)	TEWKSBURY	3-way	42.6257	−71.2682	1	No	Yes	Yes
161	SR 38 (Main Street)	TEWKSBURY	4-way	42.5984	−71.2187	2	No	Yes	No
162	SR 113 (Pawtucket Blvd.)	TYNGSBOROUGH	3-way	42.6757	−71.4182	1	No	Yes	No
163	Westford Road	TYNGSBOROUGH	3-way	42.6600	−71.4272	1	No	Yes	No
164	Audubon Road	WAKEFIELD	4-way	42.5140	−71.0414	1	Unsure	Yes	No
165	SR 1A (Main Street)	WALPOLE	4-way	42.1580	−71.2430	1	No	No	No
166	SR 32 (Palmer Road)	WARE	4-way	42.2395	−72.2808	1	No	Yes	No
167	SR 28 (Cranberry Highway)	WAREHAM	3-way	41.7730	−70.7360	1	Yes	Yes	Unsure
168	SR 28 (Cranberry Highway)	WAREHAM	4-way	41.7811	−70.7439	1	Yes	Yes	Yes
169	US 6 (Marion Road)	WAREHAM	3-way	41.7586	−70.7283	1	No	Yes	No
170	US 20 (Boston Post Road)	WAYLAND	4-way	42.3630	−71.3601	4	Unsure	Yes	Unsure
171	Cedar Street	WELLESLEY	4-way	42.3154	−71.2466	1	Yes	No	No
172	SR 12 (West Boylston Street)	WEST BOYLSTON	4-way	42.3504	−71.7854	2	No	No	No
173	Long Pond Road	PLYMOUTH	3-way	41.9347	−70.6571	1	No	No	Unsure
174	Long Pond Road	PLYMOUTH	3-way	41.9366	−70.6563	1	Yes	Yes	No
175	US 20 (East Main Street)	WESTFIELD	4-way	42.1125	−72.7187	1	No	Yes	No
176	US 20 (Springfield Road)	WESTFIELD	3-way	42.1125	−72.7134	1	Yes	Yes	No
177	SR 10 & US 202 (Southampton Road)	WESTFIELD	4-way	42.1753	−72.7272	2	No	Yes	No
178	SR 110 (Littleton Road)	WESTFORD	3-way	42.5569	−71.4387	1	No	No	No
179	SR 110 (Littleton Road)	WESTFORD	4-way	42.5552	−71.4446	1	No	Yes	No
180	SR 18 (Main Street)	WEYMOUTH	3-way	42.1533	−70.9552	1	No	Yes	Unsure
181	SR 18 (Main Street)	WEYMOUTH	4-way	42.1524	−70.9552	1	No	Yes	Unsure
182	SR 5 & SR 10 (State Road)	WHATELY	4-way	42.4691	−72.6147	2	No	Yes	No

183	SR 18 (Bedford Street)	WHITMAN	3-way	42.0738	−70.9474	1	Yes	No	No
184	US 20 (Boston Road)	WILBRAHAM	4-way	42.1487	−72.4413	1	No	Yes	No
185	US 20 (Boston Road)	WILBRAHAM	4-way	42.1489	−72.4435	2	No	Yes	No
186	SR 2 (Mohawk Trail)	WILLIAMSTOWN	3-way	42.7108	−73.1972	1	No	No	No
187	SR 38 (Main Street)	WILMINGTON	4-way	42.5581	−71.1820	1	No	Yes	Yes
188	SR 38 (Main Street)	WILMINGTON	3-way	42.5485	−71.1749	1	No	No	Unsure
189	SR 38 (Main Street)	WILMINGTON	3-way	42.5518	−71.1781	1	No	Yes	No
190	SR 38 (Main Street)	WILMINGTON	3-way	42.5423	−71.1678	1	No	Yes	No
191	SR 12 (Spring Street)	WINCHENDON	3-way	42.6660	−72.0104	1	No	Yes	No
192	Washington Street	WOBURN	4-way	42.4952	−71.1244	2	No	No	Yes
193	US 3 (Cambridge Street)	WOBURN	4-way	42.4614	−71.1678	1	No	No	No
194	US 20 (SW Cutoff)	WORCESTER	4-way	42.2117	−71.7954	1	No	Yes	No
195	SR 138 (Turnpike Street)	CANTON	4-way	42.1815	−71.1140	3	Yes	No	Yes
196	Plantation Street	WORCESTER	4-way	42.2923	−71.7606	1	No	Yes	Yes
197	SR 1A (South Street)	WRENTHAM	3-way	42.0385	−71.3460	1	Yes	Yes	No
198	SR 1A (South Street)	WRENTHAM	4-way	42.0362	−71.3470	1	No	Yes	No
199	SR 28	YARMOUTH	4-way	41.6506	−70.2421	2	No	Yes	Unsure
200	SR 203 (Gallivan Boulevard)	BOSTON	4-way	42.2828	−71.0561	2	No	No	No

7.3 Appendix C: EPDO Values for FYA and CG

EPDO Crashes by Treatment Type and Crash Sample (FYA)

	Average Annual Before	Average Annual After	% Reduction	Significant? (p-value)
Intersection Level	5976	5780.5	3%	**0.006**
Approach Level	2699	2905.5	2%	0.122
LT-Related	1533.5	1376	11%	**0.000**
LTOT-Related	1319	1152.5	14%	**0.000**

EPDO Crashes by Treatment Type and Crash Sample (CG)

	Average Annual Before	Average Annual After	% Reduction	Significant? (p-value)
Intersection Level	1415.5	1349	5%	0.039
Approach Level	820.5	889.5	-8%	**0.010**
LT-Related	348	394	-12%	**0.010**
LTOT-Related	270.5	362	-25%	**0.000**