REPORT S2-S08B-RW-1

Analysis of Naturalistic Driving Study Data: Offset Left-Turn Lanes

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The Second
STRATEGIC HIGHWAY RESEARCH PROGRAM

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Analysis of Naturalistic Driving Study Data: Offset Left-Turn Lanes

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The Second Strategic Highway Research Program

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The research reported on herein was performed by MRIGlobal and supported by Human Factors North. Jessica M. Hutton, MRIGlobal, was the principal investigator, and Karin M. Bauer, MRIGlobal, was the co-principal investigator. The other authors of this report were Chris A. Fees, MRIGlobal, and Dr. Alison Smiley, Human Factors North. The authors acknowledge the contributions to this research from John Ronchetto, Heidi Whiting, Jessica Brucker, and Douglas W. Harwood of MRIGlobal, and Tom Smahel of Human Factors North.

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FOREWORD

James Hedlund, *SHRP 2 Special Consultant, Safety Coordination*

The SHRP 2 Naturalistic Driving Study (NDS) was the largest and most comprehensive study of its kind ever undertaken. Its central goal was to produce unparalleled data from which to study the role of driver performance and behavior in traffic safety and how driver behavior affects the risk of crashes. Such research involves understanding how a driver interacts with and adapts to the vehicle, the traffic environment, roadway characteristics, traffic control devices, and other environmental features. After-the-fact crash investigations can only provide this information indirectly. The NDS data recorded how drivers really drove and what they were doing just before they crashed or almost crashed.

The Roadway Information Database (RID), created in parallel with the NDS, contains detailed roadway data collected on more than 12,500 centerline miles of highways in and around the six study sites, about 200,000 highway miles of data from the highway inventories of the six study states, and additional data on crash histories, traffic and weather conditions, work zones, and ongoing safety campaigns in the study sites.

The NDS and RID data can be linked to associate driving behavior with the roadway environment. The data will be used for years to come for developing and evaluating safety countermeasures designed to prevent or reduce the severity of traffic crashes and injuries.

The NDS collected data from more than 3,000 male and female volunteer passenger-vehicle drivers, aged 16 to 98, during a 3-year period. Most drivers participated from 1 to 2 years. It was conducted at one site in each of six states: Florida, Indiana, New York, North Carolina, Pennsylvania, and Washington. Data collected included vehicle speed, acceleration, and braking; vehicle controls, when available; lane position; forward radar; and video views forward, to the rear, and on the driver's face and hands. The NDS data file contains about 50 million vehicle miles, 5 million trips, more than 3,900 vehicle years, and more than 1 million hours of video—a total of about 2 petabytes of data.

Four contracts were awarded in 2012 under SHRP 2 Safety Project S08, Analysis of the SHRP 2 Naturalistic Driving Study Data, to study specific research questions using the early NDS and RID data. An open competition solicited proposals to address topics of the contractor's own choosing that would have direct safety applications and that would

- Lead to real-world applications and safety benefits (theoretical knowledge without potential applications was not a priority);
- Be broadly applicable to a substantial number of drivers, roadways, or vehicles in the United States; and
- Demonstrate the use of the unique NDS data (i.e., similar results could not be obtained from existing nonnaturalistic data sets).

In addition to these goals, SHRP 2 expected the projects to serve as both pilot testers and advisers. As they conducted these first substantial NDS and RID analyses, these studies' experienced researchers would discover valuable insights on a host of both pitfalls and opportunities that others should know about when they use the data.

The four projects began in February 2012 and were conducted in two phases. In Phase 1, which concluded in December 2012, contractors obtained an initial set of data, tested and refined their research plans, and developed detailed plans for their full analyses. Three projects successfully completed this proof of concept and were selected for Phase 2. These three projects obtained and analyzed a much richer, though still preliminary, data set and reported their results in July 2014. This report, *Analysis of Naturalistic Driving Study Data: Offset Left-Turn Lanes,* documents one of the three projects.

These projects were conducted while the NDS and RID data files were being built. This circumstance imposed constraints that substantially affected the researchers' work. The constraints included the following:

- *Sample size.* In summer 2013, when the projects requested full data sets, the NDS data file was only 20% to 30% complete. As a result, each project could only obtain a fraction of the trips of interest now available in the full NDS data.
- *RID not complete and not linked to the NDS.* Projects based on roads of specific types or locations could not identify these roads from the RID but instead had to use Google Earth or a similar database to identify them. They then obtained trips of interest by using searches through the NDS that were less efficient than will be possible when the NDS and RID are linked.
- *Data processing.* Some data, such as radar, had not been processed from their raw state to a form where they were fully ready for analysis.
- *Data quality.* NDS data are field data, and field data are inherently somewhat messy. At the time these projects obtained their data, some data had not been quality controlled, and some characteristics of the data were not yet well understood.
- *Tools for data users.* Not all crashes and near crashes had been identified, and a separate small data set containing only crashes, near crashes, and baseline exposure segments had not been built. In addition, a small trip summary file containing key features of each trip had not been built. Users can conduct initial analyses on many subjects quickly and easily using a trip summary file.
- *Other demands on data file managers.* The first priority for the NDS manager, Virginia Tech Transportation Institute (VTTI), and the RID manager, Iowa State University's Center for Transportation Research and Education (CTRE), was to complete data processing and quality control. Field data were being ingested continually. Data delivery for users was sometimes delayed because of these demands on their resources.

These issues are being resolved in 2014. The NDS and RID data are complete and are being linked. Data processing and quality control are being completed. Crash and near-crash files and trip summary files are being built.

If this project and the other two projects were to begin in 2015, each would have more data and would obtain the data far more easily and quickly. Readers should keep these constraints in mind as they read this report. Despite working under these constraints, the three NDS projects have produced valuable new insights into important traffic safety issues that will help reduce traffic crashes and injuries.

For an overview of the study, see the following article: K. L. Campbell, The SHRP 2 Naturalistic Driving Study: Addressing Driver Performance and Behavior in Traffic Safety, *TR News,* No. 282, September–October 2012, pp. 30–35. Additional details may be found at the study's InSight website: https://insight.shrp2nds.us/.

CONTENTS

Executive Summary

The purpose of this research project was to demonstrate one application of the SHRP 2 Naturalistic Driving Study (NDS) data, showing how these data can be used to answer a highway safety question and provide guidance for the implementation of safety countermeasures. The specific safety countermeasure evaluated in this project is offset left-turn lanes. The research team evaluated the effect of left-turn lane offset on gap-acceptance behavior, which serves as a surrogate safety measure for this study. Specifically, the objective was to evaluate left-turning gap rejection and acceptance by a large number of drivers at a large number of intersections with a broad distribution of left-turn lane offsets (ranging from negative to positive).

Negative offsets typically occur at intersection approaches with medians, in which the opposing left-turn lane is shifted to the left in the field of view of a left-turning driver. Left-turn lanes with negative offsets can create a situation in which opposing left-turning vehicles block each other's view of oncoming through vehicles. Left turn lanes with a zero offset are those that directly oppose each other. Positive offsets are a countermeasure that can be implemented by moving each left-turn lane to the left within the median (creating space between the through lanes and left-turn lanes) so that the opposing left-turn lane moves to the right of the driver's field of view. Designing the intersection such that opposing left-turn lanes are each located further to the left, in positions that provide a positive offset, reduces the instances in which a left-turning driver's view of opposing through vehicles is blocked by an opposing left-turning driver.

In this study, data were obtained for situations both when the turning driver's view was obstructed by the presence of an opposing left-turn vehicle and when it was not. This type of study would not be feasible using a traditional fixed-camera method for two major reasons. First, the cost associated with data collection at so many sites would likely be too great to be practically feasible. Second, from a fixed camera outside the vehicle, it would be difficult to determine if the driver's view was indeed obstructed.

This research was conducted in two phases. Phase 1 was designed as a proof-of-concept study, in which the research team requested and was provided small samples of the earliest data gathered from trips made by study drivers while the NDS was still in progress. The purpose of Phase 1 was to determine whether the NDS data could be used to answer the specific proposed safety research question and to demonstrate how the data would be used in a full analysis when more of the NDS data were available for querying. The Phase 1 data set was intentionally limited in size—NDS data were obtained for only six intersections. However, the research team was able to successfully demonstrate a data collection methodology and an analysis plan and was awarded a Phase 2 contract.

The purpose of Phase 2, the results of which are presented in this report, was to answer the highway safety question proposed in Phase 1 using a much larger sample of NDS data. Phase 2 was conducted at the time that the NDS was concluding. At the same time, the development of the Roadway Information Database (RID) was nearing completion, and the RID data, in a very early form, were made available to the research team to assist with intersection site selection. In Phase 2, the site selection began with a list of nearly 6,500 intersections. Through a series of steps in which the list was filtered and the intersections were reviewed, 44 signalized intersection left-turn offset pairs (at 33 intersections) and 14 two-way stop-controlled intersection left-turn offset pairs (at 14 intersections) were identified for inclusion in the analysis. This reduction from 6,500 candidate intersections to 47 intersections included in the study was due both to selection criteria and to the limited number of left turns made by NDS drivers at each intersection approach available to be queried from the NDS data at the time the research was conducted.

The primary source of data for this study consisted of the forward- and rear-facing cameras placed in the vehicles of NDS drivers. Clips of these videos were obtained for instances in which NDS drivers made a left-turning maneuver at one of the study intersections. A video data reduction interface was developed to make data reduction as efficient as possible while minimizing data entry errors and allowing synchronized viewing and control of the forward and rear videos. From the videos, data were collected for a large number of variables, including weather and lighting conditions, signal indications at specific times, the presence of opposing left-turning vehicles, the presence of following vehicles, and—most important—the start and end time of each gap rejected or accepted by the turning driver. In addition, many videos provided views of non-NDS drivers making left turns; to the extent that information could be collected about their gap-acceptance and gap-rejection decisions, this information was recorded as well. Only about 20% of the NDS data set that will ultimately be available was completed in time for inclusion in this research.

The primary analysis for the study was a logistic regression to predict the critical gap length (the length of gap equally likely to be accepted and rejected by a driver) for each offset category, both when sight obstructions were present and when they were not. The analysis of all gaps found that, in general, critical gap length increased as left-turn offset became more negative, although the differences between offset categories were not statistically significant. This result was expected since the left-turning vehicle typically has farther to travel and requires more time to clear the intersection in cases with a large negative offset. Positive offsets typically shift left-turning vehicles closer to the opposing through lanes, shortening the distance they must cross to clear the intersection and allowing them to take shorter gaps. The critical gaps in cases when sight distance was restricted by an opposing left-turn vehicle were then compared with cases when it was not restricted. Critical gaps were found to be 2 s longer when sight distance was restricted than when it was not restricted. When all offset categories were combined, this difference was statistically significant. This result indicates that intersection geometries that allow opposing left-turning drivers to block each other's sight distance can have a negative effect on intersection operation, since longer critical gaps mean that drivers must wait longer at the intersection to find a gap they feel comfortable accepting. When each driver waits longer for an acceptable gap, intersection delay increases for turning drivers and the intersection level of service decreases.

The research team requested information about any crashes or near crashes recorded in the NDS data set at any of the study intersections. While a total of six events took place at one of the study intersections, none were related to left-turn maneuvers. In addition, the video data reduction included a variable to record any instance of avoidance maneuver made by a study driver or an opposing driver during the left-turn maneuver. Of the nearly 3,500 events recorded in the database, only six included an avoidance maneuver, and none of these six events demonstrated a specific safety concern. While no safety incidents were observed in the data, an analysis of the shortest postencroachment times (the time between the initiation of the left-turn maneuver and the arrival of the next opposing through vehicle at the intersection) by offset category indicated a potential opportunity for safety improvement at negative-offset left-turn lanes. While, on average, drivers at negative-offset left-turn lanes are more cautious and wait for longer gaps than drivers at other intersections, they are apparently also more likely to leave a short amount of clearance time between their turn and the arrival of the next opposing through vehicle than drivers at other intersections.

The research team considered a range of other potential analyses, in addition to those described above. However, the data set was found to be too limited to address these other issues, especially when trying to evaluate a combination of variables (such as offset and driver age). In most cases, the researchers determined that a formal analysis would not provide meaningful results; therefore, such analyses were not conducted. However, descriptive statistics are provided in this report for a number of variables that may influence turning behavior, and general observations about trends are made. Several types of analyses related to left-turning behavior could be conducted with a larger data set—that is, if additional NDS videos were reduced for each intersection—or with a data set specifically structured to increase the number of observations under specific conditions or by drivers with specific characteristics.

The results of this research are most relevant to designers and traffic engineers who have a demonstrated or anticipated safety or operational concern related to permissive left-turn maneuvers. Differences in critical gap between specific offset categories were not statistically significant; however, the data clearly showed that negative-offset left-turn lanes resulted in longer accepted gaps than positive-offset left-turn lanes because opposing left-turn vehicles were much more likely to cause a sight restriction at negative-offset left-turn lanes than at positive-offset left-turn lanes. Therefore, even intersections with opposing left-turn lanes with a minimally negative offset (−1 ft to −5 ft) have the potential to benefit from shifting the lanes to a positive offset. In addition, the data did not show that offsetting the left-turn lanes to make them less negative (e.g., changing an offset from −16 ft to −6 ft) would have a substantial effect on safety or operational concerns.

CHAPTER 1

Introduction

The research team evaluated the effect of offset left-turn lanes on driver behavior using Naturalistic Driving Study (NDS) data recently collected by the second Strategic Highway Research Program (SHRP 2). The primary data elements were forward- and rear-facing video from left-turn maneuvers made by NDS participants. The video data were used to measure accepted and rejected gaps by study drivers making left turns through intersections with different left-turn offsets. The research was conducted in two phases. The overall objective of Phase 1 was to use a sample of NDS data collected during the first few months of the project to develop, test, and validate a data capture and analysis plan. The objective of Phase 2 of the research was then to apply that analysis plan to the full NDS data set to answer the specified research question.

This report provides a brief background of Phase 1 activities but focuses primarily on the Phase 2 research efforts and results. In addition to the discussion of the technical activities conducted to answer the research questions, this report describes the research team's experience using the NDS data. Additional information can be found on the study's InSight website (https://insight.shrp2nds.us/).

Research Problem Statement

The Safety area of the SHRP 2 program focuses on the need to reduce traffic injuries and fatalities by preventing or reducing the severity of collisions. Every 1% reduction in crashes will prevent 330 deaths and about $2.7 billion annually in medical, property damage, legal, emergency medical services (EMS), and congestion costs, as well as lost workplace productivity (Blincoe et al. 2014). Moreover, since crashes are a leading cause of nonrecurring congestion, collision prevention has added benefits in terms of reduced delay, fuel consumption, and emissions.

The SHRP 2 Safety program has identified intersection crashes as a priority area. The specific crash type being addressed in this research is angle collisions between left-turning vehicles and opposing through vehicles at intersections. Fatality Analysis Reporting System (FARS) data for 2009 show that left-turn collisions constitute 8.5% of all traffic fatalities. Sight-distance blockage by opposing left-turn vehicles, which can be remedied by offset left-turn lanes, is a likely contributing factor in many such crashes. Some substantial proportion of these fatalities occur because of the sight obstruction created by the presence of opposing left-turn vehicles at intersections with negative offset between opposing left-turn lanes. A study by Persaud et al. (2009) suggests (but does not demonstrate with statistical significance) that small corrections in offset may have limited or no effect on crashes, but that provision of substantial positive offset may be effective in reducing left-turn crashes with opposing vehicles.

Research regarding the safety effectiveness of offset left-turn lanes is important because current geometric design policy in the AASHTO Green Book recommends offsetting left-turn lanes for divided roadways with medians wider than 18 ft, without any quantitative information on how much offset should be provided (AASHTO 2011). Thus, highway designers are told that offset left-turn lanes are desirable but are given no specific or quantitative guidance on when offset left-turn lanes should be used or how much offset is needed. This lack of guidance is reflected in the range of project types evaluated in the Persaud et al. study. Each project began with an intersection in which the opposing left-turn lanes had a negative offset. In some projects, the improved left-turn lanes had a less negative offset, in some projects they had zero offset, and in others they had a positive offset. (See Figure 2.2 for an illustration of positive-, negative-, and zero-offset left-turn lanes.) Thus, it is clear that the highway agencies that designed these projects lack guidance on how best to design such locations. The Persaud et al. study is well done, but—because of the inherent limitations of crash studies—does not provide the type of specific design guidance that is needed.

Research Objectives and Scope

The objective of this research was to use the NDS data to address safety issues using analysis methods that were not possible or were not feasible before this data set became available. The results of the studies performed within this project were intended to lead to real-world applications that result in measurable safety benefits; to be applicable to a variety of roadways, vehicles, and drivers in the United States; and to provide insight to safety issues that could not be obtained through use of traditional data sets such as crash records.

The scope of this study was to answer the question, Do offset left-turn lanes (bays) affect turn behavior—for example, gap acceptance and decision to make turn? The research team took the original research question posed in the SHRP 2 Project S02 report (McGehee et al. 2009) and broke it into more specific research questions as follows:

1. How does the gap-acceptance behavior of left-turning drivers vary as a function of the amount of offset between opposing left-turn lanes for intersections with a broad range of offsets?
2. What range of offsets for left-turn lanes is effective in minimizing risk-taking for left-turning drivers by reducing the sight obstructions caused by opposing left-turn vehicles?
3. How should guidance on the desirable range of offsets be incorporated into geometric design policy for application by highway agencies?

The first two questions can be directly answered with the NDS data. The third question requires interpretation of the results from investigation of the first two questions.

The specific hypotheses tested in the study were as follows:

1. Do intersection approaches with negative offsets, zero offsets, and positive offsets for opposing left-turn vehicles differ from one another in the gap-acceptance behavior of left-turning drivers considering the following measures: critical gap (t_c or t_{50}), percentage of drivers accepting lags of specific durations less than t_c or t_{50}, and rate of occurrence for erratic maneuvers during left turns?
2. Do intersection approaches with negative offsets, zero offsets, and positive offsets for opposing left-turn vehicles differ in gap-acceptance behavior (using the same measures as for Hypothesis 1) between times when opposing left-turn vehicles are present (and potentially block the view of oncoming through traffic for both left-turning drivers) and times when only one left-turn vehicle is present (so that the driver's view of oncoming through traffic is not blocked)?

Thus, Hypothesis 1 involves a comparison of gap-acceptance behavior between intersections, while Hypothesis 2 involves a comparison of gap-acceptance behavior by drivers under different traffic situations at the same intersection. The study data were not only used to test these specific hypotheses but were also used to develop broader relationships between gap-acceptance/risk-taking measures and amount of offset to serve as a basis for establishing design guidelines (e.g., minimum desirable offset). In addition, human factors issues were explored through this research. The research attempted to determine the influence of the following factors on gap-acceptance behavior:

- Length of time spent waiting for a suitable gap;
- Presence of following left-turn vehicle(s);
- Age and gender of left-turning driver;
- Type (size) of turning and opposing through vehicle;
- Pavement and weather conditions; and
- Light condition.

While this study focused on the behavior of left-turning drivers at intersections with varying left-turn lane offset conditions, the research team hopes that this research will also provide insight into using the NDS data to address other issues related to intersection left-turn lanes that will assist future research.

Organization of the Report

The remainder of this report provides background information on the use of offset left-turn lanes and driver gap-acceptance behavior (Chapter 2), a description of the site selection and data collection efforts (Chapter 3), the statistical analysis results (Chapter 4), and recommendations for application of results and future research (Chapter 5). Appendix A presents selected research results in greater detail than Chapter 4.

CHAPTER 2

Background and Rationale

This chapter describes offset left-turn lanes, presents an overview of the relevant literature, and discusses how NDS data were used to provide new insights into driver behavior at opposing left-turn lanes.

Background: What Are Offset Left-Turn Lanes and How Do They Function?

Left-turn lanes are used at intersections to provide a safe location for storing left-turning vehicles, out of the through traffic lanes, while their drivers wait for a suitable gap in opposing traffic to turn left. The provision of a left-turn lane minimizes the potential for rear-end collisions with through vehicles approaching from behind the left-turning vehicle. The reduction in the risk of rear-end collisions provided by a left-turn lane also reduces the pressure on left-turning drivers to leave an exposed position and accept an inappropriate gap in opposing through traffic. Research for the Federal Highway Administration (FHWA) has documented that left-turn lanes reduce crashes by 10% to 44%, depending on the intersection type and area type (Harwood et al. 2002). These effectiveness estimates for left-turn lanes developed by MRIGlobal appear in the *Highway Safety Manual* (HSM) (American Association of State Highway and Transportation Officials 2010).

Highway medians, especially wider medians, are desirable in part because they generally have a positive effect on highway safety by providing greater separation between traffic traveling in opposite directions. However, wider medians may create safety concerns at intersections with conventional left-turn lanes, as vehicles in the opposing left-turn lanes may block one another's views of oncoming through traffic. This type of site obstruction is illustrated in Figure 2.1. The upper portion of Figure 2.1 illustrates that—for a driver waiting to make a left turn in a conventional turn lane—the view of opposing through traffic may be blocked by opposing left-turning vehicles. A vehicle stopped in the turn lane waiting to turn left has been referred to in the literature as an *unpositioned* left-turn vehicle. The lower portion of Figure 2.1 shows that, with a wider median, vehicles in the opposing left-turn lane waiting to turn left can block the view of oncoming through traffic even for a turning vehicle that has moved forward into the center of the intersection. Left-turning vehicles that have moved forward in this way have been referred to in the literature as *positioned* left-turn vehicles. At the intersections illustrated in Figure 2.1, the presence of opposing left-turn vehicles could cause one or both drivers to begin a left-turn maneuver without being aware of the presence of an opposing through vehicle. This could reduce the safety effectiveness of left-turn lanes, documented above.

A geometric design solution for the sight obstructions that can occur as a result of opposing left-turn vehicles, like those shown in Figure 2.1, is to offset the left-turn lanes (i.e., to move the left-turn lane laterally within the median) so that the opposing left-turn vehicles no longer block the sight lines of their drivers. The side-by-side drawings in Figure 2.2 illustrate intersections with negative offset, zero offset, and positive offset for opposing left-turn lanes.

The length of gaps (in time) rejected and accepted by left-turning drivers was used as a surrogate safety measure for left-turn angle crashes. A *gap* is the time headway between successive vehicles, defined as the time between arrivals of the front bumper of successive vehicles at a common point, such as the center of an intersection. When a vehicle is waiting to make a left-turn, each gap in opposing through traffic is either accepted or rejected by the left-turning driver.

Literature Review

Approximately 20% of all traffic fatalities occur at intersections (National Highway Traffic Safety Administration 2011). While only about 10% of intersections are signalized, one-third of the intersection fatalities occur at signalized intersections. Angle collisions involving vehicles crossing each other's paths tend to be some of the most severe crashes at intersections; they

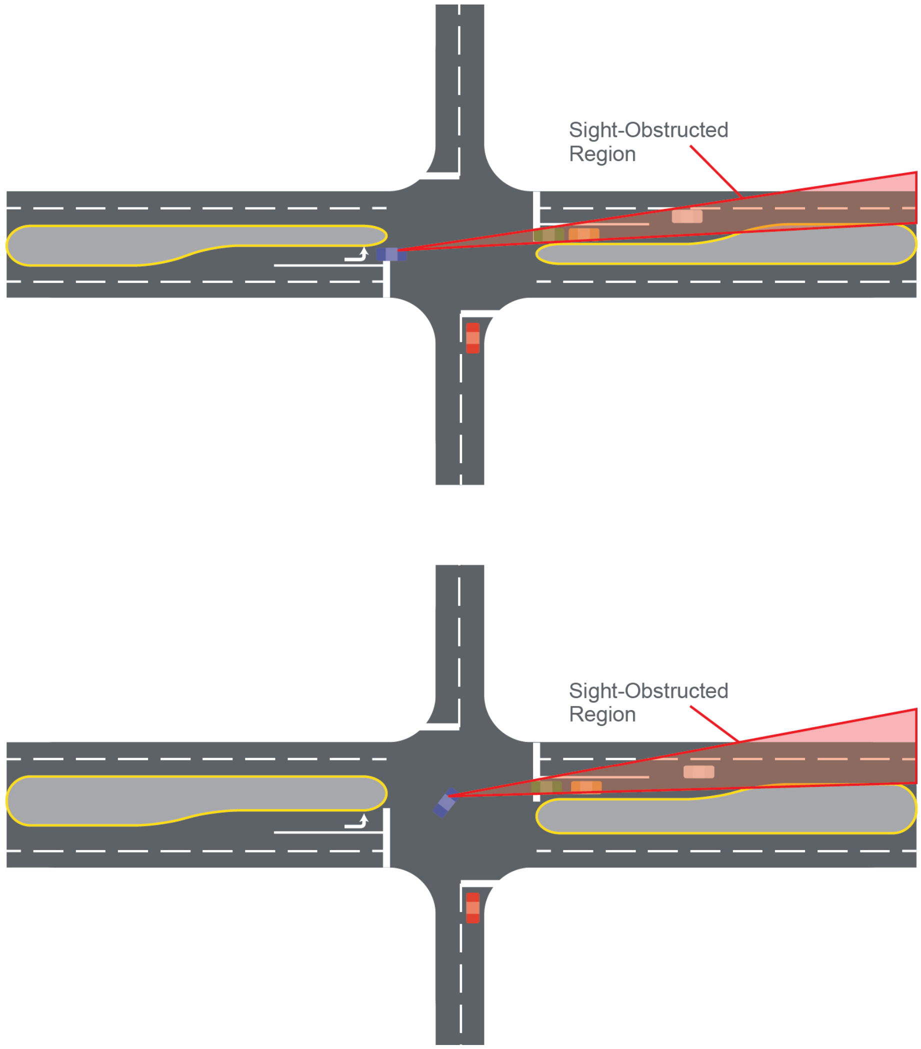


Figure 2.1. Sight-obstructed regions for unpositioned and positioned vehicles at intersection without offset left-turn lanes.

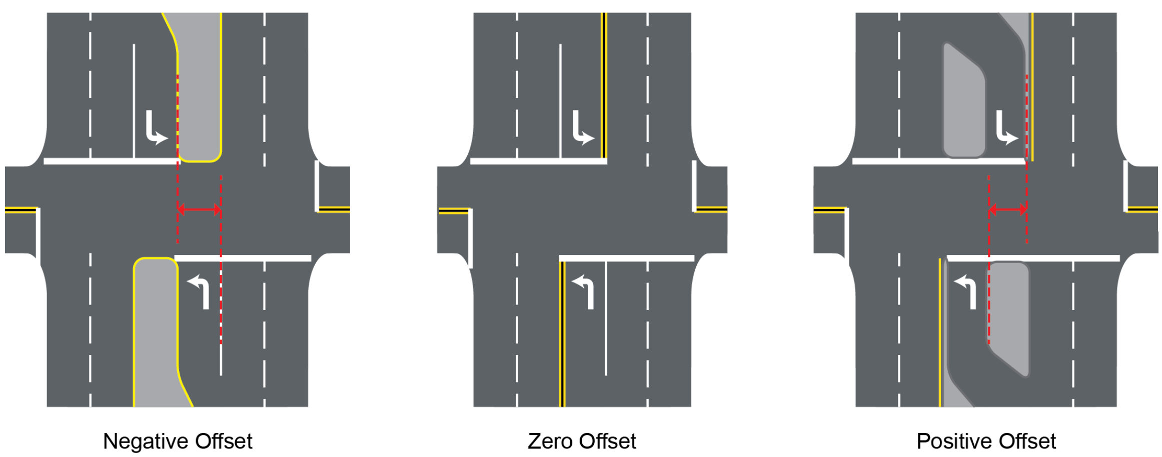


Figure 2.2. Illustration of intersection left-turn lanes with negative offset, zero offset, and positive offset.

make up over 40% of fatal crashes at signalized intersections. About half of these crashes are left-turn crashes. FARS data for 2009 show that left-turn collisions constitute 8.5% of all traffic fatalities (National Highway Traffic Safety Administration 2011). A substantial proportion of these fatalities occur when a turning driver's view of oncoming opposing through traffic is limited by the presence of another left-turning vehicle in the opposing left-turn lane.

NCHRP Report 500, Volume 5: A Guide for Addressing Unsignalized Intersection Collisions, includes offsetting opposing left-turn lanes as a "tried" strategy but provides no guidance on the desirable amount of offset or the effectiveness of implementing such a strategy (Neuman et al. 2003). NCHRP Report 500, Volume 12: A Guide for Reducing Collisions at Signalized Intersections, presents a strategy to provide or improve left-turn channelization, which includes a discussion of redesigning the intersection to provide positive visual offset as a way to improve left-turn lane geometry; but again, no specific guidance or effectiveness is provided (Antonucci et al. 2004). The AASHTO Green Book recommends that offset left-turn lanes be used in medians wider than 18 ft, which is roughly equivalent to an offset of −6 ft, but gives no specific design guidance for the desirable reduction in negative offset (AASHTO 2004).

A 1992 study provided guidance on the amount of offset required to provide unlimited sight distance for left-turning vehicles at 90-degree intersections on level, tangent roadway sections of four-lane divided roadways with 12-ft lanes. The required offset in these conditions is 2 ft when the opposing vehicle is a passenger car and 3.5 ft when the opposing vehicle is a truck (McCoy et al. 1992). Another study in the same year developed a model for determining the minimum offset requirement for ensuring adequate sight distance for left-turning drivers, which included factors for design speed and intersection geometry (Joshua and Saka 1992). These studies were simple physical models, based on intersection geometry, and did not evaluate the effect of offset on driver behavior or crashes.

A study of five signalized intersections in Nebraska evaluated the degree to which narrowing the left-turn lane using wider pavement markings between the through and left-turn lanes affected the vehicle positioning of left-turning drivers within the lane, and therefore their view of oncoming opposing through traffic. Like the earlier studies, this study used physical models of available sight distance based on intersection geometry and vehicle positioning (McCoy et al. 1999).

A more recent Empirical Bayes before-after study evaluating the safety effect of left-turn lane offset improvements at 117 signalized intersections in Florida, Nebraska, and Wisconsin showed mixed results among states. In Wisconsin, the treatment included major reconstruction to provide a positive offset; the implementations in Florida and Nebraska typically used striping treatments to narrow or shift the left-turn lane to provide offsets that were slightly less negative. The treatments in Wisconsin were found to reduce all crashes by 34%, injury crashes by 36%, and left-turn crashes by 38%, while the treatments in Florida and Nebraska showed no crash reduction. The study did not provide offset measurements at each intersection before and after the improvement, and no analysis was performed to evaluate the degree of offset that would result in improved safety (Persaud et al. 2009).

Safety studies have traditionally used historical crash data to evaluate the effect of a given countermeasure by comparing crashes before and after its implementation. However, a desire to provide countermeasures proactively, rather than only after a crash pattern develops, requires that designers anticipate the likelihood of crashes before they happen. In addition, studies conducted over a short time period or at a small number of locations tend to have too small a sample size of crashes to draw conclusions, so other measures of safety must be used. Surrogate safety measures are used to give information about near misses and crash risk in simulations, and they can help predict potential crash issues before crashes occur. For left-turn maneuvers, gap acceptance is a common safety surrogate: it stands to reason that the smaller the accepted gap, the less time there is between the clearance of the turning vehicle from the intersection and the arrival of an opposing through vehicle. When the time between those two events equals zero, one or both drivers must adjust their speed (or course), or a crash occurs.

Several measures are used in the literature related to gap acceptance. Many studies evaluate the critical gap, which is the gap length equally likely to be accepted and rejected by a driver. Conditions that decrease the critical gap are those that encourage drivers to accept shorter gaps. A project conducted for FHWA investigated the potential for deriving surrogate measures of safety for existing traffic simulation models to support the safety evaluation of new countermeasures before construction and existing countermeasures in a more cost-effective manner. The study found that *time to collision,* defined as the time between the end of the encroachment of the turning vehicle and the projected arrival of the through vehicle if the vehicle continued along its path at a constant speed, and *post-encroachment time,* defined as the time between the departure of the turning vehicle from the conflict point and the actual arrival of the conflicting vehicle at the conflict point, were two of the best measures for the likelihood of a collision (Gettman and Head 2003).

Chan defined left-turning conflicts by the difference in arrival time at the intersection between the left-turning vehicle and the next opposing through vehicle, which he called the *trailing buffer.* This is a similar measure to *time to collision* or *postencroachment time* used in other studies. Near misses were defined as occurring when the trailing buffer was 1 s, and close encounters when it was 2 s. Depending on the site, 1% to 4% of left turns were considered near misses, but the percentage of close encounters was as high as 10%, depending on the intersection (Chan 2006).

Measures related to gap acceptance not only serve as a surrogate for crash risk but also provide information about the operational performance of an intersection. Situations that cause drivers to wait for longer gaps reduce the number of left turns that can be made in a given time period. When sight distance for left-turning drivers is restricted, drivers may wait for longer than normal gaps on average, but they also have a higher likelihood of accepting a short gap because the oncoming opposing through vehicle cannot be seen. Therefore, the sight-distance issue that may be caused by opposing left-turn vehicles can decrease both safety and operational performance at an intersection.

The AASHTO Green Book suggests using a critical gap time of 5.5 s for passenger cars making a left turn from a single lane on an undivided highway, adding 0.5 s for each additional lane crossed. This gap length was used to develop intersection sight-distance guidelines (AASHTO 2004). The *Highway Capacity Manual* (HCM) has used a critical gap time of 4.5 for signalized intersections with a permitted left-turn phase (Transportation Research Board 2000).

To identify the changes in driver behavior clearly associated with restricted sight distances, one study collected field data at a signalized intersection with the potential for sight-distance restrictions for left-turning drivers due to opposing left-turning drivers. A data set of 1,485 gap decisions was observed for 323 left turns. Of those turns, 218 were completed by drivers whose view was obstructed. Both linear regression and logistic regression models were developed to estimate parameters of gap acceptances. The results showed that sight obstruction due to the opposite turning vehicles may contribute to significantly larger critical gaps (7.7 s versus 5.6 s) and mean accepted gaps (10.4 s versus 8.9 s). Follow-up time (the time between successive left-turning vehicles accepting the same gap) was also found to be longer when the driver's view was obstructed. In addition, the authors evaluated gap acceptance by the gaps that were available to drivers. Drivers whose view was obstructed tended to wait for longer gaps than drivers who had clear sight lines when available gaps were larger than 4.8 s. However, when available gaps were smaller than 4.8 s, drivers with sight obstructions tended to take shorter gaps than drivers with clear sight lines, although the sample sizes for these comparisons were quite small. A review of erratic maneuvers showed that eight of the 10 erratic maneuvers observed occurred when a left-turning driver with a restricted view of oncoming traffic took a short gap (Yan and Radwan 2007; Yan and Radwan 2008).

The decision to accept a gap to complete a left-turn maneuver at an intersection is influenced by several factors, including the gaps that are available, the time spent waiting to turn, lighting, pavement and weather conditions, the turning driver's perception of the speed and distance of the oncoming vehicles, the driver's perception of his own and his vehicle's capabilities, the driver's familiarity with the intersection or similar intersections, and the driver's tolerance for risk.

To assist left-turning drivers in evaluating adequate gaps in oncoming traffic, researchers in California conducted a study of gap-acceptance behavior at five intersections to develop guidance for when an Intersection Decision Support System should alert drivers about gaps in oncoming traffic. The study found that no driver accepted a gap shorter than 3 s, while no driver rejected a gap greater than 12 s. Other studies agree with this range of gap length within which drivers must make a decision about whether or not to turn (Gattis and Low 1999; Madanat et al. 1994). The critical gap varied by intersection but ranged from 5.6 s to 7.6 s (Shladover et al. 2006).

One study evaluated driver perceptions of the level of comfort and degree of difficulty of making left-turn maneuvers at four intersections with left-turn offsets that ranged from negative to positive. These measures were not found to improve with the increased sight distance provided by larger (i.e., more positive) offsets. Drivers were most comfortable with the −0.9-m (3-ft) offset, which the authors suggested was the most common offset found in the area, and least comfortable with the 1.8-m (6-ft) offset, which was least commonly used in the area. The authors suggest that familiarity might have had a stronger influence than available sight distance in this evaluation (Tarawneh and McCoy 1996).

A study of factors that influence aggressive driving, which was measured in terms of start-up delay, gap acceptance, and acceleration or deceleration when facing an amber signal indication or when changing lanes, was conducted at 10 major signalized intersections near Washington, D.C. It found that the major contributor to aggressive driving was traffic operations. Being stuck in long queues, surrounded by heavy vehicles, and with increasing numbers of pedestrians and vehicles caused drivers to "lose their patience" (Hamdar et al. 2008).

A study by Adebisi and Sama (1989) found that drivers who have to wait more than 30 s begin to take risks by accepting smaller gaps, indicating that drivers may accept smaller gaps when opposing traffic volumes are higher because fewer large gaps are available and the wait time for a suitable gap is longer. A more recent study evaluating the effect of wait time on driver left-turning behavior at a single intersection found that drivers become more aggressive as their search time for a suitable gap increases. The critical gap time was shown to decay in a linear fashion as the wait time increased (Zohdy et al. 2010).

A study of the effect of weather on left-turn gap-acceptance behavior was conducted at a single signalized intersection over a 6-month period. More than 11,000 gaps for a permitted left-turn maneuver were observed; approximately 10% were accepted gaps, while the remaining gaps were rejected. The study considered six combinations of weather and pavement conditions: no precipitation with dry, wet, icy, or snowy pavement surface; rain with wet pavement surface; and snow with snowy pavement surface. The critical gap measured for the dry weather, dry pavement condition was approximately 1.2 s shorter than for the snowy condition, which had the longest critical gap. It was also found that the critical gap for the dry weather with wet pavement condition was more than a second longer than for the dry pavement condition. The authors hypothesize that this may reflect that approaching vehicles are likely traveling at higher speeds than during other weather conditions and that left-turning drivers are more hesitant to turn in front of them on wet pavement. Critical gaps for all conditions and all three models evaluated ranged from about 6.2 s to 8.4 s—values substantially larger than those recommended in the Green Book or the HCM (Zohdy et al. 2011). The Zohdy et al. (2010) single-intersection study showed a linear increase in critical gap as rain intensity increased.

Signal phasing and timing plans can also affect a driver's gap-acceptance behavior. Left-turning drivers at intersections with protected/permissive phasing may be willing to wait for longer gaps knowing that if they do not find one, they will eventually be able to turn on a protected green arrow. Clearance intervals may affect left-turn decisions, as drivers waiting to turn left make assumptions about the likelihood that an opposing oncoming vehicle will slow or stop for a yellow or red light. One study found that even with modest traffic volumes, about 25% of the near misses occurred during signal transition. The author notes that "when signal transitions from green to amber and red, opposing traffic will mostly slow down to stop. Some drivers will initiate a left turn in front of these oncoming vehicles with the anticipation that the other vehicles will slow down and stop for them" (Chan 2006).

A driver's age and gender have been demonstrated to play a role in gap acceptance behavior. A New Zealand study evaluated the effects of aging on driver behavior at T-intersections. Eighty drivers in four groups of 20 (10 males, 10 females)—respectively aged under 30 years, 40–59, 60–69, and 70 years and over—participated in research to identify factors contributing to rural T-intersection crashes involving older drivers. Participants estimated safe gaps and speeds for traffic approaching from their right from a test vehicle parked at a right angle to the highway, simulating a T-intersection. Safe gaps for a right turn onto the highway were estimated using threshold (last possible moment) and single judgment procedures (go/not go). A laser device recorded traffic speed and distance. Each participant's speed at turning right across the road also was tested. Drivers over age 59 had the most visual defects and the poorest neck articulation. All participants judged speed poorly, overestimating slower traffic and underestimating faster traffic. They used distance rather than speed in gap estimation. While participants under age 30 allowed the smallest gaps, those over age 59 were the least consistent judges and were slower to clear the next lane when turning right. Older drivers may be at higher risk at intersections, especially when approaching traffic exceeds 100 km/h, through failure to detect approaching vehicles, poor speed and gap estimation once vehicles are detected, and slower lane clearance when turning (Parsonson et al. 1999).

An FHWA study examined the effect of positive versus negative offset at intersections in relation to safety of gap-acceptance behavior of older and younger drivers. A laboratory study using a video-based driving simulator was first conducted to examine left-turn gap-acceptance behavior for drivers waiting to make a left turn, facing a green ball (permissive) signal. Drivers were found to be more cautious with increasing negative offset in terms of the least safe gap they were willing to accept. Older drivers (75+) accepted disproportionately higher numbers of unsafe gaps compared with younger drivers in the partial negative geometry (Staplin et al. 1997).

In a subsequent field study, left-turn performance of 100 subjects within three age groups (aged 25–45, 65–74, and 75+) was evaluated under normal driving conditions at four intersections of different left-turn offset configurations. The results showed that large negative offsets (more than 2.95 ft or 0.9 m) significantly increase the size of the critical gaps of drivers turning left and also seem to increase the likelihood of conflicts between left turns and opposing through traffic. Older drivers and women drivers were less likely than other drivers to position their vehicles within the intersection to see beyond vehicles in the opposing left-turn lane (Tarawneh and McCoy 1996).

Another study used a driving simulator experiment for left-turn gap acceptance at a stop-controlled intersection to evaluate the effects of major traffic speed and driver age and gender on gap-acceptance behaviors. The experiment considered relationships among drivers' left-turn gap decision, driver's acceleration rate, steering action, and the influence of the gap-acceptance maneuver on the vehicles in the major traffic stream. The experiment results showed that older drivers tend to wait for larger gaps than younger or middle-age drivers do. Male drivers appeared to accept smaller gaps than female drivers. The findings suggest that older drivers and female drivers are more conservative than the other groups. Older drivers also turned the simulator steering wheel more slowly than other drivers and were more likely to use slower acceleration rates (Yan and Radwan 2007; Yan and Radwan 2008).

How NDS Data Provide New Insights

The needed research for establishing driver gap-acceptance behavior at intersections with and without offset left-turn lanes has not been done because the cost of collecting appropriate data at a sufficient number of intersections with various geometric designs through conventional methods would be quite high. Typically, studies of driver behavior at intersections use multiple cameras at fixed sites at each intersection. Placement of the cameras requires field personnel to be on site at each location. The video data must then be reduced by observers in an office setting, processed by data analysts, and then analyzed by statisticians. Within realistic budgets, field video studies with fixed-camera locations tend to provide a substantial amount of data for a relatively few sites. The NDS data provide an opportunity for the research team to bypass the expensive field data acquisition stage (since this will already have been done by SHRP 2 under other contracts) and go straight to data reduction and analysis. In addition, video segments can be requested for only the time periods that include behaviors of interest (i.e., left turns completed by NDS drivers at intersection approaches appropriate for inclusion in the analysis), making video data reduction much more efficient than it would be for continuously recorded video data. Obtaining the NDS data from the Virginia Tech Transportation Institute (VTTI), which performs the queries and formats the data, requires an initial investment by the research project, but an important objective of Project S08 is to demonstrate techniques for acquiring such data that can be applied in future research. The NDS data can be expected to provide data for more sites than would be possible in most fixed-site-camera field studies, given typical research budgets.

In addition to the benefit of reduced costs, the NDS provides the opportunity to see the traffic conditions from the driver's perspective. Other studies that have evaluated sight obstructions related to opposing left-turn lanes have simply used the presence of an opposing left-turn vehicle as a surrogate for sight-distance restrictions, or they have used physical models to calculate sight distance based on assumptions about each driver's position. This study design allows the video data analyst to record whether an individual driver's view was obstructed by an opposing driver during each accepted or rejected gap.

NDS data also provide driver demographic information that is typically not available in fixed-camera studies. While it is available in driving simulator or recruited-driver studies, the behavior observations made during such studies are not of truly naturalistic behavior, since drivers are aware of the presence of an observer. The NDS data set provides more observations of driver behavior than a recruited-driver study typically would, records truly naturalistic driving behavior, and incorporates driver variables that would not be accessible in a fixed-camera study.

In addition, the NDS data set provides the possibility of considering the interaction of effects of driver demographics and intersection geometry. Typically, recruited-driver studies can answer questions about how driver characteristics influence behavior in a limited number of scenarios. Fixed-camera studies can gather large numbers of observations at a limited number of sites as well but cannot typically incorporate driver demographics. In this research, because of the availability of the NDS data set, the effect of both offset category and driver age on gap-acceptance behavior could be investigated.

CHAPTER 3

Data Collection Methodology and Summary Statistics

Data used for the study included intersection characteristics from the Roadway Information Database (RID), visual inspection of aerial and street-view images from Google Earth and ArcGIS maps, environmental characteristics during turning maneuvers of interest observed in NDS video files, NDS driver demographic data, and time-series data related to the trip from the in-vehicle data recorders. The following sections describe how each of these data types was obtained. Chapter 4 includes descriptive statistics of the key variables gathered in the data collection process.

Intersection Selection

The intersection selection procedure used in Phases 1 and 2 of this research is described below. While some steps of the process were similar between the phases, other steps were different because of the different types of data available to help select appropriate intersections in each phase. For example:

- In Phase 1, the RID was not yet available, so initial site selection was completed manually by viewing intersections in the NDS areas in Google Earth.
- In Phase 2, the research team was able to request from Iowa State University's Center for Transportation Research and Education (CTRE) a list of intersections from the RID with specific desirable characteristics (although the benefit of this turned out to be somewhat limited, as discussed more thoroughly later in this chapter).
- In Phase 1, the research team was provided maps of trips made by NDS drivers. This information facilitated the identification of routes on which the greatest number of NDS trips had been made. The research team was able to focus the intersection review on these routes.
- In Phase 2, researchers discovered that these maps were not updated to include NDS trips made after the first few months of the NDS, so this tool was not available to help select sites in Phase 2.

The steps for intersection selection for each phase are described below.

Intersection Selection in Phase 1

Site selection for Phase 1 was conducted in four steps as follows:

- *Step 1.* Obtain early trip maps from CTRE to identify heavily traveled routes, and then intersections along these routes.
- *Step 2.* Use Google Earth to evaluate intersections identified in Step 1 for potential use in the research.
- *Step 3.* Request from VTTI the number of left turns of interest made at each intersection identified in Step 2 as being a good candidate for the study.
- *Step 4.* Narrow the initial list of intersections submitted to VTTI in Step 3 to the most promising two or three intersections from each of the offset categories (positive, negative, zero) for which to request NDS data.

In Step 1, the initial trip maps provided by CTRE included only a few months of NDS data, so most routes had a fairly low trip volume. Trip maps for the Raleigh-Durham area of North Carolina were the first received, so the initial search for intersections began there. Intersections in Buffalo, New York, and Tampa, Florida, were evaluated next. Researchers determined that these three study locations would provide enough intersections for the Phase 1 proof-of-concept study; thus, at that point, they did not need to continue looking for intersections at the other NDS locations.

While no turning movement counts were obtained from those intersections, the research team assumed that intersections along routes with higher through volumes would have higher left-turn volumes than intersections along less traveled routes.

In Step 2, geographic information system (GIS) tools, including ArcMap and Google Earth, were employed to evaluate basic intersection characteristics. Using aerial imagery within these tools, intersection characteristics were recorded, including presence of a dedicated left-turn lane, approximate offset distances, intersection skew angle, roadway curvature, and the apparent facility type of the cross street to determine whether it was likely to carry much traffic. A street-level view was then used primarily to identify the type of traffic control. While signal phasing could not always be determined with certainty using this view, researchers were able to eliminate many intersections that clearly had protected-only left-turn phasing. This review also allowed the research team to identify which of the left turns (e.g., northbound to westbound) at the intersection were appropriate for the study, since the left-turn lane geometry and signal phasing frequently varied between approaches. In addition, the street-level view provided an opportunity to evaluate whether roadway curvature or grade affected sight distance for left-turning drivers and any other factors that might be relevant to the study.

The GIS review of intersections resulted in a list of 38 intersections that were considered good candidates for inclusion in the research. Most of the intersections were in the Raleigh-Durham area, but a few intersections in Buffalo were also included. The intersections reviewed in Tampa were considered less promising and were not included in the list sent to VTTI.

In Step 3, the research team sent the list of intersections developed in Step 2 to VTTI and requested, for each left turn of interest, the number of turning maneuvers made by NDS drivers and the number of distinct drivers making the turns. The research team noted in its request that, among the 38 intersections, it was desirable to find two or three from each offset category to use for the study, and that the highest priority intersections were those with the most left-turn maneuvers, to provide as many observations as possible for the study.

VTTI fulfilled the data request by providing a spreadsheet that included the number of trips completed by study vehicles and the number of study vehicles within a 1,000-ft geofence of the center of the intersection of interest. For the intersections with the highest number of trips (knowing that only a few intersections from each offset category were needed for the Phase 1 analysis), they completed a left-turn verification process to identify the number of left turns made from the intersection approaches of interest to the research. They completed this left-turn verification for three intersections with positive offsets and three intersections with zero offsets. However, the list of negative-offset intersections had few movements within the geofence. Therefore, VTTI completed the left-turn verification for seven intersections in that category, allowing the research team to choose the intersections of greatest interest on the basis of characteristics other than highest number of trips. VTTI also indicated that if the research team was interested in specific intersections for which VTTI had not completed the left-turn verification, it could go back and look at those intersections as well.

After reviewing the first data set provided by VTTI in Step 3, the research team chose 10 intersections for which to request a full data set in Step 4. The 10 intersections were chosen to obtain a variety of left-turn offset conditions in the data set, using those with the greatest number of left turns of interest and prioritizing intersections that were unsignalized or believed to have permissive-only left-turn phasing. Of the 10 intersections, three had not been included in VTTI's left-turn verification process but were considered to be of high enough interest to request that they be included in the final data set. However, researchers discovered that either these additional intersections had no left-turning movements from the approaches of interest or the intersection's proximity to a study driver's origin or destination led to concerns about revealing personal identifying information. An additional intersection was dropped after the research team determined that the low number of left-turning maneuvers of interest made it less desirable for the research. This process resulted in six signalized intersections, each with permissive/protected left-turn signal phasing.

Table 3.1 shows the final six intersections used for the Phase 1 evaluation and the number of left turns of interest made at each one. Note that the number of intersections and left-turn maneuvers available for Phase 1 analysis were not sufficient to produce meaningful results. This small sample was instead used to demonstrate that the desired data could be obtained and analyzed as the research team had proposed.

Intersection Selection in Phase 2

Figure 3.1 illustrates the procedure used to select intersections for study in Phase 2. The figure shows six action steps, each describing a data request or filter. The figure also shows the number of signalized and stop-controlled intersections remaining in the database after each step.

As mentioned previously, the trip maps used to help with initial site selection in Phase 1 only represented the trips made by NDS drivers in the first few months of the study. These maps were not updated to reflect the remainder of the study and therefore were not useful in Phase 2 for initial intersection selection. Annual average daily traffic (AADT) counts of the routes were not considered useful substitutes for these maps, because there was no basis to assume that the

Table 3.1. Intersections Used in Phase 1 Analysis

Unique Object ID (VTTI)	Major Route	Minor Route	City	Offset Type	Number of Left-Turning Maneuvers by NDS Vehicles for Which Data Were Provided	Number of Left-Turning Maneuvers by NDS Vehicles Identified as Ideal for Analysis
7	Fayetteville Rd	Woodcroft Pkwy	Durham, NC	Positive	15	9
13	SR 54/Chapel Hill Rd	NE Maynard Rd	Cary, NC		9	1
19	MLK Jr Pkwy	Hope Valley Rd	Durham, NC	Zero	91	32
23	Apex Hwy	Riddle Rd	Durham, NC		124	25
28	Sheridan Dr	Parker Blvd	Buffalo, NY		60	23
33	Davis Dr	Hopson Rd	Triangle, NC	Negative	6	3

trips NDS drivers made were proportional to trips made by all drivers. That is, the routes heavily traveled by NDS drivers did not necessarily match the routes most heavily traveled by all drivers.

Because the RID was available (in a preliminary form) for Phase 2, and data were collected for the routes most highly traveled by NDS drivers, a first list of intersections for review was produced from the RID data.

Step 1

As a first step for intersection selection, the research team requested a list of intersections from CTRE with the following characteristics:

- Presence of dedicated left-turn lane;
- Four legs;
- No more than two through lanes on approaches of interest;

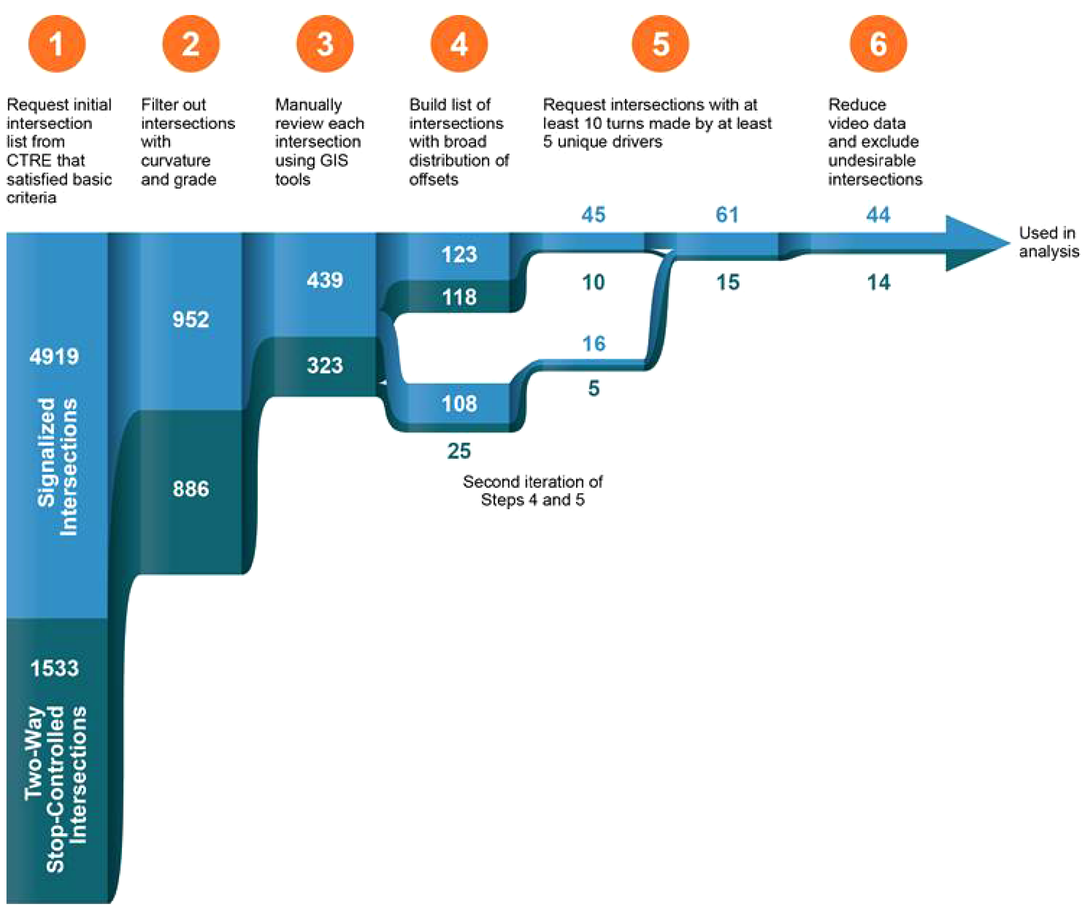


Figure 3.1. Flowchart of intersection selection procedure.

- Two-way stop control or signalized traffic control type;
- No horizontal curvature on approaches of interest;
- No significant grade on approaches of interest; and
- Posted speed limit on the approaches.

CTRE provided a list of 6,452 intersections traversed by NDS drivers from five NDS states (data from Pennsylvania had not yet been validated so were not included in the available RID). These intersections are four-leg intersections with at least one dedicated left-turn lane, have no more than two through lanes on any approach, and are either two-way stop-controlled or signal-controlled. CTRE also provided information about the presence of horizontal curvature near the intersection and grade measurements near the intersection but did not filter intersections by these criteria. A database of speed limit signs was also provided. These data were provided in a GIS database so that each intersection could be viewed on a map with ease.

For the purposes of this project, the RID, in the early form available during this research, had significant limitations. While the RID contains a wealth of information, it was not feasible at the time of the site selection process for the research team to link various data elements in a way that could help with querying intersections with certain characteristics, as was originally planned. Limitations of the RID encountered during Phase 2 include the following:

- While the RID could identify the presence of a left-turn lane at an intersection, it could not identify whether two opposing approaches each have a left-turn lane, which was critical for the study. In addition, the RID could not provide an accurate count of left-turn lanes at an intersection. For example, a 300-ft left-turn lane on an intersection approach may have been counted twice if, say, a 150-ft right-turn lane was also present. Because the cross-section of the roadway changes with the addition of the right-turn lane, the approach is broken into two segments and the left-turn lane is counted in each segment.
- Roadway names were included in the RID, but the roadway names could not be matched to the left-turn lanes accurately; thus, researchers could not search for intersections with two left-turn lanes associated with approaches with the same name. If a roadway has more than one name, or the name changes at the intersection, both names were listed, but the database could not identify which two names were associated with the same approach or roadway.
- For unsignalized intersections, there was no way to identify if the left-turn lanes were on the stop-controlled approach or the uncontrolled approach, so the data could not be filtered for intersections with left-turn lanes on the uncontrolled approaches. Instead, aerial photos had to be reviewed to make this determination.
- There was no way to distinguish the minor and major routes at an intersection without looking at a map.
- The RID provided a database of speed limit signs, but the speed limits could not be tied to intersection approaches. Therefore, the data could not be queried for intersections with specific approach speeds. The speed limit had to be obtained by viewing the database in mapping software and manually searching for the nearest sign to the intersection.
- The presence of medians was identified in the same way as left-turn lanes and, therefore, had the same limitations. The research team intended to use the presence of medians to help identify locations where positive-offset left-turn lanes were more likely to be present. However, there was no way to identify whether a given median was located on the same approach as a left-turn lane of interest.
- The RID could be queried in such a way as to identify the presence of a horizontal curve within a certain distance from the intersection. However, CTRE was not able to provide the radius of the curves identified within that range. CTRE explained that this was because the alignment data, including radius, was not yet conflated to the network. In addition, the curves that were identified were not necessarily located at the intersection approaches but instead might be located on another nearby roadway.
- Grade data for the intersection approaches were requested to try to filter out intersections on a significant grade. Grade was measured in the RID in 21-ft segments. CTRE provided several grade measurements for each intersection, including maximum grade, minimum grade, average grade, and the average absolute value of grade. It was not possible to link grade information to approaches with left-turn lanes.

Note that many of these limitations have been addressed as the RID has become more fully implemented and should not necessarily be considered limitations for future researchers.

Step 2

These limitations resulted in a labor-intensive preliminary identification of study intersections. Because the number of intersections included in the database was substantially greater than anticipated, and review of these intersections was so labor-intensive, researchers developed filters for selecting appropriate intersections in Step 2 to obtain a number that would be manageable for a manual review of desirable characteristics in aerial and street-view images. The two filters were the following:

- An intersection was eliminated if a horizontal curve was identified within 50 m of the intersection. Doing this may have eliminated some intersections that either did not have any horizontal curvature, had curvature on approaches that would not have affected the study, or had curvature but the curvature was so slight that it would have been within tolerable limits for the study.

- An intersection was eliminated if it included a grade of 2.5% or more. This was a crude method, since grade measurements were taken at all roadway segments within 500 ft of the intersection; thus, the grade averages were for all four approaches (and potentially other roadway segments within 500 ft of the intersection), rather than just for a specific approach, or for two opposing approaches.

Figure 3.2 shows the candidate unsignalized intersections as viewed using the ArcMap 10.2 interface and a portion of the GIS database of intersections provided by CTRE.

Step 3

In Step 3, the remaining intersections were reviewed in aerial and street-view maps to record the following information:

- Presence of opposing single-lane left-turn lanes;
- Direction of approaches of interest (north-south approaches, east-west approaches, or both);
- Offset measurements;
- Intersection skew;
- Approach speed limits;
- Number of legs (verification of CTRE database);
- Number of through lanes (verification of CTRE database); and
- Horizontal alignment.

In addition, signalized intersections were reviewed in Google Maps' street view to determine left-turn phasing (i.e., whether

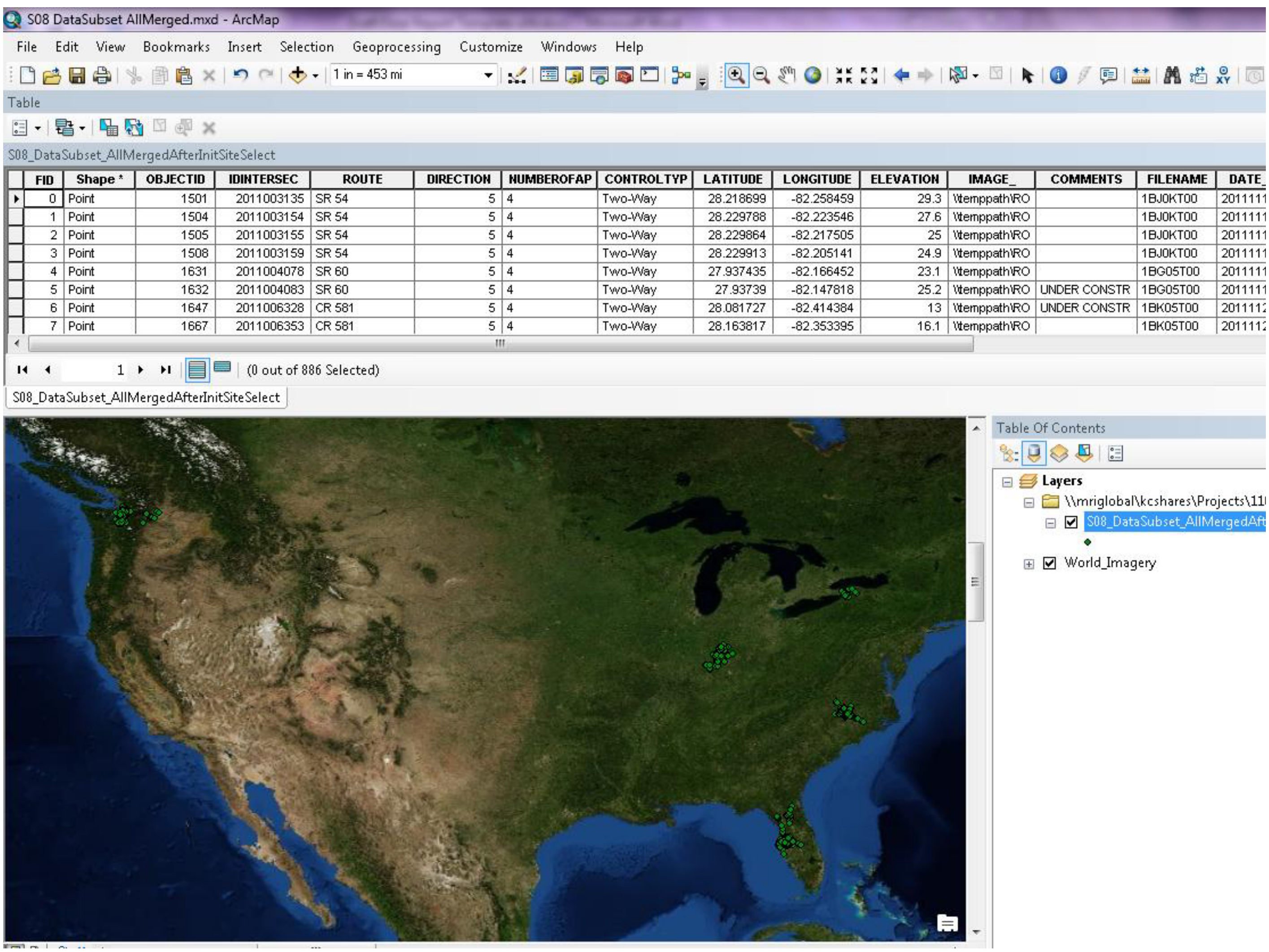


Figure 3.2. Candidate unsignalized intersections viewed in ArcMap 10.2.

the left-turn signal appeared to be protected only, permissive only, or permissive/protected). Signals with both protected and permissive phases were fairly easy to identify since they typically have five-section signal heads. However, distinguishing between permissive only and protected only was more difficult if a green indication could not be seen as the street-view images approached the intersections. Reviewers made best guesses for these cases. Figure 3.3 shows an aerial and street view for an intersection being reviewed for this research.

After completing the review of these intersections, the research team narrowed the list of intersections to include only those with opposing, single-lane left-turn lanes and a skew between 75 and 90 degrees. The following intersections were also excluded:

- Signalized intersections with protected-only left-turn phasing;
- Intersections that had other than four legs;
- Intersections with more than two through lanes opposing the left turns of interest; and
- Intersections where anything about the geometry or other characteristics would likely cause abnormal gap-acceptance behavior (e.g., significant grade, railroad tracks near the intersection).

Step 4

In Step 4, the research team organized the remaining intersections by measured offset. More than 40% of the intersections had an offset equal to zero. The distribution of offsets measured at the two-way stop-controlled intersections is shown in Figure 3.4. A subset of the intersections available at the end of Step 3 was chosen to represent a distribution of offsets. Signalized intersections with permissive-only left-turn phasing were prioritized over intersections with permissive/protected phasing. Note that for signalized intersections, both pairs of

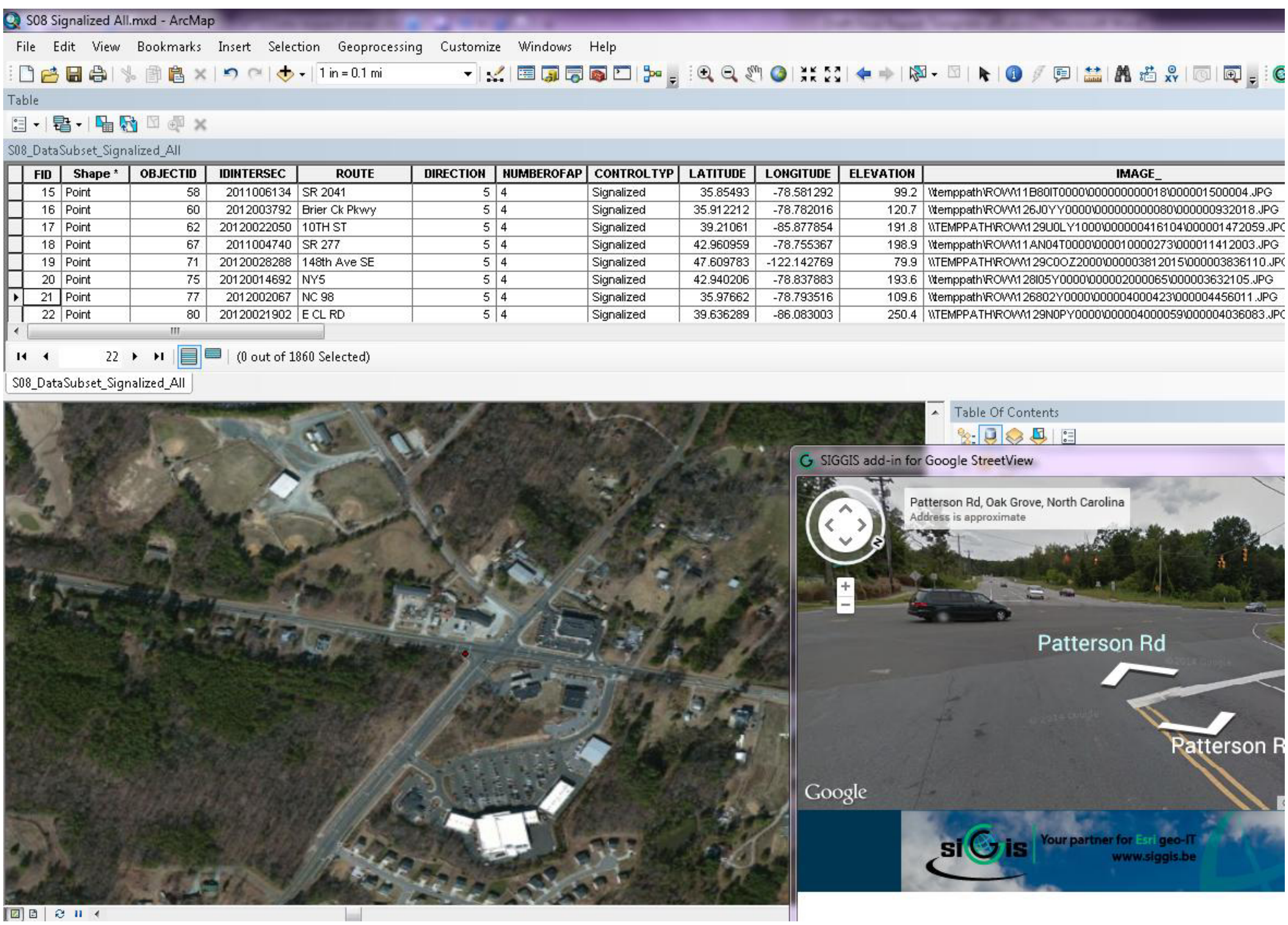


Figure 3.3. Signalized intersection viewed in ArcMap interface.

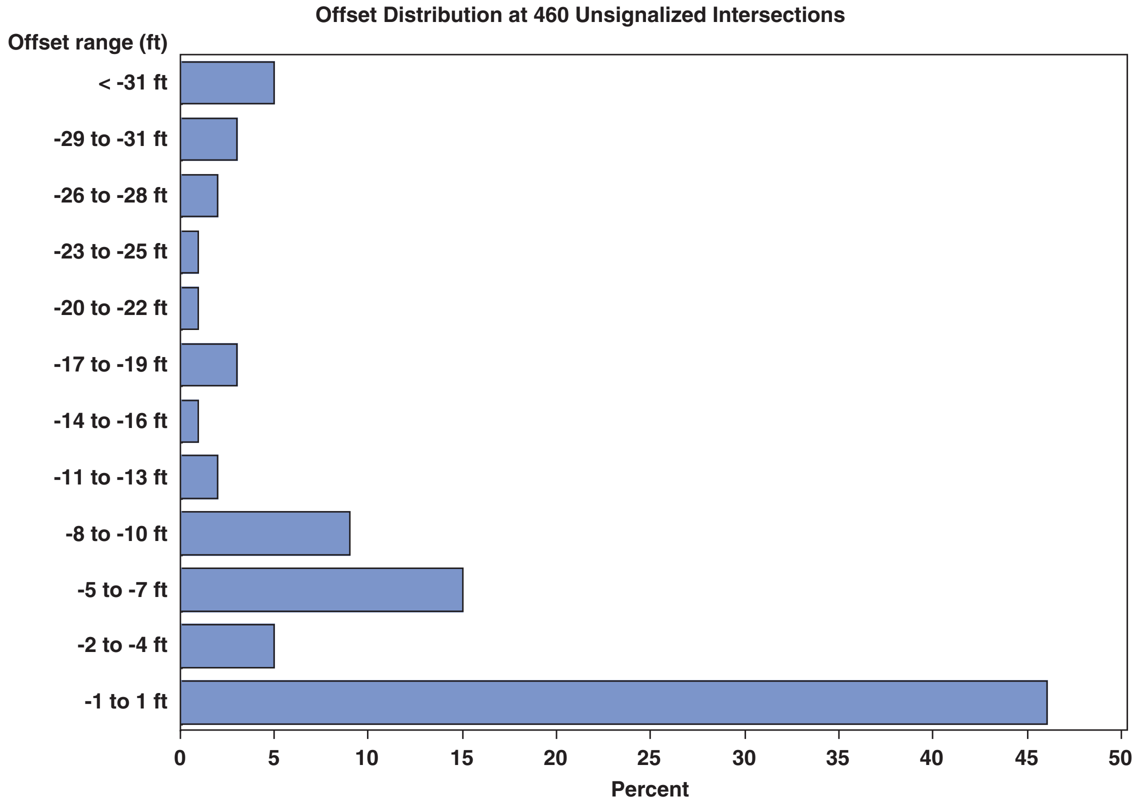


Figure 3.4. Distribution of offsets measured at unsignalized intersections.

opposing approaches might be found to be appropriate for the study. Each pair was considered as a separate observation, so the number of signalized intersections shown in Figure 3.1 truly refers to the number of signalized left-turn pairs beginning at Step 4.

The intersections chosen in Step 4 were submitted to VTTI with a request for the number of turns made by NDS drivers and the number of unique drivers making those turns. The initial request, which included only the stop-controlled intersections because they were reviewed first, took more than 6 weeks to fill as VTTI developed the methodology to provide the information. Even so, the initial results provided to the research team were later reduced by nearly two-thirds because of errors in the procedure, and then reduced again because of other concerns (e.g., the intersection had study driver privacy concerns). Follow-up requests were filled substantially faster and more accurately. Researchers learned during this step that only approximately 20% percent of the NDS trips made were available to be queried, so substantially fewer trips were identified than would ultimately be available for the same query in the future.

Step 5

In Step 5, the research team submitted a request to VTTI for forward- and rear-facing video data for all left turns made by NDS drivers at the approaches that had at least 10 turning maneuvers made by at least five different drivers. Unfortunately, few of the intersections met these criteria, especially at stop-controlled intersections. To increase the number of intersections available for analysis, the research team went back to the list that came out of Step 3 to identify additional intersections not yet submitted to VTTI that would fill in the gaps in the offset distribution. Once again, the research team requested the number of left turns made by NDS drivers at approaches of interest and the number of unique drivers making those turns. The second round of intersections proved to have even fewer turns than the first set but still provided some additional data.

Step 6

In Step 6, the video data reduction was conducted (described in detail in the next section). That process further reduced the number of intersections and the number of turns available for analysis at each intersection for the following reasons:

- A few intersections were found to have characteristics undesirable for the study, such as three through lanes in the opposing direction, geometric issues that could have affected sight distance that were not caught in earlier reviews, or intersections/railroad tracks near the intersection that affected turning behavior.

- Some intersections were given a lower priority for video data reduction because they provided information for an offset category that already had a substantial sample size. These intersections were not reviewed because of project time constraints.
- Videos that showed construction cones (indicating construction at the intersection) were removed from the database.
- Videos in which turning movements were made during a protected phase were removed from the database.

The final database for Phase 2 analysis included 44 signalized left-turn pairs (at 33 intersections) and 14 two-way stop-controlled intersections.

Video Data Reduction

The video data reduction process was similar for Phase 1 and Phase 2; however, for Phase 2, the research team developed and implemented a tool to make the data collection more efficient. While the primary variables collected were consistent, some variables were added or changed from Phase 1 to Phase 2 to better capture the conditions that might affect left-turning behavior. The video data reduction process for each phase is discussed below.

Phase 1 Video Data Reduction

In Phase 1 of the research, the data set obtained from VTTI included approximately 300 forward-facing videos that each captured a left-turn maneuver at an intersection approach of interest at one of the six study intersections. An initial review of the videos was performed to eliminate turns occurring during a protected left-turn phase and those that encountered no opposing through traffic (i.e., no opposing through vehicle could be seen in the forward or rear camera views). Ninety-three videos passed this initial criterion, and of those 93, measurable accepted gaps were observed and recorded for 67 study vehicles.

The research team developed a spreadsheet for capturing relevant information from the forward- and rear-facing videos. Each turning maneuver completed by a study vehicle was recorded on its own sheet (tab) within a workbook. The variables captured from the forward-facing video included

- Time when study vehicle entered left-turn queue (if applicable);
- Time when study vehicle reached stop bar (or stopped as first vehicle in queue);
- Time when study vehicle began left-turn maneuver;
- Position of vehicle before turn (positioned or unpositioned in intersection);
- Number of vehicles queued in front of study vehicle in left-turn lane;
- Signal indication when study vehicle joined queue;
- Signal indication when study vehicle began turn; and
- Light condition during left-turning maneuver (light, dark without overhead lighting, dark with overhead lighting).

Several other variables were collected from the forward-facing video for each gap rejected by the study driver, including the following:

- Time opposing vehicle passed through intersection (defining the end of the previous gap and the beginning of the next gap);
- Whether the opposing vehicle was queued before progressing through the intersection;
- Presence of an opposing left-turning vehicle for all or part of the gap and whether that vehicle obstructed the study vehicle's view of oncoming traffic;
- Presence of a right-turning opposing vehicle that affected gap acceptance; and
- Whether the study vehicle changed position in the intersection during the gap (e.g., moved forward).

In addition to the information gathered from the forward-facing video, the timestamp at which a gap-closing vehicle is observed passing through the intersection in the rear-facing video was also recorded when such an event was observed. Accepted gap length could be measured for approximately 20% of the NDS vehicles for which at least one rejected gap was recorded.

While the forward-facing video shows the video frame timestamp, the rear-facing video does not. The research team anticipated using the Community Viewer developed by VTTI early in the project—for synchronized viewing of both videos—but found the view not to function properly. This was a major limitation in Phase 1, and the research team had to spend project time exploring other avenues for linking the time of events in the forward- and rear-facing videos. While all the videos can be viewed using a standard video viewer, such as Windows Media Player, the videos cannot be synchronized without a more sophisticated viewer. In addition, many viewers do not easily allow viewing of the video frame number, which could be used to manually link the videos without requiring synchronized viewing. The research team found that QuickTime provides the option to view video frame number; this served as an interim solution and allowed researchers to gather the video frame number at the time when events occurred in the rear-facing videos and then link these events by video frame number to the timestamp shown in the forward-facing videos.

In Phase 1, other means of adding gap events to the analysis data set were also explored. While reviewing videos, researchers often found that when the study vehicle arrived in a queue in the left-turn lane, the gaps rejected and accepted by vehicles ahead of the study vehicle could be observed in the video. Therefore, the forward-facing video was also used to gather gap-acceptance behavior data for these non-NDS vehicles queued in front of NDS vehicles in the left-turn lane. Out of the 93 forward-facing video files of study drivers making left turns, 24 videos show 38 non-NDS vehicles ahead of the study vehicle making left-turn maneuvers. Rejected and/or accepted gaps were observed and recorded for 27 of these non-NDS vehicles. The data that could be collected for these vehicles was limited to the length of gaps rejected and accepted and only those gaps that occurred during the time period when the NDS vehicle was at or near the intersection. It is important to note the limitations of this supplementary data set, which include the following:

- Information about when the vehicle arrived in the queue and its position in the queue is typically not available.
- The gaps rejected by the non-NDS drivers before arrival of the NDS vehicle cannot be observed and included in analysis.
- In some cases, queued vehicles block the view of oncoming through drivers until they are well into the intersection; thus, while the NDS driver may be present to observe rejected or accepted gaps by non-NDS drivers ahead in the queue, those gaps cannot always be accurately measured.
- Driver demographics, such as gender and age, are not available for non-NDS drivers.

Despite these limitations, this supplemental data set has one important benefit over the data set available for turns made by study vehicles—namely, the closure of the accepted gap can often be directly observed in the forward-facing video. Therefore, non-NDS drivers have a much higher rate of measurable accepted gap lengths.

The research team also requested from VTTI a set of videos of study vehicles passing through one of the study intersections but not making a left turn of interest. The purpose of this data set was to evaluate whether it was likely that the gaps evaluated by non-NDS left-turning vehicles could be captured in the forward-facing video of instrumented vehicles at other locations in the intersection. Approximately 250 forward-facing videos of non-left-turning NDS vehicles were provided for the study intersection with the highest number of movements.

A review of these videos indicated that at this intersection, observations from NDS vehicles not making left-turn maneuvers were unlikely to include gap-acceptance behavior at left-turn lanes by non-NDS drivers. This approach has two main limitations at this particular intersection. First, it is unlikely that the NDS drivers making other maneuvers stop at the intersection long enough to observe more than one or two gaps rejected or accepted by left-turning vehicles at the intersection. Second, these vehicles are often not in a position to see the signal indication facing the left-turning vehicle of interest, so it can be difficult to know which gaps in opposing through traffic are being rejected by the left-turning vehicle and which are simply being observed by the left-turning vehicle while it waits at a red signal indication. In addition, because the relationship of the positions of the NDS vehicle and the left-turning vehicle being observed varies from one video to the next, it would be difficult to automate or streamline video data reduction for this particular situation. After reviewing these videos, the research team found only two in which a left-turning movement could clearly be observed. Even in these two videos, gaps rejected before the turning movement were not observed. Researchers therefore determined that it would not be cost-effective to reduce videos from NDS drivers making maneuvers other than the left turns of interest to add additional gap events to the analysis data set.

Phase 2 Video Data Reduction

In Phase 2, a user interface was designed using LabVIEW software to synchronize the viewing of forward- and rear-facing videos and to provide the video analysts with a more efficient method of data collection. A screen shot of this tool is shown in Figure 3.5. The key characteristics of the interface include the following:

- Synchronized viewing of rear- and forward-facing video;
- Viewing controls that pause and rewind or fast forward (by frame or time) both videos together;
- Automatic population of video file ID and intersection ID;
- One-click procedure for recording the timestamps of events of interest;
- Drop-down menus or buttons that present available event codes to the analyst, minimizing recording errors;
- Intuitive design and layout;
- Background population of database with real-time data entry (shown in Figure 3.6); and
- Opportunities for editing the database during or after entry if mistakes were noticed.

VTTI provided approximately 1,700 videos from NDS drivers making left-turning maneuvers at the intersections of interest. Three video analysts from the research team reviewed and recorded data for more than 1,000 of these videos. The remaining videos were not reviewed for one or both of the following reasons:

- A review of the first few videos at an intersection revealed an undesirable characteristic of the intersection, so the intersection was discarded.

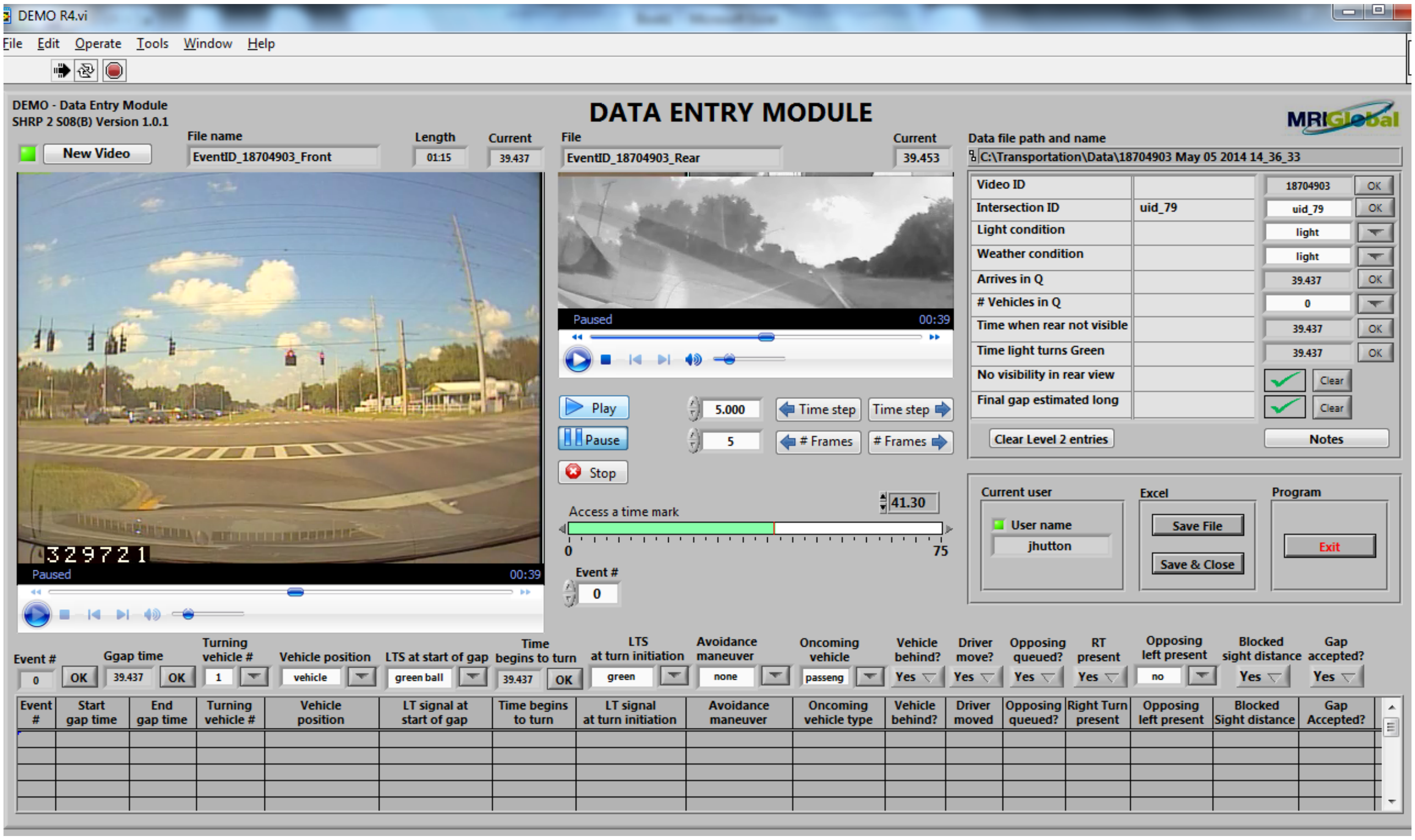


Figure 3.5. Video data reduction user interface.

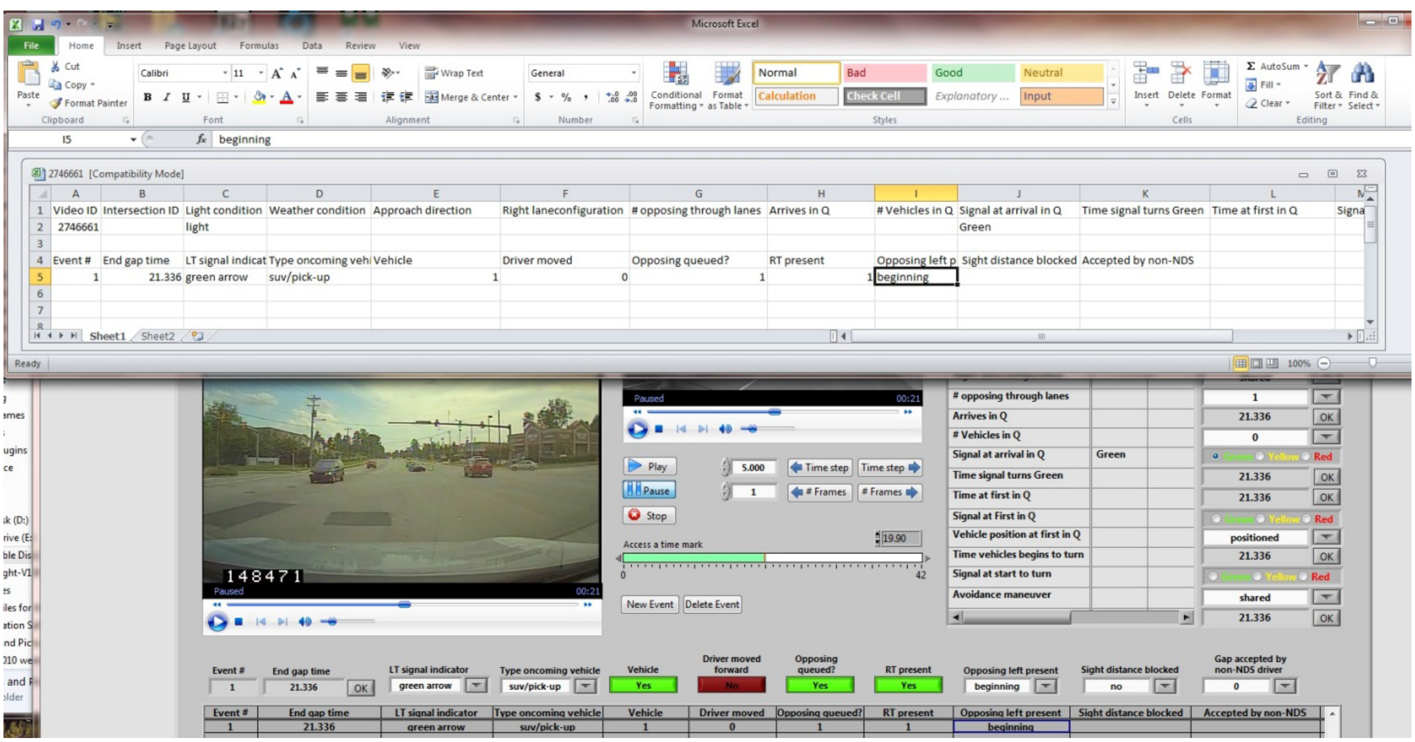


Figure 3.6. Population of Excel database as data are entered in user interface.

- A substantial number of videos for the same offset category had already been reviewed, so remaining videos in that offset were considered a lower priority.

Each video took 2–20 minutes to reduce, depending on the clarity of the video, the number of gaps that were observed, and the number of non-NDS vehicles in the video for which data could be recorded. On average, each video analyst could reduce approximately six to 10 videos per hour.

Variables Reduced from Video Data

Table 3.2 lists the variables that were collected using the video data reduction interface and provides a brief description of the coding options available to the video analyst. In general, video-level variables were those that were relevant to every event recorded in the video, such as video and intersection ID, weather condition, and lighting condition. Some video-level variables applied only to events relevant to the NDS driver, such as the time when the driver arrived in the queue (since this typically could not be observed for non-NDS drivers). Event-level variables were those recorded for each gap for which data were recorded, including both rejected and accepted gaps being judged by either an NDS or non-NDS driver. The extent to which non-NDS gaps were recorded was a function of how many gaps had characteristics clearly visible in the NDS forward- and rear-facing cameras.

Rejected and accepted gap lengths and the presence of an opposing left-turning vehicle creating a sight restriction for the turning driver were the most critical variables to be recorded for the analysis. However, many additional variables were collected to allow the research team to consider other factors that may influence gap-acceptance behavior. Such considerations included the following:

- Position in queue;
- Total time the NDS driver spent waiting for an acceptable gap;
- Presence of a following turning vehicle (which may pressure the turning driver to take a smaller gap);
- Presence of an opposing right-turning vehicle during a gap that may cause a driver to hesitate to accept a gap;
- Type of oncoming vehicle (passenger car or heavy truck);
- Light condition;
- Weather condition;
- Time between beginning of turning maneuver and end of gap, referred to as postencroachment time (the postencroachment time is the best available approximation of the accepted lag—the portion the accepted gap remaining after the turning maneuver);
- Signal information (when signal turns green, signal indication at start of gap, signal information at start of turn); and
- Collision-avoidance maneuvers observed.

It should be noted that few pedestrians were observed in any of the videos, so variables related to the presence of pedestrians were not included. In one instance, a crossing pedestrian caused a left-turning driver to slow during the turning maneuver and this was recorded as an avoidance maneuver. It is discussed in the near-crash analysis in Chapter 4. In addition, flashing yellow arrows were not used as a permissive signal indication at any of the intersections included in the analysis, so while this option was available to the research team, no data are available for consideration of this signal type in the analysis.

Variables that were not directly recorded but instead calculated from the recorded data included the following:

- *Gap length.* The end gap time minus the start gap time. Note that this variable could have a negative value in instances when the driver turned left on a red signal indication. The negative value indicates that the available gap actually ended before the driver had the opportunity to turn. These instances were rare.
- *Time spent waiting for a gap.* The time when turn begins minus the time the turning vehicle arrived in the queue. Note that this measure is only available for NDS vehicles and not any other vehicles observed in the video, since arrival in the queue was only recorded for the NDS vehicle.
- *Postencroachment time.* The time between the start of turn and the time the next opposing vehicle reached the stop bar on its approach to the intersection. Note that the postencroachment time measurements in this study are slightly differently than the measurement of postencroachment time described in the literature because of limitations of what can be viewed in the NDS videos. The measure is designed to closely approximate that described in the literature. This issue is addressed in more detail in the discussion of surrogate safety measures in the next section.

The research team conducted several rounds of testing of the data reduction interface tool. The first round of testing involved all three video data analysts and focused on finding ways to improve the features of the data reduction tool to minimize workload and ensure that all relevant information is captured. After the tool was updated in response to the findings, each of the three reviewers independently reviewed 10 videos—five at unsignalized intersections and five at signalized intersections. Discrepancies in the recorded observations were then informally evaluated. In this round of testing, differences in measurements of timestamp variables ranged from close to zero to nearly 1.5 s. The areas in which judgment played a role in determining the time of an event or the position of the vehicle were evaluated. This led to the development of a clearer protocol to better standardize the measures. The three video reviewers then each independently

Table 3.2. Variables Recorded During Video Reduction

Variable	Definition/Options
Video-Level Variables	
Video ID	Automatically recorded when video is selected
Intersection ID	Automatically recorded from video folder name
Light condition	Drop-down list: light, dawn/dusk, dark with street lights, dark without street lights
Weather condition	Drop-down list: dry, rain, snow
Arrives in queue	Timestamp: recorded when vehicle reaches rear of queue or stop bar if no queue exists
Number of vehicles in queue	Drop-down list: integers 0–7 and “8 or more”
Time when rear not visible	Timestamp: recorded when reviewer can no longer discern through vehicles passing through the intersection in the rear-facing video
No visibility in rear view	Check box: checked if this condition applies
Time light turns green	Timestamp: if signal is red at NDS time of arrival in queue, recorded at time when signal turns green
Final gap estimated long	Check box: checked if this condition applies (no oncoming vehicles visible in field of view of driver)
Notes	Text box
Event-Level Variables	
Event number	Automatic consecutive numbering for each observed event (gap)
Start gap time	Timestamp: recorded at the time of each new start of gap or lag
End gap time	Timestamp: recorded at the time the next approaching through vehicle arrives at the intersection, or at the time the left-turn signal turns red (whichever occurs first)
Turning vehicle number	Drop-down list: integers 1–5 and “NDS” (non-NDS vehicles numbered consecutively)
Vehicle position	Drop-down list: behind/at stop bar, ahead of stop bar, positioned to turn, driver never pauses (recorded at gap start time)
LT signal at start of gap	Drop-down list: green arrow, green ball, red, yellow ball, yellow flashing arrow
Time begins turn	Timestamp: recorded at the time vehicle is both accelerating and oriented toward left turn (no longer facing straight ahead)
LT signal at turn initiation	Drop-down list: green arrow, green ball, red, yellow ball, yellow flashing arrow
Avoidance maneuver	Drop-down list: none, turning driver, opposing driver, both
Type oncoming vehicle	Drop-down list: passenger car, heavy vehicle
Vehicle behind?	Yes/No (yes when vehicle is present behind turning driver)
Driver move?	Yes/No (yes when vehicle moves forward during gap)
Opposing queued	Yes/No (yes when opposing through vehicles were queued before proceeding through the intersection)
RT present	Yes/No (yes when opposing vehicle turns right during gap)
Opposing left present	Yes/No (yes when a vehicle is present in the opposing left-turn lane)
Sight distance blocked	Yes/No (yes when driver’s view of oncoming traffic is restricted by opposing left-turning vehicles)
Gap accepted?	Yes/No

reviewed 10 more videos and once again evaluated discrepancies. Timestamp variables (such as gap start and end time and time turn is initiated) fell within approximately a half second for all three video reviewers, showing that the more detailed protocol improved precision.

Some variables included in the data reduction procedure are fairly self-explanatory, and the video data reviewers agreed that formal definitions were not required. Other variables include a certain amount of judgment, so formal definitions were developed to help minimize the variance among observations from different reviewers. The data collection protocol for these variables was as follows:

- *Arrives in queue.* The time when a vehicle comes to a stop or substantially slows behind other left-turning vehicles; or, if no queue exists, the time when the vehicle crosses the stop bar or its equivalent (if no stop bar exists); or the time when the vehicle stops to wait for gaps if this location is before the stop bar or its equivalent.
- *Gap start time.*
  - For the first recorded gap, the gap start time is recorded when
    - The front of the vehicle crosses the stop bar (signalized intersections).
    - The front of the vehicle is even with the median nose or the end of the solid lane line to the right of the turning vehicle (unsignalized intersections).
    - The vehicle comes to a stop if stopped before the stop bar.
    - If the light is red at time the vehicle arrives in the queue, the front of the first opposing vehicle crosses the opposing stop bar; or, if already ahead of stop bar, when first vehicle begins forward movement. (In this case, opposing vehicles are marked as "queued.") Note that the time when the light turns from red to green is also recorded.
  - For other gaps, the gap start time is recorded when
    - The front of the opposing vehicle passes the stop bar (signalized intersections).
    - The front of the opposing vehicle passes the median nose or the end of the solid lane line to the right of the turning vehicle (unsignalized intersections).
    - If driver takes the same gap as preceding vehicle, the preceding vehicle has cleared the intersection (i.e., rear of preceding vehicle has exited far lane of traffic). Note that "time turn initiated" will often be before this gap start time when vehicles follow closely.
- *Gap end time.* The time at which the next gap begins (when the opposing vehicle crosses the stop bar). When multiple vehicles accept the same gap, their gap start times will be different, but their gap end times will be the same. For the gap accepted by the NDS driver, the gap end time is the time at which the next opposing through vehicle can be seen entering the intersection in the rear camera view.
- *Vehicle position.*
  - Vehicle position at start of gap (behind stop bar, ahead of stop bar, positioned to turn).
  - If vehicle never stops and accepts first lag, recorded as "did not pause."
- *Turn begins.* The time during the turn movement (accepted gap) when the subject vehicle's angle is oriented toward the left turn and has begun moving forward into a completed turn.
- *Time when rear view not visible.* The point at which the reviewer can no longer be certain that he or she would be able to see an opposing through vehicle pass in the rear-facing video.
- *Driver moves.* Marked as "yes" if vehicle moves forward for better turn positioning, whether or not gap is accepted.
- *Avoidance maneuver.* Marked if any vehicle makes a sudden stop, quickly accelerates, abruptly abandons a turning maneuver, or swerves to avoid a collision. Whether the evasive maneuver was made by the turning driver, the oncoming through driver, or both drivers is also indicated.
- *Sight distance blocked by opposing left-turn vehicle.* Indication of whether the presence of the left-turn vehicle actually blocks the driver's view of oncoming traffic from the perspective of the driver. This is an additional measure to the offset to isolate left-turning behavior during periods of limited sight distance.

Gap Acceptance as a Safety Surrogate

The surrogate measures that most closely describe crash risk-taking behavior by left-turning drivers for intersections with different offsets between opposing left-turn lanes are the durations of gaps accepted and rejected by left-turning drivers at intersections of various design types. A gap is the time headway between successive vehicles, defined as the time between arrivals of the front bumper of successive vehicles at a common point, such as the center of an intersection. When a vehicle is waiting to make a left turn, each gap in opposing through traffic is either accepted or rejected by the left-turning driver.

The basic data for a study of this type are the duration of each available gap and an indication of its acceptance or rejection by the left-turning driver. The durations of accepted gaps represent crash risks judged acceptable by the left-turning driver. The durations of rejected gaps represent crash risks judged unacceptable by the left-turning driver.

The distribution of the accepted and rejected gap durations is then analyzed to establish the critical gap (t_c) at which gaps are equally likely to be accepted or rejected. This can also be accomplished by determining t_{50}, the 50th-percentile gap (or the gap that is equally likely to be accepted and rejected).

Another variable used as a surrogate for crash risk is postencroachment time. In the literature, this variable is defined as the time between when the turning driver passes the conflict point and when the next opposing through vehicle arrives at that point (Gettman and Head 2003). In the data reduction process, it was difficult to determine the time at which drivers reached this conflict point, so measurements were instead taken at the respective stop bars for each vehicle group, which were more clearly defined locations in the videos. Therefore, the definition of postencroachment time used in this research was the time between the start of the turn, which presumably occurred somewhere in advance of the conflict point, and the time the next opposing vehicle reached the stop bar on its approach to the intersection. This is a rough approximate of the postencroachment time but is considered to be an appropriate substitute for this research. The approach taken to assess the effect of offset distance on those risk measures is discussed in Chapter 4.

Limitations to NDS Video Data Reduction

Limitations to using the NDS video data for this analysis include the following:

1. Accepted gaps make up only a small portion of total observed gaps (most drivers reject several gaps before accepting one), so it is critical to be able to measure the length of as many accepted gaps as possible. The primary method of gathering this data element for NDS vehicles is watching for the next opposing through vehicle to pass through the intersection in the rear-facing camera of the study vehicle after the study vehicle completes its left turn. In some cases, a gap-closing vehicle is not visible in the rear-facing camera for one of several reasons, including poor quality or angle of rear camera images, dark conditions, intersection approach geometry that limits the visibility of the intersection as the vehicle departs from the intersection, change in signal indication before the next opposing through vehicle arrives, no gap-closing vehicle present, or another vehicle follows the study vehicle through the left turn and blocks the rear-facing camera's view of the intersection. Thus, nearly half the accepted gaps observed in the videos have no measured length. In many of these cases, the end of the gap would have been more easily visible in a fixed-camera study.
2. Because the view is from the driver's perspective and not an elevated fixed-camera location, it can be difficult to determine when the turning vehicle is in a certain position. Timestamp data must be recorded at points that are fairly easy to identify in the video, such as at a stop bar, rather than at positions that are not physically marked but might be calculated in a fixed-camera study, such as the center of the intersection or the conflict point. A higher degree of variability between reviewers is noticed for variables that depend on points not clearly marked on the pavement, such as where the turning vehicle has cleared in the intersection.
3. Because the evaluation includes turns at so many intersections, the "rules" for determining when a vehicle has reached a certain location necessarily change from intersection to intersection. Identifying a visual cue to help determine when a vehicle has reached a certain point (such as an imaginary line drawn from the end of the solid lane line to the tip of the median) at one intersection approach is not helpful for the analysis of any other intersection approach. New visual cues must be identified for each intersection approach. In addition, the camera view is a moving frame of reference. These limitations are why automated video data reduction (using machine vision, for example) was not considered feasible for this study.
4. Light conditions play a significant role in the quality of the video data and how well certain elements in the video (lane lines, signal indications, type of approaching vehicle, etc.) can be seen. In addition, videos were sometimes poorly focused, making data review more difficult.

In Phase 1 of the project, the potential differences in interpretation of variables between video data reviewers were not apparent because only one staff member reviewed the video data. In addition, such a limited number of intersections were available for review at the time that the difference between what can be seen at one intersection and another was not as obvious.

Despite these limitations, there are several advantages to using the NDS data for this study. The advantages of using the NDS data over a fixed-camera study include the ability to incorporate information about the driver's age, gender, and other characteristics into the analysis and the ability to evaluate behavior at a wide range of locations with substantially fewer time and cost resources. The NDS data also provide an advantage over the use of crash history data to evaluate safety by allowing researchers to see near misses, avoidance maneuvers, and safety surrogates that are much more frequent than crashes. Compared with studies using driving simulators, the NDS data have the obvious advantage of recording truly naturalistic behaviors that occur in real-life scenarios.

Time-Series Data and Demographics

Time-series data associated with each video were requested from VTTI. Variables were recorded at regular time intervals on the trip, including the following:

- Heading;
- Latitude;
- Longitude;
- Speed;
- Acceleration;
- Month;
- Year;
- Day of week;
- Time of day (binned);
- Timestamp associated with each row of data collected;
- File ID;
- Associated video ID;
- Alcohol indicator; and
- Lighting indicator.

The research team did not use these variables in the analysis, since all relevant information for the analysis could be obtained from the video reduction.

In addition, for each video provided by VTTI, the research team requested demographic information about the NDS driver making the left turn in the video, including age, gender, and vehicle type. This demographic information was not available or recorded for non-NDS drivers. The difference in gap-acceptance behavior between men and women, and between age groups, was evaluated for NDS drivers.

CHAPTER 4

Statistical Analysis

This chapter provides a description of the data used in the analysis, the methodology used to address the primary research hypotheses, and the statistical analysis results. Results from secondary analyses are also discussed. The discussions in this chapter refer to figures and tables presented here and to figures and tables presented in Appendix A.

Database Description

From the video reviews, data were collected

- For 145 NDS and 275 non-NDS drivers;
- At 44 signalized intersection left-turn pairs;
- At 14 two-way stop-controlled intersections;
- In four states: Florida, Indiana, North Carolina, and Washington;
- For 758 left-turning maneuvers by NDS drivers; and
- For 3,350 events, where an event is defined as either an accepted or rejected gap, by either an NDS or non-NDS driver.

The analyses focused on the following measurements (or dependent variables) defined in Chapter 3:

- Gap length (duration, in seconds), denoted as follows:
  - *Available* gaps refer to all measured accepted and rejected gaps (all drivers).
  - *Accepted* gaps refer to all gaps accepted by an NDS or non-NDS driver for which the gap length could be measured (i.e., the gap end time was observed). Approximately half of the accepted gaps (54%) had no observable gap end time and, therefore, no measured gap length.
- Postencroachment time (seconds) for accepted gaps with a measured gap length.

To address the two main hypotheses stated at the beginning of this report, the potential effect of the following factors on the above measurements was investigated in this study:

- Hypothesis 1 (effect of offset on critical gap length): Offset category—seven categories for signalized intersections and four categories for two-way stop-controlled intersections.
- Hypothesis 2 (effect of sight obstruction on critical gap length): Presence of a vehicle in the opposing left-turn lane.

Basic Site, Driver, Trip, and Gap Descriptives

Site characteristics of the 44 signalized intersection left-turn pairs are shown in Table A.1 (Columns 1 through 9) and in Table A.2 (Columns 1 through 8) for the 14 two-way stop-controlled intersections. The last three columns in each table provide the number of NDS drivers who drove through each intersection and the number of trips made by NDS and non-NDS drivers. It should be noted that some NDS drivers have made a left turn at more than one intersection or intersection type, and multiple turns at the same intersection, over the course of the NDS period. As a result, the total number of drivers—when summed across various subgroups of the data (e.g., age group, gender, intersection type, offset category)—does not necessarily add up to 145 in the various tables shown in this report.

Number of trips, events, and accepted gaps for NDS and non-NDS drivers are shown, separately for each offset category, in Table 4.1. The number of NDS drivers, non-NDS drivers, and total events were substantially lower for two-way stop-controlled intersections than signalized intersections, although the number of measured accepted gaps was comparable between the two intersection types. This is not unexpected since traffic volumes are generally lower at unsignalized intersections than at signalized intersections. In addition, the distribution of left-turn offsets was not as good for stop-controlled intersections as for signalized intersections. Specifically, no

Table 4.1. Trip and Event Statistics by Intersection Type and Offset Category

Offset Category	Total Events	Number of Drivers		Number of Trips		Number of Measured Accepted Gaps	
		NDS	Non-NDS	NDS	All	NDS	All
Signalized Intersections							
(a) –16 ft or less	196	5	8	19	27	13	19
(b) –11 ft to –15 ft	100	15	20	54	74	8	11
(c) –6 ft to –10 ft	225	24	19	46	64	16	28
(d) –1 ft to –5 ft	594	35	30	79	108	41	56
(e) 0 ft	618	39	62	149	211	57	95
(f) 1 ft to 3 ft	234	21	50	76	126	20	35
(g) 4 ft to 6 ft	98	21	20	29	49	14	25
All signalized	2,065	160	209	452	659	169	269
Two-Way Stop-Controlled Intersections							
(a) –16 ft or less	45	4	2	19	21	3	5
(b) –11 ft to –15 ft	932	21	53	194	241	112	149
(c) –6 ft to –10 ft	201	9	8	66	73	34	40
(e) 0 ft	107	10	3	27	30	13	13
All two-way stop-controlled	1,285	44	66	306	365	162	207
All Intersections	**3,350**	**204**	**275**	**758**	**1,024**	**331**	**476**

intersections were found for either of the positive-offset categories or for the offset category of –1 ft to –5 ft; a substantial majority of trips were observed at intersections with left-turn lane offset between –11 ft and –15 ft. This limited the potential for identifying differences between offset categories in the analysis. NDS driver age (one of four age groups) and number of trips, accepted gaps, and events are shown, separately for each offset category, in Table 4.2. The distribution of driver age was highly skewed toward older drivers for stop-controlled intersections, again, limiting the potential for identifying differences in behavior between age groups for these intersections.

To assess how evenly the data used in the analysis are distributed across intersection type and offset category, across NDS driver demographics (age and gender), and across the type of gap (accepted or rejected), a number of bar charts were drawn; these are shown in Appendix A in the following sequence:

- Number of sites by state, offset category, and intersection type (Figure A.1);
- Number of drivers by state, age group, and gender (Figure A.2);
- Number and type of gaps by state and offset category for signalized intersections (Figure A.3); and
- Number and type of gaps by state and offset category for two-way stop-controlled intersections (Figure A.4).

Figure A.1 shows that the greatest number of sites and the most complete distribution over the offset categories of interest was found for sites in Florida. North Carolina also had a good distribution of offset categories. Only a limited number of sites were found in the other states—three sites in Washington and two sites in Indiana. Figure A.2 shows a good mix of drivers by gender and age, especially in the Florida data. Figure A.3 and Figure A.4 show that substantially more events were observed at signalized intersections than at two-way stop-controlled intersections; this reflects that traffic volumes are generally higher at signalized intersections. Figure A.3 and Figure A.4 also show that both accepted and rejected gaps were observed across the full range of offset categories. Naturally, more rejected gaps than accepted gaps were observed, since a left-turning driver may potentially reject several gaps at an intersection but can accept only one.

Table 4.2. NDS Driver and Trip Statistics by Intersection Type and Offset Category

Age Category (years)	Number of Drivers	Number of Trips	Number of Measured Accepted Gaps	Number of Events
Signalized Intersections				
16 to 20 years	25	99	43	454
21 to 25 years	35	120	30	212
26 to 65 years	34	115	44	355
66+ years	24	118	52	586
All signalized	118	452	169	1,607
Two-Way Stop-Controlled Intersections				
16 to 20 years	12	76	31	159
21 to 25 years	11	40	10	145
26 to 65 years	8	32	18	77
66+ years	11	158	103	658
All two-way stop-controlled	42	306	162	1,039
All Intersections	**160**	**758**	**331**	**2,646**

Truncated Gap Lengths

Many observations collected from the video reviews did not yield a measured gap length when the driver accepted the gap; therefore, those observations were not included in the analysis. As shown in Table 4.1, gap length was measured for just under half of the accepted gaps observed in the videos (476 of 1,024). For the remaining accepted gaps, no gap length was measured because the gap end time could not be observed due to one or more of the following conditions:

- The rear-facing camera image quality or camera position did not provide visibility of oncoming through traffic after the left turn was made for a sufficient amount of time to observe the next opposing vehicle go through the intersection.
- The geometry of the intersection obscured the visibility of the conflict area soon after the left turn was made.
- A following left-turning vehicle (or opposing right-turning vehicle) blocked sight of the intersection before the next opposing through vehicle passed through the intersection.
- The signal turned red for the opposing through traffic before the next opposing through vehicle entered the intersection.
- No opposing through vehicles were present after the left turn was made within the limits of the rear-facing camera's range of visibility.

For accepted gaps where the end gap time could not be observed in the video, video reviewers had the option to check a box indicating whether the accepted gap was estimated to be long. An accepted gap was considered "long" when no oncoming opposing vehicles were present in the forward-facing camera at the time the left-turning vehicle began the turning maneuver, or when the rear camera showed that no opposing through vehicle passed through the intersection for at least 12 s after the turn was made. Video reviewers observed traffic patterns at the signal through the rear-facing camera after the turn was made to attempt to ensure that situations in which the left-turn signal turned red—thus ending the gap shortly after the turn was made—were not marked as long gaps. Slightly more than half of the nonmeasured accepted gaps (308 of 548) were marked as long.

The research team then considered methods for including the unmeasured gaps that were estimated to be long in the analysis. To do so, a gap length would have to be assigned to these gaps. The research team considered two options: (a) setting the missing gap length equal to the 85th-percentile measured accepted gap length within an offset category, and (b) assigning them a random length from the tail of the distribution of measured accepted gap lengths within an offset category (i.e., distributing the unmeasured but estimated long gaps along the upper 15% tail of the distribution of the measured accepted gaps). However, in both cases, a large proportion of the total data used in the analysis would then be estimated (308 of 784 observations), and the original analysis results (without the truncated gap length) would be substantially skewed toward the longer gaps. This is especially problematic when considering that the remaining gaps not included in the analysis (the

240 accepted gaps not measured and not estimated to be long) likely had shorter gap lengths that could have potentially balanced that skew toward the longer gaps.

For accepted gaps that were not estimated to be long, the research team considered methods for estimating the length of the gap based on the distance of the next visible opposing through vehicle seen in the forward-facing camera at the time of left-turn initiation. However, the research team did not believe there were any reasonable methods available to make this estimation within an acceptable level of error, given the following:

- The speed of the opposing vehicle was unknown.
- The exact location of the oncoming vehicle becomes more difficult to determine the farther away it is from the intersection.
- The potential existed for these vehicles to change course (turn into a driveway or the left-turn lane) or for other vehicles to pull out of a driveway ahead of them and shorten the gap.

For these reasons, researchers decided to base the analysis only on gaps with observed begin and end gap times. While the distribution of measured accepted gaps may not be truly representative of the distribution of all accepted gaps, the critical gaps estimated in the analysis are similar to those reported in the literature, indicating that the exclusion of gaps that could not be measured is unlikely to have substantially biased the results.

Repeated Measures

The NDS data provide an opportunity to know how many of the total turning maneuvers at any given intersection, or within any given offset category, were made by the same driver during the study period, as well as how many study intersections a given NDS driver was observed passing through. All statistical analyses documented in this report assumed statistical independence of the observations. In other word, the fact that a given NDS driver could have driven through a given intersection multiple times was not accounted for statistically in the logistic regression models.

Table 4.3 summarizes statistics of repeat visits by NDS drivers at intersections within a given offset range, separately for each intersection type. For these counts, researchers assumed that non-NDS drivers for which rejected and accepted gaps were observed were all unique. The table shows that, for example, at signalized intersections with a left-turn offset of −16 ft or less, 12 drivers each made one trip through one of the intersections in that category, while one driver made 15 trips through intersections in that category. In the −11-ft to −15-ft offset category, 27 drivers each made one trip through one of the intersections in that category, one driver made 17 trips through intersections in that category, and seven drivers (35 total drivers minus the 28 previously accounted for) made the remaining 30 trips (74 trips minus the 44 already accounted for).

Although many drivers made left turns at an intersection multiple times as shown in this table, these observations cannot

Table 4.3. Repeated Trips by a Single NDS Driver by Offset Category

Offset Category	Number of All Drivers	Number of Trips for All Drivers	Highest Number of Repeats for an NDS Driver	Number of Drivers Who Made Single Visits
Signalized Intersections				
(a) –16 ft or less	13	27	15	12
(b) –11 ft to –15 ft	35	74	17	27
(c) –6 ft to –10 ft	43	64	12	36
(d) –1 ft to –5 ft	65	108	13	50
(e) 0 ft	101	211	36	85
(f) 1 ft to 3 ft	71	126	28	64
(g) 4 ft to 6 ft	41	49	3	35
Two-Way Stop-Controlled Intersections				
(a) –16 ft or less	6	21	8	3
(b) –11 ft to –15 ft	74	241	46	59
(c) –6 ft to –10 ft	17	73	31	11
(e) 0 ft	13	30	5	7

be considered repeated measures in the true statistical sense. *Repeated measures* assumes that, other than time, all other conditions affecting gap acceptance remain the same. Here, the driver is making decisions about an entirely different set of available gaps every single time he or she arrives at the intersection. In addition, conditions such as weather, lighting, reason for the trip, and other considerations may vary from trip to trip, which could influence the driver's behavior. For these reasons, a repeated measures analysis was not pursued with these data.

Available and Accepted Gap Length Distributions: All Left-Turning Situations

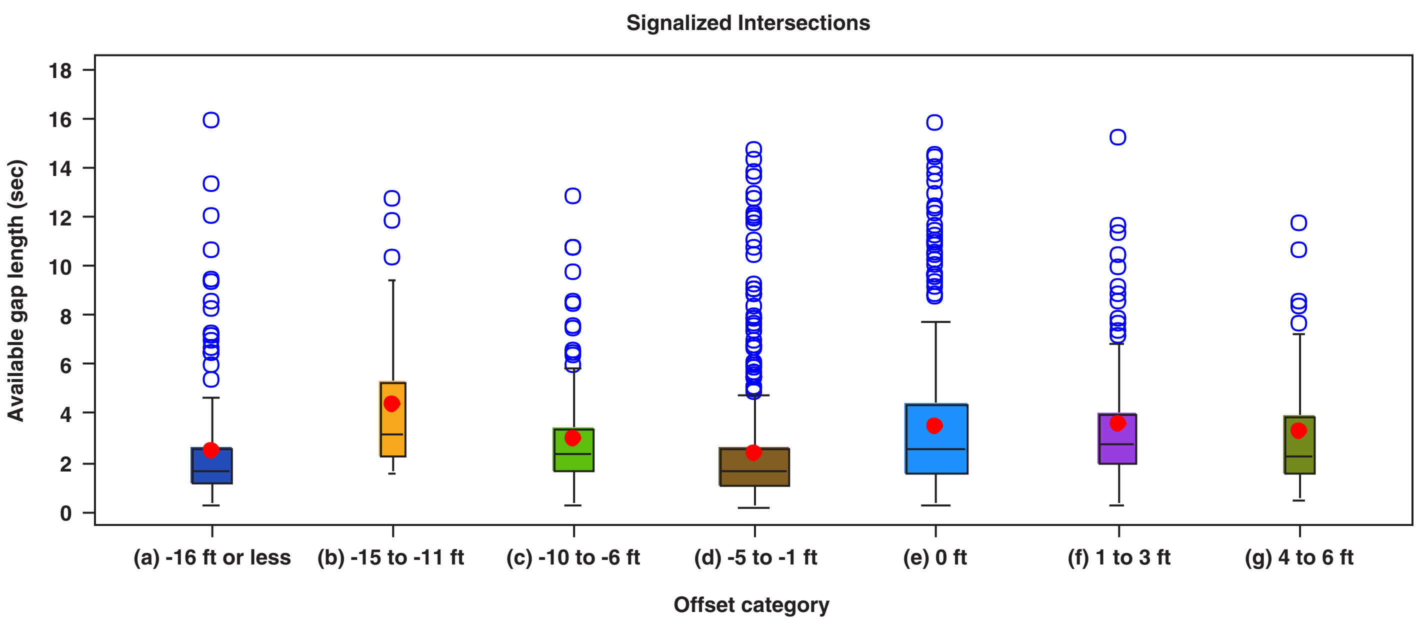
The first research question to investigate is whether varying offsets have an effect on drivers' gap acceptance. Before analysis, the distribution of available and accepted gap lengths was assessed across the various offset categories for each intersection type. Box plots were drawn for the following combinations:

- *Available* gap length by offset category (7) for signalized intersections (Figure 4.1);
- *Available* gap length by offset category (4) for two-way stop-controlled intersections (Figure 4.2);
- *Accepted* gap length by offset category (7) for signalized intersections (Figure 4.3); and
- *Accepted* gap length by offset category (4) for two-way stop-controlled intersections (Figure 4.4).

Each box plot includes the following descriptive statistics: number of gaps, minimum and maximum gap lengths, mean and median gap lengths, and standard deviation.

These distribution plots show that available gap length is relatively evenly distributed across offset categories. The research team was concerned that the magnitude of available gap lengths might be confounded with offset category; this would have made the study of the effect of offset on gap-acceptance behavior difficult. However, as shown in these figures, this concern did not arise.

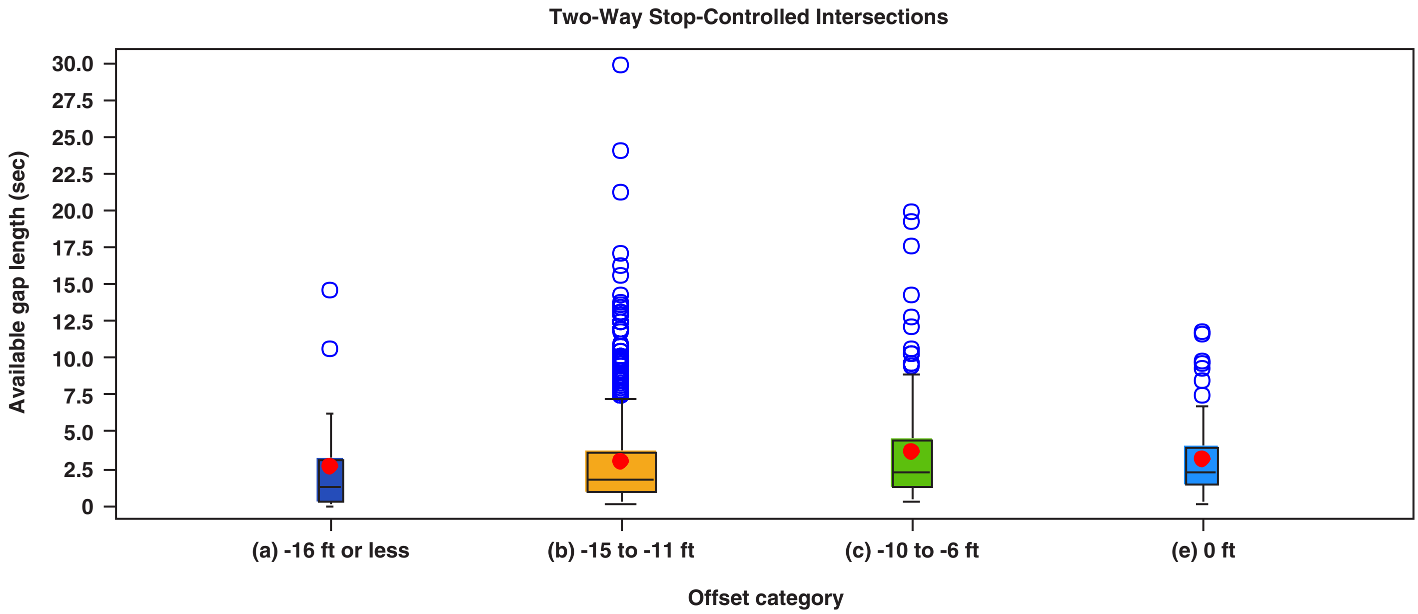
These plots also show that the distribution of gap length is skewed positive, with a number of gap lengths reaching as much as 16 s for signalized intersections and 30 s for two-way stop-controlled intersections. The data shown in these plots are the primary data used for analysis and encompass all NDS drivers.



N	140	26	134	500	367	99	55
Min	0.3	1.6	0.2	0.1	0.2	0.3	0.5
Mean	2.5	4.4	2.9	2.4	3.4	3.5	3.2
Median	1.6	3.1	2.3	1.6	2.5	2.7	2.2
Max	15.9	12.6	12.8	14.7	15.7	15.2	11.7
Std Dev	2.6	3.2	2.1	2.4	2.9	2.7	2.5

Red dot = mean; Horizontal line = median; Colored box = mid 50% of data; Blue circle = extreme value

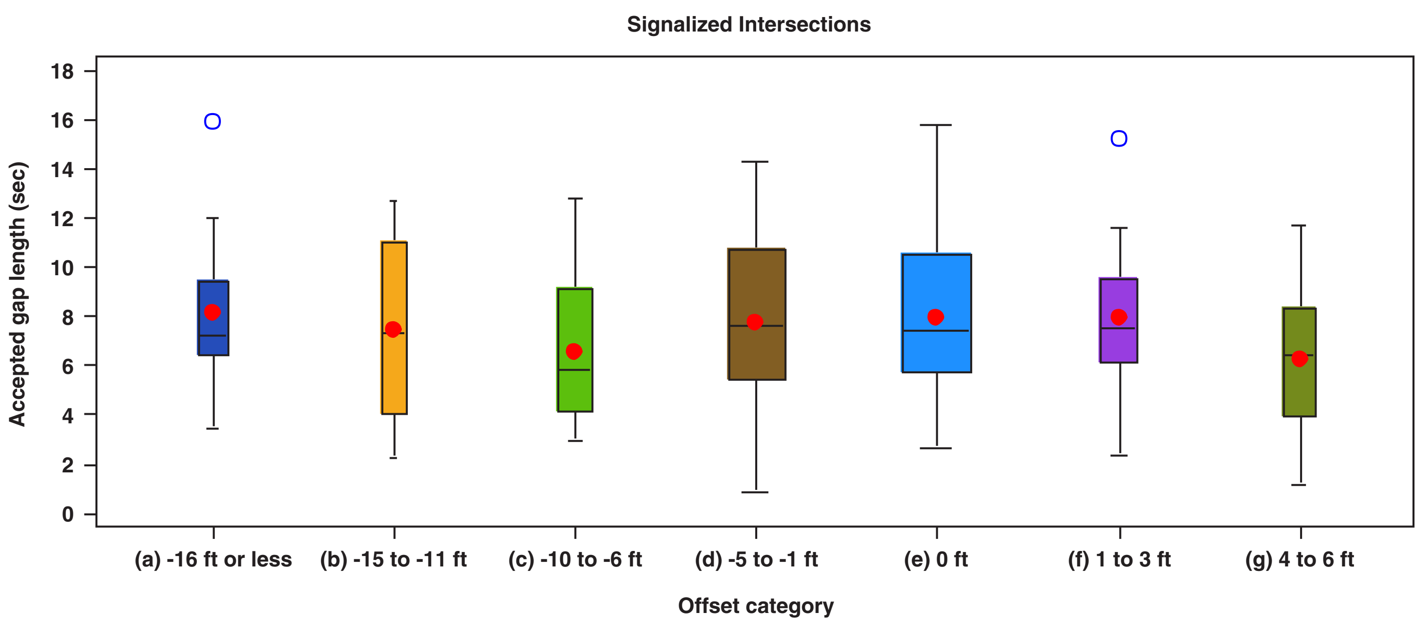
Figure 4.1. Distribution of available gap length by offset category for signalized intersections.



N	24	652	151	67
Min	0.0	0.1	0.3	0.2
Mean	2.5	3.0	3.6	3.1
Median	1.2	1.8	2.3	2.3
Max	14.5	29.7	19.8	11.7
Std Dev	3.5	3.3	3.6	2.6

Red dot = mean; Horizontal line = median; Colored box = mid 50% of data; Blue circle = extreme value

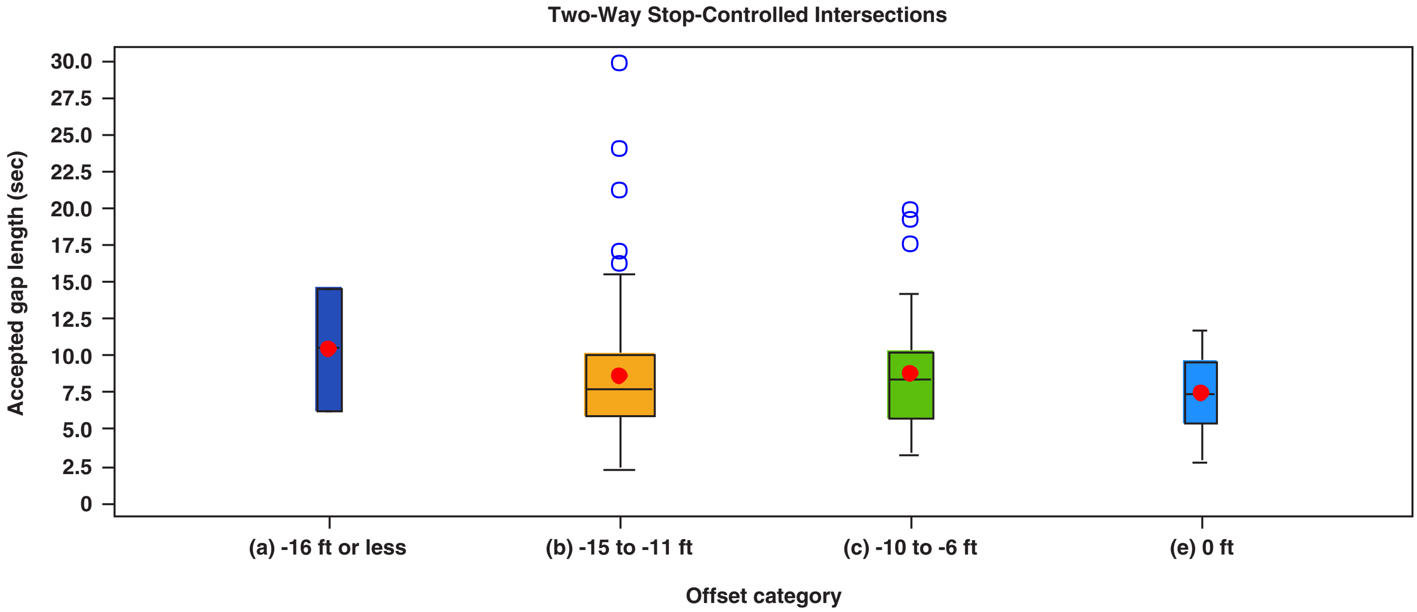
Figure 4.2. Distribution of available gap length by offset category for two-way stop-controlled intersections.



N	13	8	16	41	57	20	14
Min	3.5	2.2	3.0	0.9	2.7	2.3	1.1
Mean	8.1	7.4	6.6	7.7	7.9	7.9	6.2
Median	7.2	7.3	5.8	7.6	7.4	7.5	6.4
Max	15.9	12.6	12.8	14.3	15.7	15.2	11.7
Std Dev	3.4	4.1	3.1	3.6	3.3	2.9	3.0

Red dot = mean; Horizontal line = median; Colored box = mid 50% of data; Blue circle = extreme value

Figure 4.3. Distribution of accepted gap length by offset category for signalized intersections.



N	3	112	34	13
Min	6.2	2.3	3.3	2.8
Mean	10.4	8.6	8.8	7.5
Median	10.6	7.8	8.5	7.5
Max	14.5	29.7	19.8	11.7
Std Dev	4.1	4.1	4.0	2.8

Red dot = mean; Horizontal line = median; Colored box = mid 50% of data; Blue circle = extreme value

Figure 4.4. Distribution of accepted gap length by offset category for two-way stop-controlled intersections.

Available and Accepted Gap Length Distributions Under Sight Obstruction

The second research question to investigate is whether the presence of a sight obstruction—due to the presence of a driver in the opposing left-turn lane—affected gap acceptance. Out of all cases where gap length could be recorded in the videos (1,669 events across both intersection types), a vehicle in the opposing left-turn lane was blocking the NDS driver's view in 326 cases (approximately 20% of all cases studies). Table 4.4 shows the following statistics for obstructed and nonobstructed sight-distance situations, by intersection type and offset category, separately for available and accepted gaps:

- Percentage of events in which an opposing left-turning vehicle is present;
- Percentage of events in which driver's view is obstructed by an opposing left-turn vehicle; and
- Ratio of the two percentages.

The table shows that for all negative-offset categories, the likelihood that an opposing left-turning vehicle will restrict the view of oncoming vehicles for the left-turning NDS driver is quite high. For all *available* gaps, the percentage of opposing left-turn drivers that create a sight obstruction for NDS drivers is 86% for all negative-offset categories combined; for accepted gaps, it is 71%. Both the percentage of events in which sight distance is blocked and the likelihood that an opposing left-turning vehicle will restrict sight distance for the left-turning driver being studied are substantially smaller for the zero- and positive-offset categories. For example, at signalized intersections with an offset between –6 ft and –10 ft, a driver's view is blocked by an opposing left-turn vehicle during 45% of the gaps evaluated, while at intersections with offsets between 0 ft and 6 ft, a driver's sight is restricted by an opposing vehicle only about 3% of the time. The table also shows that the percentage of *accepted* gaps in which the driver's view is blocked was, in general, much lower than the same percentage of all available gaps, especially at left-turn lanes with negative offsets at signalized intersections. For example, while a driver's view was blocked during 30% of evaluated gaps at signalized intersections with an offset of –16 ft or less, this percentage dropped to only 7% when considering only gaps that were accepted. This indicates that drivers tended to wait

Table 4.4. Sight Obstruction Statistics

Offset Category	Available Gaps			Accepted Gaps Only		
	Percentage of Events When Opposing Vehicle Is Present	Percentage of Events When Driver's View Is Blocked	Ratio of Driver's Sight Blocked to Opposing Vehicle Present	Percentage of Events When Opposing Vehicle Is Present	Percentage of Events When Driver's View Is Blocked	Ratio of Driver's Sight Blocked to Opposing Vehicle Present
Signalized Intersections						
(a) –16 ft or less	34.7	30.1	86.8	7.4	7.4	100.0
(b) –11 ft to –15 ft	25.0	12.0	48.0	23.0	8.1	35.3
(c) –6 ft to –10 ft	48.0	44.9	93.5	32.8	25.0	76.2
(d) –1 ft to –5 ft	26.1	23.6	90.3	24.1	18.5	76.9
(e) 0 ft	26.5	3.9	14.6	21.3	4.7	22.2
(f) 1 ft to 3 ft	35.5	3.0	8.4	34.9	3.2	9.1
(g) 4 ft to 6 ft	21.4	3.1	14.3	30.6	4.1	13.3
Two-Way Stop-Controlled Intersections						
(a) –16 ft or less	4.4	0.0	0.0	9.5	0.0	0.0
(b) –11 ft to –15 ft	7.8	6.4	82.2	8.7	7.5	85.7
(c) –6 ft to –10 ft	23.9	18.9	79.2	9.6	8.2	85.7
(e) 0 ft	9.3	0.0	0.0	3.3	0.0	0.0
All Intersections Combined						
Negative offset	20.9	17.9	85.6	15.8	11.2	70.8
Zero offset	24.0	3.3	13.8	19.1	4.1	21.7
Positive offset	31.3	3.0	9.6	33.7	3.4	10.2

until their view was no longer obstructed before accepting a gap. Thus, even before analysis of the lengths of the accepted gaps, the data in Table 4.4 suggest that driver gap-acceptance behavior is affected by left-turn lane offset.

Figure A.5 (signalized intersections) and Figure A.6 (two-way stop-controlled intersections) illustrate the distribution of postencroachment time for accepted gaps by offset category and whether sight distance is obstructed.

Statistical Methodology

This research sought to answer two main questions: (1) does the amount of left-turn lane offset affect gap-acceptance behavior (specifically the critical gap length)? and (2) does the presence of an opposing left-turn driver affect driver behavior when turning left at an intersection?

The statistical analysis approach chosen in this study is driven by the two main measurements recorded from the videos: the duration (recorded in seconds) of each available gap and an indication of its acceptance or rejection by the left-turning driver. The durations of accepted gaps represent crash risks judged acceptable by the left-turning driver, while the durations of rejected gaps represent crash risks judged unacceptable by the left-turning driver. The analysis of choice is therefore regression analysis in which the distributions of the accepted and rejected gap durations are analyzed to establish the critical gap duration (t_c). The critical gap is defined as the gap that is equally likely to be accepted or rejected.

The logistic regression analysis consists of modeling the relationship between the probability of accepting or rejecting a gap of a given length and the length of the gap and the left-turn offset distance. The basic relationship can be expressed in the form of a logistic function as follows:

$$P(Y=1|X)=\frac{1}{1+e^{-(\beta_0+\beta_1 X+\beta_i I_i)}} \tag{4.1}$$

where

$P(Y=1|X)$ = probability of accepting a gap of given length X;
X = gap length (seconds);
I_i = indicator variable for the categorical offset parameter (covariate);
β_0 = overall intercept;
β_1 = common slope on X;

β_i = parameter representing the deviation of offset category I_i intercept from the overall intercept, $i = 1$ to k, where k is the number of offset categories in the model; and

$\beta_0, \beta_1, \beta_i$ = regression coefficients estimated by maximum likelihood method.

By calculating the logit of P [i.e., the (natural) log odds of the outcome] and modeling it as a linear function of the gap length, Equation 4.1 is then linearized to read:

$$logit(P) = \ln\left(\frac{P}{1-P}\right) = \beta_0 + \beta_1 X + \beta_i I_i \tag{4.2}$$

The model in Equation 4.2 assumes that the regression lines in the groups defined by offset categories are parallel. This assumption of parallel slopes is first tested by including an interaction term between offset category and gap length into the model in Equation 4.2 as follows:

$$logit(P) = \ln\left(\frac{P}{1-P}\right) = \beta_0 + \beta_1 X + \beta_i I_i + \delta_i X \tag{4.3}$$

where

δ_i = parameter representing the deviation of offset category I_i slope from the common slope, β_1.

The decision of whether to consider a parallel or nonparallel lines logit model is made based on the following modeling outcomes:

- If the interaction term is not statistically significant, then a parallel lines logit model is assumed (Equation 4.2).
- If the interaction term is statistically significant but the offset term is not, then a parallel lines logit model is assumed (Equation 4.2).
- If both the interaction and the offset terms are statistically significant, then a nonparallel lines logit model is assumed (Equation 4.3).

Either model then allows for estimating a number of gap lengths of interest, in particular, the gap length corresponding to a probability of 0.5 (i.e., the critical gap length, t_{50}).

The ultimate use of the logit model is to estimate the effect of offset on critical gap length, t_{50}. The overall offset effect is estimated by the significance level associated with the offset factor in the model, in other words, the significance of the coefficients β_i associated with the indicator variable I_i. From the logit regression models, the critical gaps, t_{50}, and their 95% confidence intervals are estimated at each level of offset. These confidence intervals are then compared in a pairwise fashion to assess which offset category differs statistically from which other offset category with respect to critical gap. This final comparison is performed using a visual hypothesis testing method modified to take into account sample sizes and variability of the data modeled in each group (Smith 1997).

All analyses were performed separately for signalized and two-way stop-controlled intersections, using PROC LOGISTIC and PROC PROBIT, two statistical procedures of SAS Version 9.3 (SAS Institute 2013). In general, a 10% significance level was used to test for the significance of the regression coefficients. However, all confidence intervals were calculated as two-sided 95% confidence intervals.

Analysis Results for Critical Gap Lengths

Three basic types of logistic regression models were developed:

1. Model Type 1 to test for the effect on the probability of gap acceptance of offset category at signalized intersections—seven offset categories—and at two-way stop-controlled intersections—four offset categories.
2. Model Type 2 to test for the effect of sight obstruction on the probability of gap acceptance, separately for each offset category at signalized intersections—five offset categories (zero and negative offsets only due to small sample sizes in the two positive-offset categories).
3. Model Type 3 to test for the effect of sight obstruction on the probability of gap acceptance at signalized intersections (all seven offset categories combined)—and at two-way stop-controlled intersections (all four offset categories combined).

Analysis Results for Critical Gap by Left-Turn Offset: Signalized Intersections

The results of model Type 1 logistic analysis applied to gaps and gap lengths observed at 44 approach pairs at signalized intersections are presented here. The following results were obtained:

- The total number of events is 1,671, with 269 accepted and 1,402 rejected gaps.
- The interaction term between gap length and offset category is significant at the 10% level (p-value = 0.06).
- Offset is significant at the 10% level (p-value = 0.09).
- The slopes of the seven regression curves are not parallel.

The seven regressions curves are plotted in Figure 4.5.

From the model, the critical gap length, t_{50}, and its 95% confidence interval were estimated, separately for each offset category. The results, along with the number of accepted and rejected gaps in each offset category, are shown in Table 4.5 and plotted in Figure 4.6.

The critical gap estimates and their confidence intervals were then compared to identify which pair of offset categories is statistically significantly different. The comparisons and test results are shown in Table 4.6. The pairs of offset categories that are statistically significantly different are shown in bold:

- −16 ft or less (7.5 s) from 1 ft to 3 ft (5.0 s) and from 4 ft to 6 ft (4.7 s);

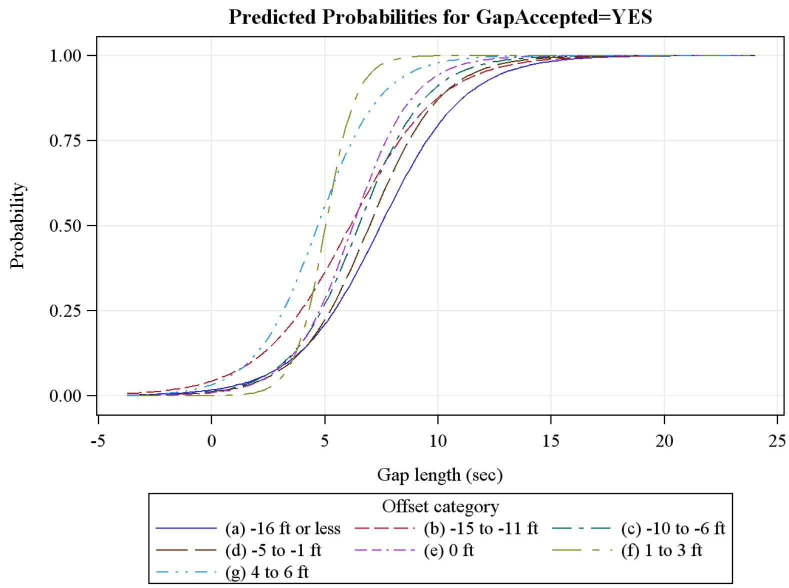


Figure 4.5. Predicted probability of accepting gap as function of gap length and offset category for signalized intersections.

- –10 ft to –6 ft (6.5 s) from 1 ft to 3 ft (5.0 s);
- –5 ft to –1 ft (7.0 s) from 1 ft to 3 ft (5.0 s) and from 4 ft to 6 ft (4.7 s); and
- 0 ft (6.2 s) from 1 ft to 3 ft (5.0 s).

The analysis of critical gap by offset category for signalized intersections shows that, in general, the critical gap is longest for intersections with negative-offset left-turn lanes and shortest for those with positive-offset left-turn lanes. This is to be expected given that the intersection geometry of a left-turn lane with negative offset requires the turning vehicle to travel a farther distance during the turning maneuver to clear the intersection. Positive-offset left-turn lanes bring the turning vehicle closer to the opposing through lanes of traffic and, therefore, shorten the travel distance (and time) required to clear the intersection. In addition, it should be noted that the provision of positive offset reduces or eliminates the potential for opposing left-turn vehicles to block their respective driver's view of opposing through vehicles, which allows drivers to more comfortably accept shorter gaps.

Analysis Results for Critical Gap by Left-Turn Offset: Two-Way Stop-Controlled Intersections

The results of model Type 1 logistic analysis applied to gaps and gap lengths observed at 14 approach pairs at two-way

Table 4.5. Critical Gap Estimates by Offset Category for Signalized Intersections

Offset Category	Critical Gap Estimate (s)	95% Confidence Limits (s)		Number of Accepted Gaps	Number of Rejected Gaps
		Lower	Upper		
(a) –16 ft or less	7.5	6.0	10.2	19	169
(b) –15 ft to –11 ft	6.1	4.4	12.0	11	26
(c) –10 ft to –6 ft	6.5	5.6	8.0	28	161
(d) –5 ft to –1 ft	7.0	6.2	8.1	56	485
(e) 0 ft	6.2	5.7	6.9	95	404
(f) 1 ft to 3 ft	5.0	4.5	5.7	35	108
(g) 4 ft to 6 ft	4.7	3.8	6.3	25	49
All				**269**	**1,402**

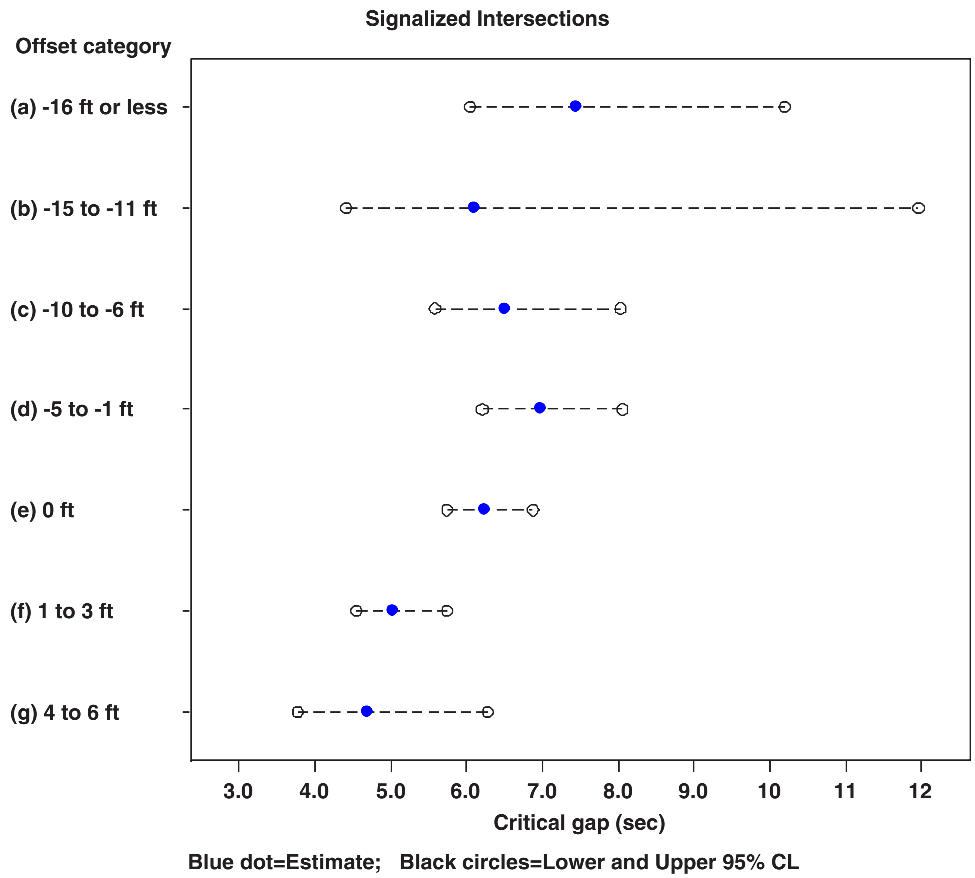


Figure 4.6. Critical gaps and 95% confidence intervals by offset category for signalized intersections.

Table 4.6. Comparison of Critical Gap Estimates Between Offset Categories for Signalized Intersections

Comparison Between:		Statistically Significantly Different?	Comparison Between:		Statistically Significantly Different?
Offset Category 1	Offset Category 2		Offset Category 1	Offset Category 2	
(a) −16 ft or less	(b) –15 ft to –11 ft	No	**(c) −10 ft to −6 ft**	(d) –5 ft to –1 ft	No
	(c) –10 ft to –6 ft	No		(e) 0 ft	No
	(d) –5 ft to –1 ft	No		**(f) 1 ft to 3 ft**	**Yes**
	(e) 0 ft	No		(g) 4 ft to 6 ft	No
	(f) 1 ft to 3 ft	**Yes**	**(d) −5 ft to −1 ft**	(e) 0 ft	No
	(g) 4 ft to 6 ft	**Yes**		**(f) 1 ft to 3 ft**	**Yes**
(b) –15 ft to –11 ft	(c) –10 ft to –6 ft	No		**(g) 4 ft to 6 ft**	**Yes**
	(d) –5 ft to –1 ft	No	**(e) 0 ft**	**(f) 1 ft to 3 ft**	**Yes**
	(e) 0 ft	No		(g) 4 ft to 6 ft	No
	(f) 1 ft to 3 ft	No	(f) 1 ft to 3 ft	(g) 4 ft to 6 ft	No
	(g) 4 ft to 6 ft	No			

Note: The pairs of offset categories that are statistically significantly different are shown in bold.

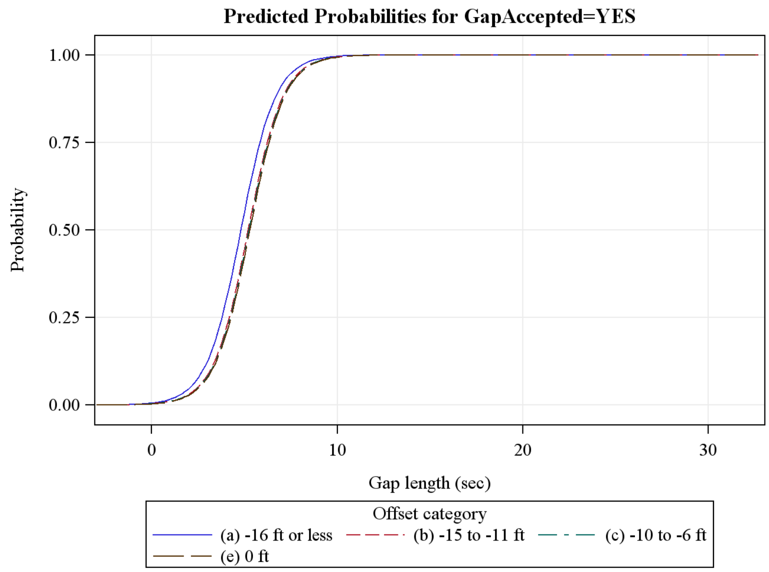


Figure 4.7. Predicted probability of accepting gap as function of gap length and offset category for two-way stop-controlled intersections.

stop-controlled intersections are presented. The following results were obtained:

- The total number of events is 1,126 with 207 accepted and 919 rejected gaps.
- The interaction term between gap length and offset category was not significant at the 10% level; thus, a parallel lines logit model was assumed.
- Offset is not significant (p-value = 0.94).

The four regressions curves are plotted in Figure 4.7. Note that the research team could not identify any two-way stop-controlled intersections with positive offsets, reducing the offset categories to four.

From the model, the critical gap length, t_{50}, and its 95% confidence interval were estimated, separately for each offset category. The results, along with the number of accepted and rejected gaps in each offset category, are shown in Table 4.7 and plotted in Figure 4.8.

Since offset was not statistically significant in the logit analysis, the critical gap estimates and their confidence intervals were not compared to identify which pair of offset categories is statistically significantly different. Clearly, none of the pairwise comparisons are statistically significant as evidenced by the widely overlapping confidence intervals in Figure 4.8.

The number of observations available for two-way stop-controlled intersections was substantially lower than that for signalized intersections. In general, all offset categories showed

Table 4.7. Critical Gap Estimates by Offset Category for Two-Way Stop-Controlled Intersections

Offset Category	Critical Gap Estimate (s)	95% Confidence Limits (s)		Number of Accepted Gaps	Number of Rejected Gaps
		Lower	Upper		
(a) –16 ft or less	4.8	3.4	6.2	5	24
(b) –15 ft to –11 ft	5.2	4.9	5.5	149	690
(c) –10 ft to –6 ft	5.2	4.7	5.9	40	128
(e) 0 ft	5.3	4.4	6.2	13	77
All				**207**	**919**

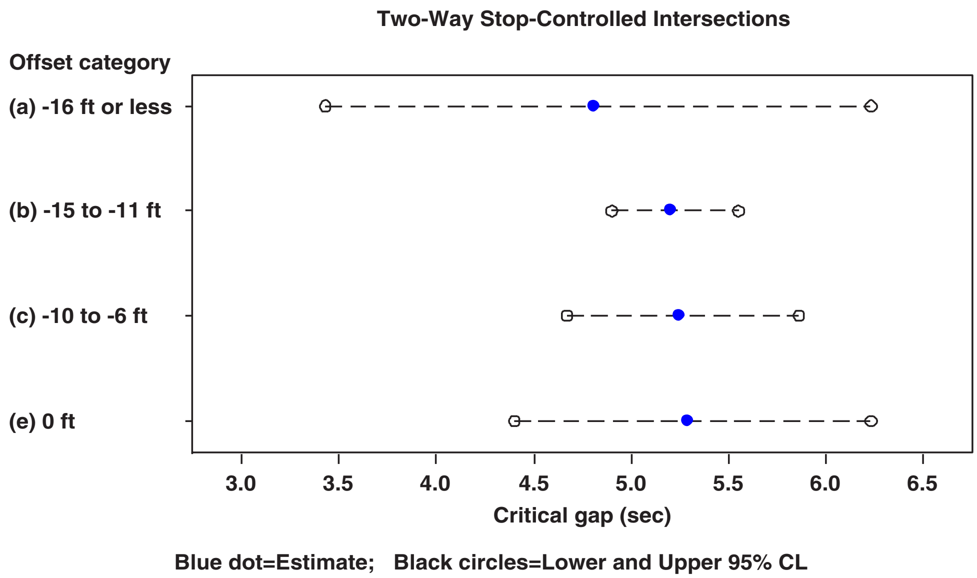


Figure 4.8. Critical gaps and 95% confidence intervals by offset category for two-way stop-controlled intersections.

similar critical gaps at two-way stop-controlled intersections. Larger sample sizes would be needed to better distinguish the gap acceptance behavior among these categories.

Analysis Results for Critical Gap by Presence of Sight Obstruction, Separately for Each Offset Category: Signalized Intersections Only

The safety concern related to the amount of left-turn lane offset is not so much the amount of offset itself (although, as discussed above, this does affect the distance traveled during the turning maneuver and, therefore, the gap length required for safe turning) but, instead, the possibility that a left-turn driver's view of potentially conflicting opposing through vehicles will be restricted by the presence of left-turning vehicles in the opposing left-turn lane. As the left-turn lanes become more negatively offset, opposing drivers are more directly in each other's line of sight to oncoming opposing traffic. Conversely, as left-turn lanes are more positively offset, the opposing left-turn driver is moved to the right of the field of view of the primary study driver and away from the line of sight to oncoming opposing traffic. The literature and common sense suggest that restricted sight distance should both increase the average gap length accepted by drivers, as they are more hesitant to accept a gap they cannot fully see, and increase the instances in which drivers accept a gap that they normally would reject because they cannot properly assess the gap length due to the sight restriction.

As Table 4.4 shows, the proportion of events for which an opposing left-turning vehicle restricts the sight distance of the primary left-turn driver is much higher for negative-offset intersections than for positive- and zero-offset intersections. In fact, there were few observations at positive-offset left-turn lanes in which an opposing vehicle restricted sight distance. A second analysis of critical gap was conducted to determine whether sight obstruction had an effect on critical gap for each of the negative- and zero-offset categories. (The positive-offset category was not included in this analysis because there were only six accepted gaps across three signalized intersections when sight distance was restricted.) Because of the limited number of observations at two-way stop-controlled intersections, this analysis was performed only for signalized intersections.

The results of model Type 2 logistic analysis applied to gap acceptance and gap lengths observed at 33 approach pairs at signalized intersections with negative or zero offset are presented here. These analyses were done separately for each of the five offset categories. The following results were obtained:

- The interaction term between gap length and sight obstruction was not significant at the 10% level in any of the five analyses, thus, parallel lines logit models were assumed.
- The statistical significance and p-values associated with sight obstruction for the five offset categories are as follows:
  - (a) −16 ft or less: not significant (p-value = 0.23);
  - (b) −15 to −11 ft: not significant (p-value = 0.23);
  - (c) −10 ft to −6 ft: significant (p-value = 0.02);
  - (d) −5 ft to −1 ft: not significant (p-value = 0.24); and
  - (e) 0 ft: not significant (p-value = 0.24).

The five pairs of regression curves are plotted in Figures 4.9 through 4.13.

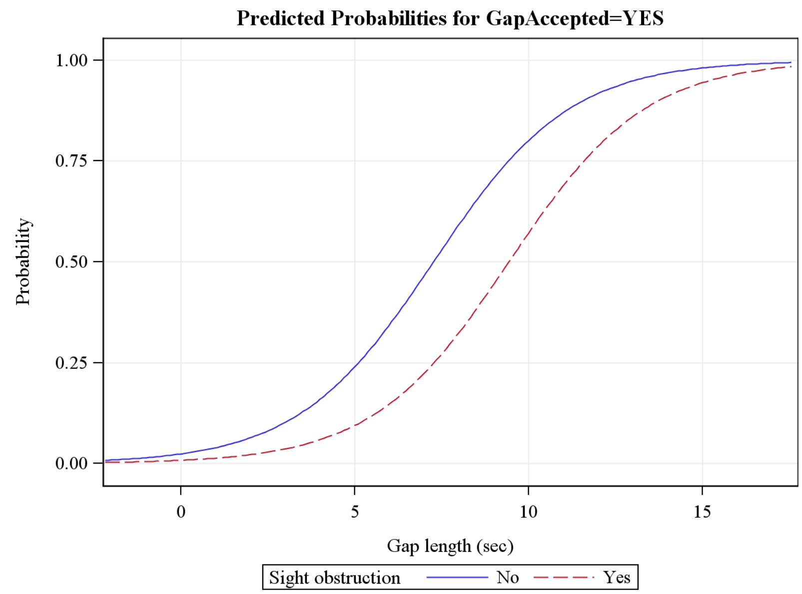


Figure 4.9. Predicted probability of accepting gap as function of gap length and presence of sight obstruction for signalized intersections with offsets of −16 ft or less.

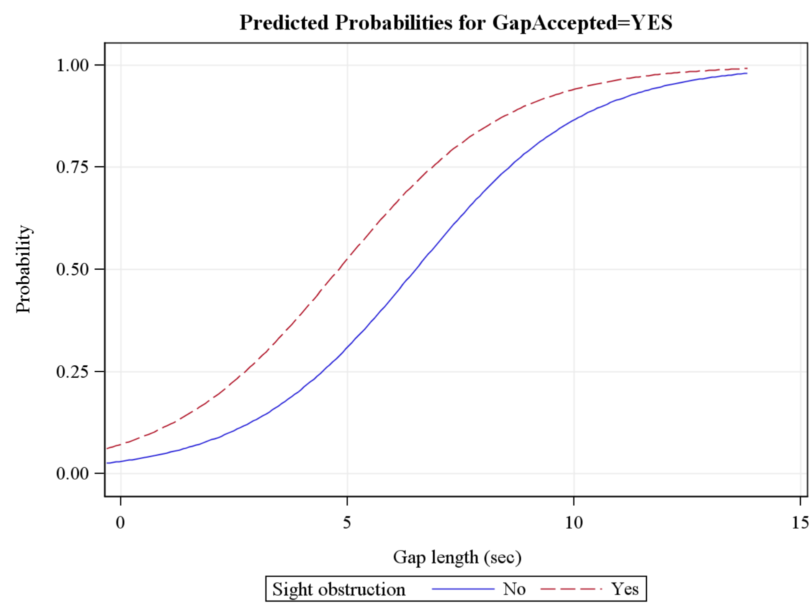


Figure 4.10. Predicted probability of accepting gap as function of gap length and presence of sight obstruction for signalized intersections with offsets between −15 ft and −11 ft.

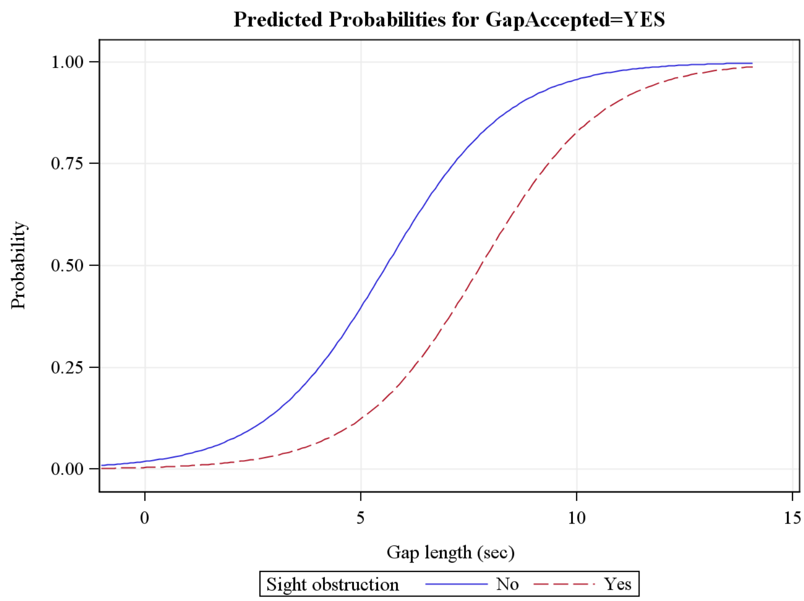


Figure 4.11. Predicted probability of accepting gap as function of gap length and presence of sight obstruction for signalized intersections with offsets between −10 ft and −6 ft.

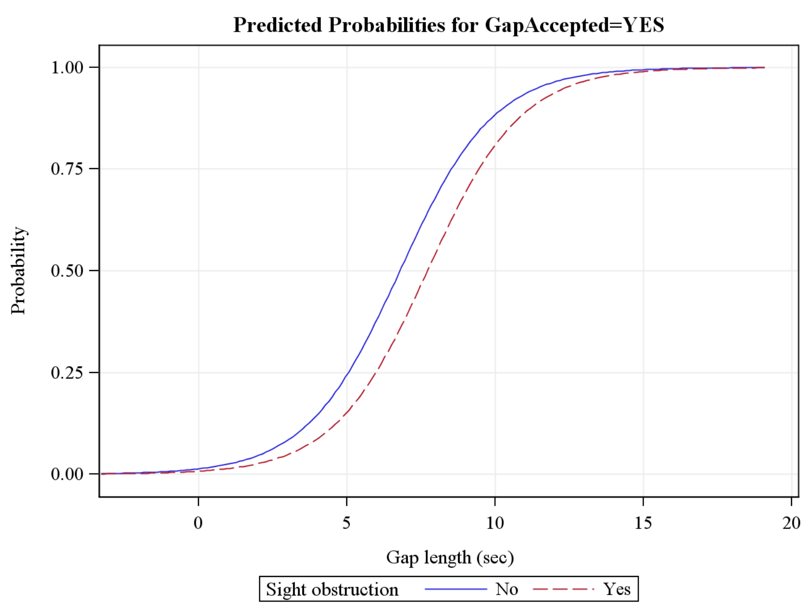


Figure 4.12. Predicted probability of accepting gap as function of gap length and presence of sight obstruction for signalized intersections with offsets between −5 ft and −1 ft.

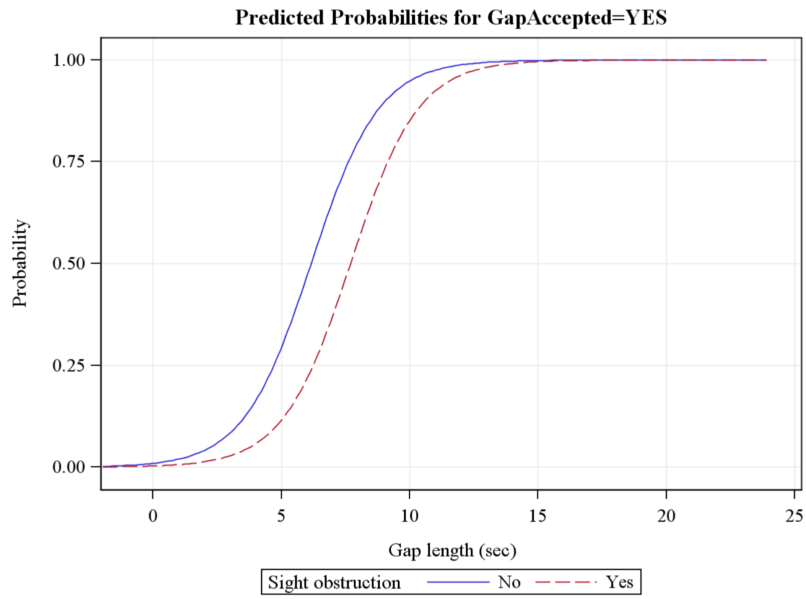


Figure 4.13. Predicted probability of accepting gap as function of gap length and presence of sight obstruction for signalized intersections with zero offset.

From the five models, the critical gap length, t_{50}, and its 95% confidence interval were estimated, separately for each offset category and sight obstruction (yes/no). The results, along with the number of accepted and rejected gaps for each combination, are shown in Table 4.8 and plotted in Figure 4.14.

With the exception of the offset range of −15 ft to −11 ft, which had the smallest number of observations, the critical gap was larger when a driver's sight distance was obstructed by an opposing left-turn vehicle than when it was not obstructed. In addition, the difference in critical gaps was greater for intersections with negative offsets than for those with zero offset. The only statistically significant effect of sight obstruction was found at intersections with offsets between −10 ft and −6 ft.

Because of the low number of events in which the left-turning driver's view of oncoming traffic was restricted, the differences are not statistically significant for most of the offset categories. For this reason, the offsets were collapsed for a third analysis to show that overall, the critical gap is longer for drivers whose view is obstructed by the presence of a left-turning driver than for drivers who have no sight obstruction. This analysis was conducted for signalized and two-way stop-controlled intersections separately and is discussed next.

Analysis Results for Critical Gap by Presence of Sight Obstruction and Intersection Type, Across All Offset Categories

The results of model Type 3 logistic analysis applied to gap acceptance and gap lengths observed at signalized and two-way stop-controlled intersections are presented here. The following results were obtained:

- The interaction term between gap length and sight obstruction was not significant at the 10% level in either of the two analyses; thus, parallel lines logit models were assumed.
- The statistical significance and p-values associated with sight obstruction for the two intersection types are as follows:
  - Signalized intersections: significant sight obstruction effect (p-value = 0.02); and
  - Two-way stop-controlled intersections: significant sight obstruction effect (p-value = 0.03).

The two pairs of regression curves are plotted in Figure 4.15 and Figure 4.16.

From the two models, the critical gap length, t_{50}, and its 95% confidence interval were estimated, separately for each sight obstruction (yes/no) and intersection type. The results, along with the number of accepted and rejected gaps for each combination, are shown in Table 4.9 and plotted in Figure 4.17.

Although sight obstruction has an overall significant effect on gap-acceptance probability over the range of available gaps in the study, the comparisons of the critical gaps between sight obstruction and no sight obstruction are inconclusive (i.e., there is not enough evidence to prove statistical significance of the difference between the two estimates.) This might seem contradictory at first, but it should be noted that the logistic regression predicts probability of acceptance (y-axis) as a function of gap length (x-axis). Inverse regression is used to

Table 4.8. Critical Gap Estimates by Offset Category and Presence of Sight Obstruction for Signalized Intersections

Offset Category	Is Sight Distance Obstructed?	Critical Gap Estimate (s)	95% Confidence Limits (s)		Significant Difference Between Obstruction and No Obstruction?	Number of Accepted Gaps	Number of Rejected Gaps
			Lower	Upper			
(a) –16 ft or less	Yes	9.4	6.0	15.2	No	2	57
	No	7.3	5.8	9.9		17	112
(b) –15 ft to –11 ft	Yes	4.8	1.7	10.7	No	3	6
	No	6.5	4.5	12.3		8	20
(c) –10 ft to –6 ft	**Yes**	**7.8**	**6.3**	**10.0**	**Yes**	**7**	**85**
	No	**5.6**	**4.6**	**7.1**		**21**	**76**
(d) –5 ft to –1 ft	Yes	7.7	6.2	9.6	No	10	119
	No	6.8	6.0	7.9		46	366
(e) 0 ft	Yes	7.7	5.2	10.3	No	2	14
	No	6.2	5.7	6.8		93	390
(f) 1 ft to 3 ft[a]	Yes	—	—	—	—	0	3
	No	—	—	—		35	105
(g) 4 ft to 6 ft[a]	Yes	—	—	—	—	2	1
	No	—	—	—		23	48
All zero and negative offsets						**209**	**1,245**
All offsets						**269**	**1,402**

[a] Not included in the analysis.

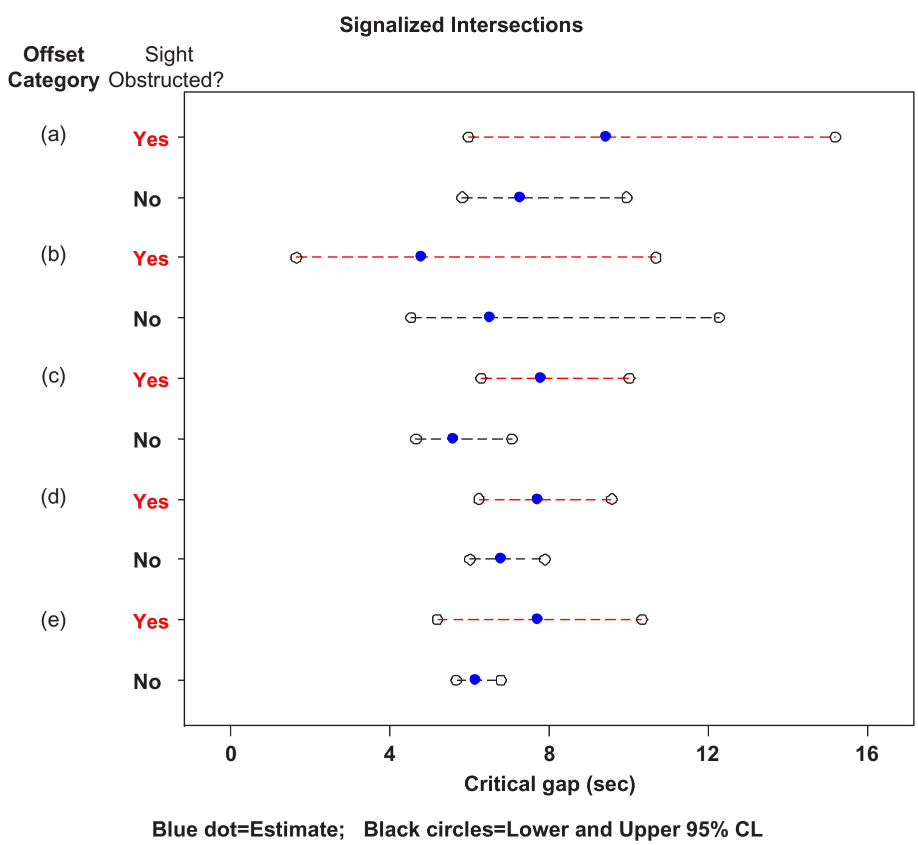


Figure 4.14. Critical gaps and 95% confidence intervals by offset category and presence of sight obstruction for signalized intersections.

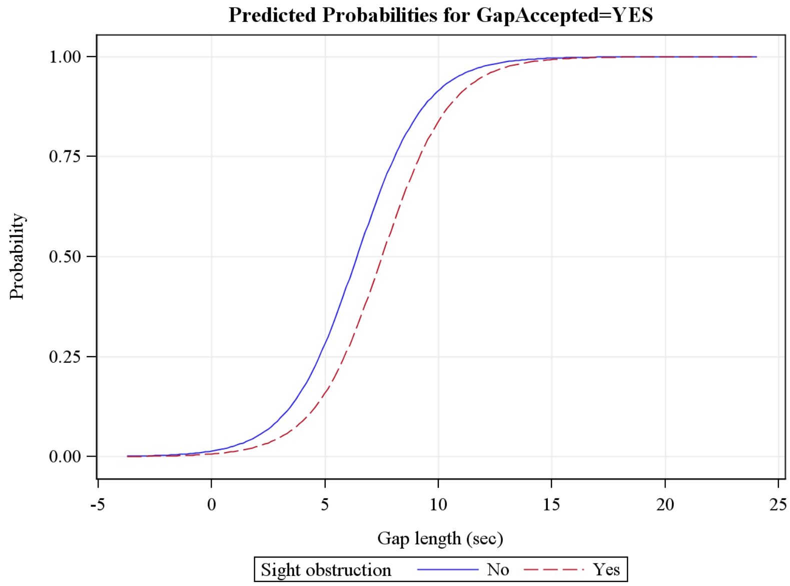


Figure 4.15. Predicted probability of accepting gap as function of gap length and presence of sight obstruction for signalized intersections—all offsets combined.

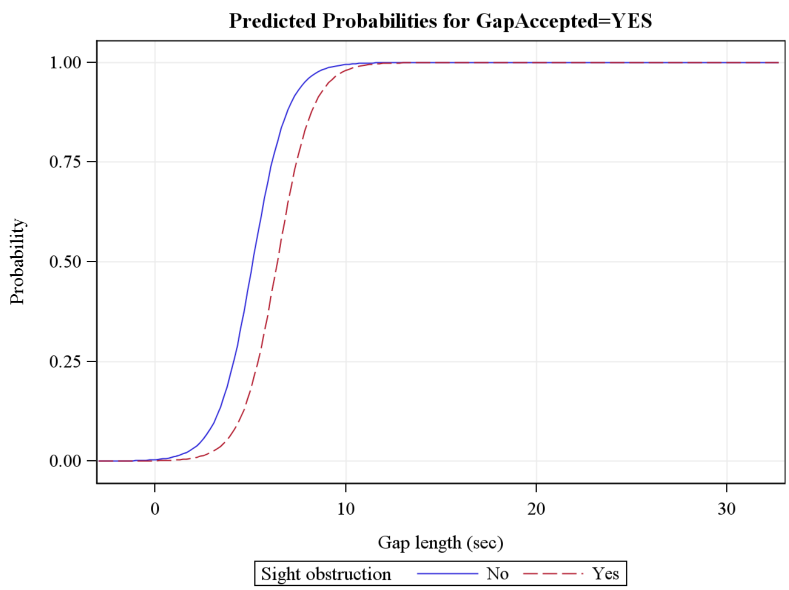


Figure 4.16. Predicted probability of accepting gap as function of gap length and presence of sight obstruction for two-way stop-controlled intersections—all offsets combined.

Table 4.9. Critical Gap Estimates by Intersection Type and Presence of Sight Obstruction: All Offsets Combined

Traffic Control Type	Is Sight Distance Obstructed?	Critical Gap Estimate (s)	95% Confidence Limits (s)		Significant Difference Between Obstruction and No Obstruction?	Number of Accepted Gaps	Number of Rejected Gaps
			Lower	Upper			
Signalized	Yes	7.5	6.6	8.5	No	26	285
	No	6.4	6.0	6.9		243	1,117
	All					269	1,402
Two-way stop	Yes	6.4	5.3	7.6	No	15	66
	No	5.1	4.8	5.4		192	853
	All					207	919

compare critical gaps. Estimates and their confidence limits corresponding to a 0.5 probability (y-axis) are computed on the gap length axis (x-axis). Therefore, the steeper the curves, the more difficult it becomes to prove statistically significant differences on the x-axis by reverse regression.

This analysis showed that the critical gaps for the two sight obstruction conditions are not statistically significantly different. However, in both cases, the critical gap when the view is obstructed is longer than when the view is unobstructed—by 1.1 s at signalized intersections and by 1.3 s at two-way stop-controlled intersections. These differences are somewhat smaller than those found by Yan and Radwan (2007). Their research showed a critical gap of 5.6 s for drivers with unobstructed view versus 7.7 s for drivers with an obstructed view resulting from the presence of a left-turning driver (difference of 2.1 s).

Analysis of Short Gap Lengths and Postencroachment Times

The analyses in the preceding sections show that, on average, drivers wait to accept longer gaps where left-turn lanes are negatively offset and when their view of opposing vehicles is obstructed. However, the shortest accepted gaps may also be taken in these conditions. That is, while many drivers wait for longer gaps when they do not have a good view of the available

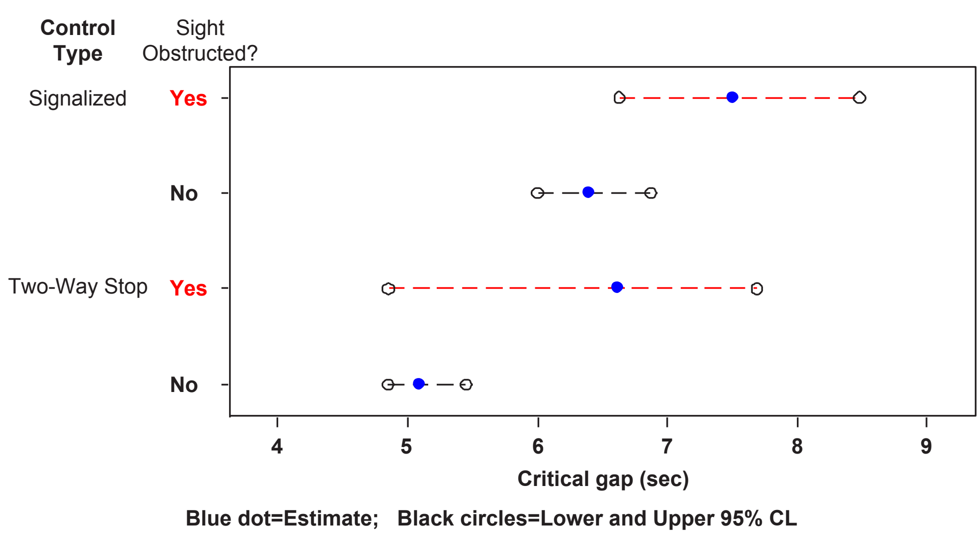


Figure 4.17. Critical gaps and 95% confidence intervals by intersection type and presence of sight obstruction—all offsets combined.

Table 4.10. 1st-, 5th-, 10th-, and 15th-Percentile Accepted Gap Lengths With and Without Sight Obstruction by Offset Category

Offset Category	All Accepted Gaps					Accepted Gaps with Sight Obstruction				
	Number of Observations	Percentile				Number of Observations	Percentile			
		1st	5th	10th	15th		1st	5th	10th	15th
Signalized Intersections										
Negative	114	–1.33	0.34	2.28	2.71	22	–0.66	2.56	2.64	2.97
Zero	95	0.02	2.15	2.97	3.58	2	5.66	5.66	5.66	5.66
Positive	60	–1.50	1.17	3.00	3.53	2	6.84	6.84	6.84	6.84
Two-Way Stop-Controlled Intersections										
Negative	196	2.14	2.42	2.85	3.38	16	2.42	2.42	2.77	3.67
Zero	13	1.76	1.76	3.97	3.97	0	—	—	—	—

gaps, a few drivers may accept gaps that are shorter than they would otherwise choose because they cannot see how short the gap is. The research team investigated this possibility in two ways:

1. For each of the six combinations of offset (negative, zero, and positive) and sight obstruction (yes or no), the 1st-, 5th-, 10th-, and 15th-percentile accepted gap lengths were estimated for comparison (Table 4.10).
2. The percentage of accepted gaps with a postencroachment time less than 4, 3, 2, or 1 s were calculated for each of the six offset and sight obstruction combinations (Table 4.11).

Both Table 4.10 and Table 4.11 show that the number of accepted gaps for which the subject vehicle's view of approaching traffic was obstructed by an opposing left-turning vehicle was low; this does not warrant a comparison of the differences in postencroachment times on the short end of the distribution between accepted gaps with and without sight obstructions. When considering all accepted gaps, Table 4.10 shows that the 1st-, 10th-, and 15th-percentile accepted gaps were shorter at negative-offset left-turn lanes than at zero- or positive-offset left-turn lanes at both signalized and stop-controlled intersections. Similarly, Table 4.11 shows that a higher percentage of accepted gaps had postencroachment times less than 2, 3, and 4 s at signalized intersections with negative offsets than at zero or positive offsets. These findings suggest that while the 50th-percentile accepted gap length is generally longer at negative-offset left-turn lanes than at zero- or positive-offset left-turn lanes, there is also a higher likelihood that drivers

Table 4.11. Percentage of Accepted Gaps With Postencroachment Times Less Than 1, 2, 3 and 4 Seconds With and Without Sight Obstruction by Offset Category

Offset Category	All Accepted Gaps					Accepted Gaps with Sight Obstruction				
	Number of Observations	Percentage of Observations with Postencroachment Time Less Than:				Number of Observations	Percentage of Observations with Postencroachment Time Less Than:			
		1 s	2 s	3 s	4 s		1 s	2 s	3 s	4 s
Signalized Intersections										
Negative	114	6	9	18	36	22	5	5	18	32
Zero	95	1	3	11	21	2	0	0	0	0
Positive	60	3	7	10	20	2	0	0	0	0
Two-Way Stop-Controlled Intersections										
Negative	196	0	1	11	19	16	0	0	13	19
Zero	13	0	8	8	15	0	—	—	—	—

will accept shorter gaps at negative-offset intersections as well. It appears that on average, drivers at negative-offset left-turn lanes are more cautious and wait for longer gaps than drivers at other intersections, but they are also more likely to leave a short amount of clearance time between their turn and the arrival of the next opposing through vehicle than drivers at other intersections. Two possible explanations for this are (1) some drivers take short, risky gaps when their view is obstructed because they cannot properly assess the risk; and (2) drivers may hesitate before initiating a left turn when their sight is obstructed, resulting in less time between the turn and the arrival of the next opposing through vehicle.

Secondary Analyses

The previous analysis sections examined the overall effect of offset distance on driver gap acceptance and whether that effect is further affected by the presence of a vehicle in the opposing left-turn lane. However, the potential influence of other factors, such as relevant intersection characteristics, human factor considerations, and driver demographics, are worth exploring as well. This section presents a number of secondary analyses, more exploratory in nature, on a number of topics, depending on the distribution of the data collected.

These secondary analyses serve two purposes. First, the data needed to be checked to ensure that some of the documented influences (such as driver age, driver gender, weather conditions, and time spent waiting for a gap) on left-turn gap-acceptance behavior were not confounded with offset. For example, the data needed to show that a given offset category did not include mostly drivers from one age category or have substantially longer time spent waiting for a gap than other offset categories. Second, it might be of interest to show researchers wanting to use NDS data in future research some of the various types of evaluations that could be conducted using the NDS data. Several of these secondary analyses are described next.

Gender and Age

From a human factors perspective, it is important to recognize the effect that driver demographics have on driving, especially left-turning, behavior. The literature suggests that the youngest drivers with the least experience and the oldest drivers, who are less likely to detect approaching vehicles and who make poor speed and gap estimates once vehicles are detected, are the least comfortable judging gaps for left-turn maneuvers (Parsonson et al. 1999). The research team wanted to show differences, if any, in accepted gap length and postencroachment time by age category and gender but also wanted to show that the effects of these factors are not confounded with offset category—that is, that any given offset category does not contain mostly one category of drivers.

Driver age categories were designed to match SHRP 2's age categories shown on the NDS data website. However, some age groups were combined to provide a large enough sample size for comparison.

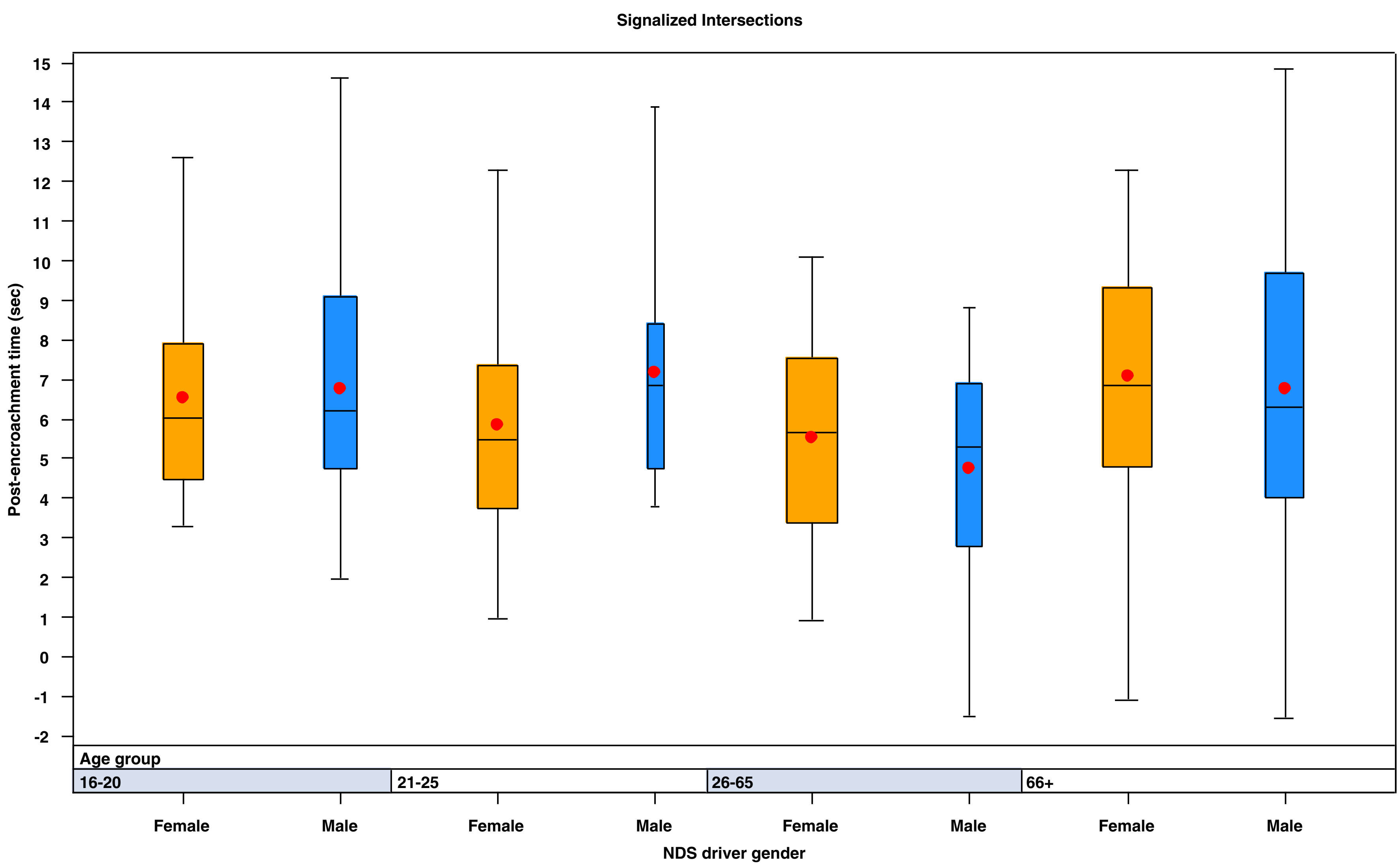
The following plots are shown in Appendix A:

- Figures A.7 through A.10: Signalized intersections, available and accepted gap lengths, by offset category and age group, and by offset category and gender.
- Figures A.11 through A.14: Two-way stop-controlled intersections, available and accepted gap lengths, by offset category and age group, and by offset category and gender.
- Figures A.15 and A.16: Signalized intersections, postencroachment time for accepted gap, by offset category and age group, and by offset category and gender.
- Figures A.17 and A.18: Two-way stop-controlled intersections, postencroachment time for accepted gap, by offset category and age group, and by offset category and gender.

These plots illustrate that, in this database, none of the driver demographics are confounded with offset categories with respect to available or accepted gap length or postencroachment time. In other words, the plots show that (1) all drivers (all ages and both genders) are equally exposed to available gaps across the entire range of gap length without a trend across offset categories; (2) there is no pattern of older drivers accepting mostly long gaps while younger drivers accept mostly short gaps, across gender and all offset categories; and (3) there is no indication that certain age/gender groups have shorter postencroachment times than others. A much larger sample than the 145 NDS drivers included in this study would be needed to undertake a rigorous statistical analysis of the effect of these demographics on accepted gaps.

Because sample sizes were small in each age and gender category when broken down by offset, the research team evaluated length of accepted gap and postencroachment time by age and gender with all offset categories combined. The analysis of length of accepted gap showed no statistically significant differences between age groups or genders and is not shown in this report. The distribution of postencroachment time by NDS driver age group and gender is shown in Figure 4.18 for all signalized intersections combined and in Figure 4.19 for all two-way stop-controlled intersections combined. A two-way analysis of variance (ANOVA) was performed to investigate whether gap-acceptance behavior, as measured by postencroachment time, varies between male and female drivers and among age groups. The interaction between age and gender was also tested.

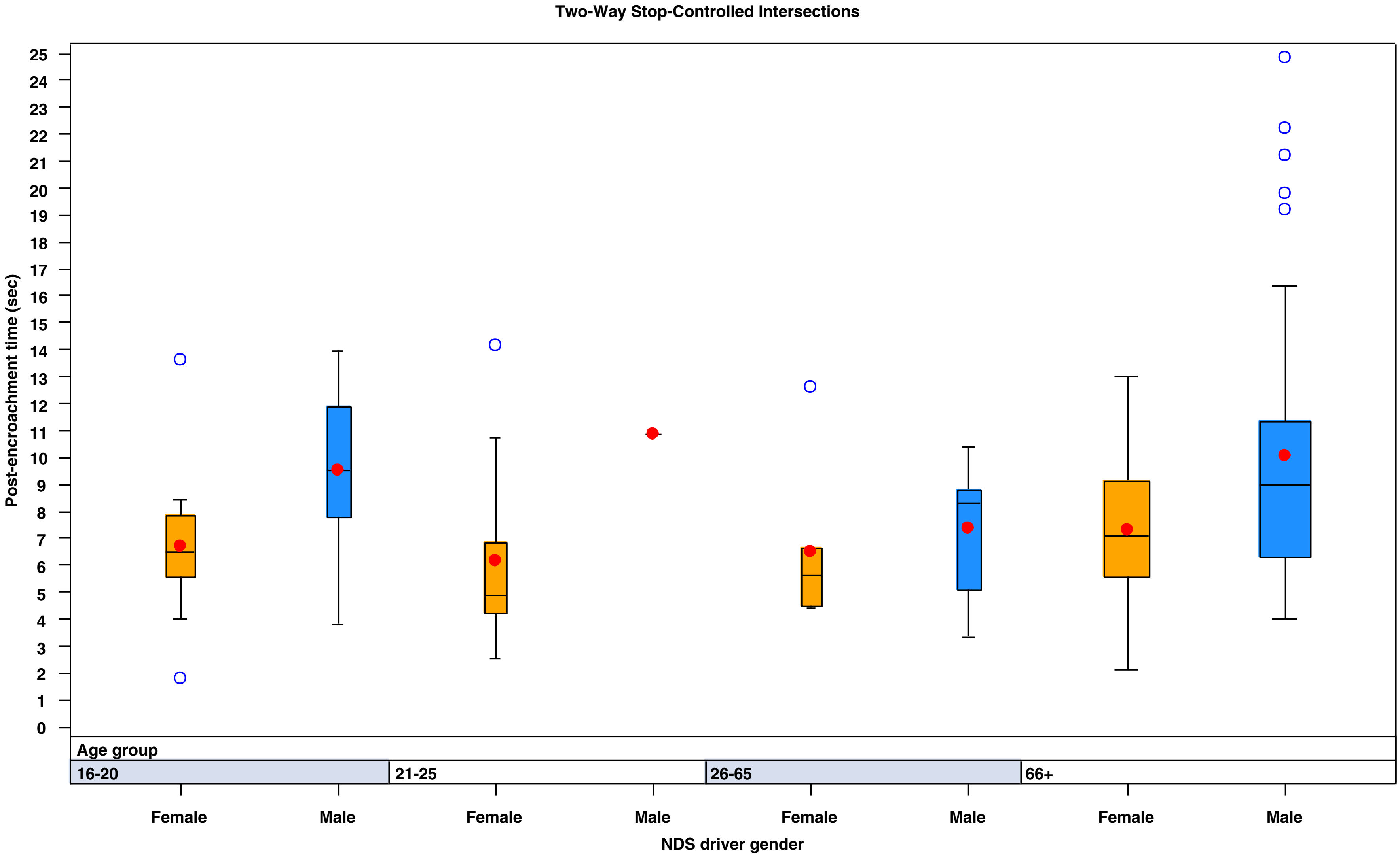
The interaction term between age group and gender in the ANOVA was not statistically significant for either intersection type (p-value of 0.60 for signalized intersections and 0.70 for two-way stop-controlled intersections); in other words, there is no evidence from these data that, for example, younger male drivers behave differently than, say, older female drivers.



N	24	19	23	7	31	13	30	22
Min	3.3	2.0	1.0	3.8	0.9	-1.5	-1.1	-1.6
Mean	6.5	6.8	5.8	7.2	5.5	4.7	7.1	6.8
Median	6.0	6.2	5.5	6.8	5.6	5.3	6.8	6.3
Max	12.6	14.6	12.3	13.9	10.1	8.8	12.3	14.9
Std Dev	2.7	3.2	2.7	3.4	2.6	2.8	3.1	3.7

Red dot = mean; Horizontal line = median; Colored box = mid 50% of data; Blue circle = extreme value

Figure 4.18. Distribution of postencroachment time for accepted gaps by NDS driver age group and gender at signalized intersections.



N	19	12	9	1	7	11	49	56
Min	1.8	3.8	2.6	10.8	4.4	3.3	2.1	4.0
Mean	6.7	9.5	6.2	10.8	6.5	7.3	7.3	10.0
Median	6.5	9.5	4.8	10.8	5.6	8.3	7.1	9.0
Max	13.6	13.9	14.2	10.8	12.6	10.4	13.0	24.8
Std Dev	2.3	2.9	3.9	.	2.8	2.2	2.7	4.7

Red dot = mean; Horizontal line = median; Colored box = mid 50% of data; Blue circle = extreme value

Figure 4.19. Distribution of postencroachment time for accepted gaps by NDS driver age group and gender at two-way stop-controlled intersections.

The ANOVA models were then estimated without the interaction term, with the following results:

- At signalized intersections
  - There is no statistically significant difference in postencroachment times between male and female NDS drivers, all age groups combined (p-value of 0.93).
  - Postencroachment time varies significantly among age groups, both genders combined (p-value of 0.05).
- At two-way stop-controlled intersections
  - Postencroachment time varies significantly between male and female drivers, all age groups combined (p-value less than 0.0001).
  - There is no statistically significant difference in postencroachment times among age groups, both genders combined (p-value of 0.18).

Least square mean postencroachment times and their 95% confidence limits are presented in Table 4.12.

Time Spent Waiting for Gap

The length of time a vehicle spent waiting for a suitable gap was calculated as the time between when the left-turning driver arrived in the queue (or at the stop bar if there was no queue) and when the driver began the turning maneuver. If the signal was red at the time of arrival in the queue, this time spent at the red light was included in the time spent waiting for a gap. The literature suggests that drivers who wait longer than 30 s for a gap tend to become impatient and select a shorter, riskier gap.

Figure A.19 (signalized intersections) and Figure A.20 (two-way stop-controlled intersections) illustrate the relationship between accepted gap length and time spent waiting to accept the gap. Similarly, Figure A.21 (signalized intersections) and Figure A.22 (two-way stop-controlled intersections) illustrate the relationship between postencroachment time of accepted gaps and time spent waiting to accept the gap. None of these plots provides sufficient evidence to conclude that drivers who spend more time waiting for a suitable gap accept a smaller, riskier gap.

Weather and Lighting Conditions

It is expected that in poor weather conditions, drivers will wait for longer gaps and proceed more slowly through the intersection. Darkness may affect accepted gap length as well, as gap length may be more difficult to judge. However, the data in this study were heavily skewed toward trips made in daylight and under dry conditions:

- 93% of the events were observed under dry conditions versus 7% under rainy or snow/icy conditions combined.

Table 4.12. Postencroachment Times by NDS Gender and Age Group Across All Intersections, by Intersection Type

Age Group/ Gender	Number of Turns	Postencroachment Time (s)			Statistically Significant Comparisons at 5% Level
		Mean	95% Confidence Limits (s)		
Signalized Intersections					
16–20 yr	43	6.6	5.7	7.5	
21–25 yr	30	6.1	5.0	7.3	
26–65 yr	44	5.3	4.4	6.2	Significant difference ($p = 0.008$)
66+ yr	52	6.9	6.1	7.8	
Female	108	6.3	5.7	6.8	
Male	61	6.2	5.4	7.0	
Two-Way Stop-Controlled Intersections					
16–20 yr	31	8.1	6.8	9.4	
21–25 yr	10	7.7	5.4	10.0	
26–65 yr	18	6.7	5.1	8.4	
66+ yr	105	8.7	8.0	9.3	
Female	84	6.5	5.6	7.4	Significant difference ($p < 0.0001$)
Male	80	9.1	8.1	10.1	

- 84% of the events were observed in daylight versus 16% in the remaining lighting conditions (dark with streetlights: 9%; dark without streetlights: less than 1%; dawn/dusk: 7%).

Figure A.23 (weather conditions) and Figure A.24 (lighting conditions) illustrate the distribution of events by offset categories across all intersections (signalized and two-way stop-controlled combined). The highly skewed distribution of events across both weather and lighting conditions did not warrant a meaningful analysis of the effect of these two conditions on gap-acceptance behavior.

Vehicle Type

The type or size of vehicle making a left turn, as well as the type or size of oncoming vehicle, may influence the length of gap a driver feels comfortable accepting. Table 4.13 shows the combinations of NDS vehicle type and oncoming vehicle type or gap-closing event (gaps may end when the left-turn signal turns red before the next opposing through vehicle arrives) for the 331 measured gaps accepted by NDS drivers. The table shows that nearly 80% of these gaps were accepted by passenger vehicles. Pickup trucks and vans were virtually unrepresented in this data set. Therefore, a comparison of the gap-acceptance behavior by the drivers of different vehicle types was not conducted. Similarly, because only eight gaps were accepted in front of an oncoming heavy vehicle, no analysis was performed by oncoming vehicle type.

Table 4.13. Combinations of NDS Vehicle Type and Gap-Closing Vehicle Type or Event for Accepted Gaps

NDS Vehicle Type	Vehicle Type or Event that Closes Gap			
	Passenger Car	Heavy Vehicle	Red Signal Indication	Not Recorded
Passenger car	234	4	7	10
Pickup truck	3	0	0	2
SUV cross-over	59	4	6	1
Van/ minivan	1	0	0	0

Presence of a Following Vehicle

The presence of a following vehicle has the potential to make left-turn drivers accept a gap as soon as possible so as not to prolong the wait time of the driver behind them.

Table 4.14 shows the percentage of all events (rejected and accepted gaps) and all accepted gaps in which a following vehicle was present while the left-turn driver evaluated a given gap. Mean and median gap lengths for each condition are presented by offset for comparison. For many of the offset categories, it appears that drivers do accept slightly shorter

Table 4.14. Event and Gap Statistics in Presence of Following Vehicle

Offset Category	Percentage of All Events with Following Vehicle	Percentage of Accepted Gaps with Following Vehicle	With Following Vehicle		Without Following Vehicle	
			Mean Accepted Gap (s)	Median Accepted Gap (s)	Mean Accepted Gap (s)	Median Accepted Gap (s)
Signalized Intersections						
(a) –16 ft or less	42.4	21.1	7.9	7.9	7.8	7.2
(b) –11 ft to –15 ft	11.1	14.8	11.0	11.0	6.2	5.0
(c) –6 ft to –10 ft	24.5	28.3	6.5	5.8	7.2	6.3
(d) –1 ft to –5 ft	34.3	32.9	7.1	6.7	8.6	8.1
(e) 0 ft	29.6	24.8	8.7	7.5	7.7	7.2
(f) 1 ft to 3 ft	36.1	30.3	7.3	6.5	8.2	7.7
(g) 4 ft to 6 ft	44.3	27.6	5.4	3.9	6.7	6.8
Two-Way Stop-Controlled Intersections						
(a) –16 ft or less	0.0	0.0	—	—	10.4	10.6
(b) –11 ft to –15 ft	15.8	9.3	6.5	5.9	9.0	8.1
(c) –6 ft to –10 ft	6.6	7.6	7.8	6.7	8.9	8.7
(e) 0 ft	7.4	11.1	2.8	2.8	7.9	7.9

gaps when a vehicle behind them is waiting to turn. However, the number of gaps accepted by NDS drivers while a following turning vehicle was present, separately for each offset category, was small. Across all intersection types and offset categories, a vehicle was waiting behind the left-turn NDS driver in only approximately 25% of events. This situation did not warrant a statistical analysis of the effect of the presence of a following vehicle on accepted gap length.

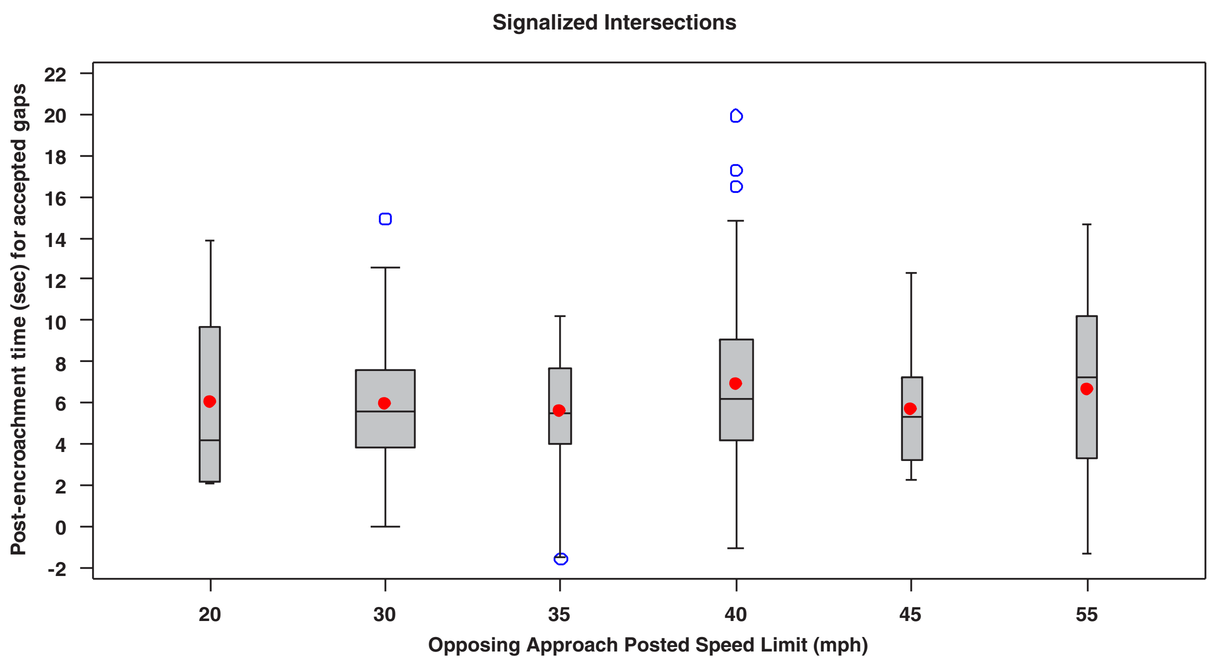
Opposing Vehicle Speed

The posted speed limit of the opposing approach was available for each left-turning maneuver observed in the study. In the absence of measured opposing vehicle speeds, the posted speed limit of the opposing approach was used as a surrogate for opposing vehicle speed. Conceivably, as the speed of approaching vehicles increases, so does the level of difficulty left-turning drivers may have in judging an acceptable gap. This potential relationship was investigated by examining the distribution of postencroachment time for accepted gaps by the various opposing speed limits. Figure 4.20 (signalized intersections) and Figure 4.21 (two-way stop-controlled intersections) show the distribution of postencroachment time for accepted gaps by the posted speed limit of the opposing approach.

The plots do not indicate a decreasing trend in the times drivers leave between the execution of their turning maneuver and the arrival of the next opposing vehicle and decreasing posted speed limit on the opposing approach increases. It should be noted that sample sizes are small in many offset categories, especially for the two-way stop-controlled intersections.

Left-Turn Signal Phasing

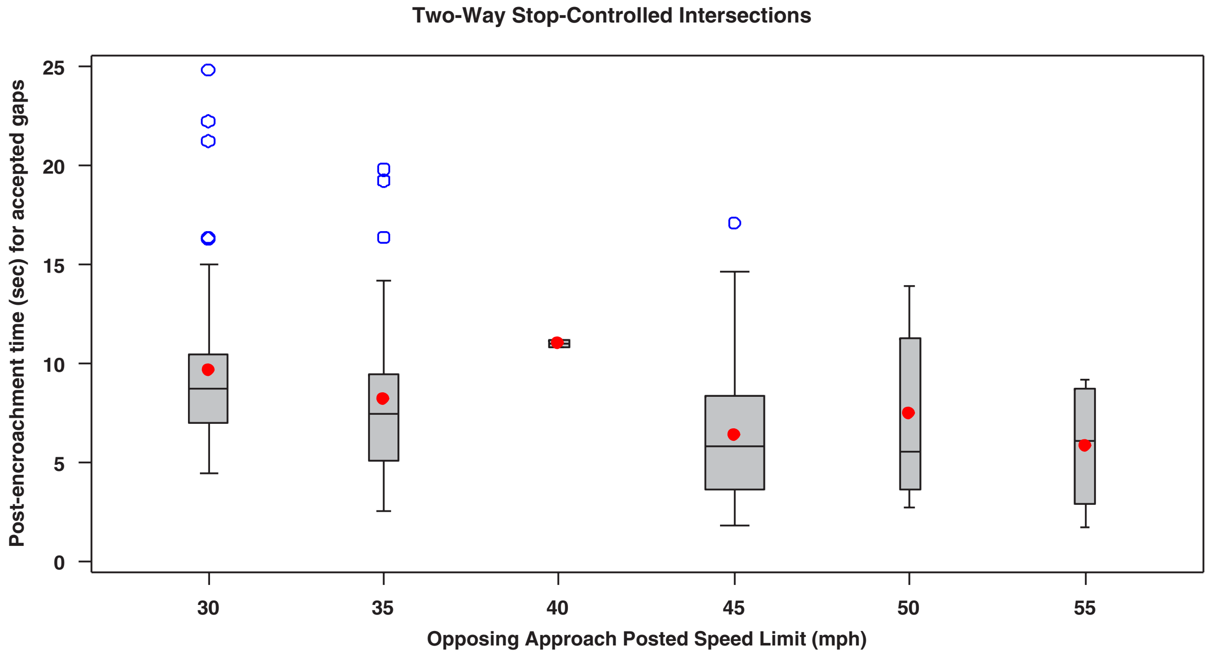
Drivers making left turns at an approach with permissive/protected phasing may be more willing to wait for a longer gap than drivers at a left-turn signal with only permissive phasing, knowing that if no suitable gap is available, they will eventually be given a protected green indication. Figure 4.22 shows the distribution and basic statistics of accepted gap length, separately for each type of signal phasing. Similarly, Figure 4.23 shows the distribution and basic statistics of postencroachment time for accepted gaps separately for each type of signal phasing. The above stated assumption could not be validated



	20	30	35	40	45	55
N	6	104	43	71	30	15
Min	2.1	0.0	-1.6	-1.1	2.2	-1.3
Mean	6.0	6.0	5.6	6.8	5.7	6.6
Median	4.2	5.5	5.5	6.2	5.4	7.2
Max	13.9	14.9	10.2	19.9	12.3	14.6
Std Dev	4.7	2.8	2.9	4.1	2.8	4.8

Red dot = mean; Horizontal line = median; Colored box = mid 50% of data; Blue circle = extreme value

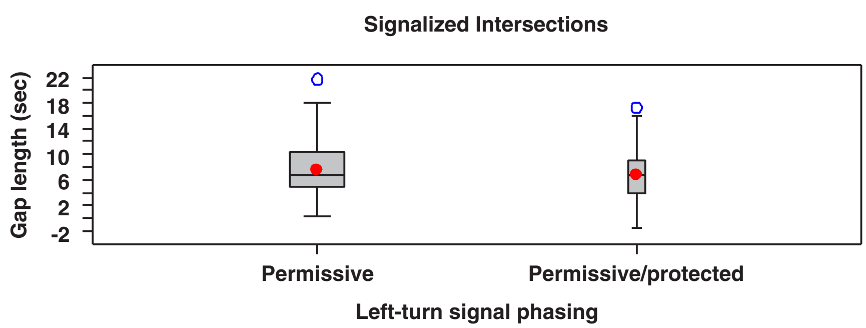
Figure 4.20. Distribution of postencroachment time for accepted gaps by posted speed limit on opposing approach at signalized intersections.



N	53	30	2	115	5	4
Min	4.4	2.6	10.8	1.8	2.7	1.8
Mean	9.6	8.2	11.0	6.3	7.4	5.8
Median	8.8	7.4	11.0	5.8	5.5	6.1
Max	24.8	19.8	11.2	17.1	13.9	9.2
Std Dev	4.2	4.4	0.3	3.3	4.9	3.5

Red dot = mean; Horizontal line = median; Colored box = mid 50% of data; Blue circle = extreme value

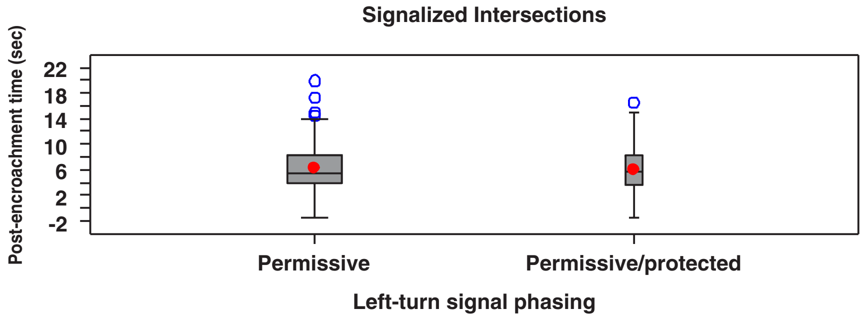
Figure 4.21. Distribution of postencroachment time for accepted gaps by posted speed limit on opposing approach at two-way stop-controlled intersections.



N	172	97
Min	0.2	-1.4
Mean	7.4	6.8
Median	6.6	6.7
Max	21.7	17.2
Std Dev	3.7	3.8

Red dot = mean; Horizontal line = median; Colored box = mid 50% of data; Blue circle = extreme value

Figure 4.22. Distribution of accepted gap length (seconds) by type of signal phasing.



N	172	97
Min	-1.6	-1.5
Mean	6.2	6.1
Median	5.5	5.8
Max	19.9	16.5
Std Dev	3.3	3.6

Red dot = mean; Horizontal line = median; Colored box = mid 50% of data; Blue circle = extreme value

Figure 4.23. Distribution of postencroachment time for accepted gaps by type of signal phasing.

with either plot. In fact, drivers at left turns with permissive/protected phasing tended to have slightly shorter (0.6 s) post-encroachment times than drivers facing permissive-only phasing. However, these results may be misleading since gaps that were accepted on a protected left-turn signal phase were not included in the analysis (although the observations of their rejected gaps during the permissive phase were included).

Analysis of Near Crashes

The research team requested from VTTI a list of all crash or near-crash events recorded in the NDS data at any of the study intersections used in the analysis. VTTI returned a list of six events—three crashes and three near crashes—that took place within 1,000 ft of one of the study intersections. None of the events were related to a left-turn maneuver at the intersection, and none of the events took place during one of the video segments reviewed for this research.

During video data reduction, reviewers recorded any observed avoidance maneuver made by either the left-turning vehicle or the opposing vehicle during a left-turn maneuver. Of the 3,350 observed gaps, avoidance maneuvers were observed during only six of them—all at signalized intersections. One event was related to the presence of a crossing pedestrian. Of the remaining five events, four occurred after the turning driver had been waiting nearly a minute or longer for a suitable gap. Table 4.15 provides a description of each of the recorded avoidance maneuvers. Because the sample of avoidance maneuvers is so small, a formal analysis of their characteristics could not be conducted.

Summary of Results

The analysis found that drivers accept longer gaps at intersections with negative offset than with positive offset. This makes intuitive sense, given that the distance drivers must travel to complete the left-turn maneuver is longer at intersections with wider medians and negative-offset left-turn lanes. In addition, drivers' view of opposing through traffic is much more likely to be blocked at left-turn lanes with negative offset. When a left-turning driver's view of oncoming through vehicles is blocked by an opposing left-turn vehicle, drivers find it more difficult to judge gaps in opposing traffic and, therefore, take more time to do so, resulting in longer accepted gaps. Specifically, when the sight distance for a left-turning driver was restricted by an opposing left-turning vehicle, the critical gap time for drivers was 1.1 s longer at signalized intersections and 1.3 s longer at stop-controlled intersections than when sight distance was not restricted. An analysis conducted to examine this difference by offset category did not produce significant results, mainly because of the limited sample size. However, the results do indicate that opposing left-turning drivers cause sight obstructions for each other much more frequently at negative-offset left-turn lanes than at left-turn lanes with zero or positive offsets. In addition, the likelihood of sight distance being blocked by an opposing left-turn driver was slightly higher at zero offsets than at positive offsets. Thus, intersections with positive offset are likely to provide the most operational and safety benefit.

The effects of gender and age on gap-acceptance behavior were considered. The data showed no patterns when evaluated

Table 4.15. Summary of Avoidance Maneuvers Recorded During Video Data Reduction

Intersection ID	Offset (ft)	Driver Age	Driver Gender	Opposing Left-Turning Vehicle Present?	Sight Distance Obstructed?	Time Spent Waiting for Gap (s)	Event Description
uid_4	–13	84	M	Yes	No	53.5	Just after light turns green, the NDS driver hesitates at beginning of gap and then proceeds to cut off opposing traffic by turning in front of them (failure to yield).
uid_48	–3	27	F	No	No	68.3	Opposing driver slowed slightly as left-turning NDS driver turned in front.
uid_50	–8	65	M	Yes	Yes	94.2	Opposing driver slowed slightly as left-turning NDS driver turned in front.
uid_51	0	19	M	No	No	81.5	Opposing driver is a right turner who stops to wait for the NDS driver to complete the turn before completing the right turn.
uid_53	0	39	F	No	No	10.7	NDS driver begins to turn, then corrects back rightward to avoid oncoming car, then completes turn.
uid_76	–11	23	M	No	No	5.3	NDS driver slows during left turn to avoid a pedestrian who is crossing in the crosswalk.

separately for each offset category; for example, older drivers did not tend to accept longer gaps than younger drivers, and men did not accept shorter gaps than women. However, the number of events recorded for specific combinations of driver age and offset condition was small. When age and gender were considered across all offsets combined, older drivers had significantly longer postencroachment times than younger drivers at signalized intersections. The distribution of all available gaps (both rejected and accepted) for each offset category by driver age, and then by gender, indicated that these factors were not confounded, and that drivers in most categories experienced a similar distribution of available gaps to choose from.

No obvious relationship between time spent waiting for a gap and length of accepted gap or postencroachment time was found in this study. The evaluation of the effect of opposing driver speed (approximated by posted speed limit on the opposing approach) on postencroachment time of left-turning drivers was inconclusive as to whether drivers leave less time between the execution of their turning maneuver and the arrival of the next opposing vehicle as opposing speed increases. No effect of left-turn signal phasing (permissive/protected versus permissive only) on postencroachment time was found. For most of the offset categories, the presence of a following driver resulted in a lower average accepted gap length and a lower median accepted gap length; however, sample sizes were small.

Lighting and weather condition were not evaluated due to small sample sizes in one or more of the categories. Most trips considered in the research were completed during daylight (84%) and in dry conditions (93%). Similarly, the effect of vehicle type on turning behavior was not evaluated due to small sample sizes for many categories of vehicle type.

An examination of crashes and near crashes recorded in the NDS data set at the study intersections found no safety concerns related to left-turning maneuvers. Avoidance maneuvers by left-turning or opposing through drivers observed in the video data reduction process were rare (only six of 3,350 events) and showed no pattern. However, an evaluation of the shortest postencroachment times showed that drivers were more likely to leave a shorter time between their turn and the arrival of the next opposing through vehicle at intersections with negative left-turn lane offset. This may indicate a greater potential for left-turn right-angle crashes at negative-offset left-turn lanes.

CHAPTER 5

Applications and Recommendations

Applications

The results of this research are applicable to highway designers and traffic engineers who are designing new intersections with uncontrolled approaches or permissive left-turn signal phasing, or who are considering safety countermeasures for demonstrated or anticipated crashes at intersections.

The critical gap times found in this research ranged from 4.7 s at intersections with the most positive offset to 7.5 s at intersections with the most negative offset. Sight-distance restrictions due to the presence of opposing left-turn vehicles, which were much more common at left-turn lanes with negative offsets, also led to longer critical gap lengths. The critical gaps observed in the research are closely aligned with the critical gap lengths reported in other studies. The AASHTO Green Book recommends a critical gap of 5.5 s for passenger cars on an undivided two-lane highway, with an additional half second added for each additional lane crossed by the turning driver (AASHTO 2011). The HCM has used a critical gap length of 4.5 s for signalized intersections with a permissive left-turn phase (Transportation Research Board 2000). The results of this study suggest that the critical gap length used for design guidance and operational analysis might be less than observed critical gaps, especially at intersections with negative-offset left-turn lanes.

While differences in critical gap were not significant between each offset category, the data clearly showed that negative-offset left-turn lanes have longer critical gaps than positive-offset left-turn lanes, and that opposing left-turning vehicles are much more likely to cause a sight restriction at negative-offset left-turn lanes than at positive-offset left-turn lanes. Therefore, even opposing left-turn lanes with a minimally negative offset (–1 ft to –5 ft) have the potential to benefit from relocating the left-turn lanes to a positive offset. In addition, the data did not show that offsetting the left-turn lanes to make them less negative (e.g., changing an offset from –16 ft to –6 ft) would have a substantial effect on safety or operational concerns. In other words, offsetting left-turn lanes will provide operational and safety benefits only if the left-turn lanes are relocated sufficiently to provide at least a zero offset, but preferably a positive offset.

The degree to which a left-turning driver's view of oncoming traffic is restricted by the presence of an opposing left-turn vehicle depends on several factors, including, but not limited to, the offset of the left-turn lanes. The geometry of the intersection, especially the width of the roadway being crossed, determines how close the opposing left-turn vehicles are to each other and to what extent they block each other's driver's view of oncoming traffic. In addition, the geometry and striping of the intersection likely play an important role in allowing or encouraging turning drivers to best position themselves for optimal viewing of oncoming traffic without encroaching into the opposing lanes. Therefore, engineers must look at the complete design of the intersection, considering the positioning of left-turning vehicles waiting for a gap, to assess the degree to which sight limitations caused by opposing left-turn vehicles might be an issue.

The analysis conducted as part of this research indicated that even at intersections with left-turn lanes that have only a small negative offset (–1 to –5 ft), the presence of opposing left-turn vehicles can restrict sight distance for their respective drivers. In addition, at negative-offset left-turn lanes, drivers are more likely to leave a shorter amount of time between their left-turn maneuver and the arrival of the next opposing through vehicle. This indicates that any degree of negative offset might create a safety concern for left-turning drivers. The Green Book suggests that offsetting the left-turn lanes should be considered at intersections with medians wider than 18 ft (which most likely corresponds to an offset of approximately –6 ft). That may be somewhat arbitrary and not conservative enough. This research indicates that eliminating negative offset to provide positive-offset (or, at minimum, zero-offset) left-turn lanes should be considered to substantially reduce instances of sight-distance restriction for left-turning drivers where feasible and practical. When potential sight-distance issues cannot be avoided, designers should consider protected-only left-turn signal phasing to eliminate the need for drivers to judge gaps in opposing traffic.

In general, the secondary analyses discussed in Chapter 4 did not show meaningful relationships or conclusive results because of limited sample size. The NDS data and the study design used have potential to show a wide range of relationships and results considering a number of possible influences on left-turn behavior; however, the limited data available at the time data requests were made (VTTI estimated that only 20% of the trips that will ultimately be included in the NDS database were available to be queried), in combination with the short schedule of this project, constrained the sample sizes the research team was able to obtain. Obtaining and reviewing another round of videos of left-turning movements made at the study intersections in this report would potentially show more meaningful results. In addition, the NDS data allow researchers to identify specific factors that may influence turning behavior and query for a distribution of those specific characteristics on which to conduct an analysis.

Recommendations for Future Research

While this research presents a range of analyses related to left-turning behavior at intersections with varying offsets, turning behavior can be evaluated in a number of ways. The NDS data could be used in future research to consider the following:

1. Additional measures of interest could be collected, such as the duration of the turning maneuver, the distance traveled to complete the turning maneuver, and the distance of stop bars from the conflict area. When sample sizes are large enough, the effect of these measures on where drivers position themselves before turns and how their positioning affects their sight distance and time required to turn could provide valuable information to intersection designers and traffic engineers.
2. The NDS data provide an opportunity to follow a single driver through many left-turn maneuvers. The factors that influence a single driver's differences in behavior from one intersection or circumstance to the next can be identified.
3. The NDS data include information about vehicle dynamics. The influence on turning behavior of a vehicle's physical turning capabilities, as well as the speed and acceleration used when approaching and during the turning maneuver, could be evaluated to provide guidance to vehicle manufacturers on designing vehicles for safe left turns.
4. Crash history could be used in the study site selection process to specifically identify intersections with similar geometric characteristics but different crash rates to explore how drivers' behaviors differ between intersections and what features or conditions might be influencing those behaviors.
5. Left-turning behavior could be evaluated in specific conditions, such as hours of darkness or during rain events. The NDS data allow for such queries so researchers can ensure desired sample sizes of more rare events.
6. The effect of left-turn lane offset on intersection operational performance (in terms of delay or level of service measures) could be evaluated. Such an analysis could identify an operational benefit–cost ratio for implementing a left-turn lane offset countermeasure.

References

Adebisi, O., and G.N. Sama. 1989. Influence of Stopped Delay on Driver Gap Acceptance Behaviour. *Journal of Transportation Engineering,* Vol. 115, No. 3, pp. 305–315.

American Association of State Highway and Transportation Officials (AASHTO). 2010. *Highway Safety Manual.* Washington, D.C.

American Association of State Highway and Transportation Officials (AASHTO). 2004. *A Policy on Geometric Design of Highways and Streets,* 5th ed. Washington, D.C.

American Association of State Highway and Transportation Officials (AASHTO). 2011. *A Policy on Geometric Design of Highways and Streets,* 6th ed. Washington, D.C.

Antonucci, N.D., K.K. Hardy, K.L. Slack, R. Pfefer, and T.R. Neuman. 2004. *NCHRP Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan, Volume 12: A Guide for Reducing Collisions at Signalized Intersections.* Transportation Research Board of the National Academies, Washington, D.C.

Blincoe, L.J., T.R. Miller, E. Zaloshnja, and B.A. Lawrence. 2014. *The Economic and Societal Impact of Motor Vehicle Crashes, 2010.* Report DOT HS 812 013. National Highway Traffic Safety Administration, Washington, D.C. http://www.nrd.nhtsa.dot.gov/Pubs/812013.pdf. Accessed June 30, 2014.

Campbell, K.L. 2012. The SHRP 2 Naturalistic Driving Study: Addressing Driver Performance and Behavior in Traffic Safety. *TR News,* No. 282, pp. 30–35.

Chan, C. 2006. Observation of Left-Turn Conflicts at Signalized Intersections and Design of Gap-Assistance Systems in Urban Environment. In *TRB 85th Annual Meeting Compendium of Papers.* Transportation Research Board of the National Academies, Washington, D.C.

Gattis, J.L., and S.T. Low. 1999. Gap Acceptance at Atypical Stop-Controlled Intersections. *Journal of Transportation Engineering,* Vol. 125, No. 3, pp. 201–207.

Gettman, D., and L. Head. 2003. Surrogate Safety Measures from Traffic Simulation Models. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1840,* Transportation Research Board of the National Academies, Washington, D.C., pp. 104–115.

Hamdar, S.H., H.S. Mahmassani, and R.B. Chen. 2008. Aggressiveness Propensity Index for Driving Behavior at Signalized Intersections. *Accident Analysis & Prevention,* Vol. 40, No. 1, pp. 315–326.

Harwood, D.W., K.M. Bauer, I.B. Potts, D.J. Torbic, K.R. Richard, E.R. Kohlman Rabbani, E. Hauer, and L. Elefteriadou. 2002. *Safety Effectiveness of Intersection Left- and Right-Turn Lanes.* Publication FHWA-RD-02-089. FHWA, U.S. Department of Transportation.

Harwood, D.W., M.T. Pietrucha, M.D. Wooldridge, R.E. Brydia, and K. Fitzpatrick. 1995. *NCHRP Report 375: Median Intersection Design.* TRB, National Research Council, Washington, D.C.

Joshua, S.C., and A.A. Saka. 1992. Mitigation of Sight-Distance Problem for Unprotected Left-Turning Traffic at Intersections. In *Transportation Research Record 1356,* TRB, National Research Council, Washington, D.C., pp. 73–79.

Madanat, S.M., M.J. Cassidy, and M.H. Wang. 1994. Probabilistic Delay Model at Stop-Controlled Intersection. *Journal of Transportation Engineering,* Vol. 120, No. 1, pp. 21–36.

McCoy, P., P.S. Byrd, G. Pesti, and V.A. Singh. 1999. Improving Sight Distance from Opposing Left-Turn Lanes. In *Transportation Frontiers for the Next Millennium: 69th Annual Meeting of the Institute of Transportation Engineers.* Washington, D.C.

McCoy, P.T., U.R. Navarro, and W.E. Witt. 1992. Guidelines for Offsetting Opposing Left-Turn Lanes on Four-Lane Divided Roadways. In *Transportation Research Record 1356,* TRB, National Research Council, Washington, D.C., pp. 28–36.

McGehee, D.V., L. Boyle, J.D. Lee, D.M. Neyens, S. Hallmark, and N.J. Ward. 2009. *SHRP 2 S02 Phase 1 Report: Integration of Analysis Methods and Development of Analysis Plan.* Unpublished report. Transportation Research Board of the National Academies, Washington, D.C.

National Highway Traffic Safety Administration. *Fatality Analysis Reporting System (FARS).* http://www.nhtsa.gov/FARS. Accessed Jan. 10, 2011.

Neuman, T.R., R. Pfefer, K.L. Slack, K.K. Hardy, D.W. Harwood, I.B. Potts, D.J. Torbic, and E.R. Rabbani. 2003. *NCHRP Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan, Volume 5: A Guide for Addressing Unsignalized Intersection Collisions.* Transportation Research Board of the National Academies, Washington, D.C.

Parsonson, B.S., R.B. Isler, and G.J. Hansson. 1999. Ageing and Driver Behaviour at Rural T-Intersections. *New Zealand Journal of Psychology,* Vol. 28, No. 1, pp. 51–54.

Persaud, B., C. Lyon, K.A. Eccles, N.X. Lefler, and F. Gross. 2009. *Safety Evaluation of Offset Improvements for Left-Turn Lanes.* Publication FHWA-HRT-09-035. FHWA, U.S. Department of Transportation.

SAS Institute Inc. 2013. *SAS/STAT 13.1 User's Guide.* SAS Institute Inc., Cary, N.C.

Shladover, S.E., D.R. Ragland, J.A. Misener, C. Chan, and S. Arroyo. 2006. Gap Acceptance for Vehicles Turning Left Across Oncoming Traffic: Implications for Intersection Decision Support Design. In *TRB 85th Annual Meeting Compendium of Papers.* Transportation Research Board of the National Academies, Washington, D.C.

Smith, R.W. 1997. Visual Hypothesis Testing with Confidence Intervals. SUGI 22 Paper No. 270. *Proc., 22nd Annual SAS Users Group International Conference,* San Diego, Calif.

Staplin, L., D.L. Harkey, K.H. Lococo, and M.S. Tarawneh. 1997. *Intersection Geometric Design and Operational Guidelines for Older Drivers and Pedestrians, Volume I: Final Report.* Publication FHWA–RD–96–132. FHWA, U.S. Department of Transportation.

Tarawneh, M.S., and P.T. McCoy. 1996. Effect of Offset Between Opposing Left-Turn Lanes on Driver Performance. In *Transportation Research Record 1523,* TRB, National Research Council, Washington, D.C., pp. 61–72.

Transportation Research Board. 2000. *Highway Capacity Manual.* TRB, National Research Council, Washington, D.C.

Transportation Research Board. 2010. *Highway Capacity Manual 2010.* Transportation Research Board of the National Academies, Washington, D.C.

Yan, X., and E. Radwan. 2007. Effect of Restricted Sight Distances on Driver Behaviors During Unprotected Left-Turn Phase at Signalized Intersections. *Transportation Research Part F: Traffic Psychology and Behaviour,* Vol. 10, No. 4, pp. 330–344.

Yan, X., and E. Radwan. 2008. Influence of Restricted Sight Distances on Permitted Left-Turn Operation at Signalized Intersections. *Journal of Transportation Engineering,* Vol. 134, No. 2, pp. 68–76.

Zohdy, I., H.A. Rakha, R. Alfelor, C.Y.D. Yang, and D. Krechmer. 2011. Impact of Inclement Weather on Left-Turn Gap Acceptance Behavior of Drivers. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2257,* Transportation Research Board of the National Academies, Washington, D.C., pp. 51–61.

Zohdy, I., S. Sadek, and H.A. Rakha. 2010. Empirical Analysis of Effects of Wait Time and Rain Intensity on Driver Left U-Turn Gap Acceptance Behavior. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2173,* Transportation Research Board of the National Academies, Washington, D.C., pp. 1–10.

APPENDIX A

Descriptive Statistics

This appendix presents tables and figures that were referenced in Chapter 4 of this report but were not shown there. They primarily show detailed descriptive statistics for many of the variables included in or considered for analysis. The significance of these tables and figures was discussed in Chapter 4 and is not repeated here.

Table A.1. Signalized Intersection Characteristics and Number of Trips in Study

Route 1 Name	Route 2 Name	Direction	Measured Offset (ft)	Intersection Skew (deg)	Number of Opposing Through Lanes	Posted Speed Limit on Turning Driver's Approach (mph)	Posted Speed Limit on Opposing Approach (mph)	Left-Turn Signal Phasing	Number of NDS Drivers	Number of NDS Driver Trips	Number of Non-NDS Driver Trips
Florida											
DEAN DAIRY RD	SR-54	N-S	–3	90	1	40	40	Permissive	4	7	5
COUNTY LINE RD	BAKER ST	N-S	–15	85	2	45	45	Permissive/ protected	2	10	2
FLORIDA AVE	WATERS AVE	N-S	–2	90	2	40	40	Split[a]	10	11	9
LAKE MAGDALENE BLVD	FLETCHER AVE	E-W	–4	90	2	40	40	Permissive/ protected	2	20	6
US-92	AZEELE ST	E-W	–4	90	1	40	40	Permissive	4	7	2
BOULEVARD N	BEARSS AVE	E-W	–4	90	2	45	45	Permissive/ protected	6	10	1
KINGSWAY RD	WHEELER AVE	E-W	–6	90	1	35	35	Permissive	3	14	2
HIMES AVE	JOHN F KENNEDY BLVD	N-S	6	90	1	40	40	Permissive/ protected	2	4	3
ANDERSON RD	SLIGH AVE	N-S	–16	75	2	45	45	Permissive/ protected	3	3	2
N BOULEVARD	W COLUMBUS DR	E-W	2	90	1	40	40	Permissive	4	10	5
N MILLER RD	SR-60	N-S	4	90	1	35	35	Permissive/ protected	3	7	7
S PARSONS AVE	SR-574	N-S	4	90	1	45	45	Permissive/ protected	2	2	1
ARMENIA AVE	WATERS AVE	E-W	–6	90	2	45	45	Permissive/ protected	8	10	4
ARMENIA AVE	WATERS AVE	N-S	4	90	1	35	35	Permissive/ protected	6	7	3
WEST SHORE BLVD	US-92	E-W	–9	90	2	45	45	Permissive/ protected	1	1	3
HANLEY RD	WATERS AVE	N-S	4	90	2	35	35	Permissive/ protected	3	4	3

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Table A.1. Signalized Intersection Characteristics and Number of Trips in Study (continued)

Route 1 Name	Route 2 Name	Direction	Measured Offset (ft)	Intersection Skew (deg)	Number of Opposing Through Lanes	Posted Speed Limit on Turning Driver's Approach (mph)	Posted Speed Limit on Opposing Approach (mph)	Left-Turn Signal Phasing	Number of NDS Drivers	Number of NDS Driver Trips	Number of Non-NDS Driver Trips
Florida											
HABANA AVE	COLUMBUS DR	E-W	0	90	2	40	40	Permissive	4	12	11
HABANA AVE	COLUMBUS DR	N-S	0	90	1	30	30	Permissive	1	1	1
ROME AVE	SLIGH AVE	N-S	0	90	1	35	35	Permissive	6	7	1
ROME AVE	SLIGH AVE	E-W	0	90	2	30	30	Permissive	5	36	10
NEBRASKA AVE	COLUMBUS DR	E-W	3	90	1	30	30	Permissive	4	8	4
NEBRASKA AVE	COLUMBUS DR	N-S	–3	90	1	35	35	Permissive	8	11	1
MACDILL AVE	CYPRESS ST	E-W	–2	90	1	30	30	Permissive	3	6	2
MACDILL AVE	CYPRESS ST	N-S	–8	90	2	40	40	Permissive	7	10	4
MCINLEY DR	BOUGAINVILEA AVE	E-W	0	90	1	40	40	Permissive	6	6	1
HIMES AVE	EUCLID AVE	E-W	0	90	1	30	30	Permissive	2	34	24
HIMES AVE	EUCLID AVE	N-S	0	90	1	35	35	Permissive	5	8	5
HIMES AVE	EL PRADO BLVD	E-W	0	90	1	30	30	Permissive	3	3	1
HIMES AVE	EL PRADO BLVD	N-S	0	90	1	35	35	Permissive	2	2	
HIMES AVE	CYPRESS ST	E-W	3	90	1	30	30	Permissive	6	35	17
HIMES AVE	CYPRESS ST	N-S	0	90	2	40	40	Permissive	6	6	4
N 15TH ST	HILLSBOROUGH	N-S	2	90	1	30	30	Permissive	7	18	24
N NEBRASKA AVE	E SLIGH AVE	E-W	6	90	1	35	35	Permissive	5	5	3
N NEBRASKA AVE	E SLIGH AVE	N-S	–2	90	2	40	40	Permissive	4	5	1
US-92	W EL PRADO BLVD	N-S	2	90	2	40	40	Permissive	4	5	
US-92	W EL PRADO BLVD	E-W	–6	90	2	30	30	Permissive	5	9	5
N MILLER RD	SR-60	E-W	–29	90	2	55	55	Permissive/ protected	1	1	
S ST CLOUD AVE	SR-60	E-W	–26	90	2	55	55	Permissive/ protected	1	15	6

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Table A.1. Signalized Intersection Characteristics and Number of Trips in Study (continued)

Route 1 Name	Route 2 Name	Direction	Measured Offset (ft)	Intersection Skew (deg)	Number of Opposing Through Lanes	Posted Speed Limit on Turning Driver's Approach (mph)	Posted Speed Limit on Opposing Approach (mph)	Left-Turn Signal Phasing	Number of NDS Drivers	Number of NDS Driver Trips	Number of Non-NDS Driver Trips
Indiana											
N DUNN ST[b]	E MATLOCK RD[b]	N-S	–13	90	1	30	35	Permissive	4	17	14
S WALNUT ST	W GRIMES LN	E-W	–11	90	1	30	30	Permissive/ protected	9	27	4
North Carolina											
CREEDMOOR RD	STONEHENGE DR	N-S	–8	90	2	45	45	Permissive/ protected	1	2	
FRANKLIN ST[b]	HILLSBORO ST[b]	NE-SW	0	90	2	20	30	Permissive	9	24	4
EBENEZER CHURCH RD	MARVINO LN	N-S	0	90	2	35	35	Permissive	2	10	
EBENEZER CHURCH RD	MARVINO LN	E-W	–2	90	1	35	35	Permissive	2	2	2
									185	452	207

[a] At this left-turn offset pair of approaches, one had permissive left-turn phasing while the other had permissive/protected phasing. In the analysis, the appropriate left-turn signal phasing was assigned to each event at that intersection.
[b] At these intersections, the posted speed limit differed between one approach and its opposing approach. Therefore, for some observations, the two speed limit values are flipped. In the analysis, the speed limits for turning and opposing drivers were appropriately assigned to individual turning maneuvers.

Table A.2. Two-Way Stop-Controlled Intersection Characteristics and Number of Trips in Study

Route 1 Name	Route 2 Name	Direction	Measured Offset (ft)	Intersection Skew (deg)	Number of Opposing Through Lanes	Posted Speed Limit on Turning Driver's Approach (mph)	Posted Speed Limit on Opposing Approach (mph)	Number of NDS Drivers	Number of NDS Driver Trips	Number of Non-NDS Driver Trips
Florida										
N NEBRASKA AVE	SINCLAIR HILLS RD	N-S	–13	90	2	45	45	7	32	2
N NEBRASKA AVE	E 124TH AVE	N-S	–9	90	2	45	45	2	2	
56TH ST N	E 127TH AVE	N-S	–28	90	2	50	50	4	19	2
E BULLARD PKWY	SUNNYSIDE RD	E-W	–11	90	2	30	30	6	74	12
E FLETCHER AVE	N 19TH ST	N-S	0	90	2	45	45	2	5	
56TH ST N	E SERENA DR	N-S	–8	90	2	35	35	6	27	
North Carolina										
HIGH HOUSE RD	CRANBORNE LN	E-W	–6	90	2	45	45	1	31	6
E MILLBROOK RD	SWEETBRIAR ST	E-W	0	90	2	35	35	2	6	
CREEDMOOR RD	MORGAN'S WAY	N-S	–7	90	2	45	45	1	6	1
FORDHAM BLVD	BRANDON	N-S	–14	90	2	45	45	3	16	5
FORDHAM BLVD	CLELAND RD	N-S	–12	90	2	45	45	3	60	26
Washington										
SR-9	108TH ST NE	N-S	0	90	1	55	55	3	10	1
5TH AVE NE	NE 205TH ST	N-S	0	90	1	40	40	3	6	2
104TH AVE SE	SE 264TH ST	E-W	–13	90	1	35	35	3	12	2
								46	306	59

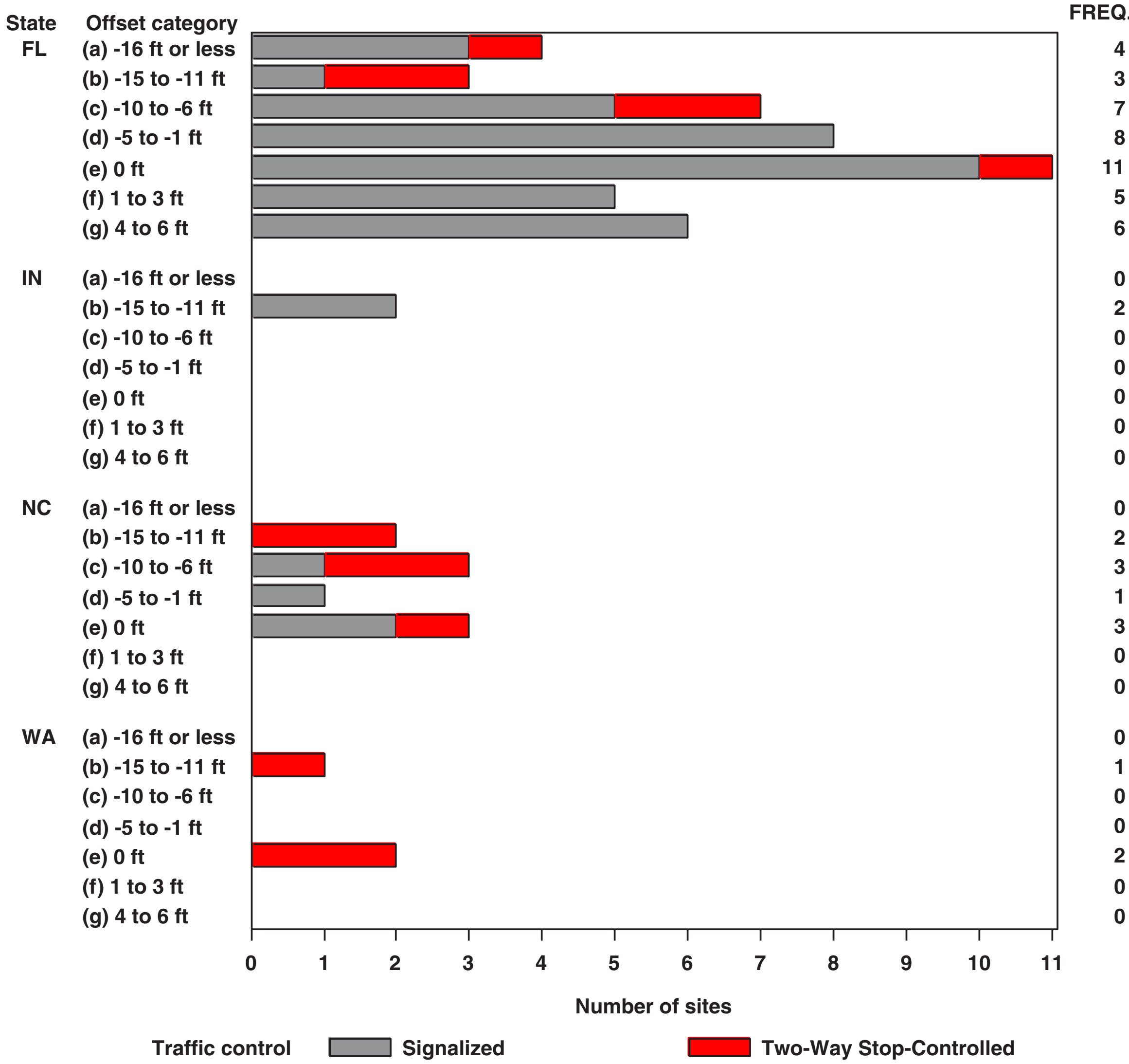


Figure A.1. Distribution of sites by state, offset category, and intersection type.

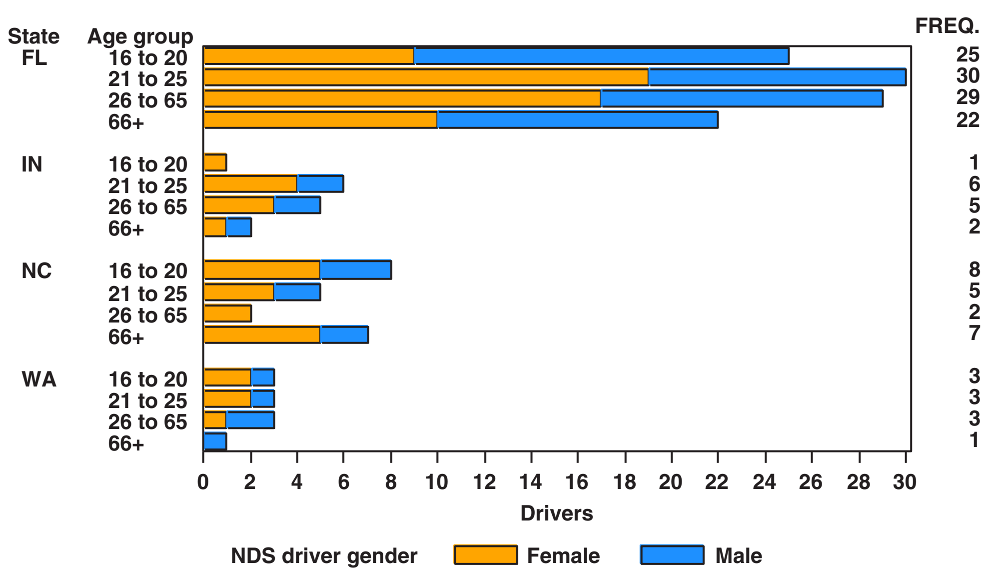


Figure A.2. Distribution of NDS drivers by state, age, and gender.

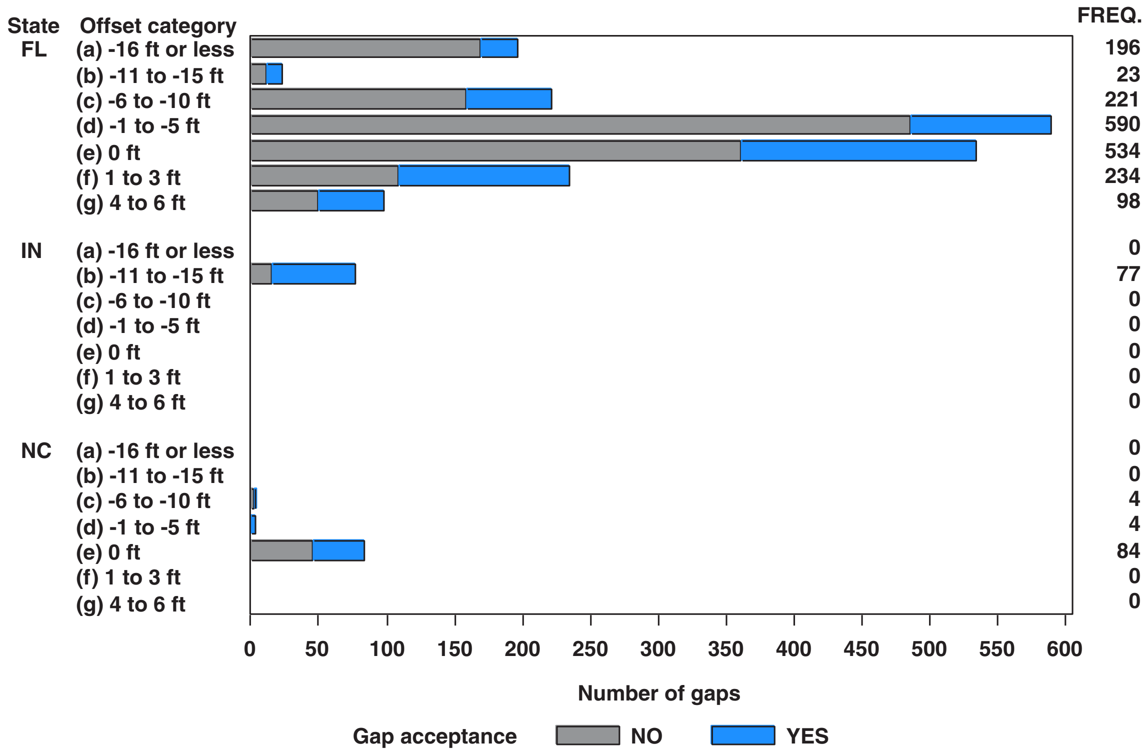


Figure A.3. Distribution of accepted and rejected gaps by state and offset category for signalized intersections.

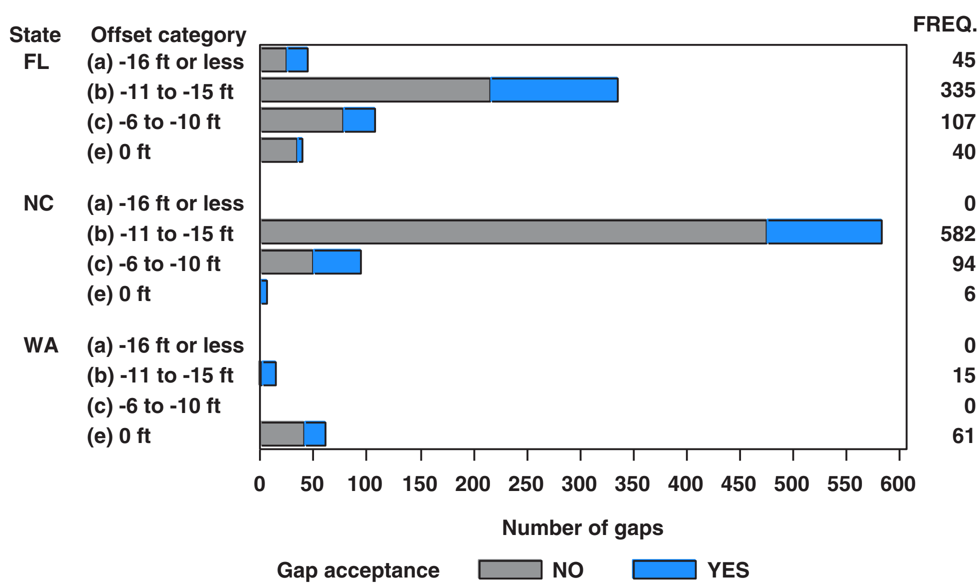
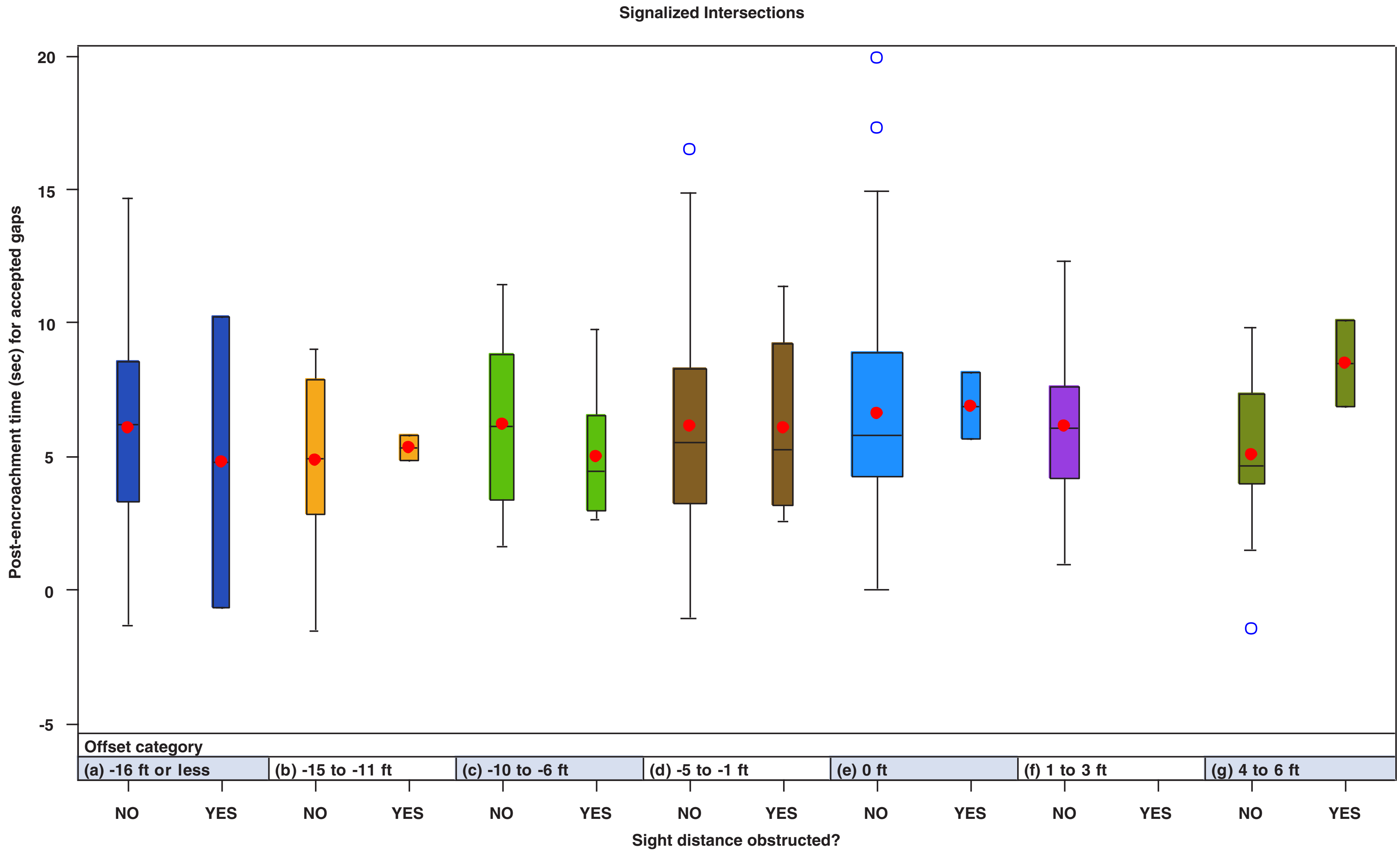


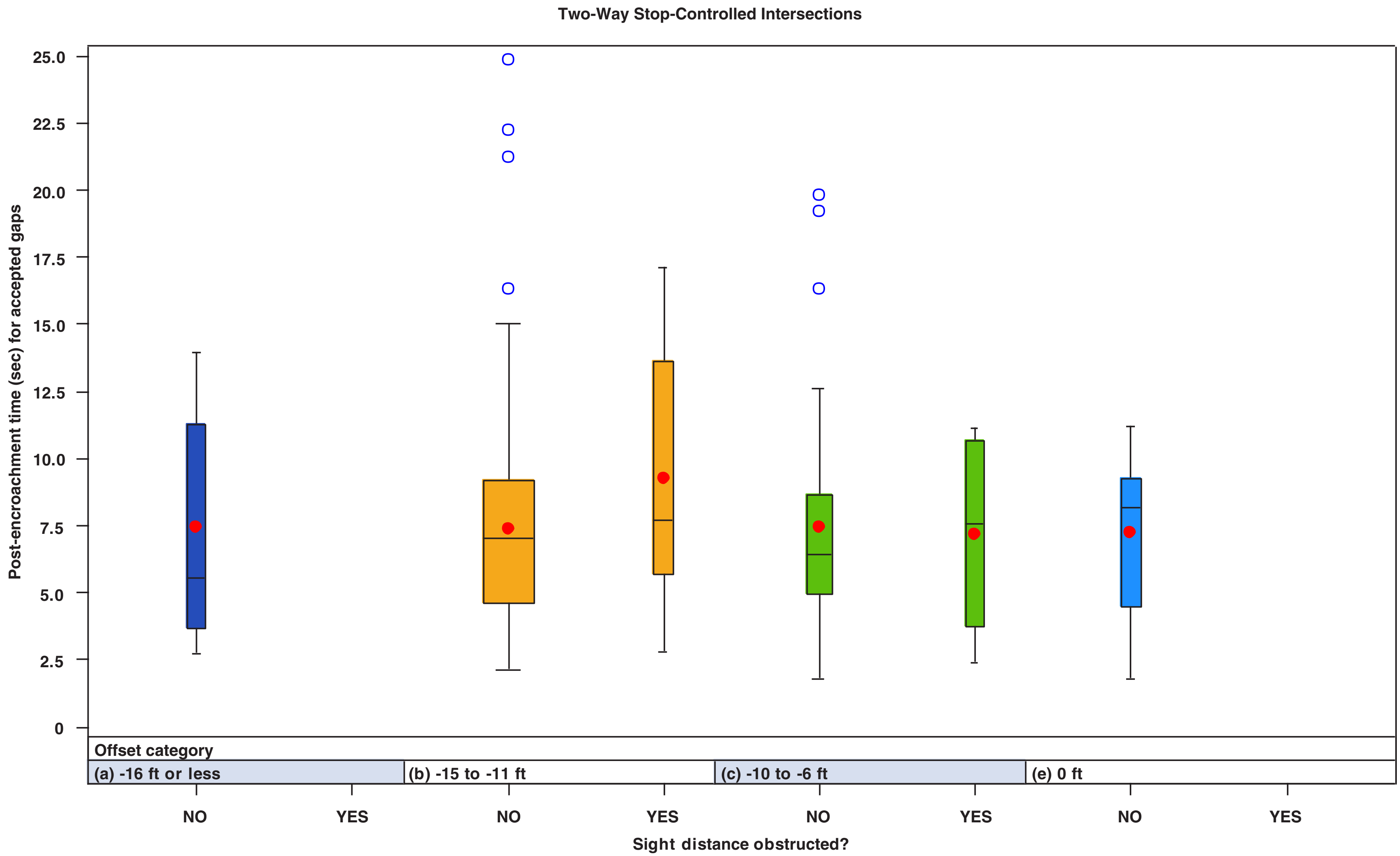
Figure A.4. Distribution of accepted and rejected gaps by state and offset category for two-way stop-controlled intersections.



N	17	2	8	3	21	7	46	10	93	2	35	0	23	2
Min	-1.3	-0.7	-1.6	4.8	1.7	2.6	-1.1	2.6	0.0	5.7	1.0	.	-1.5	6.8
Mean	6.0	4.8	4.8	5.3	6.2	5.0	6.1	6.0	6.6	6.9	6.1	.	5.0	8.5
Median	6.2	4.8	4.9	5.3	6.1	4.4	5.5	5.2	5.8	6.9	6.1	.	4.6	8.5
Max	14.6	10.2	9.0	5.8	11.4	9.7	16.5	11.4	19.9	8.1	12.3	.	9.8	10.1
Std Dev	4.3	7.7	3.6	0.5	3.0	2.5	4.0	3.1	3.6	1.7	2.4	.	2.6	2.3

Red dot = mean; Horizontal line = median; Colored box = mid 50% of data; Blue circle = extreme value

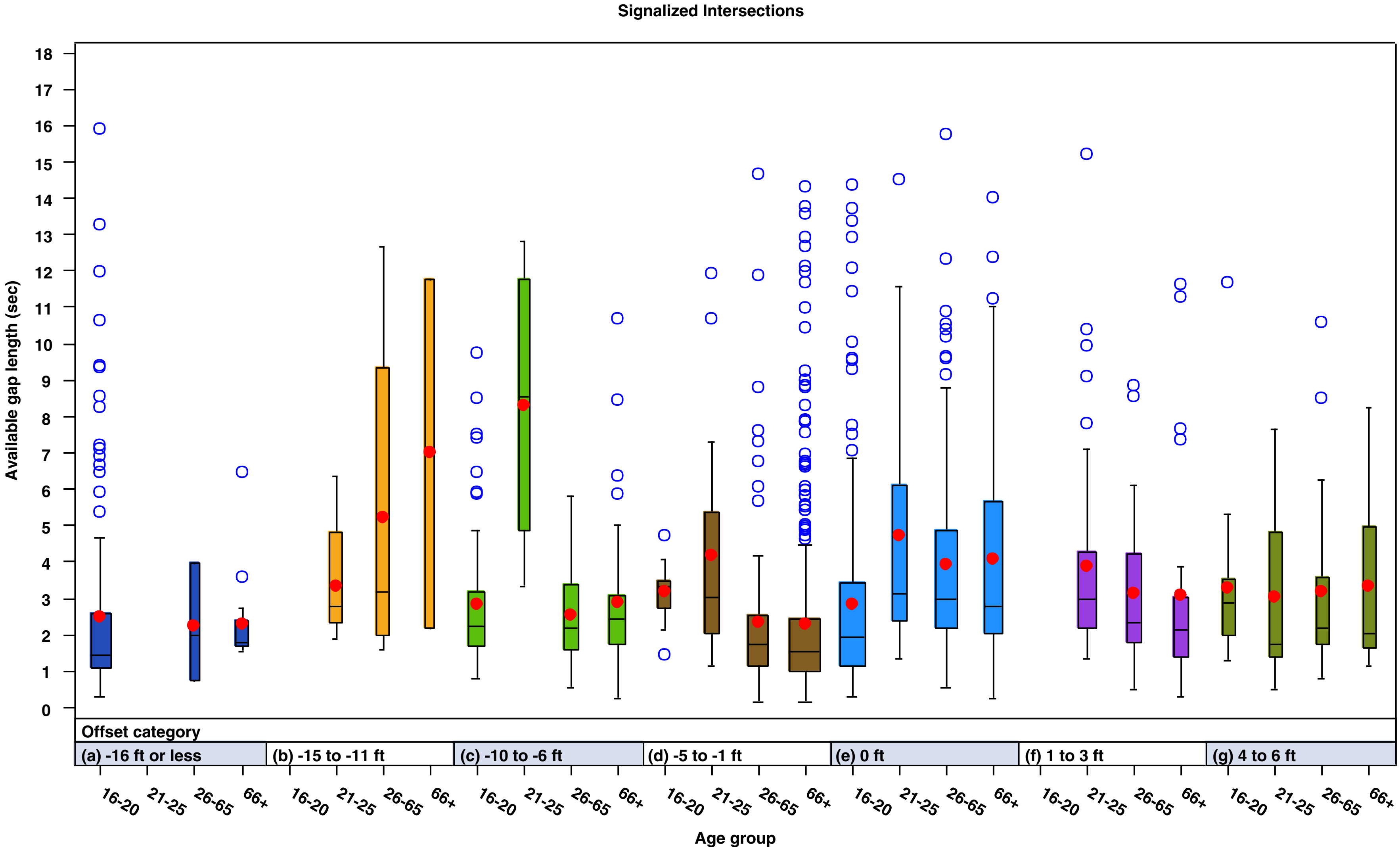
Figure A.5. Distribution of postencroachment time for accepted gaps by offset category and presence of sight obstruction at signalized intersections.



N	5	0	137	13	37	4	13	0
Min	2.7	.	2.1	2.8	1.8	2.4	1.8	.
Mean	7.4	.	7.4	9.2	7.4	7.2	7.2	.
Median	5.5	.	7.0	7.7	6.4	7.6	8.2	.
Max	13.9	.	24.8	17.1	19.8	11.1	11.2	.
Std Dev	4.9	.	3.9	5.1	4.2	4.2	3.0	.

Red dot = mean; Horizontal line = median; Colored box = mid 50% of data; Blue circle = extreme value

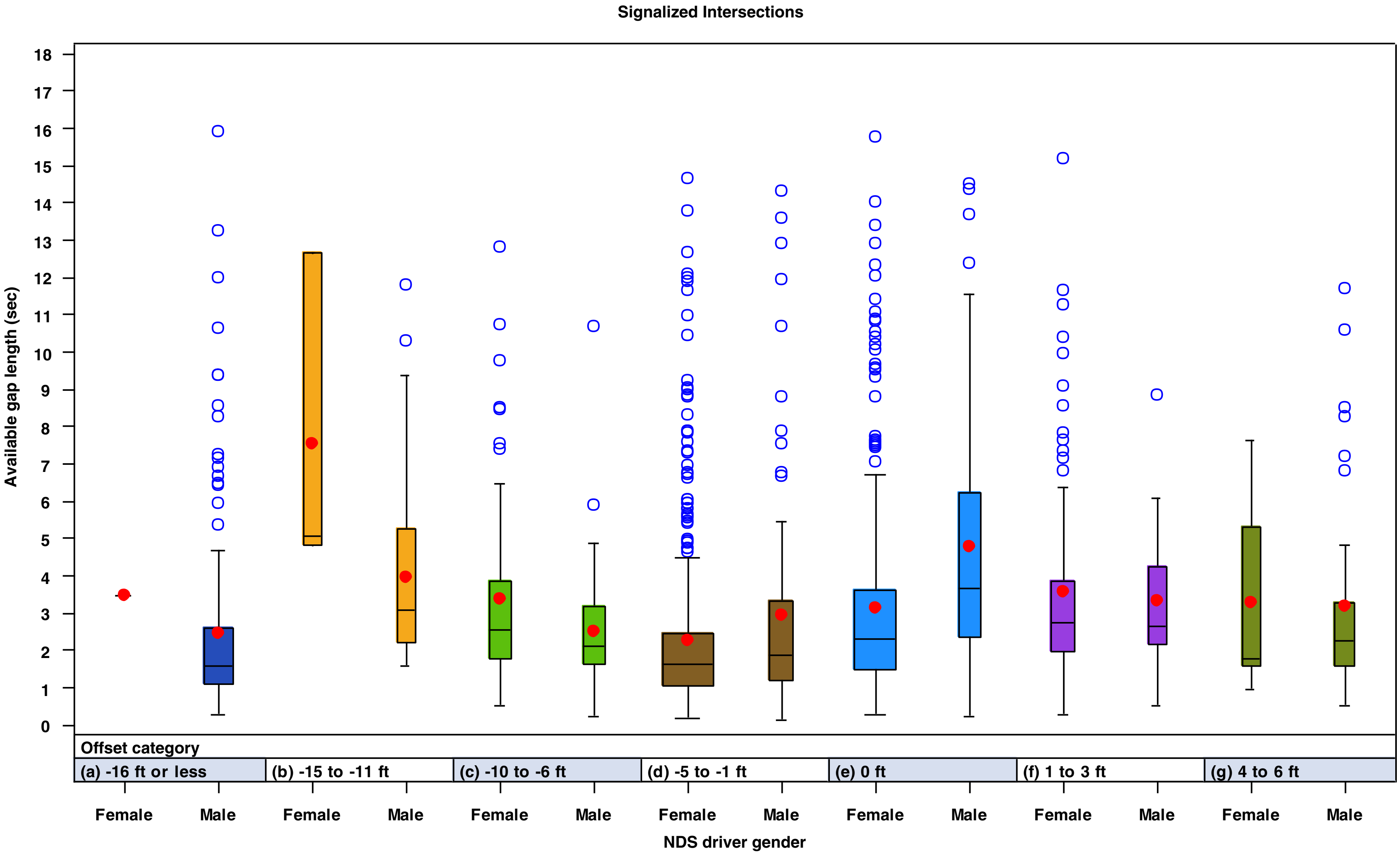
Figure A.6. Distribution of postencroachment time for accepted gaps by offset category and presence of sight obstruction at two-way stop-controlled intersections.



N	121	0	3	16	0	14	10	2	59	4	30	41	9	18	97	376	192	18	106	51	0	55	19	25	16	13	18	8
Min	0.3	.	0.8	1.5	.	1.9	1.6	2.2	0.8	3.3	0.5	0.2	1.5	1.1	0.1	0.2	0.3	1.3	0.5	0.2	.	1.3	0.5	0.3	1.3	0.5	0.8	1.1
Mean	2.5	.	2.2	2.3	.	3.3	5.2	7.0	2.8	8.3	2.5	2.9	3.2	4.2	2.3	2.3	2.8	4.7	3.9	4.1	.	3.9	3.1	3.1	3.3	3.0	3.2	3.3
Median	1.4	.	2.0	1.8	.	2.8	3.2	7.0	2.2	8.6	2.2	2.4	3.3	3.0	1.8	1.6	2.0	3.1	3.0	2.8	.	3.0	2.3	2.1	2.9	1.7	2.2	2.0
Max	15.9	.	4.0	6.4	.	6.4	12.6	11.8	9.7	12.8	5.8	10.7	4.7	11.9	14.7	14.3	14.3	14.5	15.7	14.0	.	15.2	8.8	11.6	11.7	7.6	10.6	8.3
Std Dev	2.7	.	1.6	1.2	.	1.5	4.0	6.8	1.9	4.3	1.3	2.0	1.0	3.1	2.3	2.4	2.6	3.6	2.8	3.2	.	2.6	2.4	3.1	2.5	2.6	2.7	2.7

Red dot = mean; Horizontal line = median; Colored box = mid 50% of data; Blue circle = extreme value

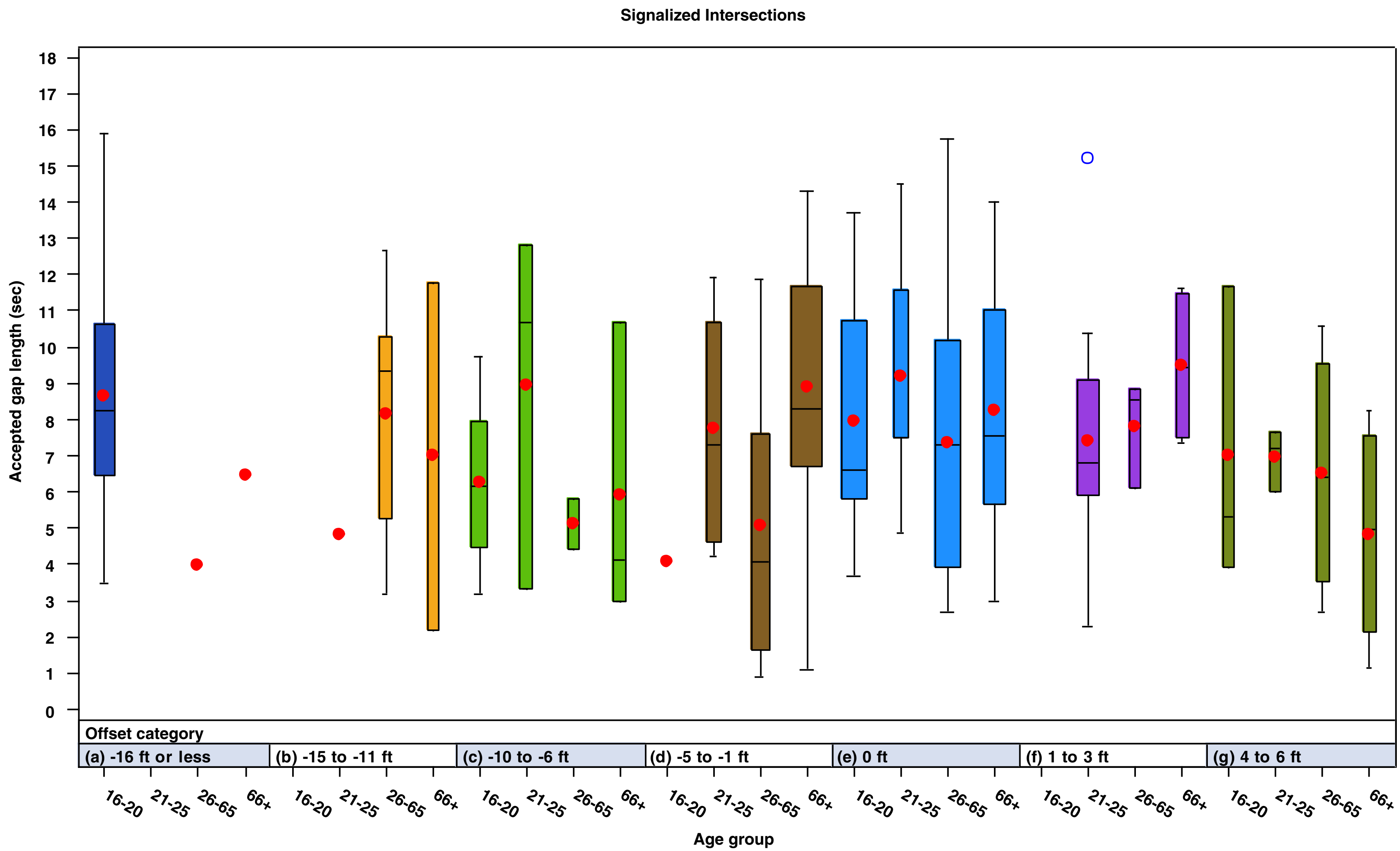
Figure A.7. Distribution of available gap length by offset category and age group at signalized intersections.



N	1	139	3	23	70	64	418	82	306	61	86	13	15	40
Min	3.5	0.3	4.8	1.6	0.5	0.2	0.2	0.1	0.3	0.2	0.3	0.5	1.0	0.5
Mean	3.5	2.5	7.5	3.9	3.3	2.5	2.3	2.9	3.1	4.8	3.6	3.3	3.3	3.2
Median	3.5	1.6	5.1	3.1	2.5	2.1	1.6	1.9	2.3	3.7	2.7	2.6	1.8	2.3
Max	3.5	15.9	12.6	11.8	12.8	10.7	14.7	14.3	15.7	14.5	15.2	8.8	7.6	11.7
Std Dev	.	2.6	4.4	2.9	2.5	1.5	2.2	3.1	2.7	3.5	2.8	2.2	2.2	2.7

Red dot = mean; Horizontal line = median; Colored box = mid 50% of data; Blue circle = extreme value

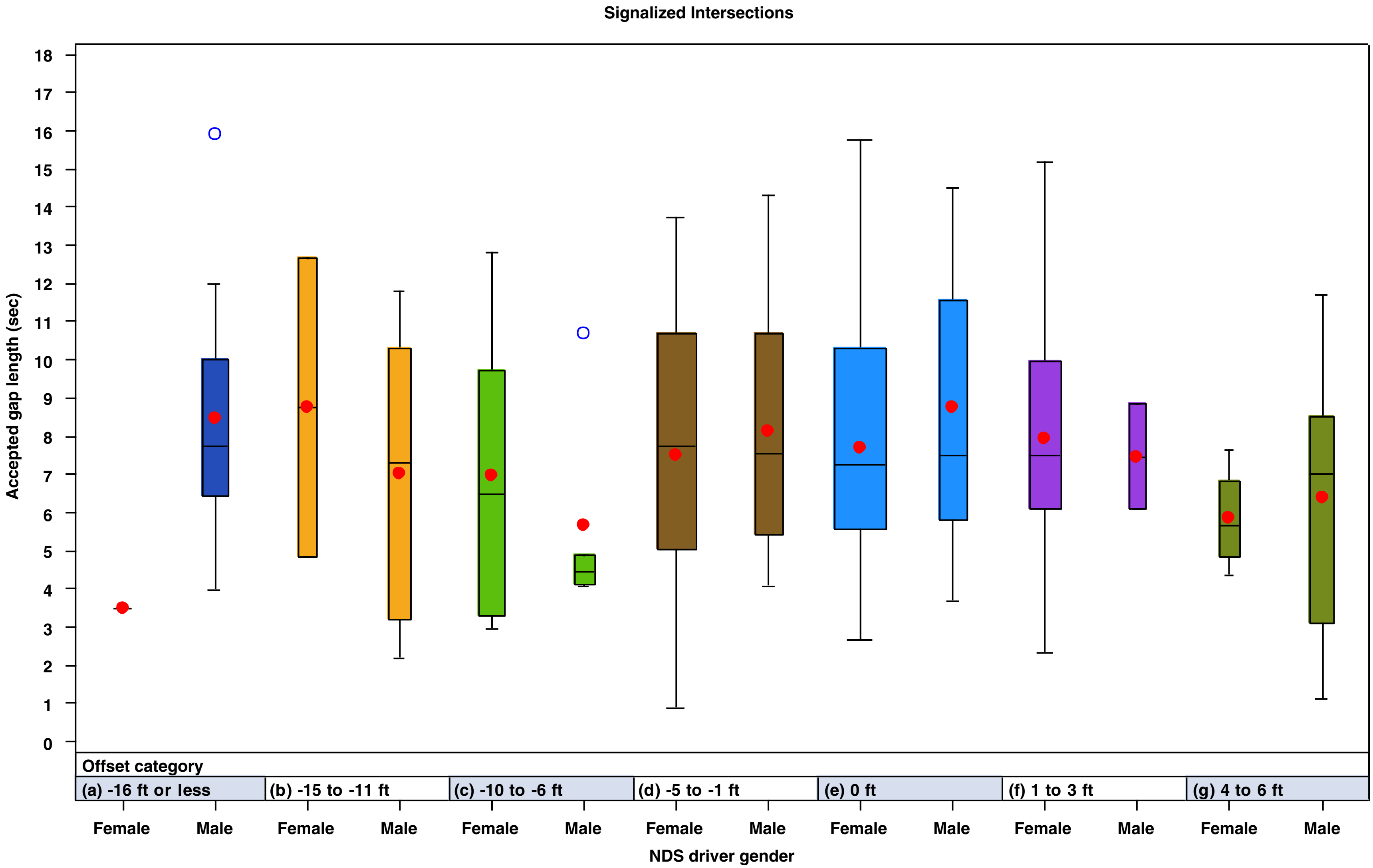
Figure A.8. Distribution of available gap length by offset category and gender at signalized intersections.



N	11	0	1	1	0	1	5	2	8	3	2	3	1	5	10	25	20	5	19	13	0	13	3	4	3	3	4	4
Min	3.5	.	4.0	6.4	.	4.8	3.2	2.2	3.2	3.3	4.4	3.0	4.1	4.2	0.9	1.1	3.7	4.8	2.7	3.0	.	2.3	6.1	7.3	3.9	6.0	2.7	1.1
Mean	8.6	.	4.0	6.4	.	4.8	8.1	7.0	6.3	8.9	5.1	5.9	4.1	7.7	5.0	8.9	7.9	9.2	7.4	8.3	.	7.4	7.8	9.5	7.0	6.9	6.5	4.8
Median	8.3	.	4.0	6.4	.	4.8	9.4	7.0	6.2	10.7	5.1	4.1	4.1	7.3	4.1	8.3	6.6	7.5	7.3	7.6	.	6.8	8.5	9.5	5.3	7.2	6.4	5.0
Max	15.9	.	4.0	6.4	.	4.8	12.6	11.8	9.7	12.8	5.8	10.7	4.1	11.9	11.9	14.3	13.7	14.5	15.7	14.0	.	15.2	8.8	11.6	11.7	7.6	10.6	8.3
Std Dev	3.3	.	.	.	.	.	3.9	6.8	2.2	5.0	1.0	4.2	.	3.5	3.6	3.1	3.2	3.8	3.4	3.3	.	3.3	1.5	2.3	4.1	0.8	3.6	3.3

Red dot = mean; Horizontal line = median; Colored box = mid 50% of data; Blue circle = extreme value

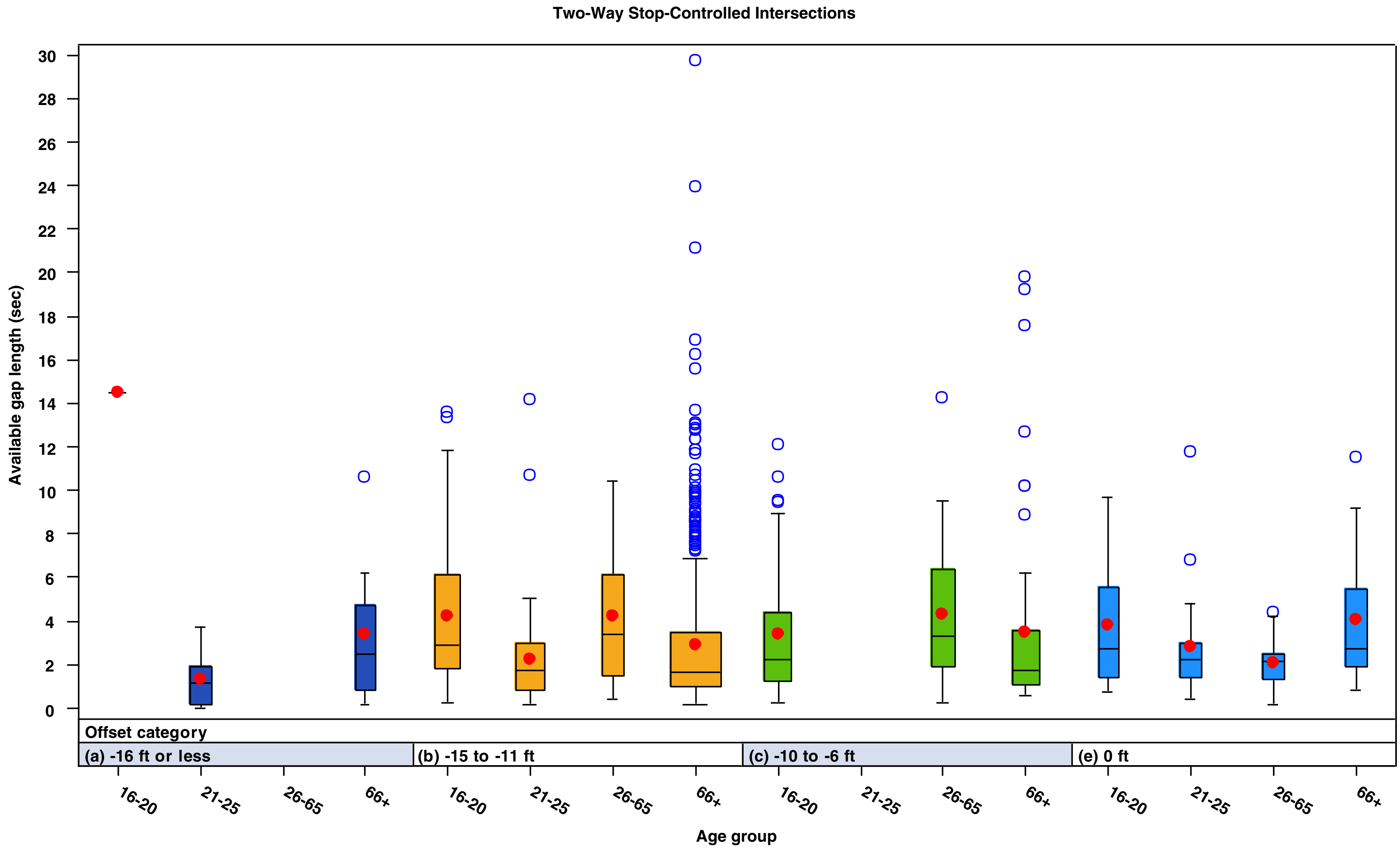
Figure A.9. Distribution of accepted gap length by offset category and age group at signalized intersections.



N	1	12	2	6	11	5	28	13	44	13	18	2	4	10
Min	3.5	4.0	4.8	2.2	3.0	4.1	0.9	4.1	2.7	3.7	2.3	6.1	4.4	1.1
Mean	3.5	8.5	8.7	7.0	7.0	5.6	7.5	8.1	7.7	8.7	7.9	7.5	5.8	6.4
Median	3.5	7.7	8.7	7.3	6.5	4.4	7.7	7.5	7.2	7.5	7.5	7.5	5.7	7.0
Max	3.5	15.9	12.6	11.8	12.8	10.7	13.8	14.3	15.7	14.5	15.2	8.8	7.6	11.7
Std Dev	.	3.2	5.5	4.0	3.2	2.8	3.7	3.4	3.3	3.5	3.1	1.9	1.4	3.5

Red dot = mean; Horizontal line = median; Colored box = mid 50% of data; Blue circle = extreme value

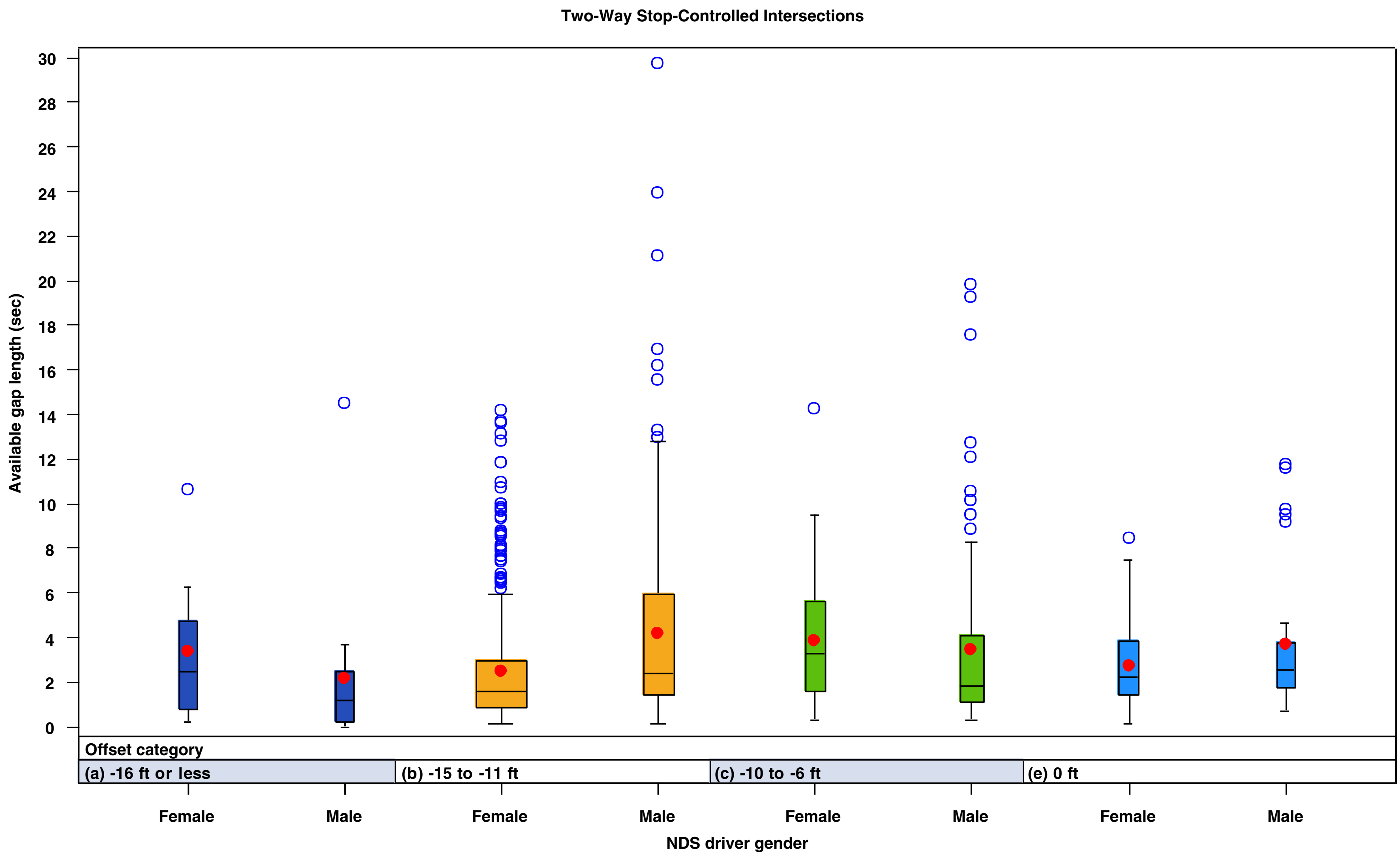
Figure A.10. Distribution of accepted gap length by offset category and gender at signalized intersections.



N	1	15	0	8	42	75	20	515	60	0	29	62	11	25	14	17
Min	14.5	0.0	.	0.2	0.2	0.2	0.4	0.1	0.3	.	0.3	0.6	0.7	0.4	0.2	0.8
Mean	14.5	1.3	.	3.3	4.2	2.3	4.2	2.9	3.4	.	4.3	3.5	3.8	2.8	2.1	4.1
Median	14.5	1.1	.	2.5	2.9	1.7	3.4	1.7	2.2	.	3.3	1.7	2.8	2.2	2.1	2.8
Max	14.5	3.7	.	10.6	13.6	14.2	10.4	29.7	12.0	.	14.2	19.8	9.7	11.7	4.3	11.5
Std Dev	.	1.3	.	3.5	3.5	2.2	3.2	3.4	2.9	.	3.2	4.3	3.2	2.3	1.2	3.2

Red dot = mean; Horizontal line = median; Colored box = mid 50% of data; Blue circle = extreme value

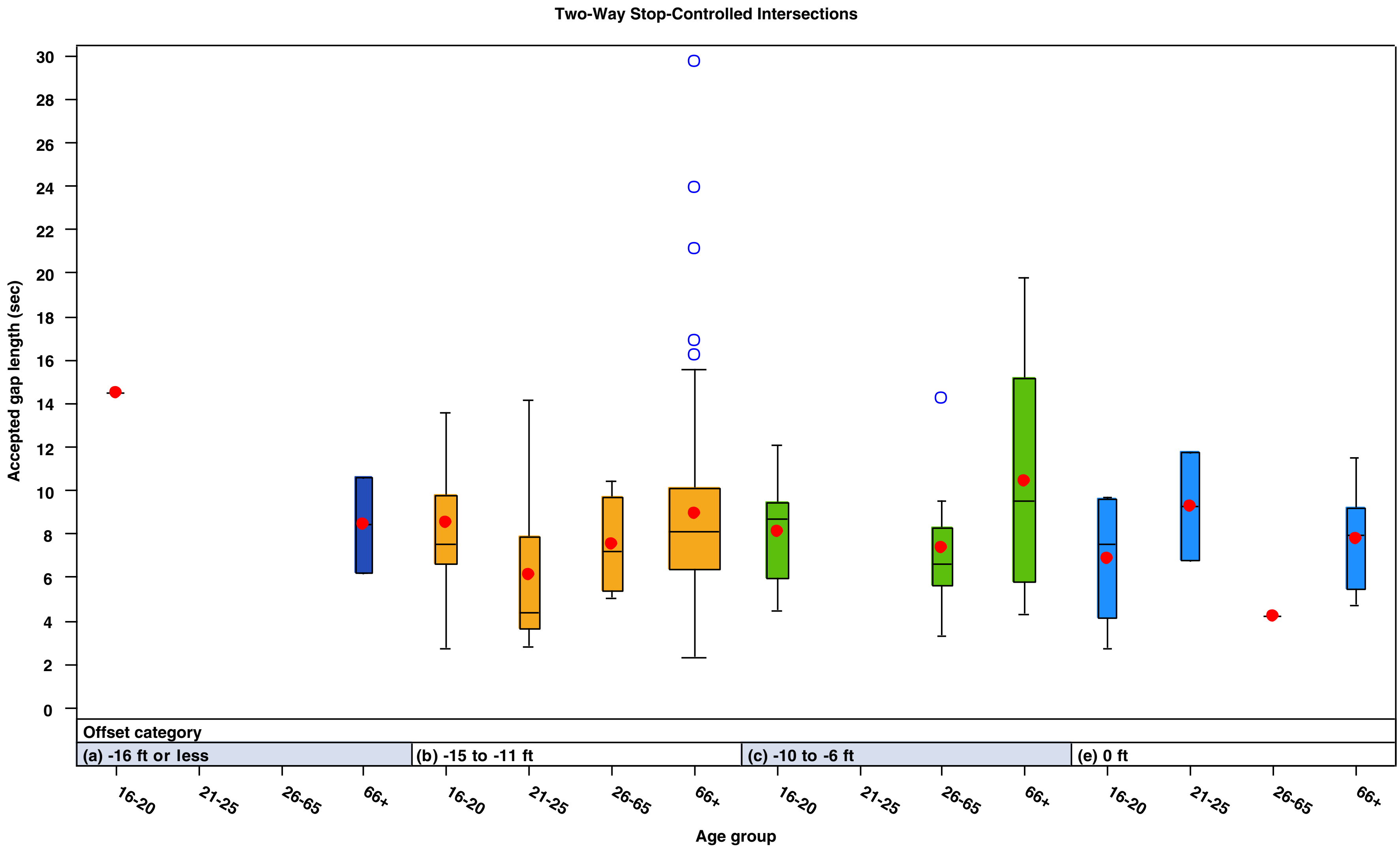
Figure A.11. Distribution of available gap length by offset category and age group at two-way stop-controlled intersections.



N	8	16	453	199	52	99	39	28
Min	0.2	0.0	0.1	0.1	0.3	0.3	0.2	0.7
Mean	3.3	2.1	2.4	4.2	3.8	3.5	2.7	3.7
Median	2.5	1.1	1.6	2.4	3.3	1.9	2.2	2.5
Max	10.6	14.5	14.2	29.7	14.2	19.8	8.4	11.7
Std Dev	3.5	3.5	2.5	4.4	3.0	3.9	2.0	3.3

Red dot = mean; Horizontal line = median; Colored box = mid 50% of data; Blue circle = extreme value

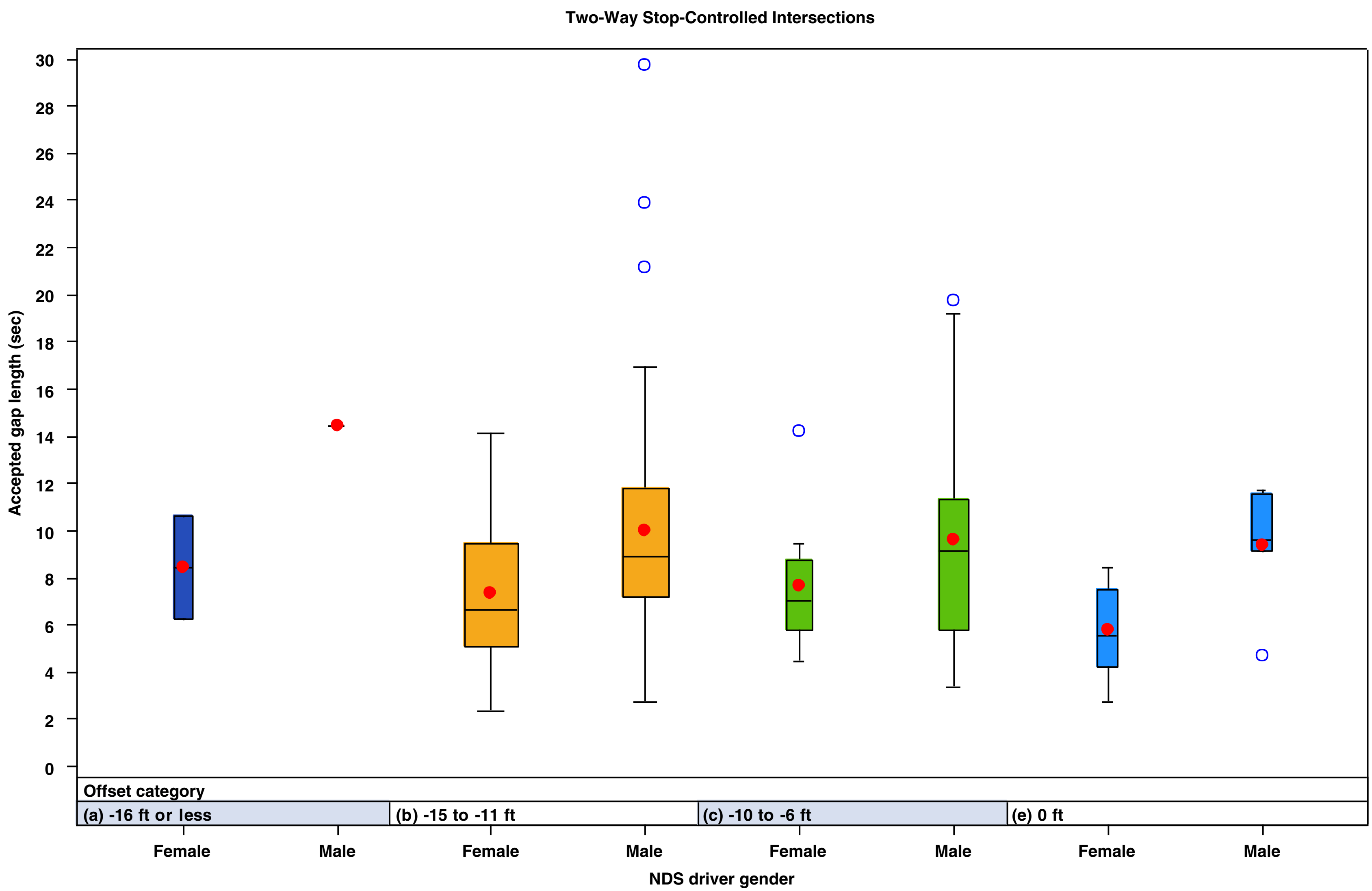
Figure A.12. Distribution of available gap length by offset category and gender at two-way stop-controlled intersections.



N	1	0	0	2	13	8	8	83	13	0	9	12	4	2	1	6
Min	14.5	.	.	6.2	2.7	2.8	5.1	2.3	4.4	.	3.3	4.3	2.8	6.8	4.2	4.7
Mean	14.5	.	.	8.4	8.5	6.1	7.5	8.9	8.1	.	7.4	10.5	6.9	9.3	4.2	7.8
Median	14.5	.	.	8.4	7.5	4.4	7.2	8.1	8.7	.	6.7	9.5	7.5	9.3	4.2	7.9
Max	14.5	.	.	10.6	13.6	14.2	10.4	29.7	12.0	.	14.2	19.8	9.7	11.7	4.2	11.5
Std Dev	.	.	.	3.1	3.1	4.1	2.2	4.3	2.2	.	3.1	5.6	3.3	3.5	.	2.5

Red dot = mean; Horizontal line = median; Colored box = mid 50% of data; Blue circle = extreme value

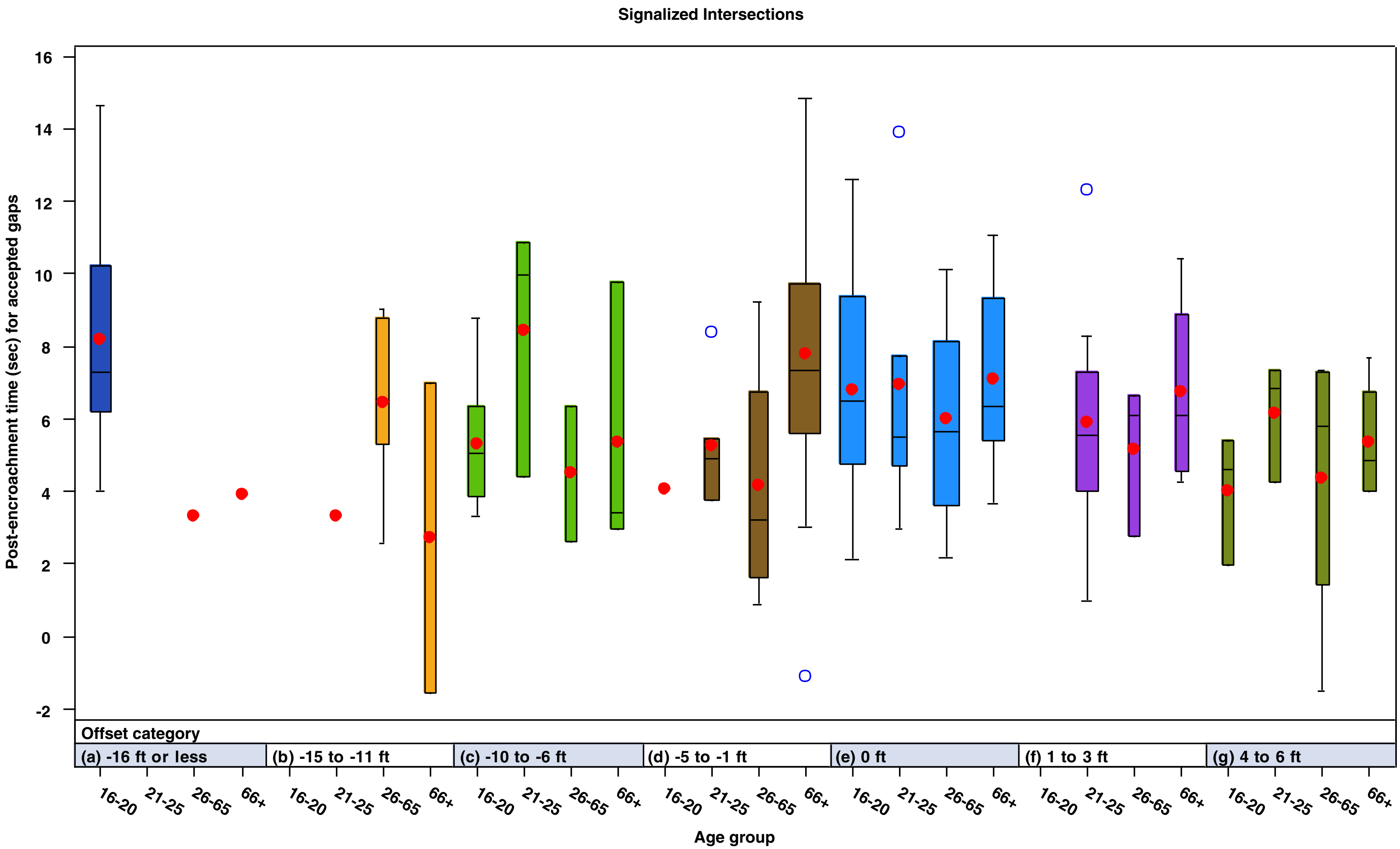
Figure A.13. Distribution of accepted gap length by offset category and age group at two-way stop-controlled intersections.



N	2	1	61	51	14	20	7	6
Min	6.2	14.5	2.3	2.7	4.4	3.3	2.8	4.7
Mean	8.4	14.5	7.4	10.0	7.6	9.6	5.8	9.4
Median	8.4	14.5	6.7	8.9	7.1	9.2	5.6	9.6
Max	10.6	14.5	14.2	29.7	14.2	19.8	8.4	11.7
Std Dev	3.1	.	2.9	4.8	2.5	4.8	1.9	2.5

Red dot = mean; Horizontal line = median; Colored box = mid 50% of data; Blue circle = extreme value

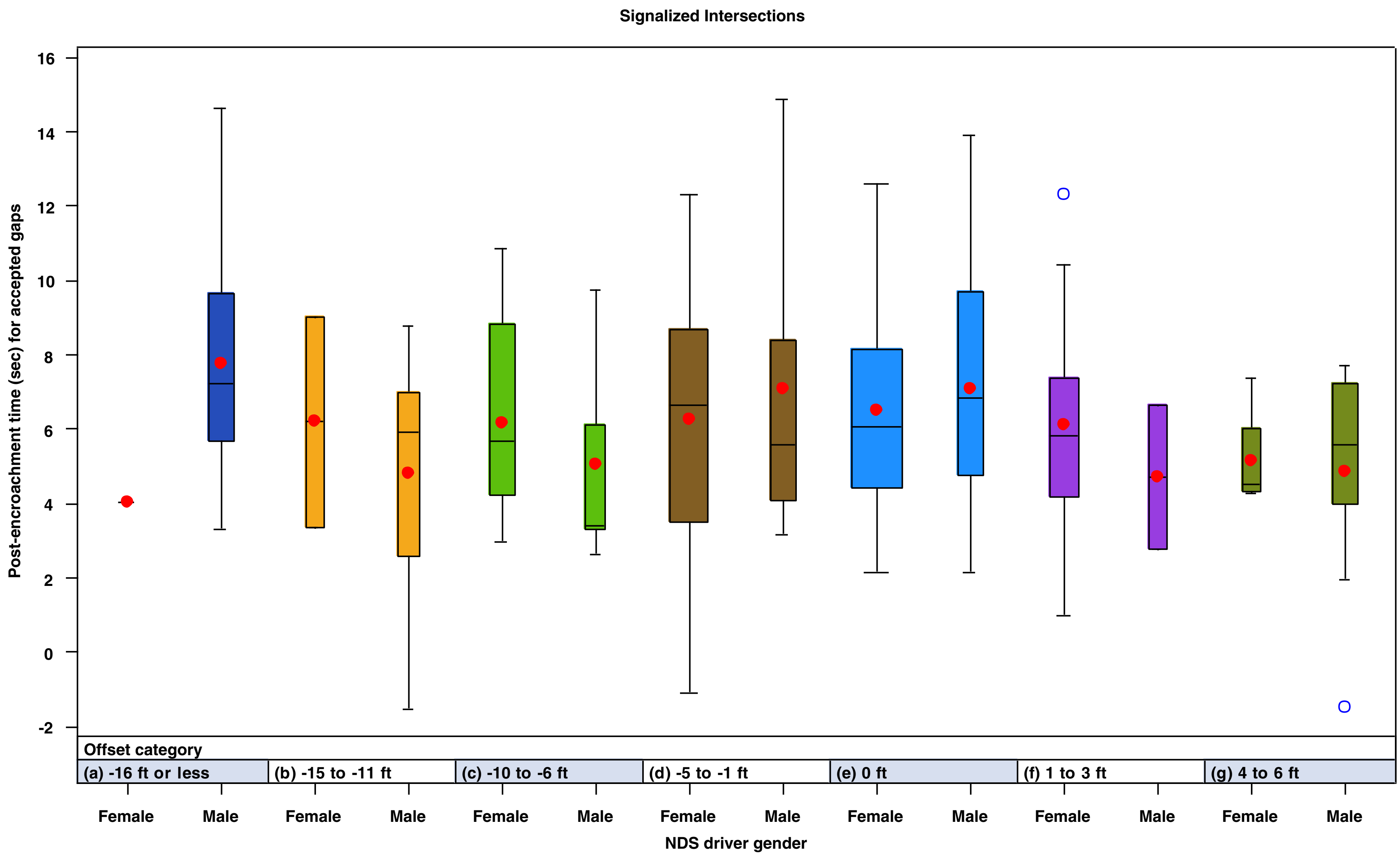
Figure A.14. Distribution of accepted gap length by offset category and gender at two-way stop-controlled intersections.



N	11	0	1	1	0	1	5	2	8	3	2	3	1	5	10	25	20	5	19	13	0	13	3	4	3	3	4	4
Min	4.0	.	3.3	3.9	.	3.3	2.6	-1.6	3.3	4.4	2.6	3.0	4.1	3.8	0.9	-1.1	2.1	3.0	2.2	3.7	.	1.0	2.8	4.3	2.0	4.2	-1.5	4.0
Mean	8.2	.	3.3	3.9	.	3.3	6.5	2.7	5.3	8.4	4.5	5.4	4.1	5.3	4.1	7.8	6.8	7.0	6.0	7.1	.	5.9	5.2	6.7	4.0	6.1	4.3	5.4
Median	7.3	.	3.3	3.9	.	3.3	6.6	2.7	5.0	10.0	4.5	3.4	4.1	4.9	3.2	7.3	6.5	5.5	5.7	6.3	.	5.6	6.1	6.1	4.6	6.8	5.8	4.9
Max	14.6	.	3.3	3.9	.	3.3	9.0	7.0	8.8	10.9	6.4	9.7	4.1	8.4	9.2	14.9	12.6	13.9	10.1	11.1	.	12.3	6.6	10.4	5.4	7.4	7.3	7.7
Std Dev	2.9	.	.	.	.	.	2.7	6.1	1.8	3.5	2.6	3.8	.	1.9	2.8	3.6	2.9	4.2	2.5	2.5	.	2.9	2.1	2.8	1.8	1.7	4.1	1.8

Red dot = mean; Horizontal line = median; Colored box = mid 50% of data; Blue circle = extreme value

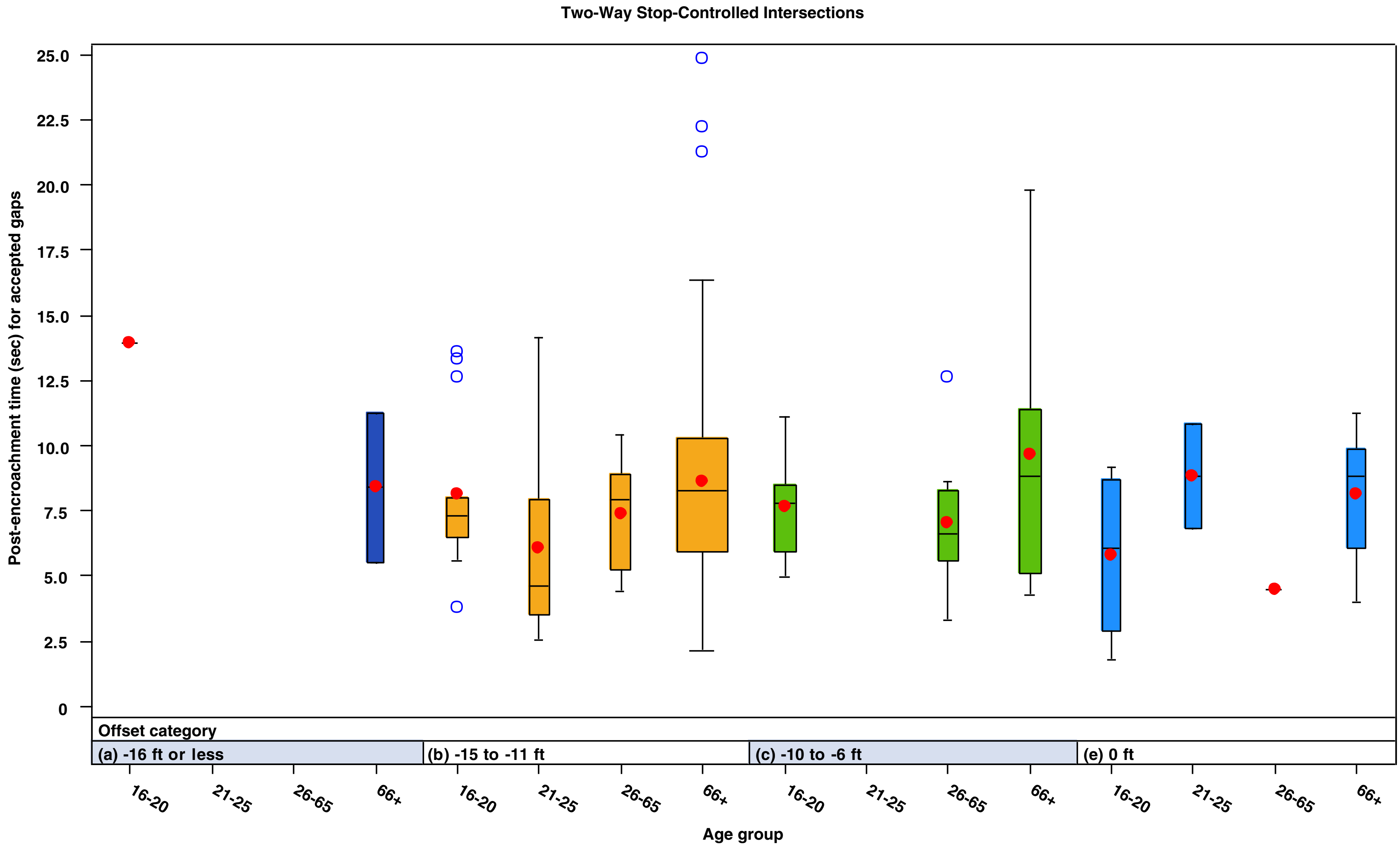
Figure A.15. Distribution of postencroachment time for accepted gaps by offset category and age group at signalized intersections.



N	1	12	2	6	11	5	28	13	44	13	18	2	4	10
Min	4.0	3.3	3.3	-1.6	3.0	2.6	-1.1	3.2	2.2	2.1	1.0	2.8	4.2	-1.5
Mean	4.0	7.8	6.2	4.8	6.2	5.0	6.3	7.1	6.5	7.1	6.1	4.7	5.1	4.9
Median	4.0	7.2	6.2	5.9	5.7	3.4	6.7	5.6	6.1	6.8	5.8	4.7	4.5	5.6
Max	4.0	14.6	9.0	8.8	10.9	9.7	12.3	14.9	12.6	13.9	12.3	6.6	7.4	7.7
Std Dev	.	3.2	4.0	3.7	2.7	3.0	3.5	3.9	2.6	3.2	2.7	2.7	1.5	2.9

Red dot = mean; Horizontal line = median; Colored box = mid 50% of data; Blue circle = extreme value

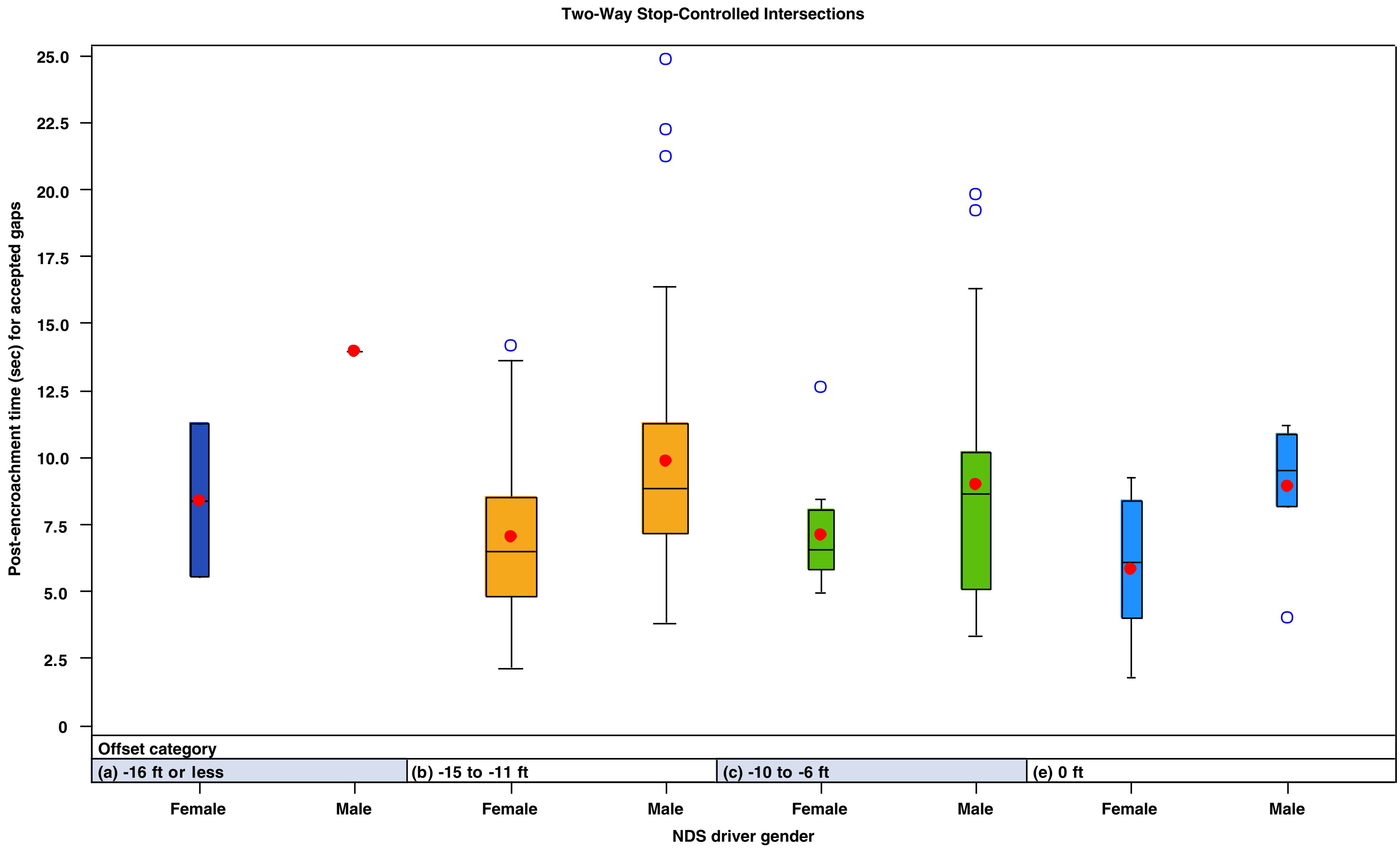
Figure A.16. Distribution of postencroachment time for accepted gaps by offset category and gender at signalized intersections.



N	1	0	0	2	13	8	8	84	13	0	9	13	4	2	1	6
Min	13.9	.	.	5.5	3.8	2.6	4.4	2.1	5.0	.	3.3	4.3	1.8	6.8	4.5	4.0
Mean	13.9	.	.	8.4	8.1	6.1	7.4	8.7	7.6	.	7.0	9.7	5.8	8.8	4.5	8.1
Median	13.9	.	.	8.4	7.3	4.6	7.9	8.3	7.8	.	6.6	8.8	6.1	8.8	4.5	8.8
Max	13.9	.	.	11.2	13.6	14.2	10.4	24.8	11.1	.	12.6	19.8	9.2	10.8	4.5	11.2
Std Dev	.	.	.	4.0	3.1	4.1	2.2	4.0	1.9	.	2.7	5.5	3.5	2.8	.	2.6

Red dot = mean; Horizontal line = median; Colored box = mid 50% of data; Blue circle = extreme value

Figure A.17. Distribution of postencroachment time for accepted gaps by offset category and age group at two-way stop-controlled intersections.



N	2	1	61	52	14	21	7	6
Min	5.5	13.9	2.1	3.8	5.0	3.3	1.8	4.0
Mean	8.4	13.9	7.0	9.9	7.1	9.0	5.8	8.9
Median	8.4	13.9	6.5	8.8	6.5	8.6	6.1	9.5
Max	11.2	13.9	14.2	24.8	12.6	19.8	9.2	11.2
Std Dev	4.0	.	2.9	4.3	1.9	4.7	2.6	2.6

Red dot = mean; Horizontal line = median; Colored box = mid 50% of data; Blue circle = extreme value

Figure A.18. Distribution of postencroachment time for accepted gaps by offset category and gender at two-way stop-controlled intersections.

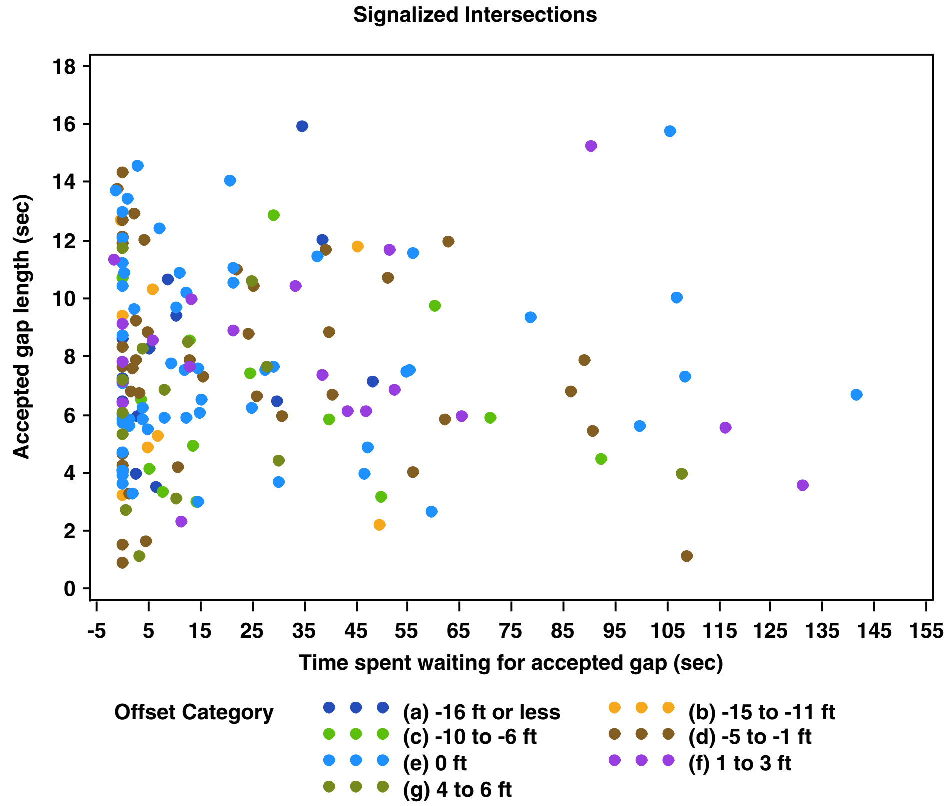


Figure A.19. Accepted gap length versus time spent waiting for gap, encoded by offset category, at signalized intersections.

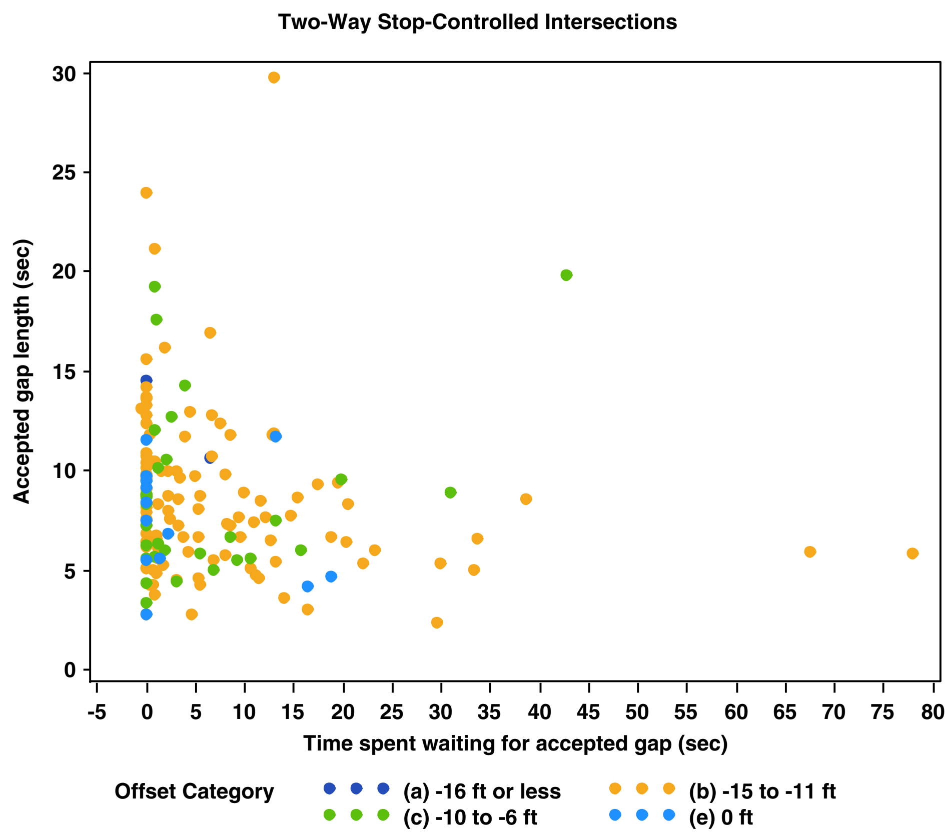


Figure A.20. Accepted gap length versus time spent waiting for gap, encoded by offset category, at two-way stop-controlled intersections.

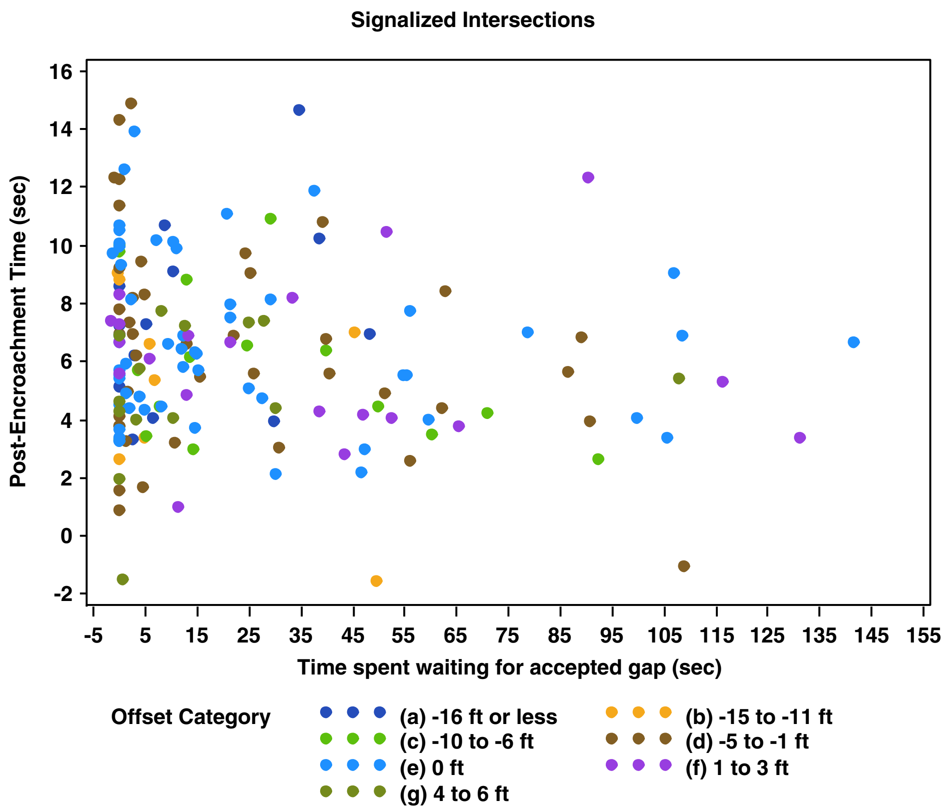


Figure A.21. Postencroachment time of accepted gaps versus time spent waiting for gap, encoded by offset category, at signalized intersections.

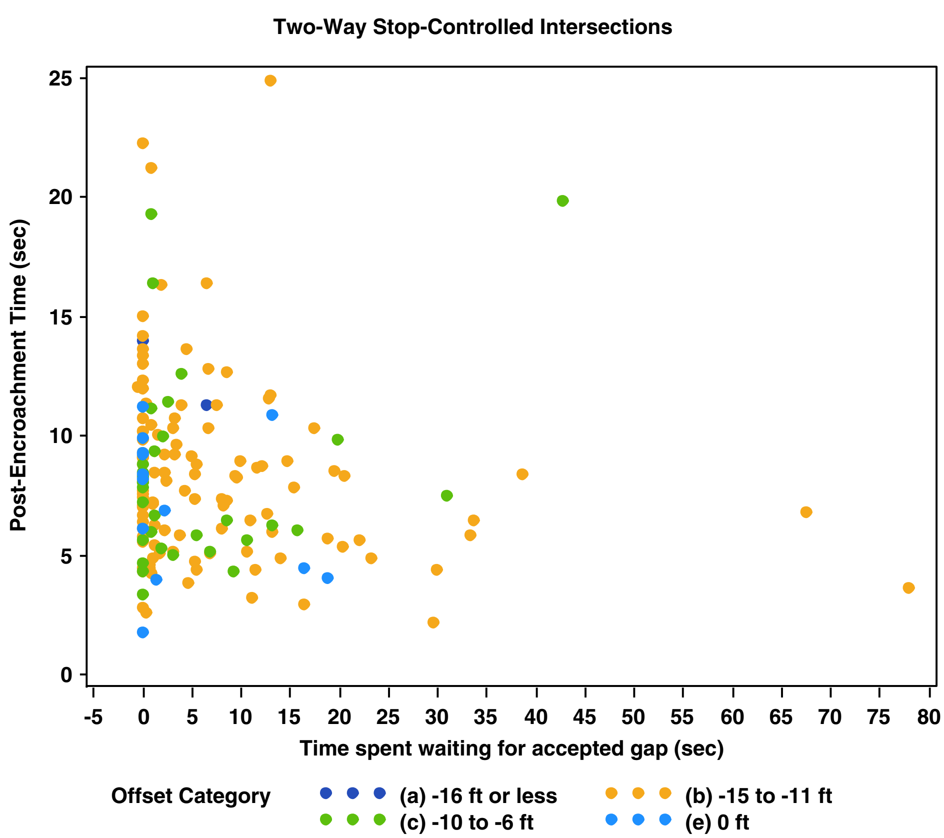


Figure A.22. Postencroachment time of accepted gaps versus time spent waiting for gap, encoded by offset category, at two-way stop-controlled intersections.

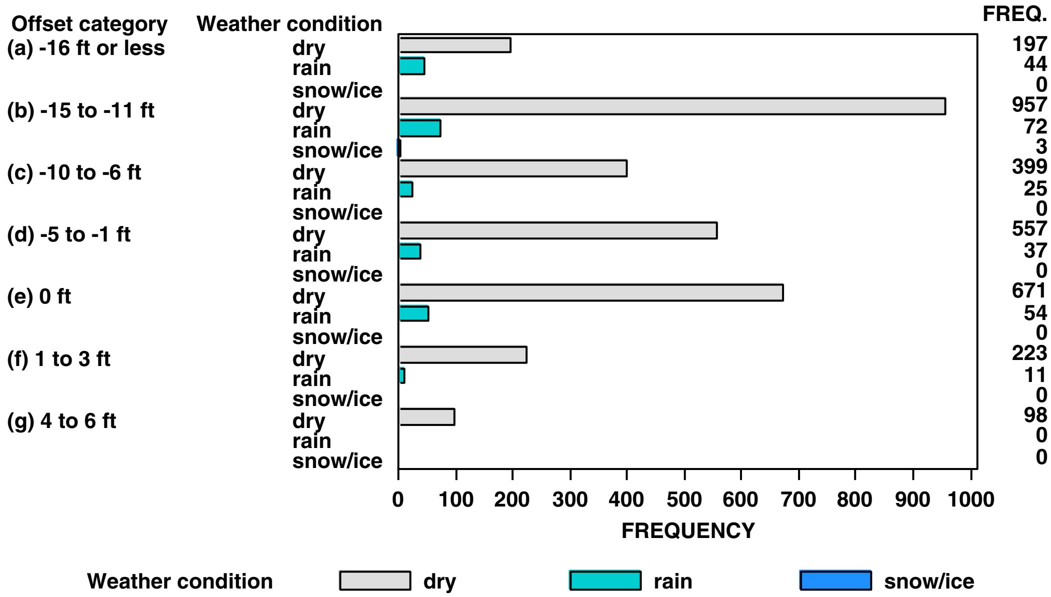


Figure A.23. Distribution of events by offset category and weather conditions.

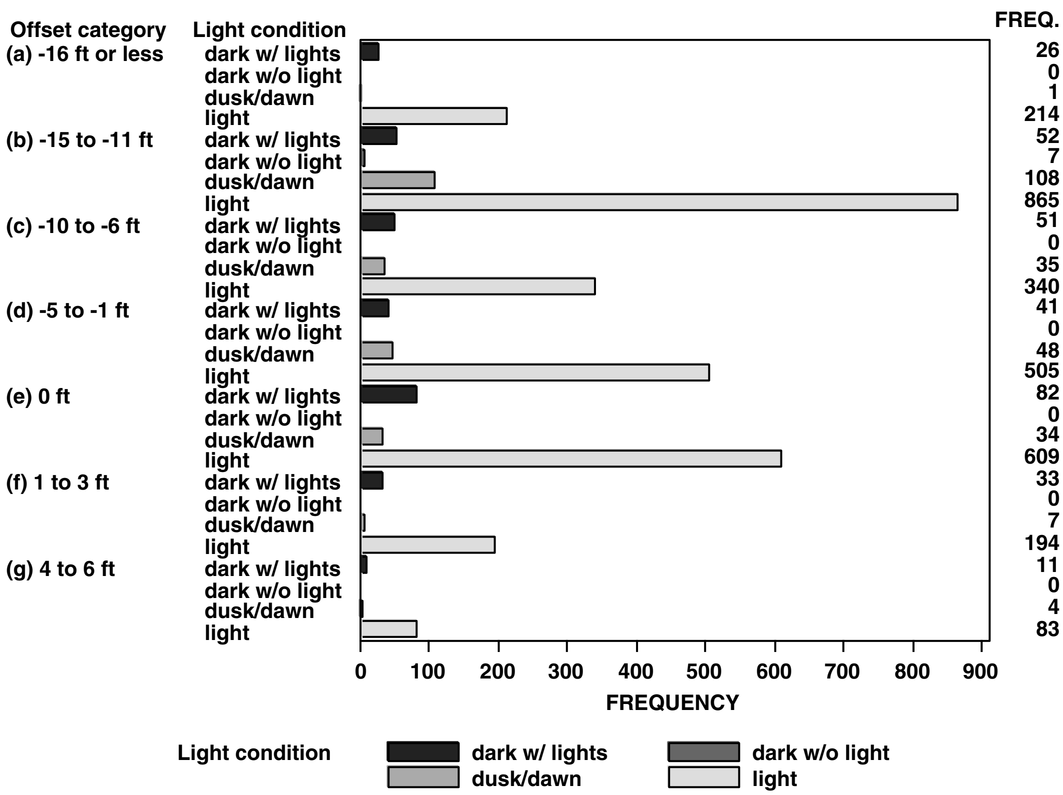


Figure A.24. Distribution of events by offset category and light conditions.

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Related SHRP 2 Research

Naturalistic Driving Study: Development of the Roadway Information Database (S04A)

Design of the In-Vehicle Driving Behavior and Crash Risk Study (S05)

Naturalistic Driving Study: Technical Coordination and Quality Control (S06)

Naturalistic Driving Study: Collecting Data on Cell Phone Use (S06)

Naturalistic Driving Study: Field Data Collection (S07)

Analysis of Naturalistic Driving Study Data: Safer Glances, Driver Inattention, and Crash Risk (S08A)

Analysis of Naturalistic Driving Study Data: Roadway Departures on Rural Two-Lane Curves (S08D)

Naturalistic Driving Study: Comparing the Study Sample with National Data (S31)

Naturalistic Driving Study: Alcohol Sensor Performance (S31)

Naturalistic Driving Study: Linking the Study Data to the Roadway Information Database (S31)