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Guidance for Left-Turn Flashing Yellow Arrow (FYA) Implementation in Nebraska

Aemal J. Khattak, Ph.D.
Professor
Department of Civil & Environmental Engineering
University of Nebraska-Lincoln

Frank Selase Dzawu
Graduate Research Assistant
Department of Civil & Environmental Engineering
University of Nebraska-Lincoln

Li Zhao, Ph.D., P.E.
Research Assistant Professor
Department of Civil & Environmental Engineering
University of Nebraska-Lincoln

Nebraska Department of Transportation Research
Headquarters Address
1400 Nebraska Parkway
Lincoln, NE 68509
ndot.research@nebraska.gov
(402) 479-4697
https://dot.nebraska.gov/business-center/research/

Nebraska Transportation Center
262 Prem S. Paul Research Center at Whittier School
2200 Vine Street
Lincoln, NE 68583-0851
(402) 472-1932
http://ntc.unl.edu

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Aemal J. Khattak, Ph.D.
Professor
Department of Civil & Environmental Engineering
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Li Zhao, Ph.D., P.E.
Research Assistant Professor
Department of Civil & Environmental Engineering
University of Nebraska-Lincoln

Frank Selase Dzawu
Graduate Research Assistant
Department of Civil & Environmental Engineering
University of Nebraska-Lincoln

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16. Abstract
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17. ORCID No. of each Researcher
0000-0002-6695-9842 (Khattak)
0000-0003-1914-1041 (Zhao)
0009-0000-6743-5728 (Dzawu)

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List of Abbreviations

Akaike Information Criterion (AIC)
Annual Average Daily Traffic (AADT)
Average Marginal Effect (AME)
Colorado Department of Transportation (CDOT)
Confidence Interval (CI)
Crash Modification Factor (CMF)
Department of Transportation (DOT)
Eastbound Left (EBL)
Eastbound Through (EBT)
Federal Highway Administration (FHWA)
Flashing Yellow Arrow (FYA)
Generalized Linear Model (GLM)
Green-to-Cycle Ratio (g/C)
Illinois Department of Transportation (IDOT)
Incidence Rate Ratio (IRR)
Indiana Department of Transportation (INDOT)
Left-Turn (LT)
Manual on Uniform Traffic Control Devices (MUTCD)
National Cooperative Highway Research Program (NCHRP)
Nebraska Department of Transportation (NDOT)
Nebraska Transportation Center (NTC)
Negative Binomial (NB)
North Dakota Department of Transportation (NDDOT)
Pennsylvania Department of Transportation (PennDOT)
Perceived Yellow Trap (PYT)
Post-Encroachment Time (PET)
Protected-Permissive Left Turn (PPLT)
Root Mean Square Error (RMSE)
Southbound Left (SBL)
Transportation Research Board (TRB)
United States Department of Transportation (USDOT)
Variance Inflation Factor (VIF)
Westbound Left (WBL)
Westbound Through (WBT)
Work Breakdown Structure (WBS)

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Abstract

This research evaluates the safety performance of flashing yellow arrows (FYA) and driver behavioral responses in Nebraska, using data from 324 FYA intersections (Lincoln 160; Omaha 164) to develop evidence-based implementation guidance. The study addresses critical knowledge gaps in local driver acceptance patterns, the effectiveness of phasing configurations, and a comprehensive safety assessment that integrates crash and conflict analyses. The methodology employed four complementary analyses: (1) negative binomial crash frequency modeling of 3945 unique left turn crashes (2015-2024) across Lincoln and Omaha; (2) binary logistic regression of 948 gap acceptance decisions across 43 intersections; (3) linear regression of post-encroachment time for 613 completed left turns; and (4) detailed video investigation of 18 crashes at three Omaha intersections with lead-lag FYA phasing. Results demonstrate no statistically significant overall crash increase post-FYA installation when controlling for exposure (Lag: Incidence Rate Ratio [IRR]=0.937, p=0.364; Lead: IRR=1.027, p=0.563), though aggregate trends were influenced by five high-volume outlier intersections. Sensitivity analysis excluding outliers revealed lag phasing produced a statistically significant 15.1% reduction in crashes (IRR=0.849, p=0.038). Perceived Yellow Trap" (PYT) phenomenon, where lead-lag phasing configurations created perceptual confusion during phase transitions, accounting for 72% of observed crashes. Gap acceptance analysis showed lag phasing associated with 10% shorter critical gaps (3.85s vs. 4.28s), enabling higher operational efficiency. Recommended operational thresholds include prioritizing lag phasing at high-exposure locations, refining exposure thresholds using cross-product metrics, optimizing signal timing, and time-of-day operation. When properly implemented and following the recommended operational thresholds, FYA installation should improve intersection safety.

Chapter 1 Introduction And Background

1.1 Background on FYA Implementation in Nebraska

Flashing Yellow Arrow (FYA) signals are increasingly being adopted for permissive left turns at signalized intersections, replacing the traditional circular green indication. The FYA signal allows drivers to make left turns after yielding to oncoming traffic and pedestrians, improving safety and operations. FYA installations may operate under either leading or lagging left turn phasing.

- **Leading left turn phase:** The protected green arrow for the left turn is displayed before the opposing through movement receives a green signal. Under FYA operation, the protected arrow may be followed by a flashing yellow arrow allowing permissive turns.
- **Lagging left turn phase:** The protected green arrow for the left turn is displayed after the opposing through movement receives green. Under FYA operation, permissive turns may occur first under a flashing yellow arrow before the protected arrow appears later in the cycle.

These phasing configurations, especially leading and lagging left-turn phases, require different driver decisions and may affect gap acceptance and safety outcomes. When FYA operates under lead or lag phasing, drivers face different timing relationships with opposing traffic, which can influence how they judge and accept gaps.

This misinterpretation can result in increased intersection-related crash rates and severity, particularly at intersections with high traffic volumes (Appiah et al., 2018). Research validating FYA's superiority began with NCHRP Report 493 (2003), which recommended its inclusion in the MUTCD, citing enhanced driver comprehension and safety outcomes. This recommendation was supported by behavioral studies showing improved caution and pedestrian yielding compared to traditional circular green indications (Jashami et al., 2019). Given these promising results, the Federal Highway Administration (FHWA) granted Interim Approval (IA-10) in March 2006 for agencies to use FYA displays, ahead of their official inclusion in the 2009 Manual on Uniform Traffic Control Devices (MUTCD) in December 2009 (*FHWA MUTCD*, 2006.; TRB, 2008). This allowed states and cities to begin installing FYAs as a proven safety enhancement.

Figure 1.1 represents the timeline of FYA installations in Nebraska, showing implementation patterns in Lincoln and Omaha from 2016 to 2023. The data represent the number of FYA intersections installed each year, demonstrating the substantial deployment that motivates comprehensive safety and operational evaluations.

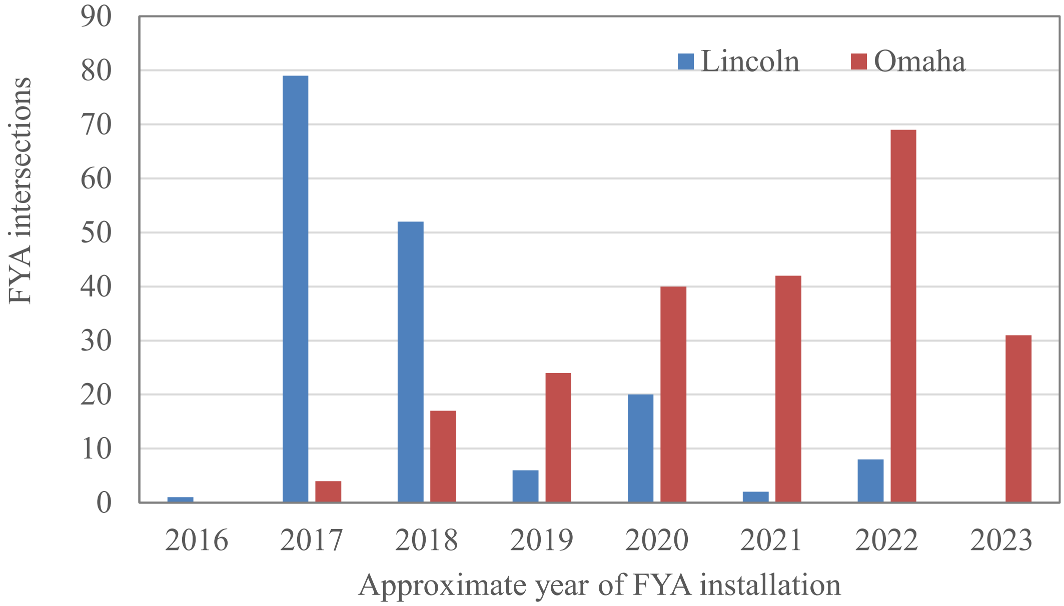


Figure 1.1 Timeline of FYA Development and Implementation in Nebraska

Following national trends and MUTCD guidance, Nebraska agencies began systematic deployment of FYA in the mid-2010s. Table 1.1 summarizes the current implementation status across major cities, showing substantial infrastructure investment that necessitates a comprehensive performance evaluation. The anticipated benefits of FYA implementation include improved safety. Research shows that drivers grasp the yielding requirement of the FYA more clearly than the circular green indication. This enhanced understanding helps avoid misinterpretation and lowers the risk of crashes (Knodler et al., 2005). FYA displays also allow traffic engineers to provide more phasing options (such as time-of-day protected/permissive operation), potentially reducing delays by providing permissive turn opportunities when appropriate. Overall, Nebraska's embrace of the FYA aligns with national trends favoring this measure as a low-cost safety improvement.

Following national trends and MUTCD guidance, Nebraska agencies began systematic FYA deployment in the mid-2010s. Table 1.1 summarizes the current implementation status across major cities, indicating substantial infrastructure investment that necessitates a comprehensive performance evaluation.

Table 1.1 Summary of FYA Implementation Status in Nebraska Cities

City/Region	**Intersections with FYA**	**FYA Signal Heads**	**Implementation Period**	**Notes**
Lincoln	168	473	2016-2023	Major deployment in 2017
Omaha	227	593	2017-2023	Gradual increase, peaked in 2022
Others in Nebraska	61	138	Installation year unknown	Smaller cities statewide
Total	456	1,204	2016-2023	Comprehensive deployment

The expected benefits of FYA implementation include improved safety through better driver understanding of yielding requirements and increased operational flexibility with different phasing options. Nebraska's adoption of FYA aligns with national trends supporting this approach as a cost-effective safety enhancement. However, a thorough evaluation of local performance results is still lacking, highlighting the need for further analysis.

Nebraska expects FYA signals to improve safety by making the yield requirement clearer and offering operational flexibility. But the Nebraska Department of Transportation (NDOT) still needs to evaluate how well they work locally. Figure 1.2 illustrates the traditional left-turn yellow trap with circular green signals, a dangerous situation where a left-turning driver enters the intersection to turn, then faces a yellow light. The driver assumes oncoming vehicles will stop when, in reality, the signals do not require them to stop, creating a crash risk. The FYA was designed to fix this by replacing the solid yellow with a flashing arrow, making it clearer that drivers must yield. However, this research identified a "Perceived Yellow Trap" (PYT) phenomenon specific to FYA lead-lag configurations, in which drivers perceive their phase is ending when the adjacent through signal changes, even though the FYA continues to flash. Thoroughly evaluating Nebraska's FYA intersections is important to identify implementation contexts that may affect safety outcomes.

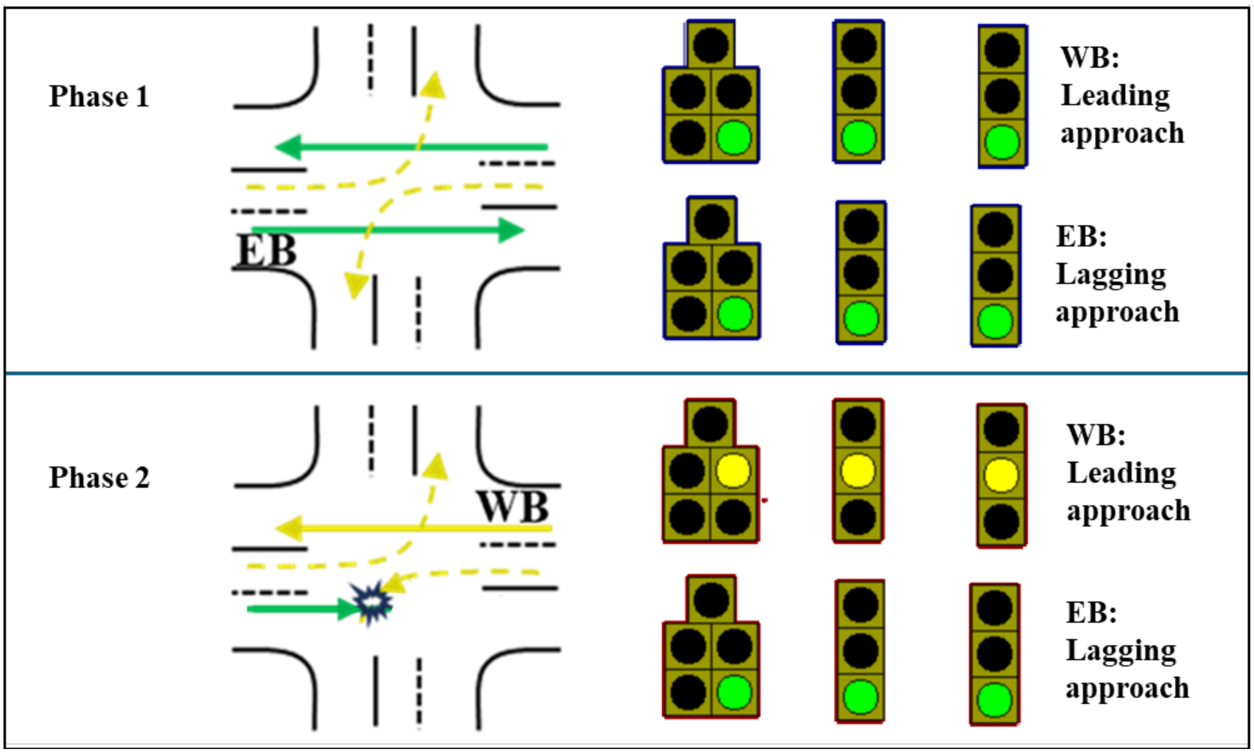


Figure 1.2 Traditional Left-Turn Yellow Trap Scenario given a Lead-Lag Condition

1.2 Problem Statement

While FYA implementation involves significant infrastructure investment, a systematic evaluation of Nebraska-specific performance remains incomplete. Three key knowledge gaps limit optimization: (1) empirical understanding of local driver gap acceptance patterns under FYA versus traditional permissive control; (2) effects of phasing configuration on safety outcomes, especially PYT mitigation effectiveness; and (3) comprehensive crash and conflict severity assessment that integrates operational and geometric factors. Without addressing these gaps, agencies cannot optimize signal timing, phasing strategies, or site selection criteria, which may result in variable safety outcomes at locations exceeding recommended implementation thresholds.

1.3 Research Objectives

Given the above problem, the research objectives of this study are designed to systematically evaluate the implementation of flashing yellow arrows from multiple angles. The study's primary objectives are:

1. Develop an evaluation framework to assess FYA safety and operational performance and determine whether phasing configuration (lead vs. lag) and operational factors significantly affect outcomes.
2. Examine driver gap acceptance behavior during permissive FYA intervals, estimate critical gaps by phase type, and assess how traffic conditions and intersection geometry influence acceptance decisions.
3. Apply Post-Encroachment Time (PET) as a surrogate safety measure to evaluate conflict severity and identify factors influencing safety risk in completed left-turn maneuvers.
4. Develop evidence-based implementation guidance for Nebraska agencies on phase selection, signal timing, and site criteria, including strategies to mitigate the PYT and optimize FYA safety performance.

1.4 Study Significance

This research addresses critical knowledge gaps in FYA implementation with implications for both Nebraska and national traffic engineering practice. The study's significance encompasses four key areas:

- Safety Validation: Analysis will confirm where and how FYA improves safety, enabling evidence-based decisions for Nebraska's intersection design. Identifying site-specific factors associated with variable safety outcomes guides agencies toward optimal implementation strategies and appropriate caution at complex locations.
- Driver Behavior Understanding: Gap acceptance analysis under FYA conditions advances behavioral theory beyond conventional signal contexts. Understanding how Nebraska drivers respond to FYA enables accurate prediction of left-turn capacity and delay, supporting optimized signal timing and intersection performance analysis.
- Implementation Guidance: Findings inform Nebraska-specific best practices, including timing adjustments for high-volume conditions and phasing strategies (lead vs. lag) that optimize safety outcomes, translating research into actionable operational guidance.
- Methodological Advancement: Integration of crash analysis, gap acceptance modeling, and PET-based conflict evaluation addresses key research gaps and provides a framework applicable beyond Nebraska for evaluating innovative signal control effectiveness.

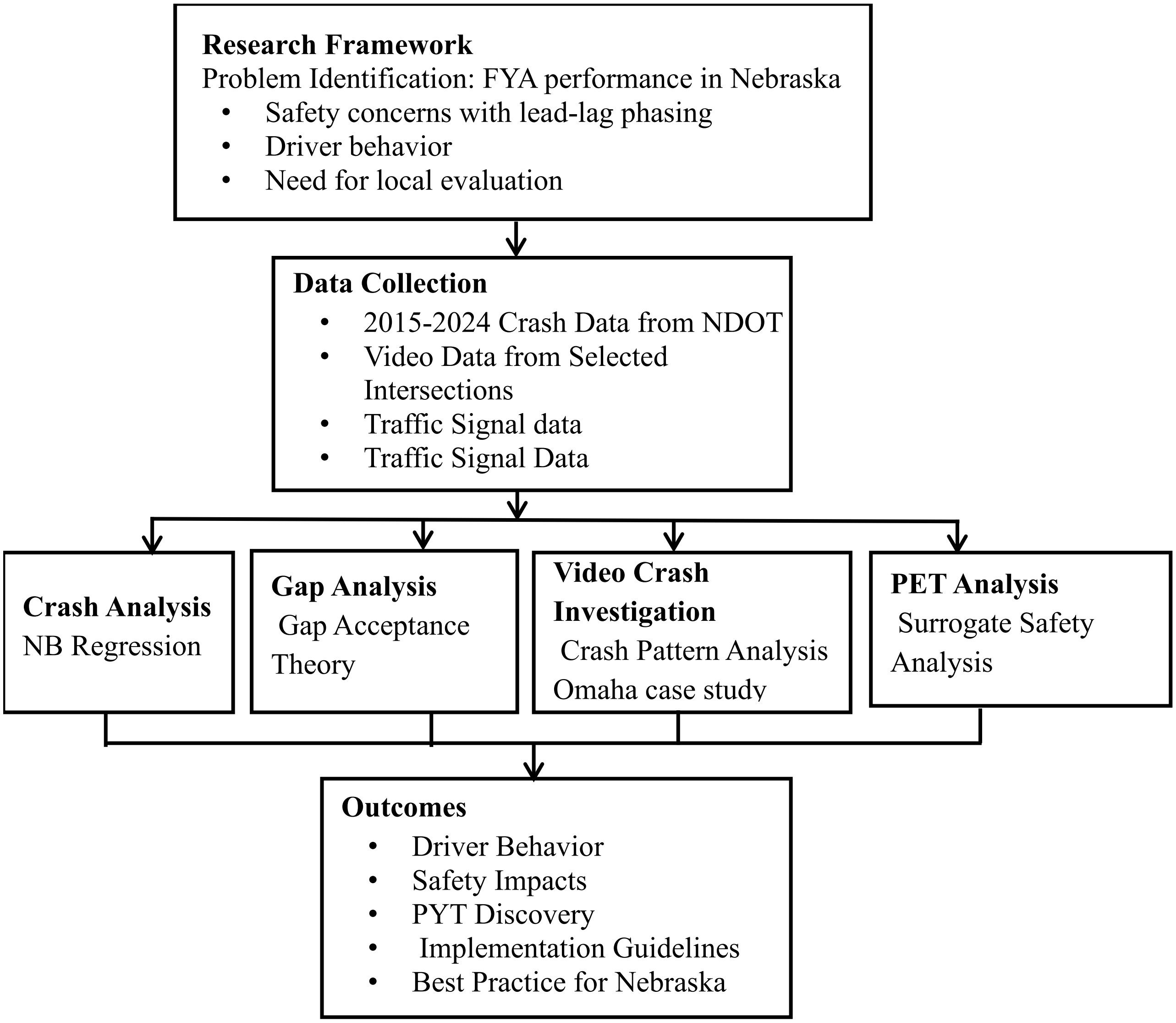


Figure 1.3 Framework for evaluating FYA performance safety performance

In summary, the significance of this research lies in enhancing safety and efficiency at signalized intersections by improving the use of the FYA. It provides Nebraska-specific insights that will help local agencies confidently implement the FYA with optimal settings and offers an understanding of driver behavior and traffic conflicts that extend beyond state lines. Ultimately, the study supports the goal of safer signalized intersections and more effective traffic management by ensuring that engineering practices keep pace with federal guidelines, while also being validated in local conditions.

Chapter 2 Literature Review

2.1 Flashing Yellow Arrow Implementation History

2.1.1 Evolution of Left Turn Signal Control

The development of left-turn signal control has evolved significantly from traditional methods to more sophisticated strategies, addressing operational and safety challenges. Traditional left-turn control methods included protected-only operations where left-turning vehicles received exclusive right-of-way with a static green arrow, and permissive operations where left-turning vehicles used circular green indications and turned when gaps in opposing traffic were available. Protected-only operations, while safe, often led to increased delays for other traffic movements (E. D. Saldivar-Carranza et al., 2021), whereas permissive operations could lead to safety issues due to potential conflicts with oncoming traffic (Ozmen et al., 2009). However, these early systems presented various operational and safety challenges that motivated the development of more sophisticated control strategies (Brehmer, 2003).

The introduction of protected-permissive left-turn (PPLT) operations has represented a significant advancement in traffic signal control, combining the safety benefits of protected phases with the operational efficiency of permissive operations. However, PPLT operations using traditional circular green indications created new challenges, particularly the traditional yellow trap phenomenon with lead-lag phasing configurations (Knodler Jr. et al., 2001). Also, while resources such as the Signal Timing Manual and other traffic engineering publications provide guidance for implementing PPLT operations, the application of these guidelines may vary slightly across agencies due to local operational practices and policies (Zhan et al., 2007). The evolution of left-turn signal control, as shown in Figure 2.1, reflects a steady advancement in safety and operational efficiency.

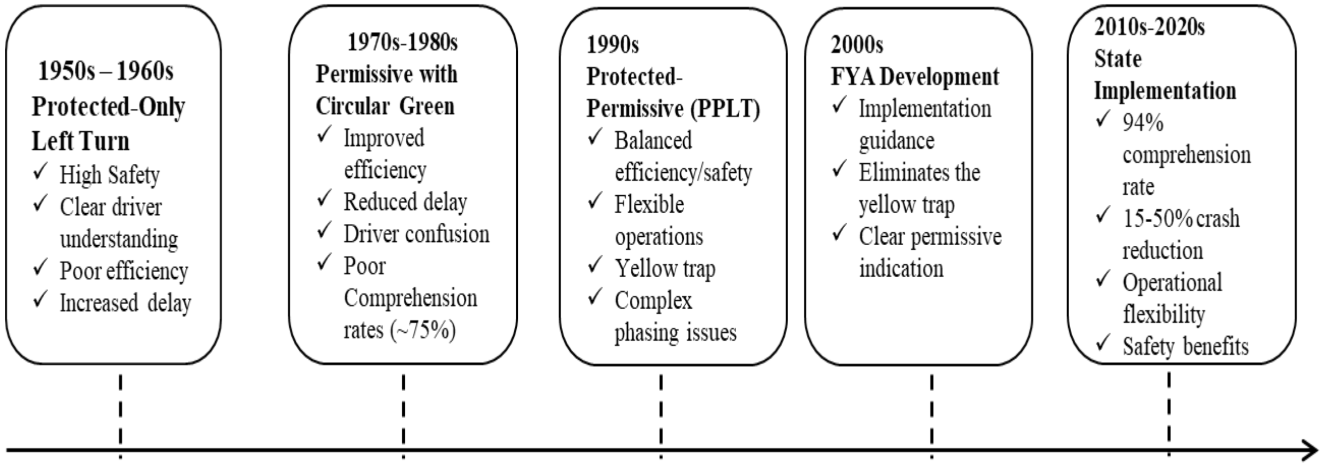


Figure 2.1 Evolution of Left-Turn Signal Control (1950-2020)

Originating from basic protected-only operations in the 1950s and 1960s that offered significant safety but lacked efficiency, each new development aimed to overcome specific limitations while also presenting new challenges that spurred further innovation (Brehmer, 2003). Figure 2.1 demonstrates how the shift from permissive operations marked by circular green indications (~75% understanding) to contemporary FYA implementations (94% understanding) significantly enhances driver comprehension and safety (Jashami et al., 2019; Srinivasan et al., 2018).

2.1.2 Development and Standardization of FYA

Building on the FYA fundamentals established the literature, specific research documented the extent of circular green misinterpretation, with drivers frequently failing to yield appropriately due to confusion between protected and permissive operations (KnodlerJr. et al., 2007; Rietgraf & Schattler, 2013).

MUTCD guidance provided the regulatory framework that enabled widespread FYA deployment and standardized implementation practices. This guidance aimed to improve the efficiency and safety of left-turn movements at intersections.

Research conducted by Brehmer (2003a) provided critical evidence supporting FYA adoption, demonstrating that the indication effectively eliminated yellow trap scenarios while maintaining high levels of driver comprehension. This research established FYA as the preferred indication for permissive left-turn operations, resulting in its rapid adoption by state transportation agencies. Research has shown that drivers generally understand the yield requirement associated with the FYA indication. Studies using driving simulators and static evaluations demonstrated that simultaneous indications in retrofit displays did not negatively affect driver comprehension (KnodlerJr. et al., 2007).

2.1.3 State Implementation Programs

Multiple states have conducted comprehensive FYA evaluations with different deployment scales and methods (Table 2.1). Illinois showed the benefits of adding signs by analyzing 164 approaches, while Missouri's evaluation of 841 signals offered strong evidence of 14-18% crash reductions. Virginia led the way in time-of-day operations, showing 12-30% reductions in crashes by crash type. North Carolina's study of 222 intersections confirmed safety improvements across diverse regional conditions. Collectively, these implementations demonstrate that FYA is effective when used properly, although the optimal conditions vary by situation.

Table 2.1 Summary of some State DOTs' FYA Implementation Practices

State	Program Scale	Key Features	Primary Benefits
Illinois (Rietgraf & Schattler, 2013; Schattler et al., 2015)	Regional (Peoria area) 2013–2016	Public education, supplemental signage	Strong driver acceptance, no operational impacts
North Dakota (City of Bismarck, 2016; NDDOT, 2014)	City-specific (Bismarck) 2014–2016	Pilot FYA implementations, early phase rollout	Improved driver comprehension, low-cost implementation
Missouri (Jones, 2023)	841 signals statewide 2018-2023	Systematic deployment, comprehensive evaluation	14–18% crash reduction in LT opposing
Virginia (King, 2017)	Multiple regions 2015-2017	Time-of-day operations, simulation validation	12–30% crash reduction by type
North Carolina (Simpson & Troy, 2015)	222 intersections 2012-2015	Regional coordination, safety focus	Significant LT crash reduction
Indiana (Rescot et al., 2015)	Statewide initiative 2013-2015	ROI analysis, mobility benefits	Improved safety and mobility ROI

These implementations generally followed guidance from MUTCD and FHWA studies, including site-specific screening criteria (adequate sight distance, limits on opposing lanes and speeds, and opposing volume thresholds).

2.2 Gap Acceptance Theory and Applications

2.2.1 Gap Acceptance Under FYA Conditions

Research on gap acceptance under FYA conditions has provided valuable insights into how signals influence drivers' actions. Lin et al. (2012) conducted a detailed before-and-after study, showing that drivers exhibited more cautious gap-acceptance behavior when FYA was used under light-to-moderate traffic conditions. This finding indicates that FYA indications encourage more cautious gap acceptance behavior, with drivers accepting larger gaps and showing greater patience when selecting gaps. The improved signal clarity from FYA may help drivers assess risks better and make more cautious decisions.

Analyzing gap acceptance under FYA conditions involves examining both accepted and rejected gaps to fully understand decision-making. Most past studies have mainly concentrated on accepted gaps, possibly missing valuable behavioral insights in rejected gap data (Devarasetty et al., 2012). For example, Research by Jashami et al. (2019) confirmed the comprehension improvements referenced in the literature, demonstrating that enhanced signal clarity contributes to more consistent gap acceptance decision-making. Integrating multiple estimation methods yields a more robust analysis of FYA-specific gap-acceptance behavior. Comparing traditional method (Raff) with advanced probabilistic approaches enables the validation of results and the identification of method-specific biases.

2.2.2 Critical Gap Estimation Methods

Several methods estimate critical gaps, each with unique advantages. The Raff method identifies critical gaps at the intersection of cumulative distributions of accepted and rejected gaps, offering visual simplicity but being sensitive to sample size (Raff, 1950). Contemporary research increasingly uses probabilistic models (logit and probit) that incorporate multiple variables and capture heterogeneity in drivers. Logit models estimate the probability of gap acceptance based on binary decisions, accounting for factors such as rejected gaps, gap duration, waiting time, and traffic volume (Devarasetty et al., 2012; Polus et al., 2003). These approaches enable advanced analysis, especially for FYA conditions in which multiple factors interact.

The present research also uses binary logistic regression models to estimate the probability of gap acceptance, including variables such as gap duration, waiting time, and traffic volume. These probabilistic methods capture driver diversity and allow analysis of complex interactions, particularly relevant for FYA conditions.

2.2.3 Factors Influencing Gap Acceptance Behavior

Multiple factors influenced drivers' gap-acceptance behavior. Waiting time has a complex relationship with risk tolerance, as longer waits increase impatience and the likelihood of accepting shorter gaps (Shubber, 2022; Zhou et al., 2017). The signal phasing sequence significantly impacts decision-making, with lead and lag configurations creating distinctly different operational environments. Lead and lag phasing configurations create distinctly different operational environments for gap acceptance decisions, with research showing variable critical gap estimates by phase type (Jolovic et al., 2016).

Traffic volume and geometric factors also play essential roles. Increased opposing volume directly decreases the availability of acceptable gaps, forcing drivers to accept smaller gaps with increased risk (Shubber, 2022). Intersection geometry, including size, number of opposing lanes, and sight distance features, significantly affects critical gap values. Larger and more complex intersections usually require longer critical gaps due to increased maneuvering difficulty (Tian, 2000).

2.3 Post-Encroachment Time as a Surrogate Safety Measure

2.3.1 PET Applications in Traffic Safety Analysis

Research has established PET thresholds ranging from 1 to 5 seconds for classifying conflict severity, with values below 1.0 seconds indicating severe conflicts that require immediate evasive action (Saha & Deshmukh, 2024; Shekhar Babu & and Vedagiri, 2018). Studies show that 25-45% of observed conflicts fall into severe categories (Lalwani et al., 2023), and validation work confirms that intersections with frequent short-PET events experience 15-20% higher crash rates (Peesapati et al., 2018). This validation establishes PET as a reliable surrogate safety measure for evaluating intersection performance without the need for extensive crash data collection.

2.3.2 PET Analysis for Signalized Intersections

PET analysis is especially useful for examining left-turn conflicts at signalized intersections, where turning vehicles encounter opposing through traffic during permissive phases. These conflicts pose serious crash risks due to angular collision dynamics and frequent driver misjudgments (Qi & Guoguo, 2017).

Combining PET analysis with FYA safety assessment fills gaps in traditional methods. While most FYA research focuses on crash frequency or driver understanding, PET analysis allows evaluation of safety margins during completed maneuvers, revealing whether signal changes affect conflict severity beyond their frequency. This method is especially helpful for understanding how FYA implementation affects the quality of left-turn execution and for providing insights into operational safety that supplement crash-based evaluations.

Environmental conditions significantly influence PET measurements and the severity of conflict. Research indicates that drivers adopt more cautious behaviors during adverse weather conditions, which can affect both gap acceptance decisions and resulting PET values (Billot et al., 2009; Kilpeläinen & Summala, 2007).

The presence of heavy vehicles in traffic streams affects PET measurements due to differences in acceleration characteristics and following behavior. Heavy vehicles tend to create larger headways and longer reaction times compared to passenger cars, influencing the temporal relationships captured in PET analysis (Aghabayk et al., 2012).

Signal phase timing and sequence (lead vs. lag) affect conflict severity, with research showing variable safety outcomes across phasing configurations. Shen & Jin (2024) found that signal phase characteristics significantly influenced conflict patterns and severity measurements.

2.4 Research Gaps

The literature review reveals critical gaps that limit a comprehensive understanding of FYA performance and optimal implementation strategies. These gaps provide the foundation for this research's contribution to traffic engineering.

1. Limited Signal Phasing-Specific Performance Analysis: While research recognizes differences between lead and lag phasing configurations, systematic analysis of how phasing impacts safety outcomes remains limited, particularly regarding PYT mitigation in lead-lag configurations. This gap limits engineers' ability to select the most effective phasing strategies based on site-specific conditions and traffic patterns, potentially missing out on safety and operational benefits. The limited of empirical evidence comparing phasing effectiveness hinders the development of design guidelines to improve FYA performance across diverse implementation settings.
2. Inadequate Regional Validation of FYA Effectiveness. Most comprehensive FYA evaluations have been conducted in a limited number of states, leaving substantial knowledge gaps about performance under diverse regional conditions. This limitation is

particularly evident in regions with extensive FYA deployment but without systematic evaluation, such as Nebraska's 456-intersection implementation. The absence of regional validation studies limits understanding of how local traffic patterns, driver characteristics, and environmental factors influence FYA effectiveness, restricting the transferability of national research findings to diverse implementation contexts.

3. Insufficient Integration of Driver Behavior and Surrogate Safety Analysis Under FYA Conditions. While gap acceptance research has primarily focused on traditional signal control, surrogate safety measures have been validated under general intersection conditions. However, no systematic analysis has been conducted linking driver gap-acceptance decisions to conflict severity under FYA operations. Important knowledge gaps include how FYA influences both critical gap values and Post-Encroachment Time distributions, whether gap acceptance patterns and conflict severity differ between lead and lag phasing setups, and how the connection between accepted gaps and safety margins varies under FYA compared to traditional permissive controls. Most existing studies examine gap acceptance and safety outcomes separately, hindering a comprehensive understanding of how driver decision-making affects safety performance and limiting the development of behavioral safety models that can predict conflict risk based on gap acceptance patterns.
4. Limited Integration of Multiple Evaluation Methodologies for Comprehensive FYA Assessment. Current research usually uses single evaluation methods, focusing separately on crash analysis, behavioral assessment, or operational performance. No studies have systematically combined crash modification factor development with detailed gap acceptance analysis and surrogate safety measures to provide a complete understanding

of FYA performance. This fragmented approach limits the creation of evidence-based guidelines that address safety, behavioral, and operational factors simultaneously. The absence of integrated methodological frameworks prevents agencies from understanding how driver behavioral changes relate to safety outcomes.

This study addresses existing gaps through: (1) a comparative analysis of lead versus lag phases performance across various evaluation metrics; (2) regional validation using Nebraska's extensive FYA deployment as a case study; (3) a comprehensive assessment linking driver gap acceptance patterns to Post-Encroachment Time to better understand how decision-making affects conflict severity; and (4) an integrated evaluation framework that combines crash modification factor development with behavioral safety analysis. This methodology advances FYA evaluation techniques and offers practical guidance for optimizing implementations in different contexts.

Chapter 3 Data and Methods

3.1 Overview

This study uses four integrated analyses to assess Flashing Yellow Arrow (FYA) performance: (1) crash frequency modeling, (2) driver gap acceptance behavior, (3) post-encroachment time (PET) conflict severity, and (4) video crash investigation. These components create a comprehensive framework for evaluating both crash outcomes and behavioral safety mechanisms. Data sources include Nebraska Department of Transportation (NDOT) crash records, City signal timing files, and traffic camera footage video.

3.2 Study Locations and Data Source

3.2.1 Crash Frequency Analysis Location

Crash data were obtained from NDOT for the 2015–2024 (10-year) period. A total of 456 signalized intersections with FYA installations were identified across Lincoln and Omaha, of which 324 intersections (Lincoln: 160; Omaha: 164) experienced at least one crash during the study period and were included in the crash analysis. Intersections were not selected based on crash history; rather, comprehensive citywide deployments were verified against the official FYA installation lists for the City of Omaha and the City of Lincoln.

After removing crashes without phase information and deduplicating multi-vehicle crashes to count unique crash events, 3,945 crashes were retained (Lincoln: 2,208; Omaha: 1,737). Traffic operational data, including volumes, geometry, and phasing information, were obtained from Synchro models developed separately for Omaha and Lincoln.

A secondary Omaha-specific dataset covers 51 intersections with 439 crashes, compiled for the PYT case study, where granular Synchro timing and verified phase data were required beyond what was available for the broader network.

3.2.2 Gap Acceptance and PET Analysis

Behavioral data were collected from city-operated traffic cameras in Lincoln between June 2023 and November 2024. Sites were selected based on FYA operation, camera visibility, and phasing variation (lead/lag). A total of 43 intersections were observed, yielding 948 gap acceptance decisions (613 accepted, 335 rejected) and 613 completed left-turn events for PET analysis. Figure 3.1 (a) displays sample output from GoodVision, a computer vision platform that extracts vehicle trajectories and event timing. Figure 3.1 (b) provides gap measurement through any pair of conflicting vehicle trajectories.

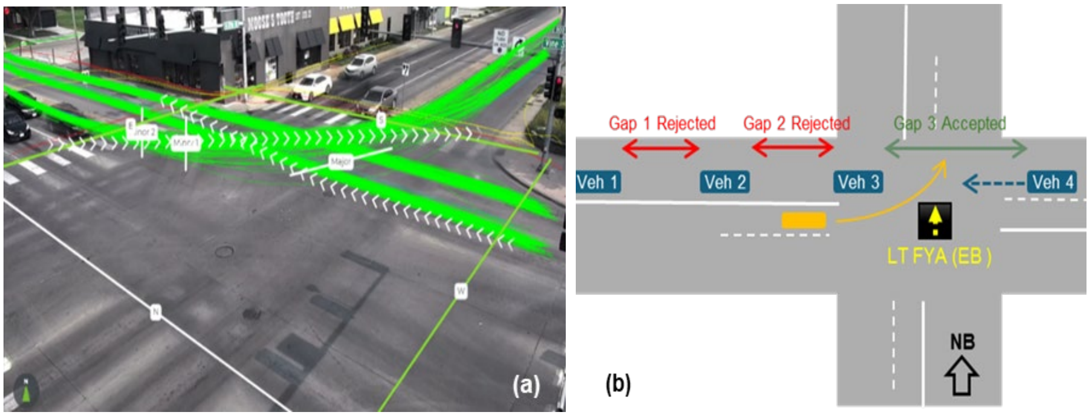


Figure 3.1 (a) Vehicle trajectories from GoodVision software (b) Gap data measure illustration

Figure 3.1 illustrates the gap acceptance process at an FYA intersection, where a left-turning vehicle evaluates sequential gaps in opposing through traffic and accepts a sufficiently large gap to complete the maneuver. Left-turn waiting time is defined as the duration from the vehicle's arrival at the intersection until it accepts a gap and completes the turn.

3.2.3 Video Crash Investigation Location

Video clips from three Omaha intersections (S 120th & W Center, 114th & W Center, 72nd & Cass) were reviewed for FYA-related left-turn crashes (December 2021–December

2022). City engineers recorded 18 crashes potentially related to FYA at targeted lead-lag approaches. Signal timing was confirmed against official documentation (yellow clearance: 4.8 seconds). Crashes were classified into three types: Phase Transition, Steady-State FYA, and Phase Ending.

3.3 Data Cleaning and Processing

3.3.1 Crash Data

Crash records were filtered for signalized intersections and left-turn conflicts with opposing through traffic. Records with incomplete identifiers were removed. Multi-vehicle crashes were deduplicated to count unique crash events rather than vehicle involvement. Intersections were matched to City FYA lists to verify operational status. Installation dates were approximated using a June 30 cutoff within the installation year to establish Before/After periods.

3.3.2 Behavioral Data Cleaning (Gap Analysis and PET)

Vehicle trajectories extracted from GoodVision were cross-checked against video footage to ensure accuracy. Accepted gaps exceeding 12 seconds were excluded as outliers, as very large gaps typically reflect non-steady traffic conditions rather than active driver gap evaluation. All rejected gaps were retained. PET values were capped at 10 seconds, and PET analysis was conducted only for accepted gaps.

3.3.3 Video Crash Investigation Data Cleaning

All video clips were thoroughly reviewed, supplemented by police reports, intersection signal diagrams, and geometric layout maps. Signal timing was confirmed against official city documentation. Each crash was classified based on vehicle movement relative to traffic signal phases, with manual checks to ensure accurate categorization into three crash types (Phase Transition, Steady-State FYA, and Phase Ending).

3.4 Variable Construction

3.4.1 Crash Frequency Analysis

The dataset was organized with left-turn crash frequency as the dependent variable and exposure and operational characteristics as independent variables. To support the Negative Binomial crash-frequency analysis, several variables were derived from crash, traffic, and signal data.

Traffic volumes were extracted from Synchro optimization files corresponding to each crash time-of-day. Two approach cross-product terms were calculated: (1) target approach cross-product, defined as target left-turn volume multiplied by opposing through volume, and (2) opposing approach cross-product, defined as opposing through volume multiplied by opposing right-turn volume. A threshold of 100,000 vehicle interactions classified each term as high or low, producing four exposure categories: neither exceeding 100,000, only target approach exceeding 100,000, only opposing approach exceeding 100,000, and both exceeding 100,000.

The number of opposing lanes was included to capture the geometric effect on conflict exposure. This variable accounts for both opposing through lanes and opposing right-turn lanes, with special treatment for shared lanes (0.5 assigned to through, 0.5 to right-turn).

The exact installation dates for FYA were not available from city records. To establish a consistent before/after framework:

Crashes that occurred on or before June 30 of the installation year at a given intersection were classified as "Before FYA."

- Crashes occurring after June 30 of the installation year were classified as "After FYA."

Table 3.1 summarizes the variables used in the Negative Binomial regression model. Table 3.2 summarizes key variables derived from GoodVision trajectory analysis for behavioral models.

Table 3.1 Variables Used in the Negative Binomial Regression Model

Variable Name	**Description**	**Unit / Coding**	**Source**
LT Crash frequency	Number of left-turn crashes per intersection approach (dependent variable)	Count	NDOT (2015–2022)
Exposure	Indicator if exposure (LT × opposing volume) exceeded 100,000	Dummy (0=Below 100k/1= Over100k)	Derived from Synchro volumes
FYA	Binary variable: Before installation (ref.) vs. After installation	Dummy (0=Before/1=After)	Omaha & Lincoln FYA lists
Opposite lane count	Number of opposing through lanes (RT lanes counted as 0.5 if shared)	Count	Synchro geometry
Actuated Green Cycle Ratio	Ratio of actuated green time to total cycle length (signal timing effect)	Continuous	Synchro timing data
Peak Period	Indicator for peak hours (AM/PM peaks) vs. off-peak (ref.)	Dummy (0=Peak/ 1=Offpeak)	Synchro schedules

Table 3.2 Behavioral Analysis Variables

Variable	Definition
Gap Duration (seconds)	Time between vehicle departure and LT opportunity (accepted and rejected)
L T Waiting Time (seconds)	Duration from vehicle stop to gap acceptance decision
Opposite Through Volume (Veh/Hr)	Opposing through traffic volume
Phase	Lead vs. Lag permissive signal operation
PET (seconds)	Time between LT clearance and opposing vehicle arrival at conflict point

3.4.2 Gap Acceptance and PET

The 'Gap' indicates the time interval between the opposing vehicle's departure and the left-turn opportunity, including both accepted and rejected decisions. 'LT Waiting Time' reflects driver’s patience. 'Phase' distinguishes between lead and lag permissive operations. 'PET' measures the safety margin in completed maneuvers, calculated as the time difference between when the left-turning vehicle's front bumper arrives at the conflict point and when the opposing through vehicle's rear bumper clears at the same point, as shown in Figure 3.2.

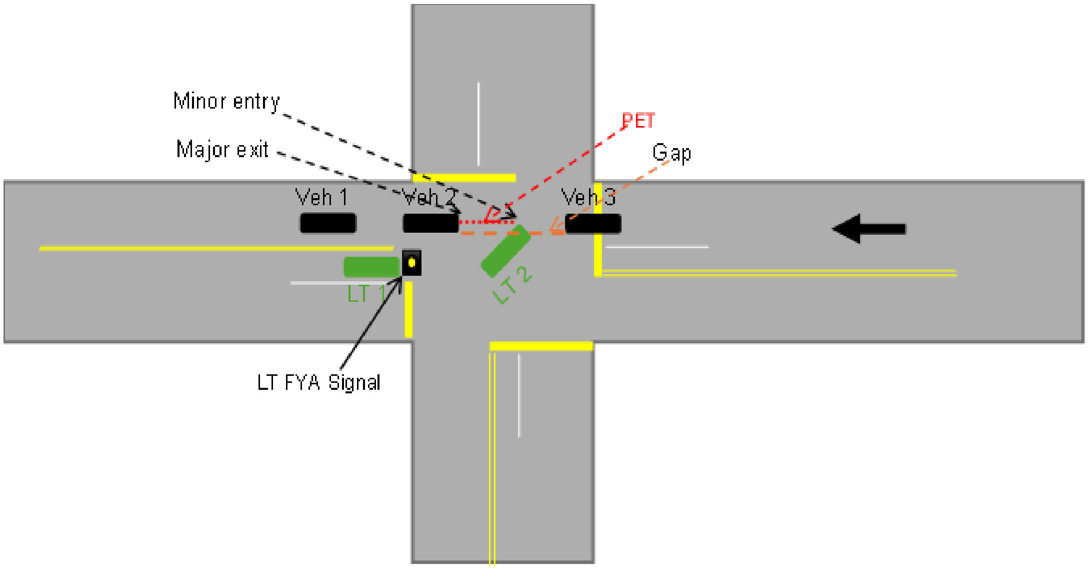


Figure 3.2 Post-Encroachment Time Calculation and Gap Measurement at FYA Intersections

Figure 3.2 Illustration of PET measurement shows the temporal relationship between left-turning vehicle clearance (LT2) and opposing through vehicle arrival (Veh 2) at the conflict point. The accepted gap represents the time interval between consecutive through vehicles (Veh 2 and Veh 3) that the left-turning vehicle (LT2) utilized to complete the maneuver. Smaller PET values indicate closer calls and higher collision risk.

$$PET = Timestamp_{minor\ entry} - Timestamp_{major\ exit} \tag{3.1}$$

Where:

- Timestamp minor entry = Time when the front bumper of the left-turning vehicle reaches the conflict point.
- Timestamp major exit = Time when the rear bumper of the opposing vehicle exits the conflict point.

A conflict event was defined as any completed left-turn maneuver during a permissive FYA interval where an opposing through vehicle subsequently passed through the same conflict point. Each event represents a successful gap acceptance followed by a measurable safety outcome.

3.5 Crash Observations and FYA Yellow Trap

Video clips from the City of Omaha were observed in this research. While the traffic signal of one approach was visible, the opposing traffic signal was not but can be inferred from other information such as the signal plan at the intersection and the movement of the opposing traffic. As an example, Figure 3.3 shows the crash between the westbound left (WBL) vehicle, highlighted in red, and the opposing eastbound through (EBT) traffic in four critical snapshots. The intersection is located at S 120th & W Center Road, Omaha and the crash occurred on 8/1/2022. Note that only the EB traffic signal heads are visible from the recorded angle. However, the signal plan document showed the yellow clearance time as 4.8 seconds. Each of the snapshots (i.e., S1 – S4) is described below.

- S1: WBL red vehicle was waiting for the opportunity to make a left turn on FYA. At 16:12:27, the WBT traffic signal was speculated to turn to a yellow ball display for clearance phase (4 seconds later EBL signal was on green arrow). The red vehicle yielded EBT vehicles No. 1 & No.2.
- S2: WBT signal was still in clearance phase with a yellow ball display. The red vehicle was moving toward the intersection, yielding EBT vehicles No. 3 & No. 4, and remained waiting to turn.

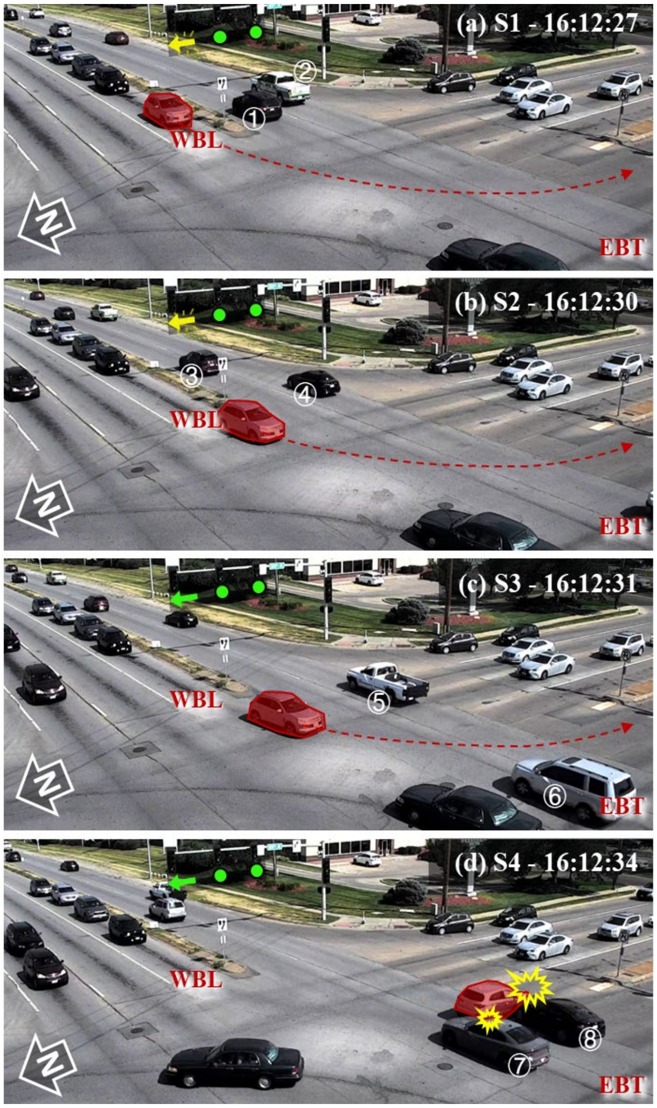


Figure 3.3 An example of a Left- Turn Crash

- S3: WBT signal displayed a red ball at the moment when the opposing EBL was on green arrow at 16:12:31. In the same direction, the red vehicle started approaching while still yielding EBT vehicles No. 5 & No. 6.
- S4: The red vehicle accelerated immediately after yielding EBT vehicle No. 6 and made a LT, then collided with the opposing EBT vehicles No. 7 & No. 8. At this point, WBL was still in FYA, and EBT had not changed from its solid green throughout the period.

Observing this video clip revealed that the LT vehicle waited on FYA, yielding to multiple opposing through vehicles, and proceeded when the adjacent through signal turned red. At the moment of collision, both the LT and opposing through signals remained unchanged (FYA and green, respectively). Although this resembles a yellow trap issue, the LT vehicle was not "trapped" in a yellow clearance phase. Regardless, this case highlights that FYA does not always eliminate yellow traps, contradicting the literature on the benefits of FYA.

Additionally, three locations in Omaha, i.e., S 120th & W Center St., 114th & W Center St., and 72nd & Cass St. were observed for potential FYA LT crashes. From December 2021 to December 2022, there were 32 LT crashes at the three intersections with a lead-lag FYA phase. The City of Omaha engineers recorded 18 crashes that were potentially related to FYA at three targeted LT approaches. All video clips were carefully observed, supplemented by police reports, intersection traffic signal diagrams, and geometric layout maps. A summary of the crash video observations at these three approaches can be found in Table 3.1. Based on vehicle movement relative to the traffic signal phases, all the LT crashes can be categorized into three situations. I) Crashes occurred in the FYA phase while the adjacent through signal was transitioning, a situation that could induce unintentional failure to yield to through traffic. II) Crashes occurred during the FYA phase while the adjacent through signal remains, a situation that could result in failure to yield to through traffic. III) Crashes occurred as the LT FYA and the opposing through phase were both ending, a situation that could result in yellow light issues or red-light running.

Table 3.3 Summary of the crash observations

Location	**Targeted LT**	**Visible signal heads**	**No of crash cases**	**Observation**	**LT vehicle citations**
S 120th & W Center St.	WBL (Lead)	EBT, EBL	7	I: 5 WBL-EBT crash cases occurred when EBL FYA was turning to green arrow. II: 1 case EBL vehicle waiting to turn left on FYA in the intersection but too close to WBT III: 1 case EBL turn left on solid yellow, WBT vehicle run fast & vehicles behind stopped.	5
114th & W Center St.	EBL (Lead)	WBT	7	I: 4 EBL-WBT crashes occurred when EBT vehicle stops (suspect WBL FYA turning green arrow); 1 EBL crash occurred when, according to witness, "the EBL light changing to red". II: 1 crash occurred during WBT is green, EBL was suspect still in FYA. III: 1 case occurred when WBT vehicle run red light, EBL was clearing in the intersection.	6
72nd & Cass St.	SBL (Lead)	NBT, NBL	4	I: 3 SBL-NBT crash cases occurred when NBL FYA was turning to green arrow. II: 1 SBL crash case occurred 5 seconds after the moment NBL FYA was turning to green arrow III: None	4
Total			18		14

Notes (All crashes involve the targeted LT and opposing through vehicles. They can be grouped into three types I, II, III)

The consistent pattern across observed crashes where left-turn vehicles waiting on FYA accelerated as adjacent through signals changed, even though opposing through traffic continued under a solid green, defines what this research calls a “Perceived Yellow Trap” (PYT). Unlike traditional yellow trap scenarios avoided by FYA design, PYT occurs when lead phasing causes perceptual confusion about when the phase ends. This phenomenon led to an expanded crash frequency analysis in a later chapter, which examines whether PYT poses a systematic safety concern across Nebraska's FYA network.

3.5.1 FYA Crash Data Compilation

After observing the cases, it was unclear whether the PYT occurrences were random or special cases that were not representative of a broader pattern in FYA-related LT crashes. Therefore, a larger FYA crash dataset was compiled to develop models for a better understanding of the patterns and contributing factors associated with FYA-related LT crashes.

The City of Omaha provided detailed intersection information regarding FYA installation times and the specific approaches where the FYA was installed. Additionally, they supplied Synchro files, which include signal timing, phases (e.g., lead/lag), and traffic data (e.g., movement counts, number of lanes). After filtering, the intersection dataset consisted of 227 FYA intersections with a total of 593 FYA LT signal heads. Figure 3.5 shows the number of FYAs installed each year in Omaha.

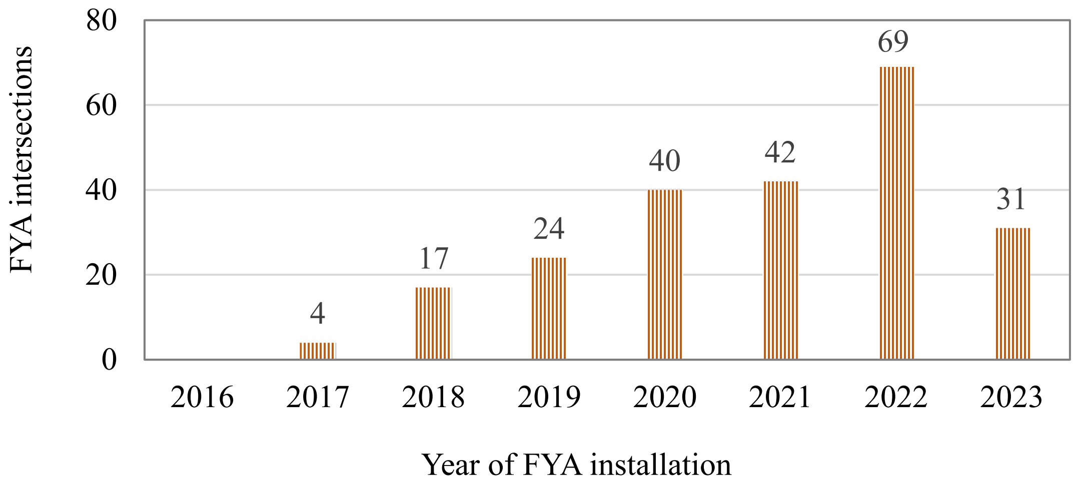
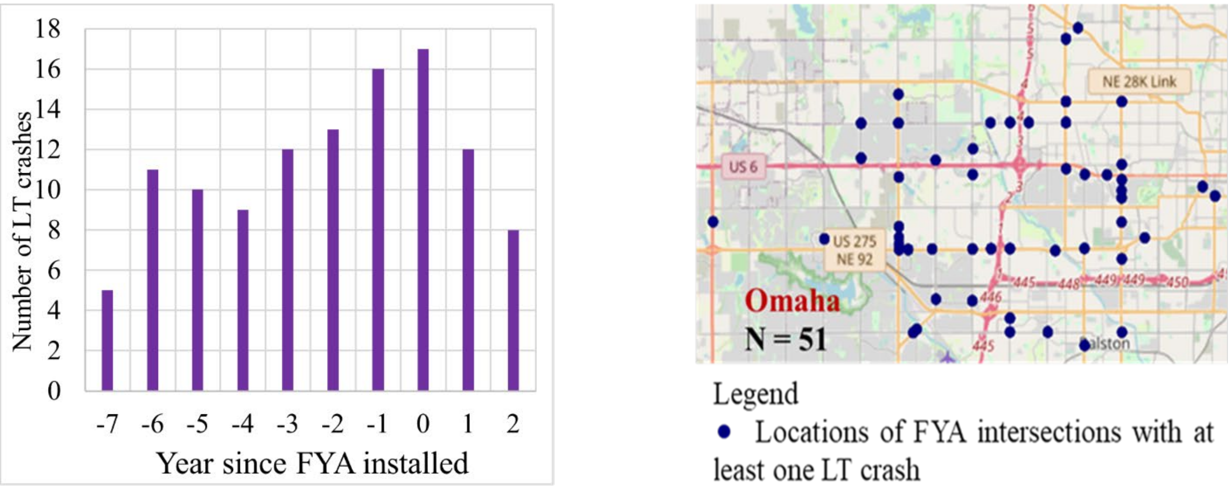


Figure 3.4 FYA intersection installation by year in the City of Omaha.

As can be seen in Figure 3.5, the City of Omaha started replacing LT signals (i.e., from a three-/five-section signal head to a four-section FYA signal head) in 2017, then increased installations year by year. It is worth noting that the FYA installation date does not necessarily coincide with when the new signal sequence became effective. This analysis used the effective sequence date to define the before-and-after periods of FYA; however, for simplicity, this study does not differentiate these dates in the subsequent paper.

Traffic crash data were obtained from the NDOT. The LT crashes on a specific approach at a specific time were identified to match the FYA intersection information. Using the FYA installation dates, all the crash dates can be rescaled so that a negative value measures the LT crashes reported before the FYA installation and a positive value measure after. Figure 3.6 (a) shows the number of LT crashes over relative time between crash dates and the FYA installation dates.



(a) Distribution of FYA crashes over time

(b) Distribution of FYA crashes over space

Figure 3.5 Change in left turn crashes by years since FYA installation

The occurrence of FYA-related LT crashes spanned from 2015 to 2022, while the installation of the FYA divided the crashes into before- and after-periods. However, these periods may not be of equal duration. To eliminate bias caused by the duration of observation time, the annual crash count, defined as the number of crashes divided by the number of days from the first to the last crash and converted to year, was used in this study.

The phase sequences at the LT approach of the FYA intersection may change throughout the day, according to a timetable with different periods: AM peak (7:00-9:00 am), PM peak (3:30-6:00 pm), daytime off-peaks (9:00-11:00 am, 11:00 am-3:30 pm, 6:00-8:00 pm), and nighttime off-peak (8:00 pm-7:00 am the next day). The timetable changed on Weekdays and Weekends as well. Therefore, the date and time of the LT crash occurrence were used to match with the exact signal phasing, specifically the lead or led phase when the crash occurred.

The traffic exposure equivalent for an LT crash was measured by the cross product of the targeted LT and its opposing through traffic, considering (1) traffic volume and (2) intersection size, i.e., the number of lanes. Traffic volumes also varied throughout the day according to the timetable. Henceforth, the time of the LT crash occurrence was used to identify the corresponding traffic volumes for the targeted LT and opposing directions at each intersection approach. Intersection size did not include the channelized area for an approach. However, the opposing right-turn lane was counted as 0.5 of an opposing through lane if the right-turn traffic shared the signal head with the through traffic. For example, if there were 2 through lanes and 1 right-turn lane in the opposing direction, the opposing through lanes were counted as 2.5.

After merging all the datasets using the intersection name and the approach direction, a result of 439 LT crashes at 51 FYA intersections were obtained. Table 3.3 provides summary of the data statistics.

Table 3.4 Summary of the data in the study

	Min	Max	Average	Std. dev
Number of crashes	0	18	1.02	2.28
Annual crash count (crash/year)	0	7.6	0.34	0.90
Volume exposure (cross product)	605	617,730	93,414	84,750
LT volume (veh/h)	1	590	121	82
Opposing through volume (veh/h)	6	1905	724	346
Lane exposure (crash product)	1	6	2.45	0.70
LT lanes	1	2	1.08	0.27
Opposing through lanes	1	3.5	2.29	0.48

	Before-Lead	After-Lead	Before-Lag	After-Lag
Number of crashes	124	134	139	42

3.6 Chapter Summary

This methodology integrates four research components to comprehensively evaluate FYA operations at signalized intersections. Crash frequency analysis utilized ten years (2015-2024) of Nebraska crash data, processing records to 3,945 high-quality unique events for before/after modeling across 324 FYA intersections with phase data. Behavioral analysis captured 948 gap acceptance decisions and 613 accepted gaps for post-encroachment time measurements across 43 Lincoln intersections. A video crash investigation analyzed 18 crashes at three Omaha intersections, revealing that 72% were Type I crashes occurring during signal phase transitions.

The integrated framework combines quantitative modeling (negative binomial and logistic regression), safety assessment through conflict analysis, and qualitative pattern recognition. Rigorous quality control involved multi-source verification, trajectory validation, and temporal matching to ensure analytical robustness for evidence-based FYA safety evaluation.

Chapter 4 Model And Results

4.1 Crash Frequency Analysis: Before/After FYA Implementation

4.1.1 Dataset Overview and Descriptive Statistics

The crash frequency analysis is based on 3,945 left-turn crashes across 324 FYA intersections in Lincoln and Omaha, covering the period 2015–2024. Lincoln contributed 2,208 crashes (56.0%) and Omaha 1,737 crashes (44.0%). Of the 3,945 crashes, 2,039 (51.7%) occurred before FYA installation, 1,504 (38.1%) occurred after installation during lead-phase operation, and 402 (10.2%) occurred after installation during lag-phase operation. Approximately 31.5% of observations (n = 1,242) exceeded the 100,000 cross-product exposure thresholds, while 68.1% (n = 2,687) fell below it. Table 4.1 presents the full distribution of the study sample.

Table 4.1 Descriptive Statistics of Left-Turn Crashes at FYA Intersections

Variable	**N**	**Percentage (%)**
Total Crashes (FYA Only)	3,945	
Lincoln	2,208	56.0
Omaha	1,737	44.0
Before Period	2,039	51.7
After period - Lead	1,504	38.1
After period - Lag	402	10.2
Exposure > 100k	1,242	31.5
Exposure ≤ 100k	2,687	68.1

4.1.2 Negative Binomial Regression Results

A negative binomial regression model was fitted to the full combined dataset (1,594 approach-period observations, 324 intersections, 3,945 crashes).

$$\begin{aligned}\log(E[Y_i]) = \beta_0 + \beta_1(After\_Lead)_i + \ \beta_2(After\_Lag)_i + \beta_3(Exposure)_i \\ + \beta_4(Opposing\_Lanes)_i + \beta_5(Actuated\_gC)_i + (Peak)_i \\ + \log(Years_i)\end{aligned} \tag{4.1}$$

where Y_i is the crash count at approach *i*, *After_Lead* and *After_Lag* are indicators for post-FYA lead and lag operation (before period as reference), Exposure is the cross-product category for just the target approach, *Opposing_Lanes* is the number of opposing through lanes, *Actuated_gC* is the actuated green-to-cycle ratio, Peak is a peak period indicator, and log(Years) is the offset term.

Results are reported as Incidence Rate Ratios (IRR), which represent the multiplicative change in expected crash frequency associated with a one-unit change in the predictor variable. The IRR is calculated as the exponential of the negative binomial regression coefficient:

$$\text{IRR} = \exp(\beta) \tag{4.2}$$

Where $\beta$is the estimated coefficient from the negative binomial model.

Interpretation:

- IRR = 1.0: No effect on crash frequency.
- IRR > 1.0: Increased crash frequency (e.g., IRR=1.213 means 21.3% more crashes).
- IRR < 1.0: Reduced crash frequency (e.g., IRR=0.849 means 15.1% fewer crashes).Neither lag-phase (IRR = 0.937, p = 0.364) nor lead-phase (IRR = 1.027, p = 0.563) operation was statistically significant in the combined model. This non-significant aggregate result is explained by the city-stratified analysis. Intersections with exposure

below 100,000 vehicle interactions showed significantly lower crash rates (IRR = 0.671, $p < 0.001$). Each additional opposing lane increased crashes by 21.3% (IRR = 1.213, $p < 0.001$).

The actuated green-to-cycle ratio showed a strong protective effect (IRR = 0.600, $p < 0.001$), indicating that longer permissive phases reduce crashes. Peak-period operation was associated with substantially fewer crashes than off-peak (IRR = 0.594, $p < 0.001$).

Table 4.2 Negative Binomial Regression Results for Left-Turn Crash Frequency

Variable	**IRR**	**95% CI**	**p-value**
Intercept	0.597	(0.497, 0.717)	<0.001
After period: Lag (vs. Before)	0.937	(0.813, 1.079)	0.364
After period: Lead (vs. Before)	1.027	(0.939, 1.123)	0.563
Exposure Under 100,000	0.671	(0.609, 0.739)	<0.001
Opposing Lanes	1.213	(1.143, 1.288)	<0.001
Actuated g/C Ratio	0.600	(0.502, 0.718)	<0.001
Peak Period	0.594	(0.545, 0.647)	<0.001

Note: Reference = Before period.

Table 4.3 presents the dual cross-product exposure model. The cross product was calculated as the product of left turn volume and the opposing conflict flow (including opposing through and right turns). For example, if the EBL is 150 veh/h and conflicts with WBT + WBR of 600 + 100 veh/h, the cross product is 150 × 700 = 105,000 (high). If the WBL is 80 veh/h and conflicts with EBT + EBR of 500 + 50 veh/h, the cross product is 80 × 550 = 44,000 (low), classifying the intersection as Only Target Approach High, which showed a 46.5 percent increase in crashes (IRR = 1.465, $p < 0.001$).

Table 4.3 Dual Cross-Product Exposure Model: Left-Turn Crash Frequency

Variable	**IRR**	**95% CI**	**p-value**
Intercept	0.408	(0.353, 0.471)	<0.001
Only Opposing CP> 100k	1.220	(1.057, 1.409)	0.007
Only Target Approach CP > 100k	1.465	(1.3, 1.652)	<0.001
Both > 100k (Dual Threshold)	1.695	(1.469, 1.956)	<0.001
Opposing Lanes	1.194	(1.124, 1.269)	<0.001
Actuated g/C Ratio	0.601	(0.499, 0.723)	<0.001
Peak Period	0.572	(0.524, 0.626)	<0.001

Note: Reference = Neither cross-product (CP) > 100,000

Target approach refers to the specific intersection approach under study

4.1.3 City-Stratified Analysis and Sensitivity

City-stratified models (Table 4.4) reveal opposing effects: Lincoln showed crash reductions for both lag (−27%, IRR = 0.726, $p < 0.001$) and lead (−23%, IRR = 0.771, $p < 0.001$), while Omaha showed a 23% increase for lead (IRR = 1.232, $p = 0.004$) and no significant effect for lag (IRR = 0.889, $p = 0.434$). This divergence explains the non-significant combined result. Exposure, opposing lanes, g/C ratio, and peak period effects were consistent across cities.

Removing five Lincoln outlier intersections (Appendix Table A3), lag becomes significant (−15%, IRR = 0.849, p = 0.038) while lead becomes null (IRR = 1.002, p = 0.967). The interaction model (Appendix Table A5) shows lag phasing attenuates the dual-threshold crash penalty by half (IRR = 0.531, p = 0.013).

Table 4.4 City-Stratified Model Comparison

Variable	**IRR (Combined)**	**p-value**	**IRR (Lincoln)**	**p-value**	**IRR (Omaha)**	**p-value**
After period: Lag	0.936	0.359	0.726	<0.001	0.889	0.434
After period: Lead	1.029	0.526	0.771	<0.001	1.232	0.004
Exposure > 100k	1.494	<0.001	1.485	<0.001	1.499	<0.001
Opposing Lanes	1.214	<0.001	1.180	<0.001	1.149	0.002
Actuated g/C Ratio	0.605	<0.001	0.556	<0.001	0.673	0.002
Peak Period	0.590	<0.001	0.539	<0.001	0.619	<0.001

Note: Reference = Before period.

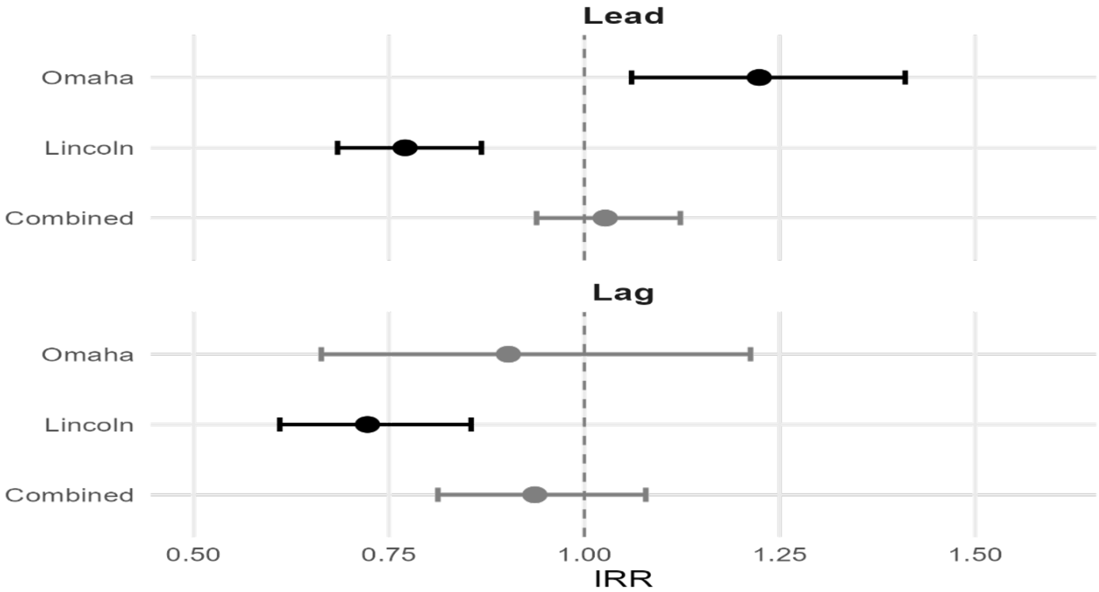


Figure 4.1 City-stratified IRRs for lead and lag phases alongside the combined model estimate

Figure 4.1 represents a forest plot of the lead/lag phase effects of left-turn crashes by city. Black points indicate statistical significance ($p < 0.05$). Lincoln shows crash reductions for both phases; Omaha shows increased crashes for the lead phase. Combined estimates mask opposing city-level effects.

4.2 Results for Gap Analysis

4.2.1 Exploratory Analysis

Descriptive analysis was conducted to examine the distribution of key continuous variables influencing gap-acceptance behavior. Table 4.5 summarizes statistics on gap duration, left-turn waiting time, and opposing traffic volume. The average available gap was 5.56 seconds, with a standard deviation of 3.28 seconds, indicating a wide range of driver decision contexts. Left turn waiting times ranged from 1.04 to 57.49 seconds, with an average of 11.91 seconds. Significant traffic volumes varied considerably across intersections, with an average of 656 vehicles per hour, reflecting the diverse traffic demand conditions observed during the study.

Table 4.5 Descriptive Statistics of Key Continuous

Variable	Min	Max	Average	Median	Std. Dev.
Gap Duration	0.17	12	5.56	5.51	3.28
LT Waiting Time	1.04	57.49	11.91	7.38	11.12
Opposing Through Volume	37	1276	656.45	700.5	266.47

The observed distributions justify the inclusion of gap duration, LT waiting time, and major volume as key predictors in the modeling framework due to their sufficient variability and range, which capture meaningful behavioral differences. The phase distribution was balanced, with 389 lead phase observations (41%) and 559 lag phase observations (59%), ensuring adequate sample sizes for comparative modeling.

4.2.2 Model Specification

A binary logistic regression model was employed to analyze drivers' decisions to accept or reject available gaps at FYA intersections. The dependent variable was a binary indicator where:

- **1** = gap was accepted
- **0** = gap was rejected

The model estimates the probability of gap acceptance as a function of key explanatory variables using the logit transformation in Equation 1.

$$n\left(\frac{P(Accept)}{1-P(Accept)}\right)=\beta_0+\beta_1.Gap+\beta_2.LT\ Wating\ Time+\beta_3.Major\ Volume \tag{4.3}$$

Where:

- $P(Accept)$ is the probability that a gap is accepted (Y =1)

- $log\left(\frac{P(Accept)}{1-P(Accept)}\right)$ is the log-odds (logit)
- β_0 is the intercept coefficient
- $\beta_1, \beta_2, \beta_3$ are the coefficients for the independent variables
- Gap: Size of the available gap (in seconds)
- LT Waiting Time: Duration the driver waited before reaching the decision point
- Major Volume: Opposing through-traffic volume at the time of the event

The model was estimated in R (version 4.4.1) using the glm() function with a binomial family and logit link.

4.2.3 Model Estimation and Results

A binary logistic regression model was estimated to examine the likelihood of a driver accepting a gap at FYA intersections. The final model included three significant predictors: Gap (in seconds), LT Waiting Time (in seconds), and Opposing through Volume (vehicles per hour). Table *4.6* summarizes the coefficient estimates. All predictors were statistically significant at the 0.05 level.

Table 4.6 Logistic regression results for gap acceptance decisions at FYA intersections

Variable	***β* Estimate**	**Std.Error**	**z-value**	**p-value**
(Intercept)	-5.8629	0.5678	-10.3247	0.0000
Gap Duration	1.4821	0.1054	14.0580	0.0000
LT Waiting Time	-0.0314	0.0137	-2.2919	0.0219
Opposing Through Volume	0.0013	0.0006	2.3379	0.0194

Log-Likelihood = -172.76

AIC = 353.52

Pseudo R^2 (McFadden) = 0.72 Observations = 948

Accuracy = 0.938 Kappa = 0.864

Sensitivity = 0.949 Specificity = 0.916

Balanced Accuracy = 0.933

Dependent variable: Gap acceptance decision (1 = accepted, 0 = rejected). Gap Duration measured in seconds; LT Waiting Time in seconds; Opposing Through Volume in vehicles per hour.

The gap duration demonstrates a positive coefficient ($\beta = 1.4821$, $p < 0.001$), indicating that larger gaps significantly increase the likelihood of acceptance. The LT waiting time shows a negative coefficient ($\beta = -0.0314$, $p = 0.022$), indicating that prolonged waiting reduces the probability of gap acceptance. Opposing Through Volume exhibits a positive coefficient ($\beta = 0.0013$, $p = 0.019$), indicating that higher opposing traffic volumes increase the likelihood of acceptance.

The logistic regression model demonstrated strong classification performance, achieving an overall accuracy of 93.8%. The model correctly identified 95% of accepted gaps (sensitivity) and 91.6% of rejected gaps (specificity), indicating balanced predictive ability across both classes. Additionally, the high Cohen's Kappa value (0.864) reflects substantial agreement beyond chance. These results suggest that the model reliably predicts drivers' gap-acceptance decisions based on the predictors. Average marginal effects (AME) were computed to interpret these effects more intuitively. Results in

Table 4.7 Indicate that every additional second in gap duration increases the probability of acceptance by approximately 7.89%, underscoring its critical role. Conversely, each additional second of waiting time decreases the probability by 0.17%, reflecting the subtle influence of driver hesitation. Similarly, each additional vehicle per hour on the major road increases the probability of acceptance by 0.007%, highlighting the nuanced impact of traffic volume.

Table 4.7 Average marginal effects (AME) of key predictors on gap acceptance probability

Variable	AME	SE	z-stat	p-value	lower	upper
Gap Duration	0.07893	0.00169	46.77752	<0.001	0.07562	0.08224
LT Waiting Time	-0.00167	0.00072	-2.31313	0.021	-0.00309	-0.00026
Opposing Through Volume	0.00007	0.00003	2.36755	0.018	0.00001	0.00013

Figure 4.2 shows the marginal effects of the key predictors on the probability of accepting the gap. As shown, the probability of acceptance sharply increases with larger gap durations, approaching 100% beyond 7 seconds. Waiting time has a negative association with drivers who become less likely to accept a gap as they wait longer, possibly due to fatigue or caution. Interestingly, higher opposing volumes slightly increase acceptance probability, suggesting that drivers may feel pressure to utilize smaller gaps in busier traffic conditions. Phase effects (lead vs. lag) were examined through separate critical gap estimations rather than

as model predictors, as the binary logistic regression focused on individual driver decisions irrespective of phasing configuration.

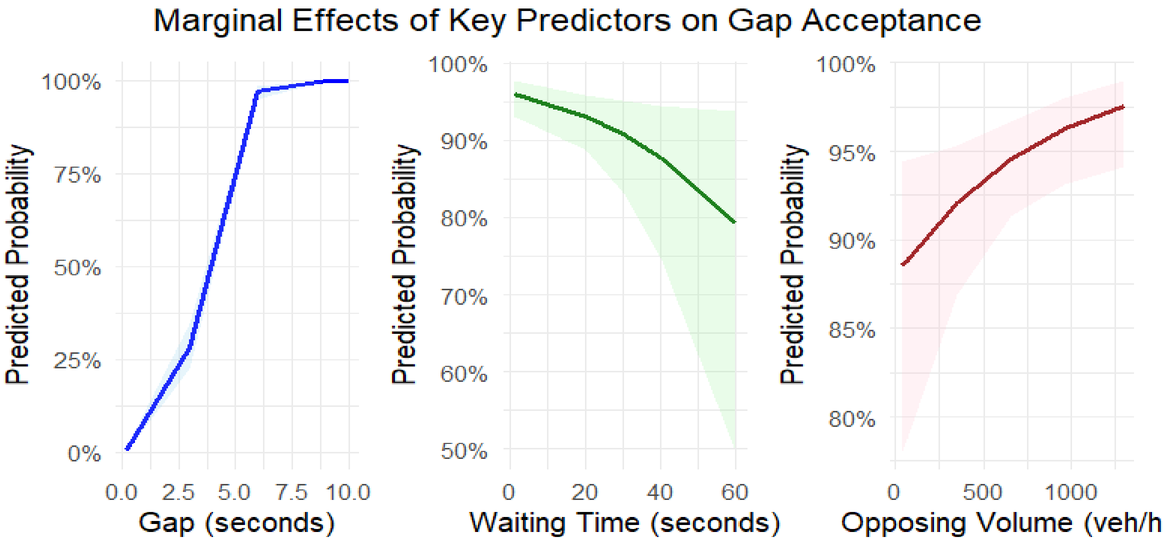


Figure 4.2 Marginal Effects of Key Predictors on Gap Acceptance

4.2.4 Critical Gap Estimation

To estimate the critical gap threshold, the Raff method was applied separately for Lead and Lag permissive phases. Using cumulative distributions of accepted and rejected gaps, the estimated critical gap was 4.28 seconds for the Lead phase and 3.85 seconds for the Lag phase, as shown in Figure 4.3.

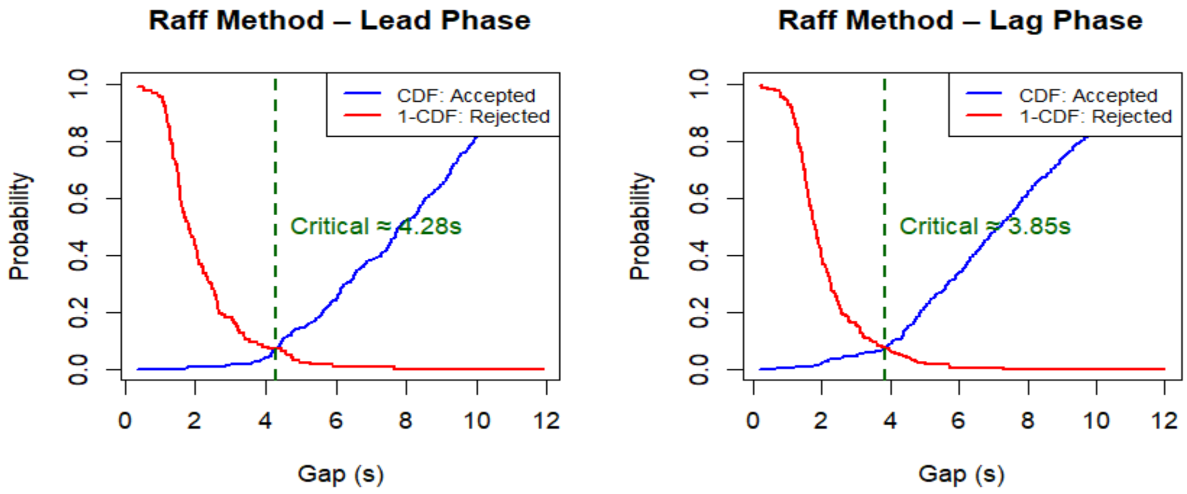


Figure 4.3 Critical gap estimates using the Raff method by phase

These lower thresholds suggest more immediate crossover in observed frequencies and may reflect the sensitivity of this method to bin width.

4.3 Post Encroachment Safety Risk Assessment

4.3.1 Dataset Overview and Descriptive Statistics

The dataset comprised 613 left-turn conflict events across 43 FYA intersections collected from June 2023 to November 2024. Descriptive statistics for continuous variables are presented in Table 4.9. PET values exhibited a right-skewed distribution (mean = 1.75s, median = 1.61s, range: 0.01-9.14s), with 20.1% of events below the critical 1.0-second threshold. Accepted gaps ranged from 0.62 to 12.0 seconds (mean = 7.45 seconds), indicating substantial variation in driver risk tolerance. Left-turn waiting times showed pronounced skewness (mean = 9.97 s, median = 5.65 s, range: 1.04-57.49 s), reflecting diverse patience levels. Traffic volumes ranged from 37 to 1,276 veh/h (mean = 653), representing low-volume suburban to high-volume urban arterials.

Table 4.8 Descriptive Statistics for Continuous Variables

Variable	Min	Max	Average	Median	Std_Dev
PET	0.01	9.14	1.75	1.61	1.05
Gap Duration	0.62	12	7.45	7.54	2.44
LT Waiting Time	1.04	57.49	9.97	5.65	10.44
Opposing Through Volume	37	1276	652.67	691	269.99

Vehicle composition was 96.4% passenger cars, which limited the analysis of large vehicles but accurately reflected typical urban intersection patterns. Weather conditions were balanced, with 51.4% clear skies and 48.6% inclement weather, supporting a thorough analysis of weather effects. Signal phasing revealed that 57.4% of operations involved lag-phase signaling, aligning with regional practices while ensuring sufficient lead-phase data for comparison.

4.3.2 PET Distribution and Safety Risk Assessment

Analysis of 613 conflict events revealed concerning safety patterns. High-risk events (PET <1.0s) comprised 20.1% of conflicts (n=123), moderate-risk events (1.0-2.5s) represented 64.3% (n=394), while only 15.7% achieved low-risk status (n=96, PET ≥2.5s). This distribution indicates that over 84% of left-turn conflicts occurred within potentially dangerous time margins. At the intersection level, 11 of 43 intersections (25.6%) were classified as high-risk (>25% near-miss events), 18 (41.9%) as moderate-risk (10-25%), and 14 (32.6%) as low-risk (<10%).

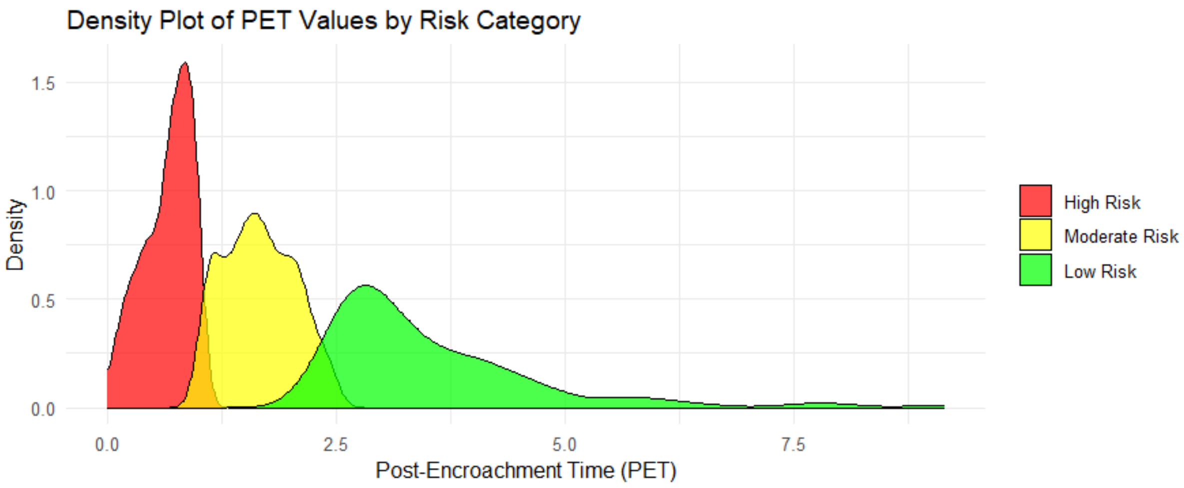


Figure 4.4 Post-Encroachment Time Distribution by Safety Risk Category

At the intersection level, 11 of 43 intersections (25.6%) were classified as high-risk (>25% near-miss events), 18 (41.9%) as moderate-risk (10-25%), and 14 (32.6%) as low-risk (<10%). The spatial distribution (Figure 4.5) revealed that the high-risk intersections are distributed across Lincoln, with no discernible pattern.

High-risk intersections experienced significantly higher traffic exposure, with an average of 692 vehicles per hour, compared to 673 vehicles per hour at moderate-risk and 443 vehicles per hour at low-risk intersections. Signal phase analysis revealed lag-phase operations at 7 of 11 high-risk intersections (63.6%), compared with 6 of 14 low-risk intersections (42.9%). The overall phase-risk distribution revealed lag phases associated with 7 high-risk, 12 moderate-risk, and 6 low-risk intersections, whereas lead phases were associated with 4 high-risk, 6 moderate-risk, and 8 low-risk intersections.

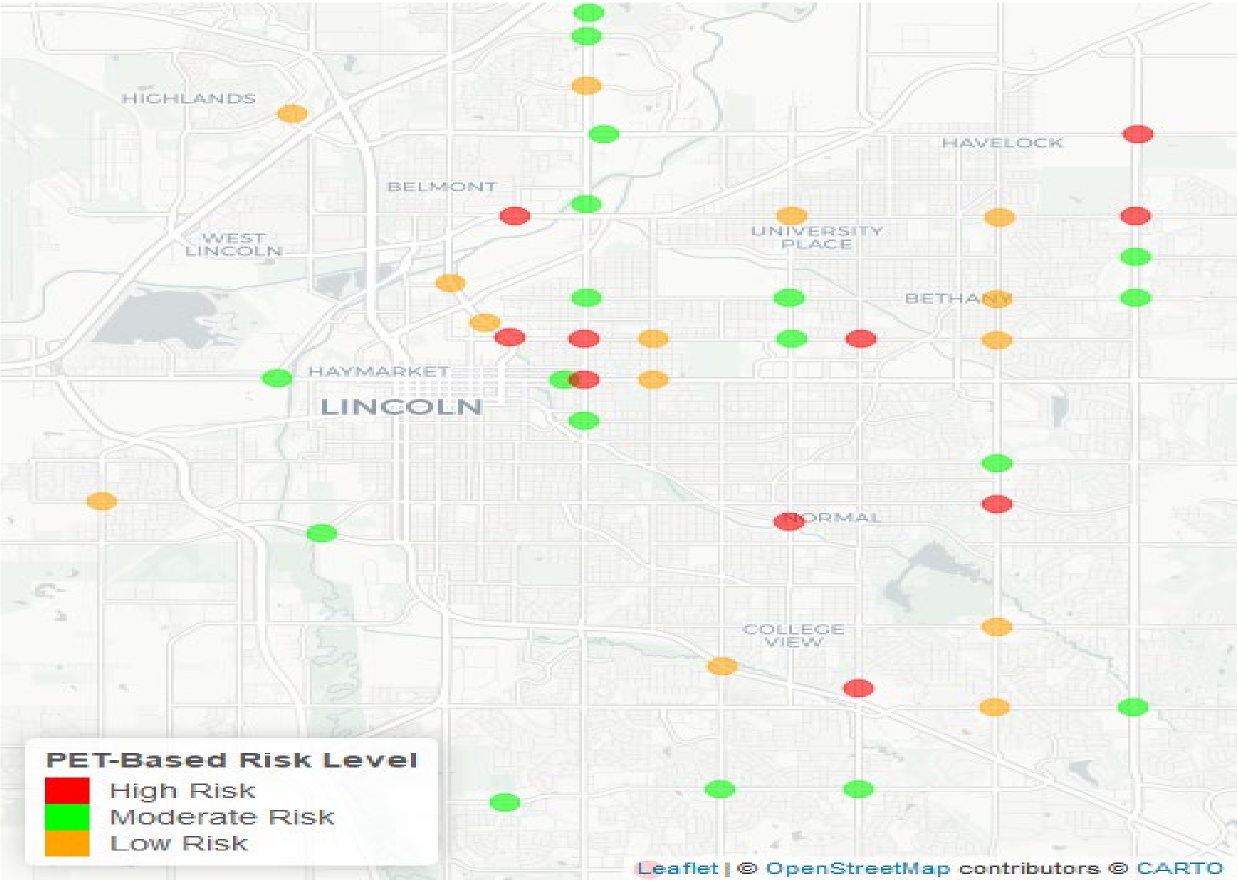


Figure 4.5 Spatial Distribution of FYA Intersection Safety Risk Levels

Signal phase analysis revealed distinct risk patterns between lead and lag operations. Of the 11 high-risk intersections, 7 (63.6%) operated under lag-phase control, compared to 4 (36.4%) under lead-phase control. Conversely, lead-phase intersections demonstrated better safety performance, with 8 of 14 low-risk intersections (57.1%) using lead-phase operations, compared with 6 (42.9%) using lag-phase control. The moderate-risk category showed the strongest association with lag-phase operations, accounting for 12 of 18 intersections (66.7%) compared to 6 (33.3%) with lead-phase control. However, this relationship between signal phasing and intersection risk level was not statistically significant ($\chi^2 = 2.02$, df = 2, p = 0.365).

4.3.3 Regression Analysis Results

The relationship between PET and predictor variables was modeled using multiple linear regression:

$$\begin{aligned} PET = {} & \beta_0 + \beta_1(Gap) + \beta_2(LT\ Waiting\_Time) + \beta_3(Major\ Volume\_TH) \\ & + \beta_4(Weather\_Clear) + \beta_5(Vehicle\_Type\_Passenger) \\ & + \beta_6(Weather\_Clear \times Vehicle\_Type\_Passenger) + \varepsilon \end{aligned} \tag{4.4}$$

Where;

Post-Encroachment Time (PET): Continuous variable measured in seconds, representing the safety margin achieved in completed left-turn maneuvers

Gap Duration: The specific gap (Accepted) duration (seconds) that the driver accepted to complete the turn

LT Waiting Time: Total time from vehicle stop to maneuver initiation (seconds)

Opposing Through Volume: Hourly volume of opposing through traffic (vehicles/hour)

Weather: Binary variable (1 = clear weather, 0 = inclement conditions)

Vehicle Type: Binary variable (1 = passenger car, 0 = large vehicles)

Weather × Vehicle Type: Interaction term to capture combined behavioral effects

The multiple linear regression analysis identified significant factors influencing PET outcomes in completed left-turn maneuvers (Table 4.10). The model achieved $R^2 = 0.112$ (Adjusted $R^2 = 0.104$, $p < 0.001$) with 613 observations and RMSE = 0.988 seconds.

Table 4.9 Multiple Linear Regression Results for PET

Variable	**estimate**	**std.error**	**t value**	**p.value**
(Intercept)	1.9587***	0.3134	6.2492	0.0000
Gap Duration	0.1094***	0.0166	6.5947	0.0000
LT Waiting Time	0.0141***	0.0039	3.5839	0.0004
Opposing Through Volume	-0.0004*	0.0002	-2.2614	0.0241
Weather (Ref: Inclement)	-1.1570*	0.4552	-2.5416	0.0113
Vehicle Type (Ref: Large)	-0.8260**	0.2635	-3.1349	0.0018
Weather: Clear*Vehicle Type: Passenger Car	0.9381*	0.4640	2.0216	0.0437

The model achieved $R^2 = 0.112$ (Adjusted $R^2 = 0.104$, $p < 0.001$) with 613 observations, RMSE = 0.988 seconds, and AIC = 1,741.2. Accepted gap duration was the strongest predictor ($\beta = 0.1094$, $p < 0.001$), with each additional second of gap associated with a 0.11-second increase in PET. Left-turn waiting time was positively associated with PET ($\beta = 0.0141$, $p < 0.001$), indicating that patient drivers achieve slightly better safety margins, whereas opposing traffic volume was negatively associated ($\beta = -0.0004$, $p = 0.024$).

Environmental conditions greatly impacted PET results, with clear weather associated with a 1.16-second reduction in PET compared to inclement conditions ($\beta = -1.1570$, $p = 0.011$). Passenger cars had shorter PETs than large vehicle types ($\beta = -0.8260$, $p = 0.002$). Additionally, a significant interaction between weather and vehicle type was found ($\beta = 0.9381$, $p = 0.044$), indicating that the combined effect of clear weather and passenger cars differs from the effects of these factors individually.

Model diagnostics confirmed that residuals were normally distributed and exhibited constant variance across predicted values, with all variance inflation factors below 2.0, indicating that the predictor variables were not highly correlated.

4.4 Case Study and Yellow Trap Model and Results

A generalized linear model was estimated to analyze LT crash counts using data collected before and after FYA installation. The model also included an interaction term representing lead or lag sequences relative to FYA deployment. Key exposure metrics included the product of LT and opposing through traffic volumes, as well as the product of LT and opposing through lanes, which were treated as offsets to adjust for varying exposure levels across intersections. The model specification is shown in equation **(**4.3). The model was estimated using R statistical software. Table 4.10 presents the estimation results for Omaha intersections.

$$E(Y_i) = Phase_i + Dispaly_i + (Phase * Dispaly)_i + log(Volume_i) + Lanes_i \qquad (4.5)$$

Y_i = Annual crash count (i.e., crash per year) of a certain LT approach *i*

$Phase_i$ = Lead vs. lag phase when the crash occurred at approach *i*

$Display_i$ = FYA vs. non-FYA display when crash occurred at approach *i,* i.e., Before vs. after the installation of FYA signals at approach *i*

$Volumes_i$ = Exposure by traffic volume, i.e., cross-product of LT traffic volume at approach *i* and its opposing through traffic volume

$Lanes_i$ = Exposure by number of lanes, i.e., cross-product of numbers of LT lanes at approach *i* and its opposing through lanes

Table 4.10 Generalized Linear Model Results for Omaha FYA Intersections

	Estimate (*β*)	**Std. Error**	**z value**	**Pr(>|z|) (*p*)**
(Intercept)	-3.30	1.79	-1.848	*0.016*
PhaseLag	-0.80	0.36	-2.218	*0.027*
Display	0.15	0.06	2.472	*0.013*
PhaseLag*DisplayFYA	-0.15	0.08	-1.784	*0.054*
log(Volumes)	0.79	0.17	4.747	*<0.001*
Lanes	-0.73	0.24	-3.000	*0.003*

As shown in the model results in Table 4.10, ost variables are statistically significant at α = 0.05, except the interaction between Phase and Display, which is marginally significant. The lag phase has a significantly lower annual crash count than the lead phase (β = −0.80, p = 0.027), while crash counts increase after FYA installation compared with the pre-FYA period (β = 0.15, p = 0.013). The negative interaction term (β = −0.15, p = 0.054) indicates that the combined effect of lag phasing and FYA operation reduces crashes, suggesting the impact of FYA depends on whether the left turn operates in lead or lag phasing.

Exposure variables also significantly impact LT crash counts. As shown in Table 4.10, the cross-product of LT and opposing through traffic volumes increases, and the annual crash count increases as well. This suggests that higher traffic volumes are associated with a higher likelihood of crashes. However, the cross-product number of LT and opposing through lanes has a negative impact on the annual crash counts. In other words, a smaller intersection with fewer LT and/or through lanes experiences fewer crash counts.

Chapter 5 Discussion

5.1 Crash Frequency Analysis

The negative binomial analysis of 3,945 left-turn crashes across 324 FYA intersections (2015–2024) reveals no statistically significant overall crash change following FYA installation when controlling for exposure (Lag: IRR = 0.937, p = 0.364; Lead: IRR=1.027, p=0.563). This indicates that FYA implementation across a comprehensive network does not inherently degrade safety performance.

Sensitivity analysis excluding five outlier intersections demonstrated that lag phasing produced a statistically significant 15.1% crash reduction (IRR=0.849, p=0.038), while lead phasing remained non-significant (IRR = 1.002, p = 0.967). All five outliers were located in Lincoln, with four operating under lead-dominant phasing and opposing volumes exceeding 750 veh/h. This confirms that aggregate trends are driven by a small subset of high-volume locations rather than system-wide failure. Intersection-level breakdown showed variable outcomes by jurisdiction:

- Omaha: 40 intersections decreased, 23 increased, 4 no change.
- Lincoln: 28 intersections decreased, 82 increased, 12 no change.

The higher proportion of increased intersections in Lincoln reflects the concentration of outlier intersections in that jurisdiction. Traffic exposure significantly influenced crash frequency. A model using the product of left-turn and opposing through volumes for both the target approach and opposing movements provided the best fit. When the conflict volume at both the target approach left-turn approach and the opposing through movement exceeded 100,000 vehicle interactions, crash risk increased 69.5% (IRR=1.695, p<0.001), supporting volume-based thresholds rather than AADT alone.

Intersection size affected safety outcomes. Each additional opposing through lane increased crash frequency by 21.3% (IRR=1.213, p<0.001), consistent with national findings on permissive left-turn operations (Srinivasan et al., 2020). Signal timing played a protective role: each 0.1 increase in actuated green-to-cycle ratio decreased crashes by 6.5% (IRR=0.600, p<0.001). Peak-period operations showed 40% fewer crashes than off-peak operations (IRR=0.594, p<0.001), supporting time-of-day strategies in which protected-only operation during peak periods transitions to FYA permissive during off-peak hours (Zhang et al., 2023).

City-stratified analysis revealed important jurisdictional differences. In Lincoln, both lag phasing (IRR=0.726, p<0.001) and lead phasing (IRR=0.771, p<0.001) were associated with crash reductions. In Omaha, lag phasing was non-significant (IRR=0.889, p=0.434), whereas lead phasing showed a significant increase in crashes (IRR=1.232, p=0.004), consistent with the PYT mechanism documented at three targeted Omaha intersections. The opposing effects between cities explain the non-significant combined result.

Interaction analysis demonstrated that the crash increase associated with high conflict volumes at both approaches is attenuated under lag phasing (Both >100k × Lag: IRR=0.531, p=0.013), indicating lag phasing provides a protective buffer at high-exposure locations where lead phasing shows elevated risk.

5.2 Gap of Acceptance and Post Encroachment Time

To understand the behavioral mechanisms underlying these crash patterns, gap acceptance behavior and conflict severity were examined at 43 Lincoln intersections.

Gap duration was the dominant factor in drivers' decisions, with each additional second increasing the acceptance probability by 7.9% (p < 0.001). Critical gap estimates using the Raff method showed important phasing differences: lead phasing produced 4.28 seconds versus 3.85

seconds for lag phasing, a 10% reduction, indicating lag phasing can handle 10–15% more left turns during the same permissive window, consistent with Li et al. (2021) and Wu (2012).

Extended waiting times slightly decreased gap acceptance probability (0.17% per second, $p=0.022$), suggesting that the flashing indication continuously reminds drivers of potential conflict, producing increased caution rather than impatience as waiting time grows (Knodler et al., 2005).

PET analysis of 613 conflict events revealed 20.1% with PET below 1.0 second, substantially higher than the typical 8–12% at conventional signals (Chen et al., 2017; Gettman et al., 2008). High-risk intersections averaged 692 veh/h in opposing volume, compared with 443 veh/h at low-risk sites. Phase type alone did not significantly predict conflict severity ($\chi^2=2.02$, $p=0.365$), indicating that individual intersection features, such as sight distance, approach speed, and signal timing, influence conflict outcomes more than phasing type alone.

Environmental conditions significantly impacted PET. Clear weather was associated with a 1.16-second reduction in PET compared with inclement conditions ($p=0.011$), consistent with risk compensation theory, in which drivers accept greater risks in favorable conditions (Pińskwar et al., 2024). Large-vehicle operators showed higher PET values than passenger cars ($\beta = -0.826$, $p = 0.002$), possibly reflecting their longer vehicle dimensions, which require earlier entry into conflict zones.

The relationship between accepted gap and PET was weak ($\beta = 0.11$, $p < 0.001$): each additional second of gap increased PET by only 0.11 seconds. This indicates that turn execution speed, hesitation, acceleration, and attentiveness matter more than gap selection in determining final safety margins (Davis & Swenson, 2004).

5.3 Perceived Yellow Trap Phenomenon

Video analysis of 18 crashes at three Omaha intersections revealed that 72% were Type I crashes occurring during signal phase transitions, defining the "Perceived Yellow Trap" (PYT): drivers perceive their FYA phase is ending when the adjacent through signal changes, even though the FYA continues flashing.

PYT is distinct from the traditional yellow trap that FYA was designed to eliminate. A traditional yellow trap occurs with circular green signals when the left-turn signal ends, while opposing through traffic continues. PYT occurs specifically in lead-lag FYA configurations, not in lead-lead, where a mismatch in signal phase timing between opposing approaches creates perceptual confusion about phase-termination timing.

Lag phasing showed a 55% reduction in crashes relative to lead phasing ($\beta = -0.80$, $p = 0.027$) in the Omaha case study model, supporting PYT mitigation through phase sequence selection.

Figure 5.1illustrates the PYT mechanism and its solution. Panels (a) and (b) show how FYA resolves the traditional yellow trap by decoupling the permissive phase from the adjacent through signal. Panel (c) shows the PYT condition, where lead-lag sequencing recreates the perceptual trap. Panel (d) shows that switching to lag sequencing eliminates it.

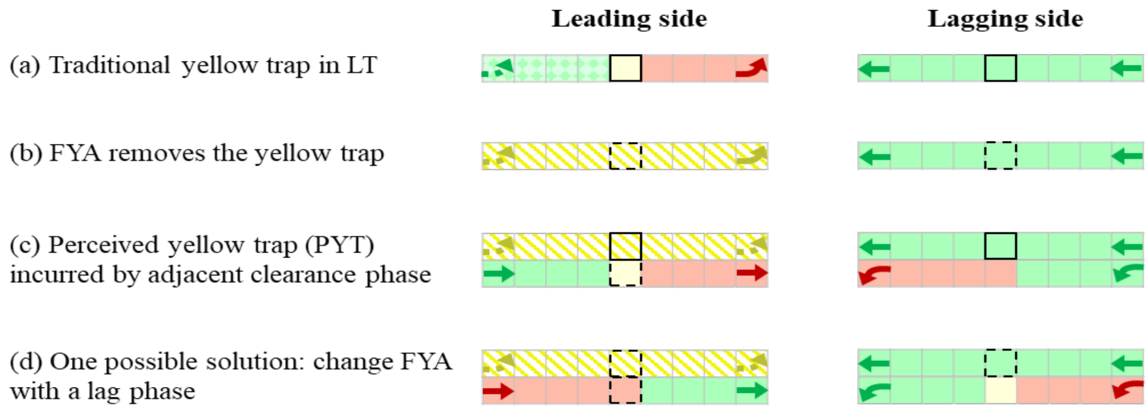


Figure 5.1 Illustration of a phase sequence solution to the PYT

5.4 Implementation Context and Site Selection

Analysis of 324 FYA intersections (Lincoln: 160, Omaha: 164) demonstrated that implementation context determines safety outcomes, not signal type alone. Five outlier intersections in Lincoln accounted for a disproportionate share of the crash increases observed in aggregate analysis.

Outlier characteristics included opposing volumes above 600 veh/h (4 of 5 intersections), three or more opposing through lanes (3 of 5 intersections), lead-dominant phasing (4 of 5 intersections), and conflict volume at both the target approach and opposing movements exceeding 100,000 vehicle interactions.

Intersections were not selected based on crash history; comprehensive citywide FYA deployments were verified against official installation lists. This distinguishes this study from before-and-after evaluations at known problem locations. National studies typically evaluate FYA at pre-screened sites, excluding high-volume locations or those with more than two opposing through lanes, which likely explains more favorable aggregate findings in the literature (Jones, 2023; Srinivasan et al., 2020).

5.5 Comparison with National Literature

Nebraska findings are consistent with national literature when outliers are excluded, with lag phasing showing a 15.1% crash reduction (IRR=0.849, p=0.038), aligning with Missouri's 14–18% reduction and Virginia's 12–30% reduction with time-of-day operations (Jones, 2023; King, 2017; Srinivasan et al., 2020).

Critical gap estimates (Lead: 4.28s, Lag: 3.85s) are consistent with (Li et al., 2021; Wu, 2012). The 10% reduction in critical gap with lag phasing supports operational efficiency benefits documented in Oregon and Indiana (Rescot et al., 2015).

PET findings extend national research by combining crash-frequency analysis with surrogate safety measures within a single FYA evaluation. The 20.1% high-risk PET rate (<1.0s) indicates residual safety risks persist even when crash frequency is stable (Peesapati et al., 2018).

Chapter 6 Guidance Development

6.1 Implementation Recommendations from Study Results

Analysis of 3,945 left-turn crashes across 324 FYA intersections (2015–2024) indicates that implementation context, not signal type alone, determines safety outcomes. No statistically significant overall crash change was observed when controlling traffic exposure (Lag: IRR=0.937, p=0.364; Lead: IRR=1.027, p=0.563). Five intersections out of the 324 FYA intersections drove aggregate trends, all characterized by high opposing volumes and three or more opposing through lanes. These locations represent operationally demanding conditions that are challenging for any permissive left-turn treatment, not deficiencies in signal operation.

Lag phasing demonstrated a 15.1% crash reduction (Appendix Table A4) when outlier intersections were excluded (IRR=0.849, p=0.038). Interaction analysis confirmed that lag phasing attenuates high-exposure risk (Both >100k × Lag: IRR = 0.531, p = 0.013). PYT occurs specifically in lead-lag configurations where the adjacent through signal transition creates perceptual confusion; lead-lead phasing does not produce this condition. The City of Omaha piloted a signal head louver treatment at the westbound approach of 120th & W Center Road to reduce the visibility of the adjacent through signal to left-turning drivers, as shown in Figure 6.1. While reported as partially effective, this approach does not fully resolve the perceptual confusion during phase transitions and is not recommended as a standalone countermeasure. Switching to lag sequencing remains the preferred solution.

Figure 6.1 Example of the possible treatments implemented at westbound approach of 120th & W Center in Omaha

From the results (Table 4.3), when conflict volume at both the target approach and the left-turn approach, and at the opposing through movement, exceeded 100,000 vehicle interactions, crash risk increased by 69.5% (IRR=1.695, $p<0.001$). Cross-product exposure captures conflict opportunities more precisely than AADT alone and is recommended as the primary screening metric for future installations.

Each additional opposing through lane increased crash frequency by 21.3% (IRR=1.213, $p<0.001$). Installations at approaches with more than two opposing through lanes warrant additional review, including consideration of protected-only operation.

Each 10% increase in actuated green-to-cycle ratio decreased crashes by 6.5% (IRR=0.600, $p<0.001$). Peak periods showed 40% fewer crashes than off-peak periods (IRR=0.594, $p<0.001$), supporting time-of-day operation with protected-only phases during peak periods and FYA permissive phases during off-peak periods.

Table 6.1 summarizes evidence-based recommendations for Nebraska agencies based on the findings in this study

Table 6.1 Nebraska-Specific Implementation Standards

Factor	**Evidence**	**Recommendation**	**Priority**
Traffic Exposure	Dual cross-product >100k increases risk 69.5%	Use cross-product thresholds; monitor high volume locations	High
Installation Symmetry	Asymmetric operation contributes to driver confusion	Install FYA on both opposing approaches or neither	High
Intersection Size	Each opposing lane increases risk 21.3%	Limit to ≤ 2 opposing through lanes unless mitigated by enhanced sight distance or lag phasing	High
Performance Monitoring	Five outlier intersections identified post-deployment	Annual crash review: revert to protected-only if thresholds exceeded	High
Phasing Type	Lag shows 15.1% reduction (outliers excluded)	Prioritize lag at high-exposure locations	High
PYT Prevention	PYT occurs in lead-lag configurations	Tie FYA to opposing through green; extend permissive phase	High
Signal Timing	6.5% reduction per 0.1 g/C increase	Optimize actuated green time within cycle length constraints; consider cycle extension if approaches are near capacity	Medium
Time-of-Day Operation	40% lower crashes during peak	Protected only during peak; FYA permissive during off-peak	Medium

The phasing type recommendation carries the highest evidentiary weight in this study. The combined model showed that neither phasing type was statistically significant overall (Lead:

IRR = 1.027, $p = 0.563$; Lag: IRR = 0.937, $p = 0.364$) (Table 4.2). However, sensitivity analysis excluding five outlier intersections, all in Lincoln, characterized by high opposing volumes and three or more opposing through lanes, revealed a statistically significant 15.1% crash reduction for lag phasing (IRR = 0.849, $p = 0.038$), while lead phasing remained non-significant (IRR = 1.002, $p = 0.967$) (Table A.4). This indicates that high-volume outlier sites mask the safety benefit of lag phasing in the combined model, and that lag phasing produces meaningful crash reductions across the broader network when unusual intersections are excluded.

The exposure threshold recommendations are grounded in the dual cross-product model, which demonstrated a clear increase in crash risk across exposure categories. Approaches where only one direction exceeded 100,000 vehicle interactions showed 22–46% more crashes, while approaches where both directions exceeded the threshold showed 69.5% more crashes (IRR = 1.695, $p < 0.001$) (Table 4.3). In practice, agencies should calculate both the target approach cross-product and the opposing approach cross-product during site selection. Any approach in which either term exceeds 100,000 warrants additional scrutiny; approaches in which both exceed the threshold should default to protected-only or time-of-day operation unless a compelling operational justification exists. The interaction analysis further confirmed that lag phasing attenuates high-exposure risk (Both > 100k × Lag: IRR = 0.531, $p = 0.013$), indicating that at high-exposure sites with permissive operation retained, lag phasing is especially important.

Signal timing optimization is an affordable strategy that agencies can implement at existing installations without making physical changes. The actuated g/C ratio demonstrated a strong protective effect (IRR = 0.600, $p < 0.001$), indicating that approaches receiving a larger share of green time relative to cycle length experience significantly fewer crashes (Table 4.2). In practice, this supports prioritizing an adequate permissive phase length during Synchro timing optimization rather than reducing left-turn green time to improve through-movement efficiency. The peak-period finding (IRR = 0.594, $p < 0.001$) further underscores the importance of switching to protected-only operation during AM and PM peak periods, thereby eliminating permissive conflict exposure during the highest-risk periods.

6.2 Alignment with National Practice

The Nebraska-specific standards in Table 6.1 align closely with national implementation guidance, which is summarized in Table 6.2. However, two key differences are noteworthy. First, national guidance considers lead and lag phasing as operationally equivalent under FYA, with no published crash-based evidence to distinguish their safety performance. This study provides the first empirical evidence that lead phasing is associated with significantly worse outcomes at high-volume urban intersections, thereby broadening the current national guidance and directly affecting agencies in Nebraska and elsewhere that deploy FYA in lead-lag corridor setups. Second, national guidance does not currently include directional cross-product exposure thresholds in site selection criteria. The dose-response pattern identified in this study, in which high combined exposure across both approaches nearly doubles crash risk, indicates that the single AADT thresholds used in the current state DOT guidelines may underestimate risk at bidirectionally heavy intersections.

Table 6.2 National Implementation Standards

Factor	Guideline	Reference
Appropriate Application	Replace existing circular green permissive; do not convert protected-only without engineering justification	NCHRP 493 (2003); FHWA (2019)
Speed Limit	Restrict permissive FYA to approaches ≤45 mph; use protected-only at higher speeds	CDOT (2015)
Opposing Lanes	Limit to ≤ 2 opposing through lanes; avoid dual left-turn lanes	PennDOT (2017)
Sight Distance	Adequate visibility required; prohibit where curves, grades, or obstructions restrict view	CDOT (2015); PennDOT (2017)
Lead-Lag Phasing	Tie FYA to opposing through green	NCHRP 493 (2003); PennDOT (2017)
Crash History	Exclude locations with >4 left-turn crashes/year; retain protected-only at high-crash sites	PennDOT (2017)
Time-of-Day Operation	Protected only during peak; permissive FYA during off-peak	PennDOT (2017)
Performance Monitoring	Annual crash review; revert to protected-only if crashes exceed thresholds	FHWA (2019); PennDOT (2017)
Equipment Requirements	Verify MMU2-compatible controller; ensure minimum 8-conductor wiring	INDOT (2015); PennDOT (2017)
Public Education	Provide outreach materials, press releases, and web resources during initial deployment	INDOT (2015)

Where Nebraska findings align with national practice, such as speed limits, sight distance, opposing lane count, supplemental signage, and time-of-day operation, agencies can implement those criteria confidently, knowing that both local evidence and national research support them. When Nebraska findings extend or refine national guidance, particularly on phasing type and bidirectional exposure thresholds, these criteria should be regarded as

Nebraska-specific additions to the standard site selection checklist rather than replacements for existing MUTCD or state DOT requirements. Together, Table 6.1 and Table 6.2 offer a layered decision framework: national standards set the baseline conditions under which FYA is suitable, and Nebraska-specific findings highlight additional operational factors that influence whether a site meets the safety benefits documented in national evaluations.

Chapter 7 Conclusion

This study provides the first comprehensive evaluation of FYA operations in Nebraska, integrating crash-frequency analysis, gap-acceptance modeling, and surrogate-safety assessment across 324 intersections and 3,945 left-turn crashes (2015–2024).

FYA implementation does not inherently degrade safety performance. No statistically significant overall crash change was observed when controlling for exposure (Lag: IRR=0.937, p=0.364; Lead: IRR=1.027, p=0.563). Five outlier intersections in Lincoln, all characterized by high opposing volumes and three or more opposing through lanes, drove aggregate trends. When these are excluded, lag phasing produced a statistically significant 15.1% crash reduction (IRR=0.849, p=0.038), consistent with national findings of 13–39% reductions at appropriately selected sites.

City-stratified analysis revealed that both phasing types reduced crashes in Lincoln, while lead phasing increased crashes in Omaha by 23.2% (IRR=1.232, p=0.004). This divergence is explained by the PYT, an original finding of this research, which posits that lead-lag FYA sequencing creates perceptual confusion during adjacent-through signal transitions, prompting drivers to complete turns into opposing traffic. Video analysis confirmed 72% of crashes at three targeted Omaha intersections were PYT-type. Lag phasing reduces this risk by 55% compared to lead phasing.

Gap acceptance analysis showed lag phasing requires shorter critical gaps (3.85s vs. 4.28s for lead), enabling 10–15% higher left-turn throughput during the same permissive window. PET analysis of 613 conflict events revealed 20.1% with PET below 1.0 seconds, substantially higher than the 8–12% typical at conventional signals, indicating residual safety risks persist even when crash frequency is stable. Execution factors matter more than gap selection in determining final safety margins.

Lag phasing should be the prioritized configuration for new FYA installations. Permissive FYA operation should be restricted to approaches with no more than two opposing through lanes and cross-product conflict volumes below 100,000 vehicle interactions at both the approach and opposing movements. Time-of-day operation is protected only during peak, FYA permissive during off-peak, and is recommended where opposing volumes exceed 700 veh/h during peak periods. Lead-lag sequencing should be avoided; where it exists, conversion to lag sequencing is the preferred PYT countermeasure.

The crash analysis does not differentiate between conversions from protected-only and circular green permissive operation, which may affect baseline crash rates and limit the ability to isolate FYA-specific effects. Exact FYA installation dates were not available; a mid-year assumption was applied to classify before and after periods, introducing potential misclassification. Gap acceptance and PET observations are limited to Lincoln, Nebraska, which may limit transferability to other contexts. PET analysis excluded aborted turns and hesitation events, which may underestimate the severity of conflict at some locations. The modest PET model fit (R^2=0.112) suggests that unmeasured factors, including driver characteristics, vehicle dynamics, and sight distance, influence safety margins. Nebraska-specific factors, such as driver population and infrastructure, may limit direct application elsewhere, though general principles should remain relevant with local calibration.

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Appendix A Data Collection Processing Details

Figure A.1 is a systematic data processing flowchart showing the reduction from 3945 initial NDOT crash records (2015-2024) to 1594 analysis-ready events through sequential filtering, matching with Synchro traffic data, verification against FYA installation lists, and quality control procedures.

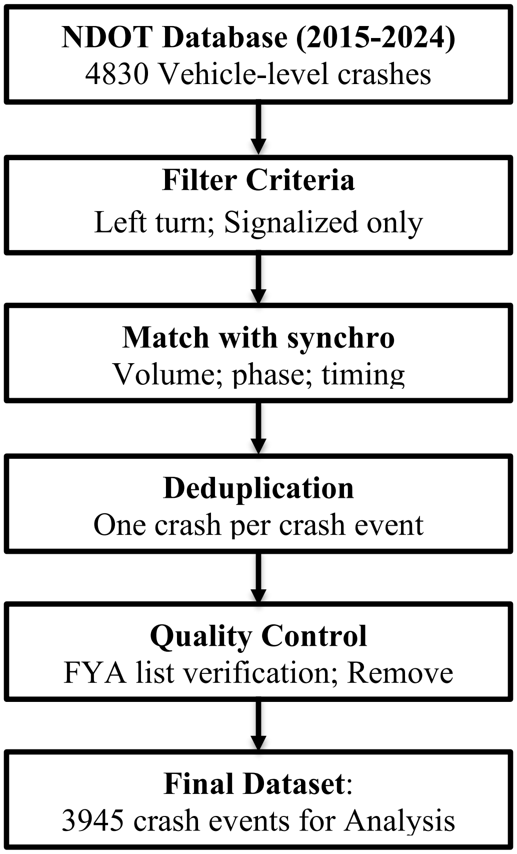

Figure A.1 Crash Data Processing Workflow

Table A.1 illustrates four integrated datasets supporting crash frequency modeling (8-year historical data), behavioral analysis (15-month observational study), conflict assessment, and video crash investigation.

Table A.1 Research Dataset Summary by Analysis Component

Analysis Component	Sample Size	Time Period	Study Locations
Crash Frequency	3945 crashes	2015-2024	Lincoln: 160 Omaha: 164 intersections
Gap Acceptance	948 decisions (613 accepted, 335 rejected)	Jun 2023 - Nov 2024 (Intermittent sampling across a 15-month period)	43 Lincoln intersections only
PET Analysis	613 completed turns	Jun 2023 - Nov 2024 (Intermittent sampling across a 15-month period)	43 Lincoln intersections only
Video Investigation	18 crashes	Dec 2021 - Dec 2022	3 Omaha intersections only

Table A.2 provides the breakdown requested by reviewers showing how many intersections experienced crash decreases, increases, or no change after FYA installation.

Table A.2 Intersection-Level Crash Direction After FYA Installation

City	Decrease	Increase	No Change	Total
Lincoln	28	81	13	122
Omaha	40	25	3	68

Note: The remaining 135 intersections had insufficient crash data for before/after comparison. Omaha shows more favorable patterns (60% decrease/no change) compared to Lincoln (33% decrease/no change), reflecting outlier concentration in Lincoln

Table A.3 identifies the five intersections driving aggregate crash trends, all located in Lincoln.

Table A.3 Top 5 Crash-Increase Intersections (Outliers)

Intersection	**Dominant Phase**	**Opp Vol**	**Avg Exposure**	**Before**	**After**	**Change**
S 56th St & Old Cheney Rd	Lead	756	128,040	4	60	56
Cornhusker Hwy & Superior St	Lag	524	63,496	1	56	55
N 48th St & Vine St	Lead	787	88,718	16	68	52
S 70th St & Pioneers Blvd	Lead	819	132,592	22	70	48
N 27th St & Vine St	Lead	782	91,496	22	68	46

Note: All outliers are in Lincoln. 4 of 5 are Lead-dominant with high opposing volumes.

Table A.4 demonstrates the influence of outlier intersections on model results and addresses aggregate trends.

Table A.4 Sensitivity Analysis: With vs. Without Outlier Intersections

Variable	**IRR_With**	**p_With**	**IRR_Without**	**p_Without**
Phase: Lag	0.936	0.359	0.849	0.038
Phase: Lead	1.029	0.526	1.002	0.967
Exposure > 100k	1.494	<0.001	1.492	<0.001
Opposing Lanes	1.214	<0.001	1.198	<0.001
g/C Ratio	0.605	<0.001	0.696	<0.001
Peak Period	0.590	<0.001	0.601	<0.001

Note: Without outliers, Lag becomes significant (p=0.038, IRR=0.849).

Table A. 5 shows that high-exposure conditions significantly increase crash risk, but this effect is reduced under lag phasing relative to lead phasing.

Table A.5 Sensitivity Analysis: With vs. Without Outlier Intersections

Variable	**IRR**	**95% CI**	**p-value**
Intercept	0.513	(0.387, 0.681)	<0.001
Both > 100k (Yes)	1.751	(1.426, 2.151)	<0.001
Lag Phase (vs. Lead)	0.999	(0.847, 1.179)	0.992
Opposing Lanes	1.169	(1.059, 1.291)	0.002
Actuated g/C Ratio	0.569	(0.416, 0.78)	<0.001
Peak Period	0.536	(0.469, 0.612)	<0.001
Both > 100k × Lag Interaction	0.531	(0.323, 0.873)	0.013

Note: Interaction shows that the Both > 100k effect is attenuated in the Lag phase (IRR = 0.531, p = 0.013).

Appendix B Site Information and Video Analysis Documentary

Figure B.1 shows the GoodVision Video Analysis results from Vine Street & 27th Street, Lincoln, location NE for June 14, 2023, at 17:25:18. The Analysis Duration was ~1 hour (shown in timeline at bottom).

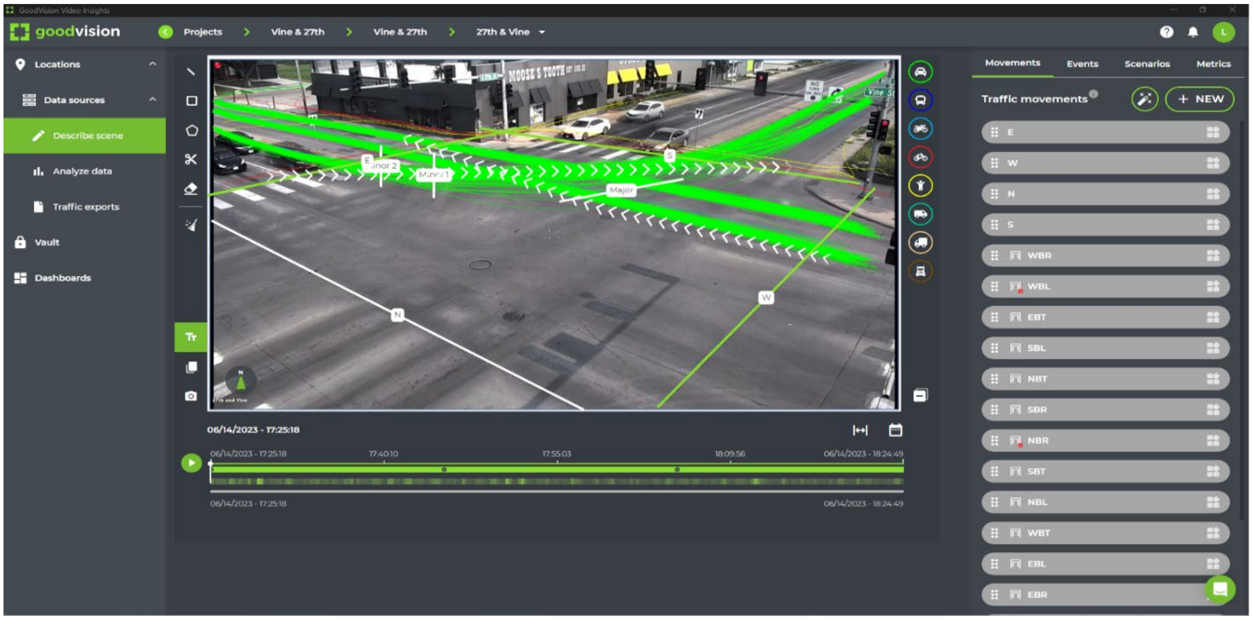

Figure B.1 GoodVision Video Analysis Platform Interface

The figure shows vehicle trajectory extraction and movement classification at the Vine & 27th Street intersection in Lincoln. The interface displays real-time tracking of multiple vehicle movements with Major (EBT) and Minor (WBL) stream designations used for gap acceptance and conflict analysis. Green trajectory lines represent tracked vehicle paths and white arrows indicate turn movements.

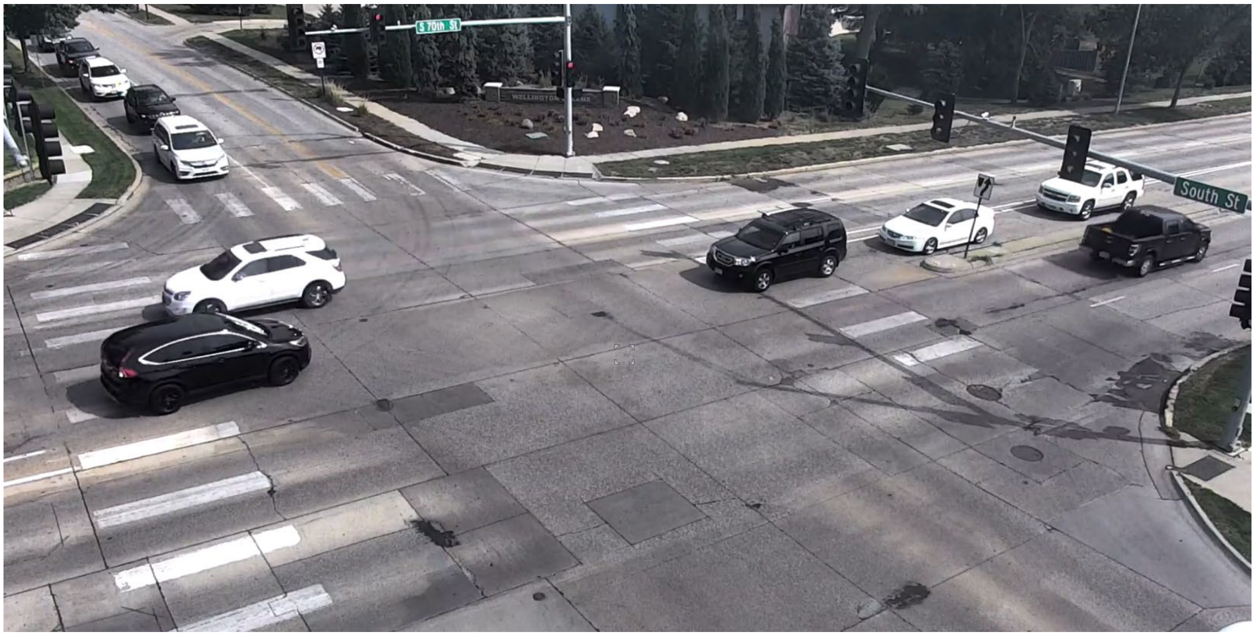

Figure B.2 Left-Turn Conflict Scenario at S70th & South FYA intersection

Figure B.2 Traffic camera view of left-turn conflict scenario at FYA intersection. The black vehicle in left-turn bay waits for an acceptable gap in opposing through traffic. Standard four-leg configuration with exclusive left-turn lanes, marked crosswalks, and visible signal heads.

Site Characteristics:

- Location: South 70th Street & South Street, Lincoln, Nebraska
- Traffic Condition: Moderate volume, clear weather, daytime operations
- Conflict Type: Left-turn vehicle vs. opposing through traffic
- Signal Configuration: Exclusive left-turn lanes on all approaches

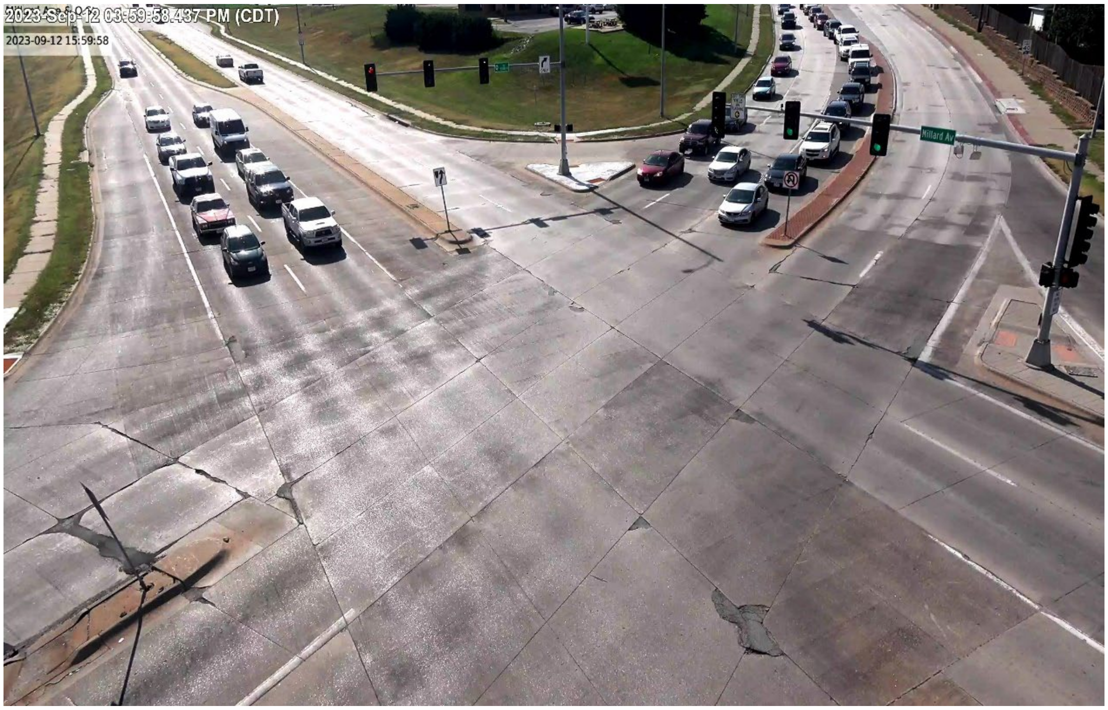

Figure B.3 Peak Period Traffic Operations at Millard Avenue and O

Figure B.3 Traffic camera view documenting peak-hour conditions at study site. Heavy queuing is visible on multiple approaches. These conditions represent scenarios in which waiting times increase and protected-only operations may be warranted.

Site Characteristics:

- Location: Millard Avenue and O Intersection, Omaha, NE
- Date/Time: September 12, 2023, 15:59:58 (PM peak period)
- Conditions: peak traffic volume

Table B.1 lists the 51 Omaha intersections included in the FYA-PYT analysis.

Table B.1 Omaha FYA Intersections (n = 51)

No.	Intersection	No.	Intersection
1	102nd St & Blondo St	27	42nd St & Leavenworth St
2	108th St & Blondo St	28	64th St & West Center Rd
3	108th St & John Galt Blvd/O St	29	72nd St & Cass St
4	108th St & Q St	30	72nd St & Farnam St
5	108th St & West Center Rd	31	72nd St & Hickory St
6	114th St & West Center Rd	32	72nd St & Jones St
7	120 ST & MIRACLE HILLS DR	33	72nd St & Maple St
8	120th St & Burke St	34	72nd St & Q St
9	120th St & I St	35	72nd St & Rose Blumkin Dr
10	120th St & West Center Rd	36	72nd St & Spring St
11	132 ST & W DODGE NORTH FRONTAGE RD	37	76th St & Dodge St
12	132nd St & I St	38	84 ST & INDIAN HILLS DR
13	133rd Plz & West Center Rd	39	84 ST & PARK DR
14	138th St/P St & Millard Ave	40	84th St & West Center Rd
15	140th St & West Center Rd	41	90 ST & INDIAN HILLS ST
16	144 ST & EAGLE RUN ST	42	90th St & Blondo St
17	144 ST & HARVEY OAKS ST	43	90th St & Fort St
18	144th St & Arbor St	44	90th St & Maple Village Plz
19	144th St & Blondo St	45	96th St & Q St
20	144th St & Canpy Dr/Overlook Rd	46	BLAIR HIGH RD & CROWN POINT
21	144th St & Pine St	47	MILLARD AVE & Q ST

No.	Intersection	No.	Intersection
22	144th St & West Center Rd	48	Millard Ave & Q St
23	156th St & Blondo St	49	PAPILLION PKWY & BLONDO ST
24	156th St & Pepperwood Dr	50	Paddock Rd & West Center Rd
25	168 ST & LAKESIDE HILLS PLAZA	51	Saddle Creek Rd & Emile St
26	204 ST & BLUE SAGE PKWY		