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Report No. UT-23.10

# PEDESTRIAN TRAFFIC SIGNAL VIOLATIONS: SAFETY, DESIGN, AND OPERATIONAL IMPLICATIONS

**Prepared For:**

Utah Department of Transportation
Research & Innovation Division

**Final Report**
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16. Abstract

The objective of this research project is to improve pedestrian safety at signalized intersections by focusing on pedestrian signal violations: measuring behaviors, associating characteristics and locations, and identifying potential mitigation strategies. In this project, we recorded videos and collected and analyzed observational data on pedestrian crossing behaviors, specifically: 5,589 pedestrian crossing events for 47 crosswalks at 39 signalized intersections in Utah. After linking these data with information about the location and traffic signal status, we performed descriptive and statistical analyses of the assembled data to identify people, conditions, and locations with greater and lesser rates of pedestrian spatial and temporal violation behaviors.

The large majority of pedestrian crossing events did not exhibit a spatial or temporal violation behavior. Nearly all pedestrians (97–98%) crossed in or within a few feet of the crosswalk; only 2–3% of crossing events happened mid-block, more than a car length away from the crosswalk. A large majority (89%) of pedestrian crossing events occurred without any time spent in the intersection against a conflicting green movement. However, about 5–6% of the time, there were pedestrians in the crosswalk for at least 5 seconds while a conflicting protected vehicle movement had the green light. Bivariate and multivariate statistical analyses identified various factors (pedestrian, waiting, crossing, temporal, and weather information; as well as crossing, intersection, land use, built environment, and neighborhood sociodemographic characteristics) associated with these behaviors. Based on the study's findings, we present several recommendations for treatments to improve intersection pedestrian safety and opportunities for future research.

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# UNIT CONVERSION FACTORS

## SI* (MODERN METRIC) CONVERSION FACTORS

### APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yard | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| | | NOTE: volumes greater than 1000 L shall be shown in $m^3$ | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact degrees)** | | |
| °F | Fahrenheit | 5 (F-32)/9 or (F-32)/1.8 | Celsius | °C |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |

### APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.314 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| °C | Celsius | 1.8C+32 | Fahrenheit | °F |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

*SI is the symbol for the International System of Units. (Adapted from FHWA report template, Revised March 2003)

## LIST OF ACRONYMS

| | |
|---|---|
| AADT | Annual Average Daily Traffic |
| ACS | American Community Survey |
| ANOVA | Analysis of Variance |
| ATSPM | Automated Traffic Signal Performance Measures |
| CSV | Comma-Separated Value |
| EPA | Environmental Protection Agency |
| FHWA | Federal Highway Administration |
| GHSA | Governors Highway Safety Association |
| HAWK | High-Intensity Activated Crosswalk |
| HLM | Hierarchical Linear Model |
| IEMRE | Iowa Environmental Mesonet Reanalysis |
| MLM | Multilevel Model |
| MPH | Miles Per Hour |
| MUTCD | Manual on Uniform Traffic Control Devices |
| NASEM | National Academies of Science, Engineering, and Medicine |
| NCHRP | National Cooperative Highway Research Program |
| NHTSA | National Highway Traffic Safety Administration |
| OLS | Ordinary Least Squares |
| PROWAG | Public Right-of-Way Accessibility Guidelines |
| QA/QC | Quality Assurance / Quality Control |
| SLD | Smart Location Database |
| SUV | Sport Utility Vehicle |
| UDOT | Utah Department of Transportation |
| UDPS | Utah Department of Public Safety |
| UGRC | Utah Geospatial Resource Center |

# EXECUTIVE SUMMARY

The objective of this research project is to improve pedestrian safety at signalized intersections by focusing on pedestrian signal violations: measuring behaviors, associating characteristics and locations, and identifying potential mitigation strategies. Based on Utah crash reports, pedestrian behaviors play a role in around half of pedestrian crashes, and a large share of pedestrian crashes occur at signalized intersections. Our literature review of 32 existing studies on pedestrian crossing behavior at traffic signals found that most studies collected data at fewer than 10 crossings, which is not enough to investigate relationships with intersection (design, operational, or locational) characteristics. Also, there are relatively few studies in the US; most have been conducted in China or other countries. There is a need for additional research on pedestrian crossing behaviors at traffic signals.

In this project, we collected and analyzed observational data on pedestrian crossing behaviors at/near signalized intersections. First, we recorded videos for 47 crosswalks at 39 traffic signals in Utah, encompassing 5,589 pedestrian crossing events. Next, trained researchers watched the videos and marked details of pedestrian behaviors and violations, including information about pedestrians themselves, as well as waiting and crossing behaviors, conditions, and timestamps. These data were then linked to traffic signal phase data and to various locational information about crossing and intersection characteristics, measures of the built environment, and neighborhood demographics. Finally, we performed descriptive and statistical analyses of the assembled data. Analysis methods included descriptive statistics, chi-square tests, and multilevel regression models. The analyses identified people, conditions, and locations with greater and lesser rates of pedestrian behaviors, including spatial violations and temporal violations.

The large majority of pedestrian crossing events did not exhibit a spatial or temporal violation behavior. Regarding spatial violations: Nearly all pedestrians (97–98%) crossed in or within a few feet of the crosswalk. Only 2–3% of crossing events happened mid-block, more than a car length away from the crosswalk. Among pedestrians crossing in the crosswalk or crosswalk area, a large majority (85%) stayed within the crosswalk markings for all/most of the crossing. Only 7% of crossing events involved pedestrians being outside of the crosswalk markings for most/all of the crossing. Several factors were associated with higher chances of both types of spatial violations: not riding a bicycle, waiting less time, hours with warmer temperatures, and locations with longer crossing distances and/or higher traffic volumes.

Regarding temporal violations: A large majority (89%) of pedestrian crossing events occurred without any time spent in the intersection against a conflicting green movement. However, about 5–6% of the time, there were pedestrians in the crosswalk for at least 5 seconds while a conflicting protected vehicle movement had the green light. Regarding just the pedestrian signal status itself, a large majority of pedestrians started crossing on the *walk* indication (58%) or the flashing *don't walk* indication (19%); but, a sizable share (22%) did start crossing when the walk signal showed steady *don't walk*. Several factors were associated with higher chances of both types of temporal violations: not walking with a child, waiting less time, with no one else crossing, during overnight hours, and locations with higher traffic volumes, in neighborhoods with higher shares of people of Hispanic or non-white race/ethnicity, and the one mid-block crossing that was included in the study.

Based on the findings of this study, we present several possible recommendations for implementation consideration. Because several locations with medians saw higher rates of pedestrians crossing mid-block, installing median fencing or other barriers could discourage mid-block crossing behaviors. Signal timing strategies that implement pedestrian recall and rest-in-walk or use a "ped recycle setting" (especially in areas and at times of day with regular pedestrian volumes) could help reduce the number of pedestrians who cross on steady *don't walk*, although they might also have adverse operational impacts. We also measured walking speeds while crossing, and (based on the data) the use of a slower walking speed (3.5 instead of 4.0 ft/sec) for signal timing would accommodate the observed walking speeds of 5–6% more pedestrians, especially older adults. Ensuring that push-buttons and crosswalks are located in convenient locations that avoid out-of-direction travel for pedestrians might also increase compliance at signals. We also have several recommendations for future research, including studying pedestrian behavior specifically at mid-block crossing locations.

# 1.0 INTRODUCTION

## 1.1 Problem Statement

Pedestrian injuries and fatalities are increasing (in both number and share) nationally and in Utah. According to a recent report from the Governors Highway Safety Association (GHSA, 2020), pedestrian fatalities in the US have increased by around 50% over the last 10 years and now represent 17% of all traffic deaths. The majority of pedestrian fatalities occur on non-freeway arterials that may be difficult to cross except at signalized intersections. In 2018, more than 35 deaths and over 800 injuries to people walking on Utah streets and highways were reported (UDPS, n.d.). As vulnerable road users, pedestrians are more likely to be injured or killed when involved in a collision.

Based on Utah crash reports, pedestrian behaviors play a role in around 50% of pedestrian crashes, including contributing factors such as: improper crossing, darting, not visible, inattentive, failure to obey traffic signs/signals, in roadway improperly, and failure to yield right of way (UDPS, n.d.). Many of these behaviors and violations are particularly relevant at signalized intersections. Furthermore, several recent pedestrian fatalities have involved pedestrian signal violations, including: crossing outside of the crosswalk, failing to call the *walk* indication by pressing the push-button, and/or crossing against opposing motor vehicle traffic. These behaviors may be more common in certain locations or under certain conditions, but there is limited research documenting these locations and conditions. This research project helps to fill this gap by measuring pedestrian signal violations at a variety of locations, analyzing factors and characteristics contributing to greater violation rates, and identifying potential design and operational treatments (and educational or enforcement initiatives) to improve pedestrian safety.

## 1.2 Objectives

The objective of this research project is to improve pedestrian safety at signalized intersections by focusing on pedestrian signal violations: measuring behaviors, associating characteristics and locations, and identifying potential mitigation strategies.

## 1.3 Scope

This research involved the following major tasks:

1. *Review literature*: Review literature on pedestrian traffic signal and crossing violations, and identify factors associated with violations from previous research.
2. *Record pedestrian behaviors*: Watch recorded videos of pedestrian crossings at/near signalized intersections for 47 crosswalks at 39 signals in Utah. Using trained students, mark details of pedestrian behaviors and violations. Recorded data include: date, origin and destination, pedestrian information, waiting information, and crossing information. Link behavior data with traffic-signal phase data using timestamps. Link behavior data with location data about crossing and intersection characteristics, measures of the built environment, and demographic information.
3. *Analyze data*: Perform descriptive and statistical analyses of assembled data. Analyses include the calculation of descriptive statistics, chi-square tests, and multilevel regression models. These analyses identify people, conditions, and locations associated with (greater and lesser rates of) pedestrian behaviors, including spatial violations and temporal violations.
4. *Identify potential strategies*. Based on the findings regarding locations and conditions, identify potential interventions, design and operational treatments, and educational/enforcement initiatives to reduce pedestrian traffic signal violations and improve intersection safety.

## 1.4 Outline of Report

This report is organized into the following chapters:

- Chapter 1.0 Introduction presents the research problem statement, project objectives, project scope, and organization of the report.
- Chapter 2.0 Research Methods includes a literature review of studies investigating pedestrian crossing behaviors at intersections, and an introduction to the data collection and analysis approach.

- Chapter 3.0 Data Collection includes details about the video recording and video data collection processes, the assembly of other traffic signal and geospatial data, and the combination of these various data into specific datasets for analysis.
- Chapter 4.0 Data Evaluation includes the results of the data analysis, specifically the descriptive analyses and statistical analyses of pedestrian behaviors, including spatial violations and temporal violations.
- Chapter 5.0 Conclusions summarizes the report by highlighting major findings, comparing those findings with earlier research, noting limitations, and outlining potential steps for future work.
- Chapter 6.0 Recommendations and Implementation provides recommendations for implementation of the research findings.
- References follow the main chapters.

# 2.0 RESEARCH METHODS

## 2.1 Overview

This chapter contains a literature review of studies investigating pedestrian crossing behaviors at intersections. The literature review presents the methods for identifying relevant literature, summarizes the data collection and analysis methods used in various studies, outlines key empirical findings from existing research literature, and describes gaps in the literature that this research project (or others) could fill. The chapter ends with an introduction (based on the literature) to the data collection approach presented in the subsequent chapter.

## 2.2 Literature Review

### 2.2.1 Introduction

Pedestrians and vehicles interact with each other all over the world. Pedestrian–vehicle interactions are most likely to occur at intersections. One way to streamline these interactions and reduce the number of potential conflicts is by using traffic signals. Signalized intersections were developed to increase the overall safety and efficiency of conflicting movements involving motorists and pedestrians. The number of signalized intersections is increasing across the US as population grows and travel increases. This means that pedestrian–vehicle interactions at signals are likely to be an increasing safety concern. Pedestrian–vehicle interactions can have serious, even fatal consequences if not appropriately managed.

The number of pedestrian-involved crashes is on the rise. In 2009, there were 4,109 pedestrian fatalities in the United States. By 2018, the number of pedestrian fatalities was up to 6,283. This corresponds to about a 3% increase in pedestrian fatalities every year. Approximately 17% of all pedestrian fatalities occur at intersections (NHTSA, 2020). There are several possible reasons for the increase in fatalities, including but not limited to: changes in pedestrian behavior and/or characteristics, increased error and/or distraction (by drivers or pedestrians), and/or inadequate intersection design in the face of changing conditions. Recent National Cooperative Highway Research Program (NCHRP) reports (NASEM, 2018, 2020) identify several factors associated with increased pedestrian crashes at intersections: higher motor vehicle traffic volumes (including turning movements and truck volumes), locations with more than three legs, more lanes, more transit stops and driveways, and arterial roadways. An analysis of multiple decades of US pedestrian fatalities found recent increases in the proportion of pedestrian fatalities under certain conditions: in the dark, involving trucks and SUVs, and on roadways with higher speeds ($\geq$ 35mph) and more lanes ($\geq$ 4) (Schneider, 2020). Some of this increase in pedestrian injuries/deaths and contributing factors to pedestrian crashes may be related to pedestrian behaviors at signals. However, pedestrian behavior is rarely measured in relation to crashes, so observations of pedestrian behaviors in general could provide insights into behavioral factors affecting safety outcomes.

The purpose of this section is to review past studies on pedestrian behavior at signalized intersections. The review covers different data collection methods, pedestrian behaviors to watch for, and how to collect the data in a useable format. The review also identifies gaps in past research and recognizes appropriate data analysis methods.

The following sections summarize the literature review on these topics. First, literature on pedestrian behavior studies is discussed. Research has been conducted globally on pedestrian behavior at intersections, looking at behavioral patterns as well as the influence of pedestrian characteristics, groups or crowds, time of day, weather, crossing location, and signal timing. Next, a summary is provided of various data collection methods and analysis methods used in the reviewed studies. Frequently used methods to gather data included physical observations, video observations, and questionnaires/surveys. The most common methods of analyzing data included logistic regression, analysis of variance (ANOVA), chi-squared tests, and binomial tests. Then, empirical findings from key literature are presented. Finally, the review concludes with a recap of the key findings and implications of pedestrian behavior at intersections.

### 2.2.2 Review Methods

To identify relevant scientific literature on these topics, the research team conducted a literature search in Summer 2021. Using the Google Scholar database, the first 1,000 results for the search term “pedestrian crossing violations signals” were scanned. Search results were reviewed for relevance, starting with the title, abstract, and full text (if necessary). In order to be included in the review, studies had to have: focused on pedestrian crossing behavior; been conducted at signalized intersections; and had an available full-text document written in English. After the search and screening process, there were 32 studies to include in the literature review. The reviewed literature is listed in Table 2.1, which includes: first author, year of publication, study area, number of observations/questionnaires, data collection, and the analysis method used.

Studies on these topics have been conducted around the world, including in Asia, North America, South America, and Europe. Ten of the 32 studies reviewed took place in the US or Canada, nine were conducted in China, and the remaining 13 took place in other countries. Studies conducted outside of North America were primarily used for background (and methodological) information because of the difference in transportation systems. Only one study was conducted in the western US (in Las Vegas, Nevada), so there is a knowledge gap to be filled by this research in Utah. The timeline of the research reviewed ranged from 1955 to 2021, but most studies were conducted in the past 10 years.

Overall, every study focused on pedestrian crossing behavior at intersections. However, each study focused on a specific aspect of pedestrian behavior within a small area or site, employing a variety of data collection and analysis techniques. Given this, it may be difficult to generalize research findings across studies. In the following sections, the research team summarizes the different data collection and analysis methods used in the various studies and reviews and presents their empirical evidence regarding pedestrian behavior at signalized intersections.

**Table 2.1 Reviewed literature on pedestrian crossing behaviors at intersections**

| *First Author* | *Year* | *Study Area* | *# of Sites* | *# of Observations* | *Data Collection Method(s)* | *Analysis Method(s)* |
|---|---|---|---|---|---|---|
| Lefkowitz | 1955 | Austin, Texas | 3 signalized intersections | 2103 pedestrians | manual observations | chi-squared tests |
| Jason | 1982 | Chicago, Illinois | 1 signalized intersection | 4011 pedestrians | manual observations | Mann-Whitney U test |
| Eustace | 2001 | Manhattan, Kansas | 2 signalized intersections | 688 pedestrians | manual observations | none |
| Cooper | 2011 | San Francisco Bay Area, California | 12 intersections (9 signalized near transit stations) | 1656 pedestrians | manual observations | none |
| Vasudevan | 2011 | Clark County Las Vegas, Nevada | 3 sites (2 signalized intersections) | 2361 pedestrians | manual observations and videos | Z-test for Proportions |

| *First Author* | *Year* | *Study Area* | *# of Sites* | *# of Observations* | *Data Collection Method(s)* | *Analysis Method(s)* |
|---|---|---|---|---|---|---|
| Russo | 2018 | New York, New York & Flagstaff, Arizona | 4 signalized intersections | 3038 pedestrians | video recordings | OLS regression, binary logit regression |
| de Lavalette | 2009 | Montreal, Canada | 10 signalized intersections, 19 crossings | 4000+ pedestrians | manual observations | ANOVA |
| Cinnamon | 2011 | Vancouver, Canada | 8 signalized intersections (at ped injury hotspots) | 9808 pedestrians | manual observations | none |
| Brosseau | 2013 | Montreal, Canada | 13 signalized intersections | 2938 pedestrians | manual observations | logistic regression |
| Lachapelle | 2017 | Quebec, Canada | 135 street crossings sites with signals | 2073 pedestrians | manual observations | chi-squared tests, ANOVA, multilevel mixed-effects |
| Kruszyna | 2013 | Wroclaw and Poznan, Poland | 11 signalized intersections | 8502 pedestrians | manual observations | proportions |
| Paschalidis | 2016 | Thessaloniki, Greece | 1 signalized intersection | 202 pedestrians | manual observations, questionnaire | binary logistic regression |
| Guéguen | 2001 | France | unknown | 2883 pedestrians | manual observations | chi-square tests |
| Dommes | 2015 | Lille, France | 6 signalized intersections | 442 pedestrians | manual observations, questionnaire | logistic regression |
| Pelé | 2017 | Nagoya, Japan & Strasbourg, France | 7 signalized intersections | 3666 pedestrians | manual observations | generalized linear model |
| Freeman | 2015 | Brisbane, Australia | N/A | 636 pedestrians | questionnaire | chi-square tests, logistic regression |
| Yagil | 2000 | Israel | N/A | 203 students | questionnaire | independent samples t-tests, linear regression |
| Shaaban | 2018 | Doha, Qatar | 1 six-lane divided arterial | 2766 illegal maneuvers | manual observations | chi-square tests, linear regression |
| Bendak | 2021 | Sharjah, United Arab Emirates | 10 crossings | 708 pedestrians | manual observations | chi-square, normality test |
| Koh | 2014 | Singapore | 7 crossings near transit stations | 3448 pedestrians | manual observations | logistic regression |
| Chai | 2016 | Singapore | 1 jaywalk, 1 crosswalk | 1335 pedestrians | video recordings | fuzzy logic models, Kolmogorov-Smirnov tests |
| Tiwari | 2007 | Delhi, India | 7 intersections | 1868 pedestrians | manual observations | survival analysis, Spearman rank correlation |
| Mukherjee | 2020 | Kolkata, India | 55 signalized intersections | 65,500 pedestrians; 3250 survey respondents | manual observations, questionnaire | negative binomial model, beta regression model, |
| Guo | 2011 | Beijing, China | 7 crosswalks | 1497 pedestrians | manual observations from video, questionnaire | hazard-based duration model |

| *First Author* | *Year* | *Study Area* | *# of Sites* | *# of Observations* | *Data Collection Method(s)* | *Analysis Method(s)* |
|---|---|---|---|---|---|---|
| Ren | 2011 | Nanjing, Wuhan & Shizuishan, China | 26 signalized intersections | 6,628 pedestrians; 598 surveys | manual observations from video, questionnaire | ANOVA |
| Ding | 2015 | Changchun, China | unknown | unknown | questionnaire | none |
| Yang | 2015 | Beijing, China | 5 signalized intersections | 1181 pedestrians | manual observations from video | binary logit model, hazard-based duration model |
| Zhang, Tan | 2016 | Guangdong, China | 1 province | 4817 crashes | crash data | logistic regression |
| Zhang, Wang | 2016 | Hefei, China | 1 city | 631 respondents | questionnaire | logistic regression |
| Zhou | 2016 | Dalian, China | 1 city | 260 respondents | questionnaire | structural equation model |
| Chen | 2017 | Suzhou, China | 13 intersections | 1075 pedestrian violations | manual observations | logistic regression |
| Zhuang | 2018 | Beijing, China | 4 intersections | 486 pedestrians | manual observations from video | logistic regression |

### 2.2.3 Findings from the Literature

#### *2.2.3.1 Data Collection Methods*

The most common method of data collection in the reviewed literature was manual observation of pedestrian behaviors. Overall, 25 studies included some form of behavioral observation. Historically, most manual observations were conducted on site by observing pedestrian behaviors and counting pedestrians by hand in real time. Recently, as technology has improved, it has become more common to first record videos and then conduct manual observations from the video recordings. Observations from recorded videos are faster to collect because the videos can be watched at a faster rate than real time. Videos also offer the opportunity to check data collection work for accuracy by referring back to the original recordings.

In nine studies, pedestrian behavior data were collected through questionnaires or surveys conducted by researchers. Such questionnaires were usually filled out by pedestrians on site, after having been intercepted by researchers. In most cases, the purpose of these surveys was to determine the reason for a pedestrian’s previously observed movements (also known as revealed preference studies), although they can also ask questions about perceptions of safety or traffic rules. Although questionnaires/surveys can be a useful supplement to manual observations, they are also time consuming to collect.

Another type of data used for one study in China (Zhang, Tan et al., 2016) was crash data. Crash data were collected from collision reports, which allowed the researchers to identify the pedestrian incident “hotspots” throughout the research area and study the causes of each incident. One major challenge with using crash data is that researchers must interpret the pedestrian behavior which may or may not have contributed to the pedestrian/vehicle interaction. Furthermore, reported crashes only scratch the surface of all potential road user behaviors at signalized intersections.

Different pedestrian behaviors were noted in the reviewed studies. These behaviors included the following crossing violations: crossing on the (flashing) *don’t walk* signal, crossing mid-block, crossing outside of crosswalk markings, or crossing during cross-traffic’s green light. Pedestrian waiting time and walking time/speed were observed. Waiting time is defined as the time between when the pedestrian arrives at a waiting area and when the pedestrian starts to cross the street. Walking speed is calculated by dividing the time required for the pedestrian to cross (walking time) by the distance of the crosswalk. The behavior of pedestrians as they crossed were also studied, which included pedestrians being distracted as they crossed, pedestrians scanning or looking for cars before they crossed, or changes in speed during the crossing.

The studies reviewed also considered many different explanatory variables in their research. Data were gathered about pedestrian characteristics: gender, group size, age, clothing type, carrying a load, walking with children, or using a cellular device. Site conditions were also collected, such as approach direction, crossing location, crossing direction, destination, number of travel lanes, presence of median, number of other pedestrians waiting, number of other pedestrians crossing in the same direction, and number of pedestrians crossing in the opposite direction. Traffic signal timing and phasing were also considered. Each study evaluated a unique combination of pedestrian characteristics and site conditions.

While most studies observed or surveyed several hundred to several thousand pedestrians, studies rarely investigated more than 10–15 sites. Many studies only looked at one location. Only a few exceptions exist: Ren et al. (2011) studied 26 intersections in China, Mukherjee and Mitra (2020) studied 55 signals in India, and Lachapelle and Cloutier (2017) studied 135 street crossing sites in Canada. This gap is a limitation of previous research because it is difficult to make generalized conclusions from limited study sites about the impact of intersection design and operational features on pedestrian crossing behaviors.

#### *2.2.3.2 Analysis Methods*

In the studies reviewed, most authors used a variety of statistical tests to analyze pedestrian behavior data and determine statistically significant associations or sufficiently strong/noticeable patterns with other explanatory variables.

Some simpler statistical analyses that have been used include t-tests or Z-tests, chi-squared tests, Mann-Whitney U-tests, Spearman rank correlation, and analysis of variance (ANOVA). All of these methods are statistical hypothesis tests that can be used to measure the difference or relationship between two variables. The t-test (or Z-test for larger samples) is used to compare the difference in means for two continuous variables or groups. ANOVA generalizes this comparison for more than two variables or groups. The Mann-Whitney U-test is used to examine differences in ranked data. The chi-squared test is used to determine if there is an association between two categorical variables. Spearman's rank correlation measures the association between two sets of ranked data.

Other studies used regression techniques to identify associations between a pedestrian behavior and multiple explanatory variables. In general, these analysis methods were selected based on how the behavioral outcome data were measured. For binary outcomes (e.g., pedestrian crossed against the light or not), binary logistic regression is appropriate. When comparing shares of something across multiple locations (e.g., percentage of pedestrians who crossed against the light), an appropriate method is beta regression. Negative binomial models are a common way of modeling an outcome that is a count variable (e.g., number of pedestrians who crossed against the light). Survival analysis (most commonly using a hazard-based duration model) is a way of modeling an outcome that is a time duration (e.g., time a pedestrian waited before crossing the street). Even more advanced analysis methods included structural equation modeling (used by Zhou et al., 2016) and fuzzy logic models (used by Chai et al., 2016).

*2.2.3.3 Empirical Results*

This section includes detailed discussion of the studies most relevant to this research project, i.e., recent studies conducted in the US. This section also provides an overview of general findings throughout all of the literature reviewed. Patterns and similarities between studies are noted in this section.

A study done in Austin, Texas, (Lefkowitz et al., 1955) investigated social pedestrian crossing behavior. The researchers determined that 14% of people violated traffic laws if they were following someone who appeared to be high-class/high-income and who violated traffic laws first. If the actor appeared to be a low-class/low-income individual who committed a traffic violation, only 4% of pedestrians followed suit. In the control study, it was found that 9% of pedestrians committed a traffic violation when no actors were present. Three signalized intersections were studied with manual observations. The analysis method used a chi-squared test.

Researchers at DePaul University (Jason & Liotta, 1982) conducted a study at one signalized intersection in Chicago, Illinois. The team observed 2,011 pedestrians through manual observation. They found that pedestrian traffic violations increased as the waiting time for pedestrians trying to cross the street increased. Pedestrians crossing in a clockwise direction were found to have a longer wait time than pedestrians who crossed in a counterclockwise direction, due to the timing of the specific traffic signal studied. Overall, 7% of pedestrians violated traffic laws when crossing in the counterclockwise direction compared to 26% of pedestrians violating traffic laws when crossing in the clockwise direction. The analysis method used was a Mann-Whitney U-test.

Two signalized intersections in Manhattan, Kansas, were used in the assessment of pedestrian reaction to crossing delay (Eustace, 2001). Researchers observed 688 pedestrians by manual observation, collecting data on pedestrian behavior and time delayed or saved due to the behavior. This study focused on college students. Because the sites were located on a college campus, pedestrian familiarity with the intersections greatly impacted pedestrian behavior. Up to 12% of pedestrians crossed on flashing *don’t walk* signals; one site had 18% of pedestrians crossing on a steady *don't walk* signal; and the other site had 69% of pedestrians walk on a steady *don't walk* signal. No analysis method was specified in this study.

A study was conducted in the San Francisco Bay Area, California, with manual observations (Cooper et al., 2011). The study covered 12 intersections with 9 nearby transit stations, resulting in 1,144 pedestrians being observed. Almost 45% of pedestrians arrived on a red pedestrian signal. On average, 8% of pedestrians were using a mobile device. Some sites had up to 18% of pedestrians using a mobile device. Violations ranged from 3% to 70% depending on the site. No analysis method was specified in this study.

In 2011, a study was conducted in Las Vegas, Nevada (Vasudevan et al., 2011). The researchers studied three sites, two of which were signalized. The researchers collected data through manual observation supplemented by videos, and analyzed the data with z-tests of proportions. The objective was to determine if and when pedestrians looked before crossing the street. The study found that pedestrians are more likely to look before crossing the street when there is a flashing pedestrian warning sign or a crossing sign with a picture of eyes and the word "LOOK." Also, the installation of a pedestrian push-button with an activation confirmation light reduced the share of pedestrians violating the signal.

Northern Arizona University researchers conducted a study in 2018 that considered one intersection in Flagstaff, Arizona, and three intersections in New York, New York (Russo et al., 2018). Data were collected for 3,038 pedestrians through video recordings and manual transcriptions. The average walking speed of pedestrians at these sites was found to be 4.8 ft/s. Overall, 13% of pedestrians were found to be distracted, 23% of pedestrians violated the traffic signal, and 16% of pedestrians had a crosswalk violation. The analysis was completed with ordinary least squares (OLS) regression and binary logit regression.

Of the studies reviewed, six were completed in the US, four in Canada, five in Europe, one in Australia, and 16 in Asia. The following four paragraphs highlight patterns that can be drawn between the studies conducted in different parts of the world.

In the United States, the main variables researchers considered included the influence of other pedestrians on a person's crossing behavior, how often violations occur, what the violations look like, and the number of pedestrians distracted (with or without a mobile device). One study also observed the walking speed of pedestrians as they crossed. In Canada, the studies focused on the violations of the pedestrian crossing signals specifically. Researchers then determined the rate of "dangerous" violations to "non-dangerous" violations. They also looked at the crossing time of pedestrians compared to the allowed signal time at crosswalks. It is important to consider all three of these variables—crossing time, signal timing, and type of violations—carefully to determine what is happening at intersections on a broad scale.

The studies in Europe focused on similar variables as the studies in Canada, including violations of pedestrian signals, the walking speed of pedestrians, and the time individuals started crossing the street, which is essential in determining the walking speed of the pedestrian and the status of the pedestrian signal.

The only study done in Australia looked at the knowledge of traffic rules and violations. The researchers surveyed hundreds of people to determine which violations were deliberate errors or ignorance of an uncommon traffic law. The team also considered the number and type of violations to find the majority of traffic violations are due to ignorance (Freeman & Rakotonirainy, 2015).

In Asia, one factor came up repeatedly: the number and type of violations. Factors assessed exclusively in Asia included driver behavior, intersection characteristics, and the beliefs or motives about violations. For example, many pedestrians believed that if there is a large group of pedestrians willing to cross together, they do not need to wait for a signal to tell them it is safe to cross (Ding et al., 2015).

Comparing results between the different studies, several patterns emerged regarding gender, age, and wait time. Most studies found that males are more likely to perform a traffic violation than females. The rate for male violations is highest for the age range of 18-35 (Brosseau et al., 2013). Age was also found to be a significant factor with implications for older adults' violations. Walking speed was found to decrease with age (Paschalidis et al., 2016). Because of decreased mobility and walking speed, older adults require a longer time to complete a safe crossing, so they are more likely to wait for a safe crossing than young adults (Lachapelle & Cloutier, 2017).

Waiting time has been demonstrated to have a significant influence on pedestrian behavior. Ten of the studies found that pedestrians are more willing to violate traffic signals if the waiting time for a safe crossing time is too long (Jason & Liotta, 1982; Russo, et al., 2018; Brosseau, et al., 2013, Koh et al., 2016; Guo et al., 2011; Ren et al., 2011; Ding et al., 2015; Yang et al., 2015; Zhang, Wang et al., 2016; Chen et al., 2017). For instance, Brousseau et al. (2013) found significantly more crossing violations at signals with waiting times (red phase times) more than 56 sec. The groups that are less likely to make a risky crossing to save time are women and older adults (Tiwari et al., 2007). Some reasons that a waiting or crossing time may be considered to be too long for some pedestrians include the closeness of public transit times or that they are in a hurry for their commute (Kruszyna & Rychlewski, 2013).

Two studies showed a relationship between pedestrian violations and familiarity with the intersection. Pedestrians were more likely to violate traffic rules when they used the intersection frequently and were familiar with the timing of the light (Jason & Liotta, 1982). Another factor that is impacted by familiarity is pedestrian distraction. Distraction may include the use of a mobile device, carrying a load, or traveling in a group. Five of the studies reviewed noted a relationship between pedestrian distraction and the negative impact on their behavior resulting in more traffic violations (Cooper et al., 2011; Russo et al., 2018; Shaaban et al., 2018; Mukherjee & Mitra, 2020; Zhuang et al., 2018).

One observation seen throughout the studies was the range of pedestrian violation rates. For studies that looked at more than one intersection, a considerable range of data was gathered within a single city. For example, in the study done in the San Francisco Bay Area, the average proportion of pedestrian violations was 29%, but the range between sites was 3% to 70% (Cooper et al., 2011). This means each study has variability. Studying more sites would help to find a true average or distribution, and to identify factors that contribute to these varied rates of pedestrian violation behaviors.

Another pattern which appeared throughout the literature was the type of pedestrian violations. The most common types were entering or exiting the crosswalk at the wrong time based on the signal and stepping outside of the crosswalk.

### 2.2.4 Conclusion

The purpose of this literature review section was to summarize the data, methods, and findings of the existing literature (represented by 32 studies) on pedestrian crossing behaviors at signalized intersections. Data collection methods, analysis methods, empirical results, and other findings from the literature have been discussed. This final section summarizes key points, notes limitations, and suggests future work.

Ten studies were conducted in North America, nine were from China, and the remaining 13 took place in other countries. Most studies used behavioral observations to collect their data, while a few utilized questionnaires. Different kinds of pedestrian behaviors have been recorded, including but not limited to: crossing against the signal, crossing mid-block or outside of the marked crosswalk, distraction, looking for cars, speed changes, waiting time, walking time, and walking speed. Different explanatory variables were investigated, but general categories included: characteristics of the pedestrians (age, gender, etc.), site (intersection/roadway), and situation (signal timing/phasing, pedestrian/traffic volumes). Most studies looked at less than 10 to 15 sites. Different types of statistical/regression analysis methods have been used, depending on their appropriateness for the data in question. The empirical findings determined that waiting time has a significant impact on the number of pedestrian violations: the longer the waiting time, the higher the number of violations. Age of pedestrians was found to influence walking speed, but older adults seem to compensate for their slower walking speed by being more willing (than younger adults) to wait for a safe crossing.

There were several limitations and gaps in the existing research literature that could be remedied in future work. First, few studies collected data at more than 10 intersections. To understand a broad and general problem in a large area such as a state, many more than 10 intersections need to be studied. Having a wide variety of study locations allows for the analysis of intersection conditions (related to roadway geometries, traffic signal operations, and surrounding land uses and neighborhood characteristics) and their relationship with pedestrian crossing behaviors. Second, there are insufficient studies conducted in the US, especially in western states like Utah. Pedestrian behavior in an older city like Chicago or New York may differ from behavior in a younger area with large streets/blocks like Salt Lake City. Third, it would also be useful to study pedestrian behaviors at various times of day and weather conditions. These variables may impact pedestrian behavior, but they have rarely been studied in past research.

## 2.3 Summary

This chapter presented the literature review of research, methods, and results about pedestrian crossing behaviors at intersections. The literature review informs the data collection and analysis approaches taken in this research project, as described in the following chapters. Because pedestrian crashes are fairly rare events and often do not include details about pre-crash pedestrian behaviors, the research team instead used a common data collection method for research like this: manual observations from recorded videos. Pedestrian behaviors that were collected included the most relevant and common ones from the literature: violations such as crossing on (flashing) *don't walk*, crossing mid-block, and crossing outside of the crosswalk; other behaviors or behavioral indicators such as waiting time, crossing time, walking speed, and distractions; and pedestrian characteristics as could best be determined. Like in some previous studies, other data—including site conditions and traffic signal timing and phasing—was also collected and/or assembled. Together, these data allowed the research team to measure pedestrian behaviors and associated factors and contextual conditions, so that a multivariate statistical analysis could be conducted to identify factors that are associated with specific pedestrian violations and other behaviors.

# 3.0 DATA COLLECTION

## 3.1 Overview

This chapter contains detailed information about the data collection and assembly processes. First, we present information about the recording of videos and how data were collected from those videos. Next, sections describe the assembly of data from traffic signals and various geospatial databases. The final section summarizes the process of assembling these data into datasets to be analyzed in the subsequent chapter.

## 3.2 Video Recording

As discussed in the literature review of Section 2.0, manual observation from a video recording is the most common method for obtaining information about pedestrian crossing behaviors at intersections. Therefore, we adopted this method in this study. Furthermore, recall that one of our objectives and contributions was to collect data from a variety of locations over different times of day, days of the week, seasons, etc., in order to capture the variety of conditions that pedestrians experience and see if those differences affect pedestrian crossing behaviors. Thus, we needed a way to easily obtain videos of pedestrians at intersections in many locations and over time.

To satisfy this need, we turned to existing videos that were recorded using UDOT traffic cameras at signalized intersections in Utah in 2019 for a different pedestrian research project (Singleton et al., 2020). That project first used stratified random sampling to select 90 signals from a variety of locations: in different regions of Utah, on state and locally owned roads, and in places with low, medium, and high pedestrian volumes. Then, using live feeds from UDOT's traffic cameras, the authors recorded at least 24 hours (and usually 48-60 hours) of video for each crosswalk, resulting in around 10,900 hours of video. Videos were recorded during all hours of the day, days of the week, and all months of the year throughout 2019.

Not all videos recorded for that project were useful for the efforts required in this research. Specifically, in order to collect specific information about pedestrian crossing behaviors (detailed in the next section), we needed videos that: showed an entire crossing/crosswalk (including waiting areas), and showed the street approaching the crossing/crosswalk. The entire crossing was required in order to record information about waiting times and behaviors, as well as to record crossing behaviors and specific times spent occupying the crosswalk. The street approach was required in order to record any pedestrians who may have crossed near to the intersection but outside of the crosswalk, as well as any pedestrians who may have crossed mid-block. Despite these requirements, a considerable portion of videos from 2019 were able to be used in this study. Three additional videos were recorded in September 2021 to capture additional data at specific locations.

Figure 3.1 shows the locations of signals where video data collection was completed. Signals are concentrated in the Wasatch Front region (where the greatest population and number of signals are located), but there are also sites throughout other parts of Utah. Locations are also in dense urban, suburban, and small-town areas. Each signal in Utah is assigned a 4-digit code/ID by UDOT to identify the unique signal. Table 3.1 and Table 3.2 list the signals studied, sorted by city (Table 3.1) and by the 4-digit signal ID (Table 3.2). Only one signal was studied in the majority of cities, however some cities saw more. The most signals studied in a single city were studied in Salt Lake City (eight); this was determined because the highest population of people in Utah reside in Salt Lake City. Looking at the most densely populated area can give the best result of pedestrian behavior. Overall, 47 crosswalks at 39 signals were included in this study.

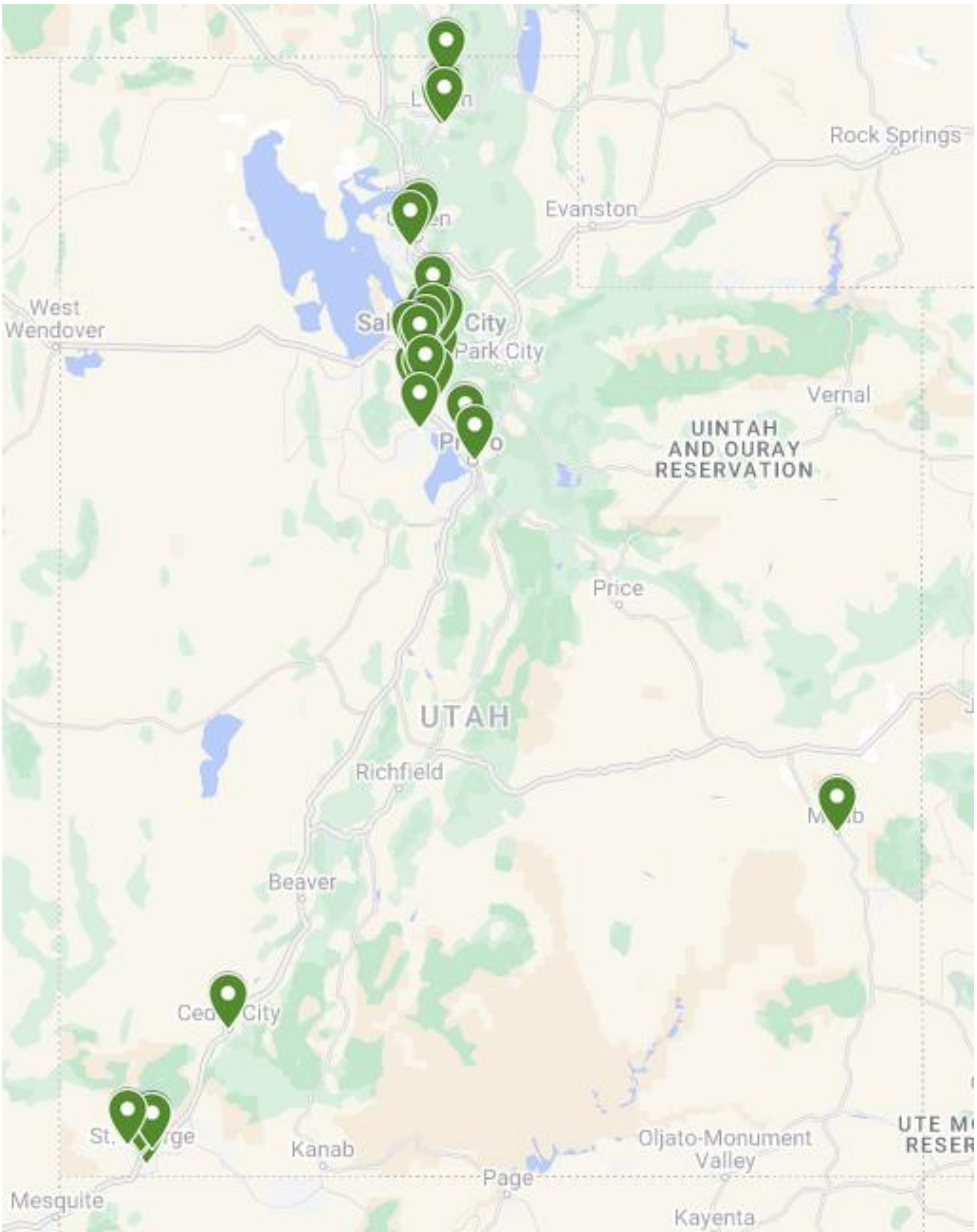



**Figure 3.1 Map showing data collection locations**

**Table 3.1 Study locations by city**

| *City* | *# Signals* | *Signal IDs* |
|---|---|---|
| Bountiful | 2 | 5363*, 5702 |
| Cedar City | 1 | 8222 |
| Cottonwood Heights | 1 | 4301* |
| Draper | 1 | 7355 |
| Eagle Mountain | 1 | 6146 |
| Herriman | 1 | 4662 |
| Kearns | 2 | 7328, 7464 |
| Logan | 4 | 5305, 5311, 5330, 5332* |
| Moab | 1 | 8302 |
| Midvale | 1 | 4301* |
| Ogden | 1 | 5024 |
| Orem | 1 | 6393 |
| Providence | 1 | 5332* |
| Provo | 1 | 6407 |
| Richmond | 1 | 5299 |
| Riverton | 1 | 7374 |
| Roy | 1 | 5093 |
| South Jordan | 1 | 7622 |
| Salt Lake City | 6 | 1021, 1229, 7086, 7184, 7218, 7475 |
| Santa Clara | 1 | 8725 |
| St. George | 4 | 8113, 8117, 8627, 8634 |
| Taylorsville | 2 | 4130, 7332 |
| Washington | 1 | 8828 |
| West Bountiful | 1 | 5363* |
| West Valley City | 4 | 4502, 4511, 7099, 7381 |

* Signal was located in two or more cities.

**Table 3.2 Study locations (39 signals, 47 crosswalks)**

| *Signal ID* | *N/S Street* | *E/W Street* | *City* | *County* | *Crosswalks* |
|---|---|---|---|---|---|
| 1021 | 1300 S | 300 W | Salt Lake City | Salt Lake | North, East |
| 1229 | 2100 S | 1300 E | Salt Lake City | Salt Lake | North |
| 4130 | 6200 S | Jordan Canal Rd / Margray Dr (1950 W) | Taylorsville | Salt Lake | North |
| 4301 | Fort Union Blvd (7000 S) | Union Park Ave (1090 E) | Midvale/Cottonwood Heights | Salt Lake | North, West |
| 4502 | 3100 S | Constitution Blvd (2700 W) | West Valley City | Salt Lake | West |
| 4511 | 4100 S | 3200 W | West Valley City | Salt Lake | South, West |
| 4662 | Herriman Pkwy (12600 S) | Herriman Main St (5100 W) | Herriman | Salt Lake | South |
| 5024 | 24th St | Washington (US-89) | Ogden | Weber | West |
| 5093 | 4800 S | 1900 W (SR-126) | Roy | Weber | West |
| 5299 | Main St (SR-142) | US-91 (200 W) | Richmond | Cache | East |
| 5305 | 200 N (SR-30) | Main St (US-89 / US-91) | Logan | Cache | North, East |
| 5311 | 1400 N | Main St (US-91) | Logan | Cache | North, West |
| 5330 | 1700 S / 800 W | US-89/US-91 | Logan | Cache | East |
| 5332 | 1200 S | Main St (SR-165) | Logan/Providence | Cache | North |
| 5363 | 400 N (SR-106) | 500 W (US-89) | Bountiful/West Bountiful | Davis | North |
| 5702 | 500 S | Main St | Bountiful | Davis | East |
| 6146 | Cory Wride Hwy (SR-73) | Ranches Pkwy | Eagle Mountain | Utah | North |
| 6393 | 1600 N | State St (US-89) | Orem | Utah | North, West |
| 6407 | Center St | University Ave (US-189) | Provo | Utah | West |
| 7086 | North Temple | Redwood Rd (SR-68) | Salt Lake City | Salt Lake | North, West |
| 7099 | 2320 S | Redwood Rd (SR-68) | West Valley City | Salt Lake | West |
| 7184 | 900 S | 700 E (SR-71) | Salt Lake City | Salt Lake | East |
| 7218 | Wakara Wy | Foothill Blvd (SR-186) | Salt Lake City | Salt Lake | Southwest |
| 7328 | 5400 S (SR-173) | 4015 W | Kearns | Salt Lake | North |
| 7332 | 5400 S (SR-173) | 2200 W | Taylorsville | Salt Lake | North |
| 7355 | 13800 S | Bangerter Hwy (SR-154) | Draper | Salt Lake | South |
| 7374 | 12600 S (SR-71) | 2700 W | Riverton | Salt Lake | West |
| 7381 | 3500 S (SR-171) | 5600 W (SR-172) | West Valley City | Salt Lake | East |
| 7464 | 5415 S (SR-173) | 4420 W | Kearns | Salt Lake | North |
| 7475 | 50 S HAWK | 300 W (US-89) | Salt Lake City | Salt Lake | North |
| 7622 | 11400 S (SR-175) | Redwood Rd (SR-68) | South Jordan | Salt Lake | East |
| 8113 | Main St/Hilton Dr | Bluff St (SR-18) | St. George | Washington | East |
| 8117 | St. George Blvd (SR-34) | Main St | St. George | Washington | South |

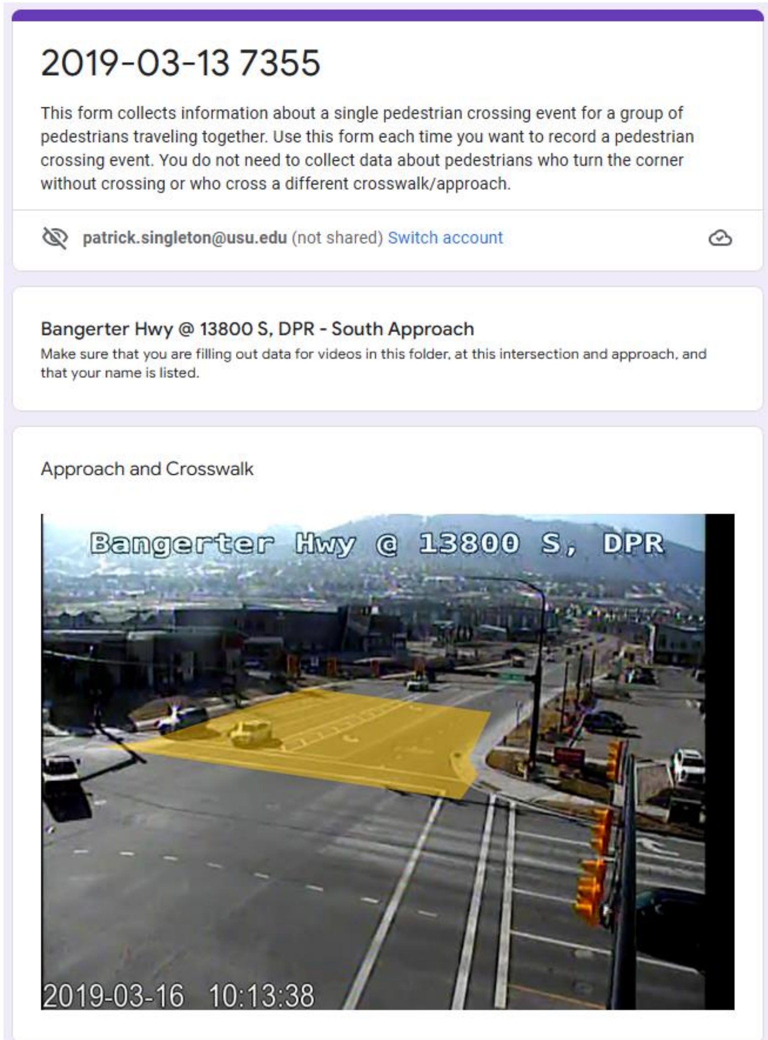
| | | | | | |
|---|---|---|---|---|---|
| 8222 | 200 N (SR-56) | I-15 NB Ramps/1225 W | Cedar City | Iron | South |
| 8302 | Center St | Main St (US-191) | Moab | Grand | North, East |
| 8627 | 850 N | 3050 E | St. George | Washington | West |
| 8634 | Brigham Rd | River Rd | St. George | Washington | North |
| 8725 | Pioneer Pkwy | Rachel Dr | Santa Clara | Washington | North |
| 8828 | Red Cliffs Dr / Telegraph St | Green Springs Dr | Washington | Washington | West |

## 3.3 Video Data Collection

Much of the data collection process involved trained undergraduate research assistants viewing recorded videos and transcribing data. Students watched a video at a faster-than-real-time speed, and then paused or slowed down when they saw a pedestrian crossing the street being studied. When this happened, the students recorded information about the pedestrian (or group of pedestrians traveling together) in a data collection form. They then proceeded to the next pedestrian/group. This information was saved in an online form, and survey data were later downloaded as a CSV file. A trained graduate research assistant and one of the principal investigators then performed quality checks on the data and made corrections as needed. These steps from data collection through quality control are described in the following subsections.

### 3.3.1 Data Collection Form

The data were collected in a consistent manner through a custom Google Form survey developed specifically for this project. The survey included six sections: Date, Origin, Pedestrian Information, Waiting, Crossing, Destination, and Final Notes. Each section contained multiple questions about a certain type of information, as described in the following paragraphs. The sections were designed to collect required information in roughly the order that they were observed in the video. At the end of each section, there was also a free response question to allow for unique information to be collected if a rare situation was observed that could not be adequately documented using the existing questions. Each survey was customized with a title and figures (relating to several questions) that were specific to each video location, to aid in obtaining information from a specific camera and field of view. For example, Figure 3.2 shows the start of an example data collection form.


2019-03-13 7355

This form collects information about a single pedestrian crossing event for a group of pedestrians traveling together. Use this form each time you want to record a pedestrian crossing event. You do not need to collect data about pedestrians who turn the corner without crossing or who cross a different crosswalk/approach.

patrick.singleton@usu.edu (not shared) Switch account

Bangerter Hwy @ 13800 S, DPR - South Approach

Make sure that you are filling out data for videos in this folder, at this intersection and approach, and that your name is listed.

Approach and Crosswalk



**Figure 3.2  Example pedestrian event data collection form**

The next section asked questions about where the pedestrian (or group) came from before crossing the street. A custom figure showed the potential origin locations. For example, as shown in Figure 3.3, the blue shading represents crosswalk areas, the green shading represents connecting streets to the one being studied, and the yellow shading represents the approach on either side of the street. This type of figure was used in both the Origin and Destination sections.


**Figure 3.3 Example figure showing origins and destinations**

The third section collected pedestrian information about the person or people being observed. Questions covered topics including group size, age, and gender (assessed as best as could be seen from the video); there were options for “adult of unknown age” and “unknown gender.” This section also contained a question about whether or not the person was traveling by a different mode of active transportation than walking—such as a bicycle, skateboard, or wheelchair—or pushing a stroller or carrying a load. Figure 3.4 was included in the training documents as an example, but it was not shown in the data collection forms.


**Figure 3.4 Figure showing example pedestrian information**

After information on each pedestrian was gathered, the behavior of the pedestrian(s) while waiting to cross was collected. Questions included the waiting location (as depicted graphically in each form, see example in Figure 3.5), the time the pedestrian arrived in the waiting area, the number of other people waiting there, the number of vehicles that passed the crossing location 10 seconds before and 10 seconds after the pedestrian arrived, and other waiting behaviors observed (e.g., pressed the pedestrian push-button, paced, or left before crossing). Waiting behavior was recorded to measure impatience or delay (which can affect crossing behaviors) as well as opportunities/gaps to cross at the time when the pedestrian(s) arrived at the intersection.


**Figure 3.5  Example figure showing waiting areas**

The fifth section, about the pedestrian crossing event itself, was the longest and most important section. First, a question asked about the crossing location, aided by a figure (see Figure 3.6 for an example): in the crosswalk area, mid-block away from the crosswalk, or in the middle of the intersection. This measured whether or not the pedestrian(s) crossed in an area where they were not expected to be. Other data collected in this section included the direction of crossing (e.g., left to right or right to left), the time the pedestrian(s) departed the near curb, and the time they arrived at the far curb. These last two questions allowed for the calculation of crossing times and (along with crossing distance) walking speeds. The number of other pedestrians and their crossing directions was also noted in this section, since research suggests that pedestrian crossing behaviors are affected by the presence and behavior of other pedestrians. Other information collected in this section included additional pedestrian behaviors (changed speed, paused, or appeared to be distracted) and any obstacles encountered, such as a car, water, snow, or other debris blocking the crosswalk.

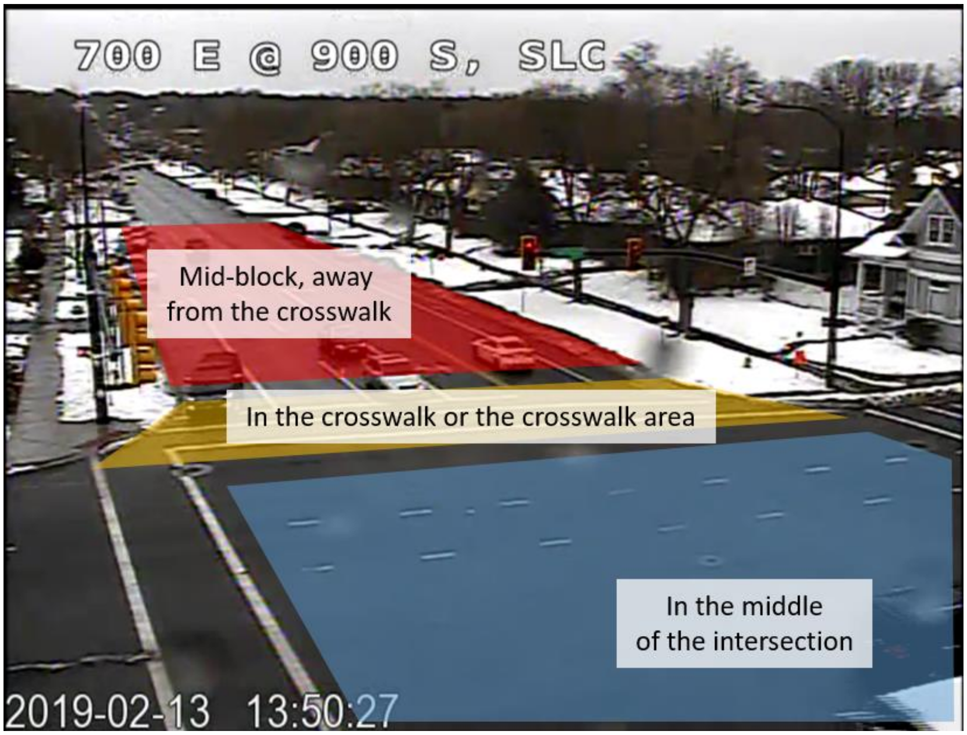



**Figure 3.6 Example figure showing crossing locations**

The final sections asked for the destination of the pedestrian(s) (see Figure 3.3) and any final notes about the pedestrian crossing event. This gave the data collectors an opportunity to note anything out of the ordinary or anything which required a closer look.

### 3.3.2 Quality Assurance / Quality Control (QA/QC)

All data collection personnel (usually undergraduate research assistants) were trained on the use of the data collection form. After collection, the data were spot-checked by a trained graduate research assistant to ensure accurate information had been collected. A video was selected at random and then three to five events were checked for accuracy. Three events were checked for smaller video files, four for medium-sized video files, and five for large video files. Answers to each question in the data collection were reviewed to find any mistakes in data collection. Any mistakes found were corrected and then the file was analyzed in more detail to catch any other potential mistakes. Data collectors making consistent mistakes were contacted and re-trained while their incorrectly collected data were corrected.

Additionally, one of the principal investigators also performed many logical checks on the entire dataset to ensure records were as complete as possible and information in each event was consistent across fields. For example, there were some instances where timestamps implied negative or very long crossing times, due to a timestamp entry error. In most cases, data entry errors and missing data were corrected by returning to the original videos and editing the records.

Despite these best efforts and quality control, some errors may remain in the datasets. For example, some data collection personnel may have been more or less accurate or had different perceptions of the age and gender of people being observed (the most subjective questions on the survey). Minor errors may also remain in terms of the timestamps recorded from the videos or the behaviors observed. However, the researchers believe there are no systematic errors that remain in any of the items of data that were collected from the videos. The analysis was done in steps, as more data were collected and as the sample size increased. At each step, the same patterns emerged; therefore, the researchers concluded any remaining errors likely do not significantly bias the data analyses or results.

## 3.4 Traffic Signal Data Collection

In addition to data about pedestrian behaviors, we also collected data about the traffic signal status at times when pedestrians were observed. By comparing pedestrian crossing timestamps to the statuses of the pedestrian/walk indication and vehicle signal heads for conflicting movements, we could determine if the pedestrian started/finished crossing on the *Walk*, flashing *Don't Walk*, or steady *Don't Walk* indications, or if the pedestrian was crossing against a green indication displayed for any conflicting protected vehicle movement, which was then used to measure specific types of pedestrian violation behaviors. We obtained this information from high-resolution data logs from traffic signal controllers, archived by UDOT.

Traffic signal controllers manage many events at signalized intersections, including active phase or pedestrian events, phase control and overlap events, detection and preemption events, etc. Until recently, this rich set of signal event data was not being systematically logged. Smaglik et al. (2007) developed a general method and module for automatically logging time-stamped event data from traffic signal controllers. Each record includes a timestamp, an event code, and an event parameter representing a phase or overlap number, detector channel, or other information (Sturdevant et al., 2012). This information can then be obtained through the deployment of the Automated Traffic Signal Performance Measures (ATSPM) system (Day et al., 2016). UDOT is a national leader in the development and deployment of ATSPMs; as of Fall 2018, UDOT was centrally archiving data from more than 1,900 state- and locally owned signals (Taylor and Mackey, 2018).

For the purposes of this project, three pedestrian active phase events were relevant. These events are also depicted in Figure 3.7.

- *Event code 21, Pedestrian Begin Walk*: This event occurs with the activation of the *walk* indication for a particular phase.
- *Event code 22, Pedestrian Begin Clearance*: This event occurs with the activation of the flashing *don't walk* indication for a particular phase.
- *Event code 23, Pedestrian Begin Steady Don't Walk*: This event occurs when the *don't walk* indication becomes steady, with the termination of the pedestrian clearance interval.


**Figure 3.7 Pedestrian active phase events 21 (left), 22 (center), and 23 (right)**

We were also interested in the status of the vehicle signal heads (green, yellow, red) for any protected motor vehicle movements that conflicted with the crosswalk where the pedestrian was crossing. Figure 3.8 shows an example of which protected vehicle phases we considered to be conflicting with the pedestrian crossing.

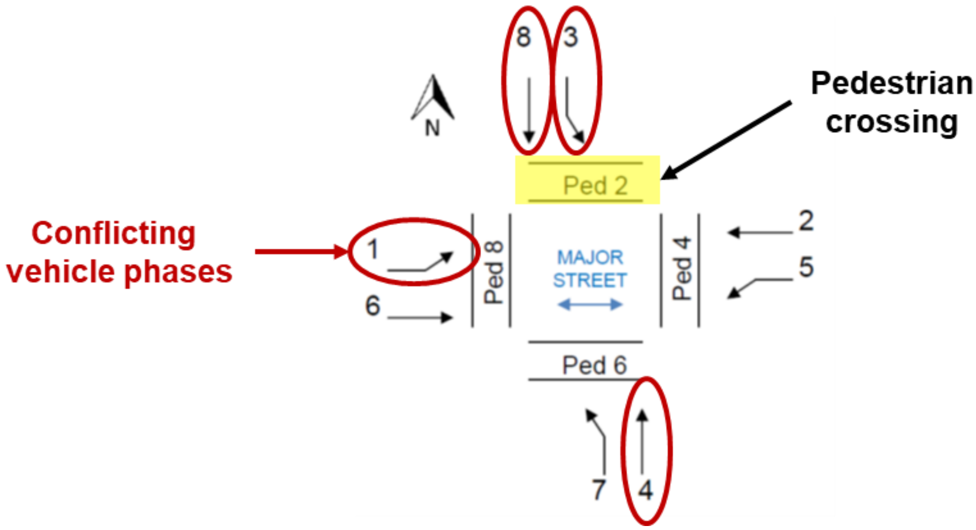



**Figure 3.8  Example of conflicting protected vehicle movements**

For each video, we downloaded the relevant event codes from ATSPM and then filtered them for the particular crossing being studied, using phase number as a filter. As described later in this section, we then used data processing to automatically calculate the status of the pedestrian signal for the crossing in question (and all conflicting motor vehicle movements) at each timestamp recorded by the video observers: time arrived in the waiting area, time departed the near curb, time arrived at the far curb. Together, this information aided in the identification of temporal violations.

One final note about traffic signal status: Sometimes the timestamps in the videos were slightly different from the timestamps in the signal data, due to latency in the communication methods (between the video feed and the computer on which it was recorded). To address this, each set of videos was watched and a sample of between four and eight events were captured at different points during the data collection. The timestamp for the relevant controller log event (e.g., *walk* indication turns on) was compared to the video timestamp, and a time difference was noted. These differences were then averaged for each video, and all events were adjusted accordingly. In almost all cases, the average difference was no more than 3 seconds, and many were less than 1 second. It should be noted that some videos had inconsistent timestamp shifts, starting positive at some points and going negative at other points. This should be kept in mind when evaluating the temporal violations later in Chapter 4.0.

## 3.5 Geospatial Data Collection

Recall that one of the objectives of this study was to identify site characteristics—including roadway geometry, traffic signal timing, land uses, and neighborhood built environment and socio-demographic characteristics—that may affect pedestrian behaviors at signalized intersections. As such, detailed data regarding different features at selected sites were gathered from existing geospatial databases and through manual data collection utilizing aerial and street-level imagery.

### 3.5.1 Crossing and Intersection Characteristics Obtained Through Manual Data Collection

Several potentially relevant intersection and road network characteristics were collected manually utilizing satellite and street-level imagery and some databases. These characteristics were: intersection type, crosswalk marking types, distances and lanes crossed, traffic volume and speed limit of street crossed, presence and width of median, distance to the nearest crosswalk, and the presence of street lighting, bike lanes, and nearby bus stops along the street being crossed. The following paragraphs briefly summarize these crossing and intersection characteristics and how their attributes were obtained.

**Intersection type** is the number or configuration of legs (approaches) that join to form an intersection. Signals with more legs or approaches may be less safe for pedestrians than intersections with fewer legs/approaches due to greater opportunities for exposure and increased intersection complexity. Such complexity may also make it more difficult for pedestrians to cross, leading to different pedestrian behaviors and violation rates. The vast majority of Utah signals are at 4-leg intersections, but there are also 3- and 5-leg intersections with signals. Mid-block signals or pedestrian hybrid beacons (also known as high-intensity activated crosswalks or HAWK signals) are also present in the dataset. While some Utah signals are located at single-point urban interchanges or diverging diamond interchanges, none of the videos in this study were located at these types of signals.

While we did not expect major variations in pedestrian behaviors due to different **crosswalk marking** types, it could be that pedestrians are more or less likely to step outside of the crosswalk when it is marked in a certain way. The nomenclature of marked crosswalks varies across jurisdictions, but a common typology is shown in Figure 3.9. Some agencies may give crosswalks with longitudinal markings different names (e.g., high-visibility crosswalks) or use them in certain typical situations (e.g., at school crossings). In Utah, most crosswalks at signals have standard markings; continental markings tend to be more common near schools.

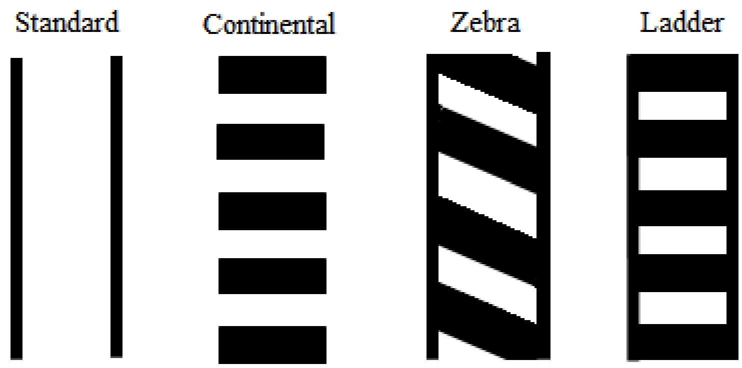



**Figure 3.9  Crosswalk marking types**

Pedestrians may behave differently at intersections with shorter or longer **crossing distances**, or those with more or fewer lanes to cross. Shorter street crossings mean that it takes pedestrians less time to cross the street, which means pedestrians crossing against the signal can accept a smaller gap in motor vehicle traffic. Crossing lengths were calculated in Google Earth, measuring the curb-to-curb distance along the center of the crosswalk. The average crosswalk length at Utah signals in our study was 85 ft, reflecting both the location of many signals along multi-lane arterials as well as the fact that Utah city streets are generally wider than elsewhere in the US (Smith, 2015).

Similarly, pedestrian behavior may differ depending on traffic conditions, notably the **traffic volumes** and **speed limits** of the streets being crossed. Where available, speed limits were taken from UDOT open data about speed limits and speed limit signs; otherwise, Google StreetView imagery was searched to find speed limits for the approaching roadway. Similarly, annual average daily traffic (AADT) volumes for the crossed streets were obtained from UDOT open data. AADT was not available for 9 locations (mostly smaller side streets), so it was assumed that these had an AADT of 2,000 vehicles/day.

Several other crossing, intersection, or roadway characteristics were collected in order to test whether or not they were significantly associated with pedestrian behaviors at signals. The presence and width of any **median** was recorded. Street lighting information was taken from nighttime screenshots of the videos; all signals in the study had some degree of working streetlights. The presence of **bike lanes** (of any type) as well as the presence of a **transit stop** on the portion of each leg approaching/leaving the intersection (within 300 ft of the crosswalk) were identified and recorded. We also recorded whether or not there was a **gas station and convenience store** at the intersection. Finally, we measured the **distance to the nearest marked crossing** upstream of the study crosswalk, as a measure of crosswalk spacing (and potentially walking distance to the next crossing) on that approaching roadway.

3.5.2 Other Geospatial Data

Several other signalized intersection attributes relevant for the study of factors affecting pedestrian crashes were obtained from existing databases, including land use and built environment data, and neighborhood sociodemographic characteristics. When appropriate, these data were calculated for a circular area within 0.25-mi (400 m) of each intersection. The assembly of each of these types of data is described in the notes below.

- The number of nearby transit stops, liquor stores, schools, and places of worship were calculated from point data obtained from the Utah Geospatial Resource Center (UGRC) website. From the same source, we also obtained the acreage of parks near each signal.

- Several built environment characteristics were obtained from data contained in the EPA's Smart Location Database (SLD). Variables obtained were: housing unit density, population density, employment density, jobs per household (a measure of land use diversity), and intersection density. Originally measured at the Census block group level, we calculated our values using an area-weighted average of the portions of each block group that fell within the 0.25-mi circular buffer around each intersection.

- A similar calculation process was used to generate information about sociodemographic composition of neighborhoods around each signal. Using block group data from the U.S. Census Bureau's 2016-2020 5-year American Community Survey (ACS) estimates, we obtained information on average household size, median income, average household vehicle ownership, percentage of the population with a disability, and percentage of the population with Hispanic or non-white race/ethnicity.

### 3.6 Data Assembly and Processing

We assembled and processed multiple data sources in order to conduct various statistical analyses of pedestrian behavior at intersections. The following paragraphs describe our process of assembling, calculating, and merging datasets together in order to prepare for these analyses.

As described later in Chapter 4.0, the statistical analyses describe the crossing behaviors of pedestrians at signalized intersections and identify associated factors and contextual conditions. Each unit (row) of the dataset was an observed pedestrian or pedestrian group, obtained directly from the video data collection process described in Section 3.3. To this dataset were added other information about the pedestrian traffic signal status (Section 3.4) and the geospatial data about the roadway, intersection, and surrounding characteristics (Section 3.5). This process is described in the next two paragraphs.

First, in order to add information about the pedestrian and vehicle traffic signal statuses, a custom script and functions were written in the open-source statistical program R. Given a signal ID, phase number, and timestamp, the function returned the pedestrian signal status (*Walk*, flashing *Don't Walk*, steady *Don't Walk*) as well as other information about the previous/next event code and time since/until the walk indication. Another function took a set of timestamps and a pedestrian phase number, and returned the number of seconds during which a conflicting protected vehicle movement had a green indication. (See Section 4.5 for more details about how this information was used to determine temporal violations.) Next, geospatial data about the roadway, intersection, and surrounding characteristics were linked using the common signal ID field.

Finally, additional information about conditions (time of day, weather, etc.) was added. Time-of-day and day-of-week information was converted directly from the timestamps of the pedestrian events. Weather information for the time of the crossing event was obtained from a weather model developed by Iowa State University. The Iowa Environmental Mesonet

Reanalysis (IEMRE) dataset provided hourly estimates of temperature and precipitation for a given latitude and longitude point anywhere in the US, taken from modeling and interpolation between validated site-specific weather station observations.

### 3.7 Summary

This chapter presented details about the processes of data collection and assembly. Data were obtained from a number of sources, including recorded videos, traffic signals, and geospatial databases. Together, these data were processed and assembled into a master dataset in preparation for the various statistical analyses that are presented in the following chapter.

# 4.0 DATA EVALUATION

## 4.1 Overview

This chapter contains results from the descriptive and statistical analyses of pedestrian crossing behaviors and violations. The first section provides the descriptive statistics of the different datasets as well as a descriptive analysis of the data collected. The second section describes the statistical analysis method employed: multilevel regression modeling. Later sections report the results of the various statistical analyses for pedestrian behaviors, spatial violations, and temporal violations.

## 4.2 Descriptive Statistics and Descriptive Analysis

This descriptive analysis covers 5,589 pedestrian events recorded at 47 crosswalks at 39 signals in 25 cities across the state of Utah. First, we describe the pedestrian crossing events and their characteristics. Next, we summarize characteristics of the crossing and intersection locations.

Note that we are using the word "pedestrian" to describe the people involved in these events. As will be seen, a meaningful share of these crosswalk users were actually operating a vehicle while crossing: riding a bicycle or scooter, rolling on a skateboard or in a wheelchair, etc. Our use of "pedestrian" is for convenience sake only, and is meant to include all crosswalk users (unless otherwise specified).

### 4.2.1 Pedestrian Events

Table 4.1 shows the descriptive statistics for the 5,589 pedestrian events in this study.

**Table 4.1 Descriptive statistics for pedestrian events (N = 5,589)**

| *Variable* | *#* | *%* | *Mean* | *SD* |
|---|---|---|---|---|
| **Pedestrian information** | | | | |
| Group size (# pedestrians) | | | 1.41 | 1.07 |
| Age | | | | |
| Child | 165 | 3.0% | | |
| Teen | 305 | 5.5% | | |
| Young adult | 2084 | 37.3% | | |
| Middle-aged adult | 1867 | 33.4% | | |
| Older adult (65+) | 146 | 2.6% | | |
| Adult of unknown age | 1317 | 23.6% | | |
| Gender | | | | |
| Male presenting | 3466 | 62.0% | | |
| Female presenting | 1777 | 31.8% | | |
| Unknown gender | 1187 | 21.2% | | |
| Other characteristics | | | | |
| Stroller | 63 | 1.1% | | |
| Carrying load | 221 | 4.0% | | |
| Wheelchair | 51 | 0.9% | | |
| Skateboard | 56 | 1.0% | | |
| Scooter | 80 | 1.4% | | |
| Bicycle | 634 | 11.3% | | |
| Other | 191 | 3.4% | | |
| **Waiting information** | | | | |
| # other people waiting | | | 0.20 | 0.71 |
| # vehicles passing (past 10 sec) | | | 3.71 | 4.31 |
| # vehicles passing (next 10 sec) | | | 3.17 | 4.04 |
| Waiting behaviors | | | | |
| Pressed pedestrian push-button | 2802 | 50.1% | | |
| Paced or otherwise seemed impatient | 289 | 5.2% | | |
| Left waiting area without crossing street | 328 | 5.9% | | |
| Other | 211 | 3.8% | | |
| Waiting time (sec) | | | 25.65 | 28.41 |
| **Crossing information** | | | | |
| Crossing location | | | | |
| In the crosswalk or the crosswalk area | 5133 | 97.6% | | |
| Mid-block, away from the crosswalk | 124 | 2.4% | | |
| In the middle of the intersection | 4 | 0.1% | | |
| # other people crossing (same direction) | | | 0.30 | 0.97 |
| # other people crossing (opposite direction) | | | 0.24 | 0.92 |
| Crosswalk markings | | | | |
| Stayed within the crosswalk markings for all or almost the whole crossing | 4355 | 77.9% | | |
| Stepped outside of the crosswalk markings for part of the crossing | 536 | 9.6% | | |
| Was outside of the crosswalk markings for most if not all of the crossing | 479 | 8.6% | | |
| Other | 30 | 0.5% | | |
| Crossing behaviors | | | | |
| Changed speed (e.g., walk to run, or run to walk) | 315 | 5.6% | | |
| Paused in the middle of the street | 85 | 1.5% | | |
| Seemed distracted by phone or something else | 31 | 0.6% | | |
| Crossing obstacles | | | | |
| Car blocking the crosswalk | 228 | 4.1% | | |
| Snow pile, water puddle, or debris | 92 | 1.6% | | |

| | | | | |
|---|---|---|---|---|
| Other | 10 | 0.2% | | |
| Crossing time (sec) | | | 16.29 | 6.27 |
| **Temporal information** | | | | |
| Day of week | | | | |
| Weekday | 4895 | 87.6% | | |
| Weekend | 694 | 12.4% | | |
| Time of day | | | | |
| Overnight (00:00–05:59) | 221 | 4.0% | | |
| Morning (06:00–11:59) | 1303 | 23.3% | | |
| Afternoon (12:00–17.59) | 2905 | 52.0% | | |
| Evening (18:00–23.59) | 1156 | 20.7% | | |
| AM peak hours (06:00–07:59) | 283 | 5.1% | | |
| PM peak hours (16:00–17:59) | 1107 | 19.8% | | |
| **Weather information** | | | | |
| Temperature (°F) | | | 48.72 | 20.30 |
| Less than 32°F | 988 | 17.7% | | |
| 32–49°F | 2569 | 46.0% | | |
| 50–64°F | 780 | 14.0% | | |
| 65–79°F | 563 | 10.1% | | |
| 80°F or more | 685 | 12.3% | | |
| Hourly precipitation (in) | | | 0.00 | 0.02 |
| 0.01in or more | 455 | 8.1% | | |
| 0.05in or more | 85 | 1.5% | | |

Figure 4.1 shows summaries of the pedestrian and crossing event characteristics. Understanding the age and gender demographics of the sample is important; age and gender were noted in several previous research studies as important factors affecting pedestrian behaviors. Overall, most pedestrians appeared to be adults of working age. We identified roughly a third of all pedestrian events as involving either a young adult (37%) and/or a middle-aged adult (33%). Less frequently observed were teens (6%), children (3%), and older adults (3%). Regarding gender, male pedestrians were observed more frequently (62%) than female pedestrians (32%). Note that for a fifth to a quarter of events, the age (24%) or gender (21%) of pedestrians could not be determined. This is expected because signal camera angles, resolution, and lighting did not always allow for a determination of age or gender. It is important to note that these categorizations are subjective and may have been affected by systematic biases related to the guesses of the data collectors (who were mostly undergraduate students). Also, numbers may add up to more than 100% because events with multiple pedestrians could have multiple genders or ages selected.

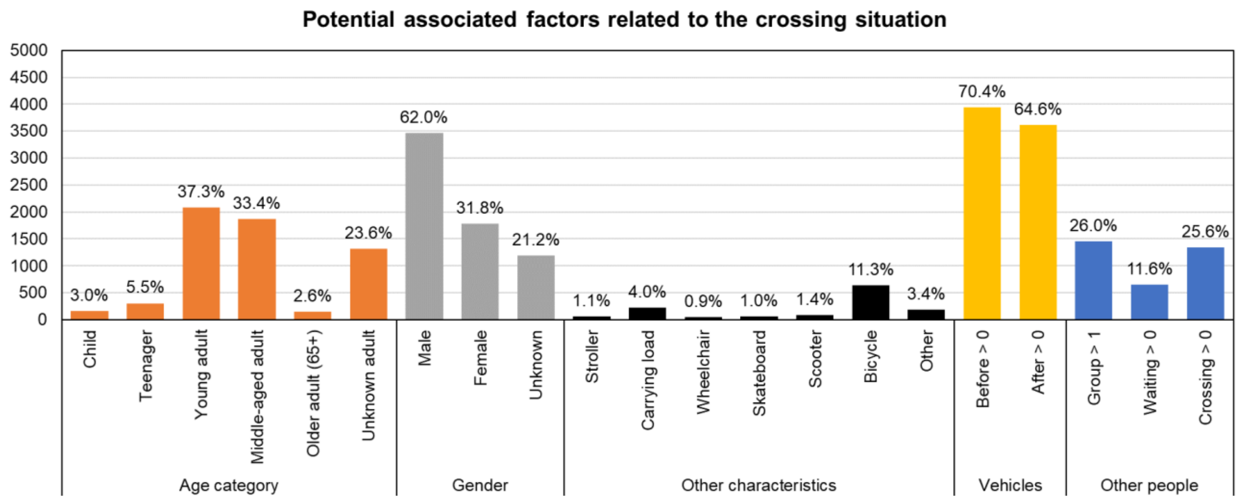



**Figure 4.1 Characteristics of pedestrians and pedestrian crossing events**

We feel more comfortable with our ability to accurately record other, less subjective characteristics of pedestrians. Notably, 11% of events involved a person riding a bicycle in the crosswalk. Around 4% of events had someone carrying a visible load, such as bags of groceries. The use of other pedestrian equipment and micromobility modes—strollers, wheelchairs, skateboards, and scooters—were observed in about 1% of events, each. The "other" event category (3%) was used to allow data recorders to note other situations; many recorded people walking pets.

Other pedestrian event characteristics recorded include group size, the presence of other people, and the presence of vehicles. The average group size was 1.4 people; 26% of events involved pedestrians traveling in a group of 2+ people. 12% of events involved other pedestrians in the same waiting area, while 26% of events involved other pedestrians crossing at the same time; these numbers are for pedestrians traveling in a different group than the subject pedestrian(s). When pedestrians arrived at the waiting area, most of the time there were other vehicles traveling along the street being crossed. Vehicles had passed the crossing location in the previous 10 seconds for 70% of events (average 3.7 vehicles), while vehicles were passing in the next 10 seconds for 65% of events (average 3.2 vehicles). In other words, most of the time pedestrians had to wait when arriving at the intersection.

Figure 4.2 shows the distribution of pedestrian waiting times and other behaviors observed while waiting. Waiting time was measured as the difference between when the pedestrian arrived in the waiting area (adjacent to the street) and when they started to cross the street by stepping off the curb. As previously noted, very few pedestrians (5%) did not wait when reaching the intersection. The plurality of pedestrians (39%) waited only between one and 10 seconds, with a decreasing share waiting each 10-second increment longer. More than half of pedestrians (56%) waited 20 seconds or less, while most (91%) waited 70 seconds or less. 12% of pedestrians waited longer than one minute, and only 1% waited longer than two minutes. The average waiting time was 26 seconds (0.43 minutes).

Regarding waiting behaviors, we observed around 50% of pedestrians who pressed the push-button. It should be noted that this may be an underestimate of the true push-button rate, since it was sometimes difficult to determine button-press behavior at far sides of the intersection or at night. There are also other reasons why this is not higher: someone else might have already pressed the button, or crossings can also be set to pedestrian recall (where the *walk* indication turns on automatically without having to press the button). Around 5% of pedestrians appeared to pace or otherwise seem impatient while waiting; this could be runners trying to keep active, or people looking for a gap in traffic. We also captured 6% of pedestrians who approached the intersection, waited briefly, and later left the waiting area without crossing the street. These observations were removed from later analyses of pedestrian crossing behaviors and spatial/temporal violations.

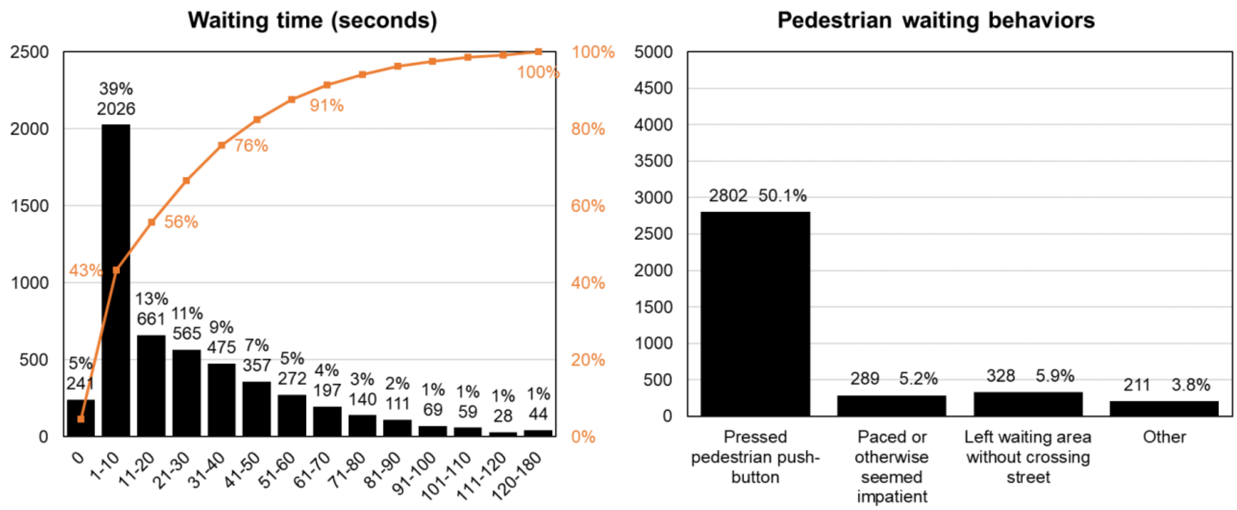



**Figure 4.2 Pedestrian waiting time distribution and waiting behaviors**

Figure 4.3 shows the distribution of pedestrian crossing times, measured as the difference between when the pedestrian started crossing (left the first curb) and finished crossing (reached the second curb). The figures show an approximate normal distribution; the mean crossing time was 16 seconds (0.27 minutes). Almost half of people (46%) took 15 seconds or less to cross the street, while only 2% took longer than 30 seconds to cross. Most pedestrians (59%) crossed from curb to curb in between 11 and 20 seconds.

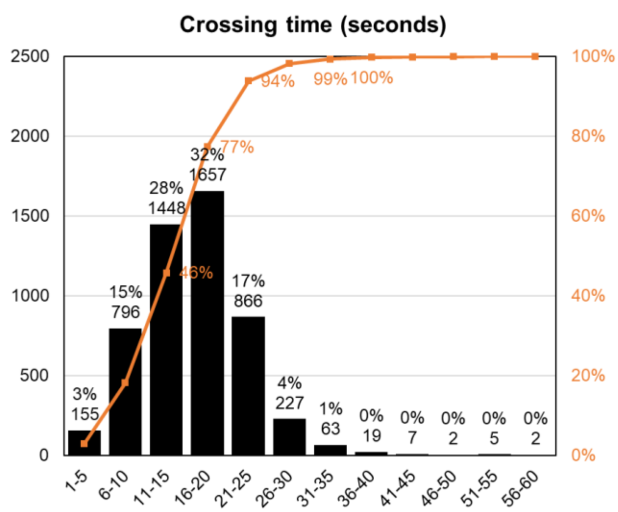



**Figure 4.3 Pedestrian crossing time distribution**

Of course, these crossing times depend on both walking speed and crossing distance. Figure 4.4 plots observations to show the relationship between crossing distance, crossing time, and implied walking speed. In general, crossing time is longer for longer-distance crosswalk lengths, although there is still considerable variation in crossing time at all distances. The orange line shows an implied 4.0 ft/s walking speed (as suggested in the Utah MUTCD), which falls at the upper end of where most of the points are clustered; 8.5% of pedestrian crossings were slower than this. The red line shows an implied 3.5 ft/s walking speed (as suggested in FHWA's MUTCD); only 3.0% crossings were slower than this. In the MUTCD, walking speed is used to determine the pedestrian clearance time, which affects the length of the pedestrian change interval (flashing *don't walk*). These findings suggest that timing Utah signals using an assumed walking speed of 3.5 ft/s (instead of the current 4.0 ft/s) would accommodate the walking speeds of at least 5% more pedestrians, and over 95% of all pedestrians.

Notice also the lower band of observations (in the lower portion of Figure 4.4) at an implied speed much faster than the other observations. At any given crossing distance, there appear to be two peaks of crossing times. This is likely the group of crosswalk users running or riding bicycles, who can travel at a higher speed than pedestrians walking.

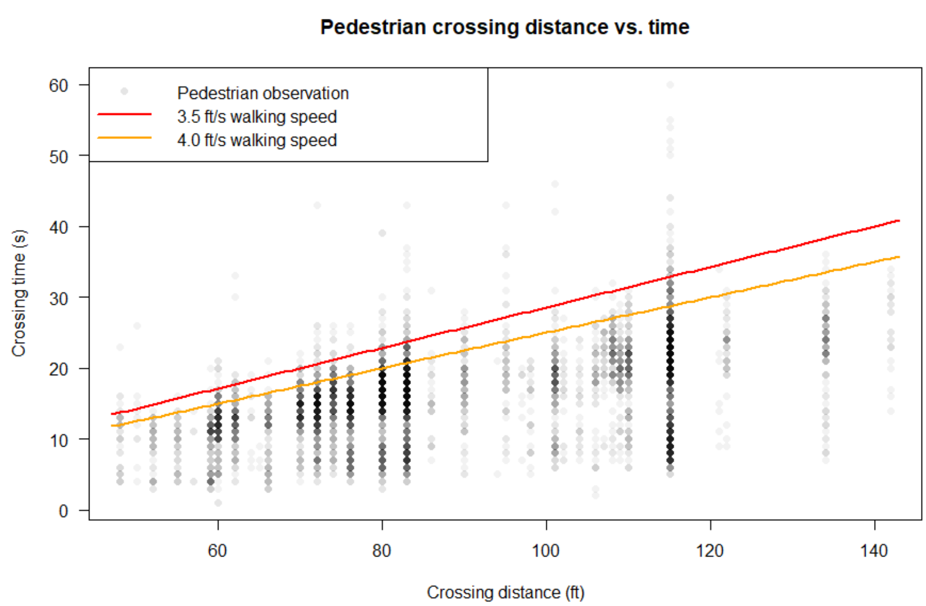



**Figure 4.4 Scatterplot of crossing distance by pedestrian crossing times**

Another recent UDOT research project, conducted by Brigham Young University (BYU) in 2018 (Schultz et al., 2019) looked specifically at pedestrian walking speeds at signalized intersections. To compare our results with those from the BYU study, we also calculated crossing speed percentiles and the share of observations greater/less than 4 ft/s. Results are shown in Table 4.2. Since the two studies used different inclusion criteria for pedestrians, we also filtered our dataset to better match the BYU study; however, they also excluded runners and joggers, but we did not have this information in our dataset, so our speeds may be slightly faster.

**Table 4.2 Crossing speeds by various characteristics**

| | | *Percentile speed (ft/s)* | | | | | *% w/ speed (ft/s)* | |
|---|---|---|---|---|---|---|---|---|
| *Category* | *Sample size* | *5th* | *10th* | *15th* | *50th* | *85th* | *≥ 4.0* | *< 4.0* |
| **All observations (not filtered)** | | | | | | | | |
| All users | 5247 | 3.71 | 4.00 | 4.24 | 5.19 | 9.17 | 91.5% | 8.5% |
| Other characteristics | | | | | | | | |
| Wheelchair | 51 | 3.30 | 3.79 | 4.04 | 5.59 | 7.67 | 84.3% | 15.7% |
| Skateboard | 55 | 5.24 | 6.00 | 6.59 | 9.83 | 12.10 | 100.0% | 0.0% |
| Scooter | 78 | 5.56 | 6.68 | 7.89 | 11.87 | 16.43 | 97.4% | 2.6% |
| Bicycle | 616 | 5.22 | 6.39 | 7.69 | 11.00 | 14.84 | 98.5% | 1.5% |
| Other | 174 | 3.62 | 3.82 | 4.00 | 4.80 | 6.55 | 86.2% | 13.8% |
| None of the above (pedestrians) | 4295 | 3.69 | 4.00 | 4.21 | 5.00 | 6.11 | 90.6% | 9.4% |
| **Filtered to match BYU study*** | | | | | | | | |
| All users | 3612 | 3.77 | 4.00 | 4.21 | 5.00 | 5.94 | 91.5% | 8.5% |
| Other characteristics | | | | | | | | |
| Stroller | 50 | 3.61 | 3.75 | 3.88 | 4.55 | 5.08 | 82.0% | 18.0% |
| Carrying load | 167 | 3.60 | 3.73 | 4.00 | 4.61 | 5.53 | 85.0% | 15.0% |
| Wheelchair | 42 | 3.33 | 3.95 | 4.20 | 5.50 | 7.65 | 85.7% | 14.3% |
| Not wheelchair (pedestrians) | 3570 | 3.77 | 4.00 | 4.21 | 5.00 | 5.93 | 91.6% | 8.4% |
| Age | | | | | | | | |
| Child | 104 | 3.60 | 3.75 | 4.00 | 4.65 | 5.84 | 85.6% | 14.4% |
| Teen | 179 | 3.71 | 4.00 | 4.14 | 4.91 | 6.00 | 91.6% | 8.4% |
| Young adult | 1386 | 3.95 | 4.21 | 4.37 | 5.07 | 6.05 | 94.4% | 5.6% |
| Middle-aged adult | 1138 | 3.66 | 3.92 | 4.11 | 4.88 | 5.75 | 88.8% | 11.2% |
| Older adult (65+) | 73 | 2.99 | 3.43 | 3.51 | 4.61 | 5.79 | 71.2% | 28.8% |
| Adult of unknown age | 912 | 3.75 | 4.00 | 4.21 | 4.88 | 5.93 | 90.7% | 9.3% |
| Gender | | | | | | | | |
| Male presenting | 2158 | 3.79 | 4.10 | 4.22 | 5.00 | 5.90 | 92.4% | 7.6% |
| Female presenting | 1219 | 3.69 | 3.95 | 4.12 | 4.79 | 5.78 | 89.3% | 10.7% |
| Unknown gender | 798 | 3.75 | 3.96 | 4.21 | 4.93 | 6.00 | 89.7% | 10.3% |
| Group size | | | | | | | | |
| 1 | 2609 | 3.83 | 4.15 | 4.36 | 5.07 | 6.05 | 92.9% | 7.1% |
| 2 | 743 | 3.72 | 3.95 | 4.12 | 4.73 | 5.53 | 89.2% | 10.8% |
| 3+ | 260 | 3.56 | 3.75 | 3.89 | 4.56 | 5.36 | 83.8% | 16.2% |

* Observations were filtered to best match BYU study (Schultz et al., 2019). The following were excluded:
  - Other characteristics: Skateboard, Scooter, Bicycle, Other.
  - Crossing location: Mid-block; away from the crosswalk; in the middle of the intersection.
  - Crossing behaviors: Changed speed (e.g., walk to run, or run to walk); Paused in the middle of the street.
  - Ped signal status when started crossing: Steady *Don't Walk*; and
    Ped signal status when finished crossing: Steady *Don't Walk*.

Our results are quite similar to those from Schultz et al. (2019). Overall, the 15th-percentile pedestrian crossing speed was 4.2 ft/s (vs. 4.1), and 91.5% (vs. 89%) of pedestrians crossed with a speed of at least 4.0 ft/s. People pushing strollers and carrying loads crossed slower than average, while people in wheelchairs had a wider range of speeds than other pedestrians. Older adults had the slowest crossing speeds, followed by children, while young adults had the fastest crossing speeds. For older adults, the 15th-percentile crossing speed was 3.5 ft/s (vs. 3.7), and 71% (vs. 73%) crossed with a speed of at least 4.0 ft/s. As was also found in the BYU study, women walked slightly slower than men, and crossing speed decreased as group size increased. As Schultz et al. (2019) note, the 15th-percentile pedestrian crossing speed is recommended for calculating pedestrian clearance intervals. Using this criterion, more than 15% of older adults, people crossing in groups of 3 or more, and people pushing strollers travel slower than 4.0 ft/s, and the same can be said for around/almost 15% of children, wheelchair users, and people carrying loads. Using a more stringent criteria of the 5th-percentile, 95% of observed crossing speeds were faster than 3.5 ft/s for all studied groups, except for older adults and people in wheelchairs. These results might suggest populations or locations where a slower walking speed could be assumed.

Figure 4.5 shows other crossing behaviors recorded from the videos. Regarding crosswalk markings, a large majority of pedestrians (78%) crossed within the crosswalk markings for all or most of the crossing. Another 10% were both within and outside of the crosswalk markings for part of the crossing. 9% of pedestrians crossed outside of the markings for most or all of the crossing. Regarding crossing behaviors, we observed 5–6% of people changing speed while crossing, and 1–2% of people paused in the middle. We observed very few pedestrians (less than 1%) who appeared to be distracted by their phone, although the video quality was often not sufficiently detailed to determine phone use, and phone use does not always imply distraction. Instead, we did notice that cars were blocking the crosswalk for 4% of all crossings, and other things (snow, water, or debris) were blocking the crosswalk around 1–2% of the time, too. These situations could cause pedestrians to leave the crosswalk in order to start or finish crossing the street.

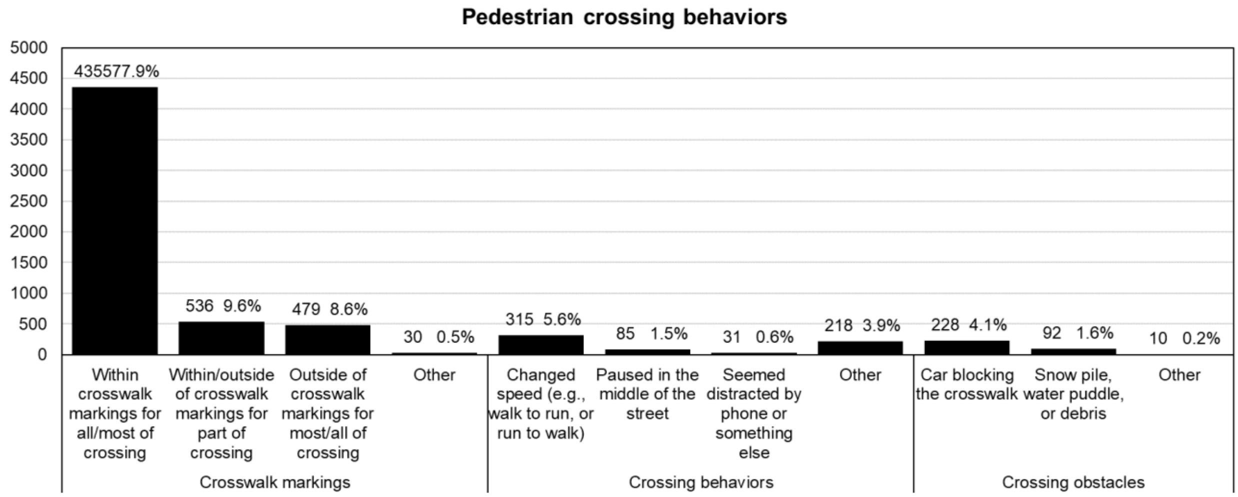



**Figure 4.5 Pedestrian crossing behaviors**

Figure 4.6 shows the distribution of temporal dimensions regarding the pedestrian crossing events observed in this study. We attempted to capture events at all times of day, all days of the week, and multiple seasons throughout the year. Since most videos were 24–48 hours, the hourly distribution roughly highlights the times of day when more pedestrians are walking: midday (23% during noon–3pm) and afternoons (29% during 3–6pm). Only 4% of pedestrians were observed overnight (midnight–6am). The distribution of observations by weekday reflects both the greater pedestrian activity at these locations during weekdays and the fact that more videos were recorded on weekdays than on weekends. More than half of events were captured during March, but observations were also made during summer and early fall months. We do not expect much variation in crossing behavior due to seasonal factors that cannot be captured by weather variables (e.g., temperature, precipitation).

Weather characteristics of pedestrian crossing events also reflect the time of year in which videos were recorded. Almost half of observations (46%) were made when the ambient surface air temperature was between 32 and 50°F. Fewer but still some observations happened when the temperature was below freezing (18%) or 80°F or higher (12%). It was raining during the hour for only 8% of crossing events.

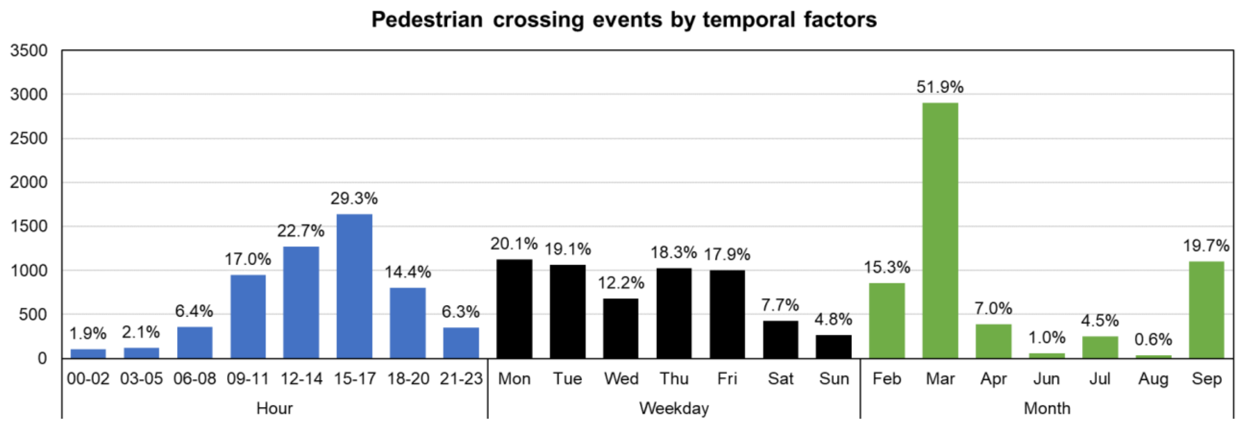



**Figure 4.6 Temporal distributions of pedestrian crossing events**

### 4.2.2 Crosswalk and Signal Information

The crossings investigated in this study had a variety of characteristics that might be related to pedestrian crossing behaviors and spatial/temporal violations. Table 4.3 shows the descriptive statistics for information about the 47 crosswalks at 39 signals studied in this project. Most intersections had four legs, while we did study one mid-block crossing (with a pedestrian hybrid beacon) and three three-leg intersections. Most crossings had standard (two line) crosswalk markings, while four locations were painted with continental (sometimes called high-visibility) markings. Since most intersections were on state highways, and Utah roads tend to be larger and wider than streets in other parts of the country, the crossings were rather large and the streets were rather busy. On average, the crossings were 85 ft wide and traversed five motor vehicle lanes. The average street crossed had an AADT of 16,700 vehicles per day and a speed limit between 30 and 35 mph. Twelve crossings had a center median. Many streets were major arterials with large intersection spacing; the average upstream distance to the nearest crossing was 1,700 ft (0.32 mi). All crossings had some working street lighting to illuminate crossings at night (as verified from watching the videos). 13% of crossings had bike lanes, and 15% had a bus stop on the approach within 300 ft of the intersection. Notably, 43% of intersections had a gas station and convenience store on one of the corners, which might affect pedestrian demand and pedestrian crossing behavior. The table also shows other average characteristics of the land use, built environment, and neighborhood in the area surrounding each intersection.

**Table 4.3 Descriptive statistics for crosswalks at signals (N = 47)**

| *Variable* | *#* | *%* | *Mean* | *SD* |
|---|---|---|---|---|
| **Crossing and intersection characteristics** | | | | |
| Intersection type | | | | |
| 2-leg (mid-block) | 1 | 2.1% | | |
| 3-leg | 3 | 6.4% | | |
| 4-leg | 43 | 91.5% | | |
| Crosswalk marking type | | | | |
| Standard | 43 | 91.5% | | |
| Continental | 4 | 8.5% | | |
| Crosswalk length (ft) | | | 85.45 | 22.86 |
| Number of lanes being crossed (#) | | | 5.02 | 1.58 |
| AADT of street being crossed (1,000s) | | | 16.71 | 14.29 |
| Speed limit of street being crossed (mph) | | | 32.98 | 6.97 |
| Median presence at crossing | 12 | 25.5% | | |
| Median width (ft) | | | 1.94 | 5.37 |
| Distance to nearest marked crosswalk (100ft) | | | 17.35 | 14.99 |
| Street lighting presence at crossing | 47 | 100.0% | | |
| Bike lane presence on approach | 6 | 12.8% | | |
| Transit stop presence on approach (within 300 ft) | 7 | 14.9% | | |
| Presence of gas station/convenience store at intersection | 20 | 42.6% | | |
| **Land use & built environment characteristics** [a] | | | | |
| Residential density (housing units/acre) | | | 2.67 | 1.64 |
| Population density (people/acre) | | | 7.03 | 3.64 |
| Employment density (jobs/acre) | | | 6.41 | 6.96 |
| Jobs-housing balance (jobs/household) | | | 3.08 | 3.06 |
| Street intersection density (#/mi$^2$) | | | 103.67 | 45.30 |
| Transit stops (#) | | | 5.04 | 4.11 |
| Liquor stores (#) | | | 0.13 | 0.34 |
| Schools (#) | | | 0.43 | 0.71 |
| Places of worship (#) | | | 0.66 | 0.92 |
| Park (acres) | | | 2.02 | 6.23 |
| **Neighborhood sociodemographic characteristics** [a] | | | | |
| Household size (mean, people/household) | | | 2.87 | 0.70 |
| Household income (median, $1,000s) | | | 61.60 | 23.55 |
| Vehicle ownership (mean, cars/household) | | | 1.91 | 0.47 |
| Population with a disability (%) | | | 14.05 | 6.03 |
| Population of Hispanic or non-white race/ethnicity (%) | | | 31.58 | 16.92 |

[a] These variables were measured using a quarter-mile network buffer.

## 4.3 Statistical Analysis Methods

One advancement upon existing research is that this study collected data from dozens of sites. Recall from Chapter 2.0 that empirical studies in the research literature rarely investigated more than 10–15 sites. A small number of sites limits the amount of variation in site-specific conditions that can be measured and therefore modeled in relation to pedestrian crossing behaviors. Including data from more than three dozen different locations improved the research team's ability to analyze the influence of different site characteristics, including roadway geometry, traffic signal timing, land uses, and neighborhood built environment and socio-demographic characteristics. Also, collecting data from several dozen different locations also provided a large enough sample size to perform a **multilevel regression analysis** that appropriately handles the statistical association between two types or levels of independent variables: (1) behavior-specific data collected for each pedestrian crossing event, and (2) site-specific data collected for each crosswalk or intersection—with pedestrian violations and behaviors. Together, the data and analyses provide insights into the factors affecting pedestrian crossing behaviors at signalized intersections and offer potential recommendations to improve pedestrian safety at intersections in Utah.

Multilevel regression models (MLM)—sometimes called hierarchical linear models (HLM)—can represent two or more levels or ways in which the records within a dataset are nested. In the case of this study, we have recorded information about each pedestrian crossing event (level-one units $i$), nested within or observed for each studied crosswalk (level-two units $j$). Through a multilevel model, we can relate our outcomes of interest ($Y_{ij}$) measured for each level-one unit (e.g., pedestrian behaviors) to other factors or variables measured for either level-one ($x_{ij}$) units (for instance, group size or weather) or level-two ($z_j$) units (for example, built environment characteristics). Relationships are represented by the strength, direction, and significance of the intercept and slope coefficients, and such coefficients can be the same for all observations ($\beta_0$, $\beta_h$) or different for observations within each level-two unit ($\beta_{0j}$, $\beta_{hj}$), assuming either fixed or random coefficients. If assuming random coefficients, there can be multiple random components to the equation, one overall and one for each random intercept or slope coefficient in the model. For instance, in this study, we apply a multilevel model containing a normally distributed random intercept term and no random slopes (or cross-level interactions). This specific situation can be represented by the following equations:

$Y_{ij} = \beta_{0j} + \sum_h \beta_h x_{hij} + R_{ij}$, where

$\beta_{0j} = \gamma_{00} + \sum_g \gamma_{g0}\, z_{gj} + U_{0j}$, or (combining into one equation)

$$Y_{ij} = \gamma_{00} + \sum_h \beta_h x_{hij} + \sum_g \gamma_{g0}\, z_{gj} + R_{ij} + U_{0j}$$

One way to interpret this multilevel model is as follows. Level-one factors ($x_{hij}$)—pedestrian information, waiting information, crossing information, temporal information, and weather information—affect the chance that each pedestrian crossing event contained a violation behavior. Level-two factors ($z_{gj}$)—crossing and intersection characteristics, land use and built environment characteristics, neighborhood sociodemographic characteristics—affect which locations tended to see more or fewer pedestrian crossing violations (represented by the location-specific intercept $\beta_{0j}$), after controlling for significant level-one factors.

## 4.4 Pedestrian Behaviors and Spatial Violations

### 4.4.1 Descriptive Results

Figure 4.7 shows the distribution of pedestrian crossing behaviors related to spatial violations. The left portion shows the pedestrian crossing location. The vast majority (97–98%) of pedestrians crossed in the crosswalk or within a few feet of the crosswalk (termed the crosswalk area). We only observed 2–3% (124) of crossing events where people were crossing mid-block, away from the crosswalk by more than a car length or two. Only four events of pedestrians crossing in the middle of the intersection were recorded. Our **first measure of a spatial violation** is crossing NOT in the crosswalk or crosswalk area, so in a location where pedestrians may not be expected and may not be intended to be. For the purposes of our analysis, we refine this definition to be **crossing mid-block, away from the crosswalk**. (There were too few observations of crossing in the middle of the intersection to analyze these.)

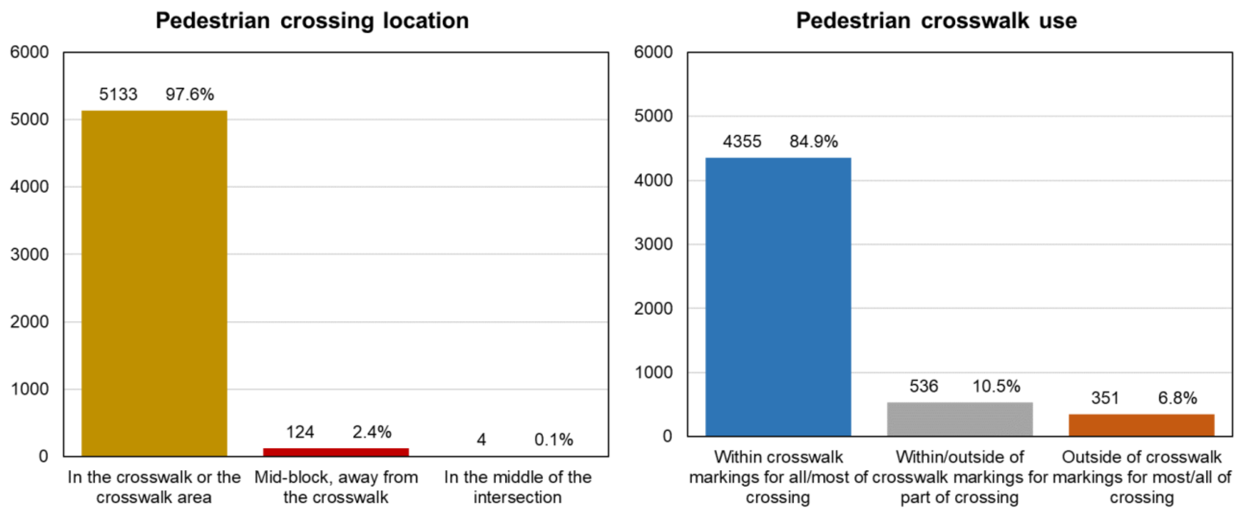



**Figure 4.7 Distribution of pedestrian crossing behaviors related to spatial violations**

The right portion of Figure 4.7 shows the use of the pedestrian crosswalk markings. In this figure (compared to the numbers in Table 4.1), we are only counting crossing events that happened in the crosswalk or crosswalk area (since all mid-block crossings happened outside of the crosswalk markings). Again, the large majority of pedestrians (85%) stayed within the crosswalk markings for all or most of the crossing. Only 7% (351) were observed to be outside of the crosswalk markings for most or all of the crossing. Note that the numbers/percentages may not add up to 100% because different members of the pedestrian group could have crossed within/outside of the crosswalk markings. Our second (admittedly weaker) measure of a spatial violation is crossing NOT within the crosswalk markings for most/all of the crossing, so in a location where pedestrians may not be expected. For the purposes of our analysis, we refine this definition to be crossing outside of the crosswalk markings for most/all of the crossing. We should note that this measure might help identify places where people are feeling tempted to cross almost mid-block, while it might also show places where the crosswalk itself is so far out of direction that many pedestrians are not using it and crossing slightly next to it. In other words, this measure could help identify places with a mismatch between crosswalk marking location and desired crossing location.

Table 4.4 shows the detailed results of these measures of pedestrian spatial violations for each signal and crosswalk. For many crossings, we did not observe either of these behaviors. For others, the percentage may be higher than the overall percentage of violations, but the small number of observations means we cannot determine if these behaviors are higher at this location due to some systematic reason or just due to random chance. Therefore, in the following notes we will focus only on those locations that were determined to have a higher-than-average percentage of the behavior, according to chi-squared tests ($p < 0.05$).

- *Locations with high instances of crossing mid-block*: We saw a lot of this behavior in the north crosswalk at signal 7086 (57, 6%). Other locations of note include: the north crosswalk of signal 4130 (2, 20%), the south crosswalk at signal 4511 (9, 7%), the west crosswalk at signal 7099 (11, 11%), and the south crosswalk at signal 8222 (7, 15%).

- *Locations with high instances of crossing outside of markings*: We observed a lot of this behavior in the east crosswalk at signal 8302 (205, 37%). Other locations of note include: the north crosswalk at signal 7464 (26, 74%), the south crosswalk at signal 8117 (8, 15%), and the south crosswalk at signal 8222 (10, 26%).

**Table 4.4  Results for pedestrian spatial violations by signal and crosswalk**

| *Location* | | *Crossed mid-block* | | | | *Crossed outside of markings* | | | |
|---|---|---|---|---|---|---|---|---|---|
| *Signal* | *Crosswalk* | *False* | *True* | *Total* | *% True* | *False* | *True* | *Total* | *% True* |
| All | All | 5133 | 124 | 5257 | 2% | 4778 | 351 | 5129 | 7% |
| 1021 | East | 184 | 2 | 186 | 1% | 178 | 6 | 184 | 3% |
| 1021 | North | 686 | 1 | 687 | 0% | 674 | 12 | 686 | 2% |
| 1229 | North | 289 | 1 | 290 | 0% | 283 | 6 | 289 | 2% |
| **4130** | **North** | **8** | **2** | **10** | **20%** | 8 | 0 | 8 | 0% |
| 4301 | North | 47 | 0 | 47 | 0% | 47 | 0 | 47 | 0% |
| 4301 | West | 37 | 0 | 37 | 0% | 37 | 0 | 37 | 0% |
| 4502 | West | 117 | 1 | 118 | 1% | 115 | 2 | 117 | 2% |
| **4511** | **South** | **126** | **9** | **135** | **7%** | 123 | 3 | 126 | 2% |
| 4511 | West | 86 | 0 | 86 | 0% | 83 | 3 | 86 | 3% |
| 4662 | South | 14 | 0 | 14 | 0% | 14 | 0 | 14 | 0% |
| 5024 | West | 201 | 0 | 201 | 0% | 200 | 1 | 201 | 0% |
| 5093 | West | 18 | 0 | 18 | 0% | 16 | 2 | 18 | 11% |
| 5299 | East | 5 | 0 | 5 | 0% | 5 | 0 | 5 | 0% |
| 5305 | East | 94 | 0 | 94 | 0% | 93 | 1 | 94 | 1% |
| 5305 | North | 8 | 0 | 8 | 0% | 8 | 0 | 8 | 0% |
| 5311 | North | 95 | 0 | 95 | 0% | 95 | 0 | 95 | 0% |
| 5311 | West | 58 | 1 | 59 | 2% | 58 | 0 | 58 | 0% |
| 5330 | East | 2 | 0 | 2 | 0% | 2 | 0 | 2 | 0% |
| 5332 | North | 22 | 0 | 22 | 0% | 22 | 0 | 22 | 0% |
| 5363 | North | 48 | 0 | 48 | 0% | 46 | 2 | 48 | 4% |
| 5702 | East | 46 | 0 | 46 | 0% | 45 | 1 | 46 | 2% |
| 6146 | North | 2 | 0 | 2 | 0% | 1 | 1 | 2 | 50% |
| 6393 | North | 111 | 0 | 111 | 0% | 109 | 2 | 111 | 2% |
| 6393 | West | 159 | 0 | 159 | 0% | 157 | 2 | 159 | 1% |
| 6407 | West | 100 | 3 | 103 | 3% | 92 | 8 | 100 | 8% |
| **7086** | **North** | **948** | **57** | **1005** | **6%** | 937 | 11 | 948 | 1% |
| 7086 | West | 24 | 0 | 24 | 0% | 24 | 0 | 24 | 0% |
| **7099** | **West** | **85** | **11** | **96** | **11%** | 84 | 1 | 85 | 1% |
| 7184 | East | 29 | 1 | 30 | 3% | 29 | 0 | 29 | 0% |
| 7218 | Southwest | 110 | 5 | 115 | 4% | 102 | 8 | 110 | 7% |
| 7328 | North | 105 | 0 | 105 | 0% | 105 | 0 | 105 | 0% |
| **7332** | **North** | **4** | **1** | **5** | **20%** | 4 | 0 | 4 | 0% |
| 7355 | South | 28 | 1 | 29 | 3% | 27 | 1 | 28 | 4% |
| 7374 | West | 103 | 0 | 103 | 0% | 103 | 0 | 103 | 0% |
| 7381 | East | 112 | 1 | 113 | 1% | 101 | 11 | 112 | 10% |
| **7464** | **North** | 36 | 2 | 38 | 5% | **10** | **26** | **36** | **72%** |
| 7475 | North | 55 | 3 | 58 | 5% | 53 | 2 | 55 | 4% |
| 7622 | East | 7 | 0 | 7 | 0% | 7 | 0 | 7 | 0% |
| 8113 | East | 57 | 0 | 57 | 0% | 57 | 0 | 57 | 0% |
| **8117** | **South** | 55 | 0 | 55 | 0% | **47** | **8** | **55** | **15%** |
| **8222** | **South** | **39** | **7** | **46** | **15%** | **29** | **10** | **39** | **26%** |
| **8302** | **East** | 553 | 14 | 567 | 2% | **344** | **205** | **549** | **37%** |
| 8302 | North | 190 | 0 | 190 | 0% | 175 | 15 | 190 | 8% |
| 8627 | West | 11 | 0 | 11 | 0% | 11 | 0 | 11 | 0% |
| 8634 | North | 4 | 0 | 4 | 0% | 4 | 0 | 4 | 0% |
| 8725 | North | 2 | 1 | 3 | 33% | 1 | 1 | 2 | 50% |
| 8828 | West | 13 | 0 | 13 | 0% | 13 | 0 | 13 | 0% |

#### 4.4.2 Statistical Analysis Results

Recall that our statistical analysis of the two measures of pedestrian spatial violation behaviors utilized multilevel regression analysis. Given the dichotomous or binary (0/1, True/False) nature of the dependent variables, our base model was a binary logistic regression. To make this a multilevel model, we added a random intercept term that varied (following a normal distribution) across the 47 crosswalks.

We then proceeded with the statistical analysis following a two-step process. In the first step, we tested each potential independent variable (from Table 4.1 and Table 4.3) to the model, one at a time. These models told us which independent variables had a statistically significant (bivariate) association with the dependent variable, all on their own. In the second step, we took all the significant variables from the first step, and added them to the model altogether. We then performed backwards elimination, removing the least significant (highest p-value) variable, until all remaining variables were at least marginally significant ($p < 0.10$). This final model told us which independent variables had a statistically significant (multivariate) association with the dependent variable, when controlling for all other significant variables.

Table 4.5 shows independent variables with significant (bivariate) positive or negative associations with each of the two measures of pedestrian spatial violations. Table 4.6 reports results from the (multivariate) multilevel analysis on the first type of spatial violation: crossed mid-block. Table 4.7 presents results from the multilevel analysis on the second type of spatial violation: crossed outside of markings.

**Table 4.5 Bivariate model results for pedestrian spatial violations**

| *Association** | *Crossed mid-block* | *Crossed outside of markings* |
|---|---|---|
| Positive | • **Time of day: Overnight (00:00–05:59)**<br>• **Temperature (°F)**<br>• **Population of Hispanic or non-white race/ethnicity (%) (within 0.25mi)** | • # other people waiting<br>• **# other people crossing (both directions)**<br>• **Temperature (°F)**<br>• Schools (#) (within 0.25mi) |
| Negative | • Group size (# pedestrians)<br>• Age: Teen<br>• **Gender: Female presenting**<br>• **Other characteristics: Wheelchair, Skateboard, Scooter, or Bicycle**<br>• **Waiting time (sec)**<br>• **Other people crossing (either direction)**<br>• Crosswalk length (ft)<br>• **AADT of street being crossed**<br>• Liquor stores (#) (within 0.25mi) | • **Other characteristics: Wheelchair, Skateboard, Scooter, or Bicycle**<br>• **# vehicles passing (average of past 10 sec and next 10 sec)**<br>• **Waiting time (sec)**<br>• **Crosswalk length (ft)**<br>• AADT of street being crossed<br>• Distance to nearest marked crosswalk (ft)<br>• Presence of gas station/convenience store at intersection |

*All other variables (not shown) were not statistically significant ($p \geq 0.10$).
**Bold** relationships were the same in the multivariate model.

**Table 4.6 Multilevel logistic regression model results for crossed mid-block**

| *Variable* | *Estimate* | *Std. err.* | *z-score* | *p-value* |
|---|---|---|---|---|
| Intercept (std. dev. = 0.974) | -4.628 | 0.785 | -5.898 | <0.001 |
| Gender: Female presenting | -0.989 | 0.254 | -3.887 | <0.001 |
| Other char.: Wheelchair, Skateboard, Scooter, or Bicycle | -1.787 | 0.352 | -5.080 | <0.001 |
| Waiting time (sec – 60 sec) | -4.646 | 0.722 | -6.439 | <0.001 |
| Other people crossing (either direction) | -1.392 | 0.327 | -4.252 | <0.001 |
| Time of day: Overnight (00:00–05:59) | 0.675 | 0.303 | 2.227 | 0.026 |
| Temperature (°F) | 0.027 | 0.008 | 3.461 | 0.001 |
| AADT of street being crossed (1,000s) | -0.074 | 0.029 | -2.568 | 0.010 |
| Population of Hispanic or non-white race/ethnicity (%) | 0.030 | 0.015 | 2.021 | 0.043 |

N (level 1) = 5,242; N (level 2) = 47.
Log-lik. (this model) = -425.5; log-lik. (intercept-only model) = -586.8; McFadden's pseudo-$R^2$ = 0.275.

**Table 4.7 Multilevel logistic regression model results for crossed outside of markings**

| *Variable* | *Estimate* | *Std. err.* | *z-score* | *p-value* |
|---|---|---|---|---|
| Intercept (std. dev. = 1.251) | -3.862 | 0.432 | -8.945 | <0.001 |
| Other char.: Wheelchair, Skateboard, Scooter, or Bicycle | -0.401 | 0.200 | -2.009 | 0.045 |
| # vehicles passing (average of past 10 sec and next 10 sec) | -0.070 | 0.034 | -2.056 | 0.040 |
| Waiting time (sec – 60sec) | -0.784 | 0.268 | -2.922 | 0.003 |
| # other people crossing (both directions) | 0.124 | 0.051 | 2.444 | 0.015 |
| Temperature (°F) | 0.013 | 0.007 | 1.948 | 0.051 |
| Crosswalk length (ft – 80ft) | -0.035 | 0.012 | -2.904 | 0.004 |

N (level 1) = 5,114; N (level 2) = 47.
Log-lik. (this model) = -888.2; log-lik. (intercept-only model) = -1,273.8; McFadden's pseudo-$R^2$ = 0.303.

Several factors were significantly associated with the first pedestrian spatial violation behavior: crossing mid-block (instead of in the crosswalk area). Female-presenting pedestrians, as well as those using some mobility device (bicycle, scooter, wheelchair, etc.), were less likely to cross mid-block. When there were other people crossing at the same time, pedestrians were also less likely to cross mid-block. As waiting time increased, people were less likely to cross mid-block; but higher temperatures saw more mid-block crossing behaviors. Crossing mid-block was also more likely during overnight hours (between midnight and 6am). Only two location characteristics were significant. Mid-block crossings were less likely on streets with higher AADT, but mid-block crossings were more likely in neighborhoods with higher shares of Hispanic or non-white populations.

Some similar yet other different factors were significantly associated with the second pedestrian spatial violation behavior: crossing outside of the crosswalk markings for most or all of the crossing, among those who crossed in/near the crosswalk. People using a mobility device (bicycle, etc.) were less likely to cross outside of the markings, and such behavior was less likely when there were more vehicles passing when the pedestrian arrived at the waiting area. When the number of other people crossing at the same time increased, pedestrians were more likely to cross outside of the markings. As waiting time increased, people were less likely to cross outside the markings; but higher temperatures saw more crossings outside of the crosswalk markings. Only one location characteristic was significant. Longer crossings (of wider streets) had fewer people who crossed outside of the crosswalk markings.

## 4.5 Pedestrian Behaviors and Temporal Violations

### 4.5.1 Descriptive Results

Table 4.8 shows information related to the pedestrian signal status at the time of the crossing event, for pedestrian crossings that happened in the crosswalk or the crosswalk area. Recall that this information was obtained by comparing timestamps of when pedestrians stepped off/onto the curbs and the pedestrian signal indication at those times. Most pedestrians (58%) started crossing on *walk*, and most pedestrians (73%) finished crossing on either *walk* or flashing *don't walk*, as expected; 55% of people met both criteria. However, this means that a sizable share of pedestrians either started crossing on flashing *don't walk* (19%) or steady *don't walk* (22%) and/or finished crossing on steady *don't walk* (27%). Notably, 12% of people started and finished crossing when the pedestrian signal showed steady *don't walk*.

Our **first measure of a temporal violation** is crossing against the pedestrian signal, when a pedestrian may not be expected and may not be intended to be in the crosswalk. For the purposes of our analysis, we refine this definition to be **starting to cross on steady *don't walk***. The reason for this selection is that some signals may not give slower pedestrians time to finish crossing during the *walk* or flashing *don't walk* indications. Also, we assume that some people who start crossing on flashing *don't walk* know that they can cross fast enough to make it before opposing motor vehicle traffic receives a green indication.

**Table 4.8 Pedestrian signal status temporal violations**

| *Ped signal status when started crossing* | Ped signal status when finish crossing | | | | | | Total | |
|---|---|---|---|---|---|---|---|---|
| | *Walk* | | *Flashing Don't Walk* | | *Steady Don't Walk* | | | |
| *Walk* | 1139 | 22.3% | 1677 | 32.8% | 177 | 3.5% | 2993 | 58.5% |
| *Flashing Don't Walk* | 1 | 0.0% | 406 | 7.9% | 590 | 11.5% | 997 | 19.5% |
| *Steady Don't Walk* | 250 | 4.9% | 280 | 5.5% | 598 | 11.7% | 1128 | 22.0% |
| *Total* | 1390 | 27.2% | 2363 | 46.2% | 1365 | 26.7% | 5118 | 100% |

However, it should be noted that just because a pedestrian is crossing against a steady *don't walk* pedestrian indication, it does not mean that they are necessarily putting themselves in danger. For instance, we noticed that several of these instances occurred when pedestrians did not press the push-button (to actuate the *walk* indication) but crossed at the same time as the parallel green motor vehicle movements. In other words, they were crossing when there was no conflicting protected vehicle movement. This discussion leads us to our **second** and perhaps stronger **definition of a temporal violation**: crossing against a green indication for a conflicting vehicle movement. For the purposes of our analysis, we refine this definition to be **spending more than 5 seconds in the intersection while there is a conflicting protected vehicle phase showing green** (see Section 3.4 for more information on this calculation).

Figure 4.8 shows information related to the vehicle signal status at the time of the crossing event, for pedestrian crossings that happened in the crosswalk or the crosswalk area. The average crossing took 16.2 seconds, of which 94% was when all conflicting vehicle movements showed red. On average, only 0.9 seconds of each crossing occurred when a conflicting protected phase showed green. Around 11% of crossing events occurred with some (1+ seconds) time when there was a conflicting green vehicle movement. This rate decreases to 5–6% when considering a more than 5- (6+) second threshold, and 3% for more than 10 seconds. We had several reasons to go with the >5 second threshold. First, there is a startup loss time for vehicle movements, so a pedestrian in the crosswalk at the start of green might have a few more seconds before vehicles enter the crosswalk. Second, recall the timestamp matching issue discussed in Section 3.4 (where video times may have been slightly different than signal controller times). By using a 5-second buffer, we can be very confident that these events did involve a pedestrian crossing against a green indication for a conflicting protected vehicle movement.

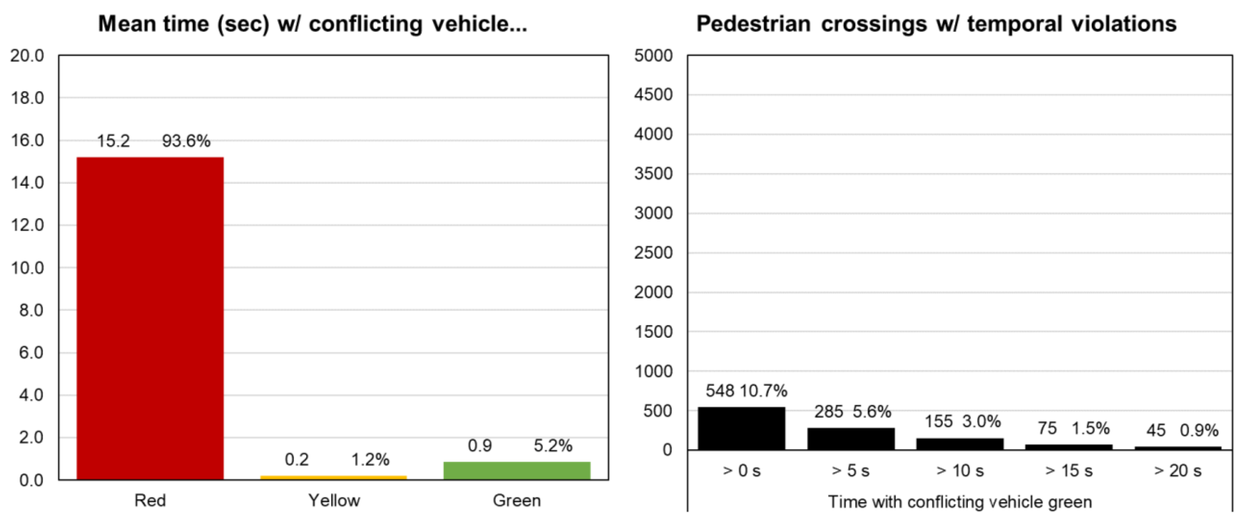



**Figure 4.8 Vehicle signal status temporal violations**

Table 4.9 shows the detailed results of these measures of pedestrian temporal violations for each signal and crosswalk. Similar to our work with spatial violations, in the following notes we will focus only on those locations that were determined to have a higher-than-average percentage of the behavior, according to chi-square tests ($p < 0.05$).

- Locations with high instances of crossing with some conflicting green time: We saw a lot of this behavior in the north crosswalk at signal 7086 (137, 14%). Other locations of note include: the south crosswalk at signal 7355 (5, 18%) and the north crosswalk at signal 7475 (32, 58%).

- Locations with high instances of crossing on steady *don't walk*: We observed a lot of this behavior in the north crosswalk at signal 1229 (106, 37%), the north crosswalk of signal 7475 (43, 78%), and the north crosswalk of signal 8302 (78, 41%). Other locations of note include: the south crosswalk of signal 4511 (40, 32%), the north crosswalk of signal 7086 (241, 25%), the south crosswalk of signal 7355 (11, 39%), and the west crosswalk of signal 8627 (7, 64%).

**Table 4.9 Results for pedestrian temporal violations by signal and crosswalk**

| *Location* | | *Crossed with >5 seconds green* | | | | *Started on steady don't walk* | | | |
|---|---|---|---|---|---|---|---|---|---|
| *Signal* | *Crosswalk* | *False* | *True* | *Total* | *% True* | *False* | *True* | *Total* | *% True* |
| All | All | 4839 | 285 | 5124 | 6% | 3997 | 1130 | 5127 | 22% |
| 1021 | East | 179 | 5 | 184 | 3% | 151 | 33 | 184 | 18% |
| 1021 | North | 673 | 13 | 686 | 2% | 568 | 118 | 686 | 17% |
| **1229** | **North** | 281 | 8 | 289 | 3% | **183** | **106** | **289** | **37%** |
| 4130 | North | 8 | 0 | 8 | 0% | 7 | 1 | 8 | 13% |
| 4301 | North | 47 | 0 | 47 | 0% | 44 | 3 | 47 | 6% |
| 4301 | West | 36 | 1 | 37 | 3% | 29 | 8 | 37 | 22% |
| 4502 | West | 110 | 7 | 117 | 6% | 83 | 33 | 116 | 28% |
| **4511** | **South** | 118 | 8 | 126 | 6% | **86** | **40** | **126** | **32%** |
| 4511 | West | 83 | 2 | 85 | 2% | 65 | 21 | 86 | 24% |
| 4662 | South | 14 | 0 | 14 | 0% | 13 | 1 | 14 | 7% |
| 5024 | West | 200 | 0 | 200 | 0% | 172 | 29 | 201 | 14% |
| 5093 | West | 18 | 0 | 18 | 0% | 16 | 2 | 18 | 11% |
| 5299 | East | 5 | 0 | 5 | 0% | 1 | 3 | 4 | 75% |
| 5305 | East | 94 | 0 | 94 | 0% | 84 | 10 | 94 | 11% |
| 5305 | North | 8 | 0 | 8 | 0% | 6 | 2 | 8 | 25% |
| 5311 | North | 94 | 1 | 95 | 1% | 87 | 8 | 95 | 8% |
| 5311 | West | 58 | 0 | 58 | 0% | 53 | 5 | 58 | 9% |
| 5330 | East | 2 | 0 | 2 | 0% | 2 | 0 | 2 | 0% |
| 5332 | North | 22 | 0 | 22 | 0% | 16 | 5 | 21 | 24% |
| 5363 | North | 48 | 0 | 48 | 0% | 43 | 5 | 48 | 10% |
| 5702 | East | 44 | 2 | 46 | 4% | 33 | 13 | 46 | 28% |
| 6146 | North | 2 | 0 | 2 | 0% | 1 | 1 | 2 | 50% |
| 6393 | North | 111 | 0 | 111 | 0% | 96 | 15 | 111 | 14% |
| 6393 | West | 155 | 4 | 159 | 3% | 121 | 38 | 159 | 24% |
| 6407 | West | 98 | 2 | 100 | 2% | 93 | 7 | 100 | 7% |
| **7086** | **North** | **811** | **137** | **948** | **14%** | **707** | **241** | **948** | **25%** |
| 7086 | West | 20 | 4 | 24 | 17% | 17 | 7 | 24 | 29% |
| 7099 | West | 83 | 1 | 84 | 1% | 59 | 26 | 85 | 31% |
| 7184 | East | 28 | 0 | 28 | 0% | 29 | 0 | 29 | 0% |
| 7218 | Southwest | 102 | 8 | 110 | 7% | 84 | 26 | 110 | 24% |
| 7328 | North | 101 | 4 | 105 | 4% | 94 | 9 | 103 | 9% |
| 7332 | North | 4 | 0 | 4 | 0% | 4 | 0 | 4 | 0% |
| **7355** | **South** | **23** | **5** | **28** | **18%** | **17** | **11** | **28** | **39%** |
| 7374 | West | 102 | 1 | 103 | 1% | 102 | 1 | 103 | 1% |
| 7381 | East | 111 | 1 | 112 | 1% | 94 | 18 | 112 | 16% |
| 7464 | North | 35 | 1 | 36 | 3% | 29 | 7 | 36 | 19% |
| **7475** | **North** | **23** | **32** | **55** | **58%** | **12** | **43** | **55** | **78%** |
| 7622 | East | 7 | 0 | 7 | 0% | 4 | 3 | 7 | 43% |
| 8113 | East | 57 | 0 | 57 | 0% | 47 | 10 | 57 | 18% |
| 8117 | South | 55 | 0 | 55 | 0% | 51 | 4 | 55 | 7% |
| 8222 | South | 39 | 0 | 39 | 0% | 33 | 6 | 39 | 15% |
| 8302 | East | 528 | 20 | 548 | 4% | 428 | 124 | 552 | 22% |
| **8302** | **North** | 173 | 17 | 190 | 9% | **112** | **78** | **190** | **41%** |
| **8627** | **West** | 10 | 1 | 11 | 9% | **4** | **7** | **11** | **64%** |
| 8634 | North | 4 | 0 | 4 | 0% | 4 | 0 | 4 | 0% |
| 8725 | North | 2 | 0 | 2 | 0% | 1 | 1 | 2 | 50% |
| 8828 | West | 13 | 0 | 13 | 0% | 12 | 1 | 13 | 8% |

4.5.2 Statistical Analysis Results

Recall that our statistical analysis of the two measures of pedestrian temporal violation behaviors also utilized multilevel regression analysis. The model forms (multilevel binary logistic regression) and the analysis process were identical to what we performed for the spatial violation analysis.

Table 4.10 shows independent variables with significant (bivariate) positive or negative associations with each of the two measures of pedestrian temporal violations. Table 4.11 reports results from the (multivariate) multilevel analysis on the first type of temporal violation: crossed with >5 seconds green. Table 4.12 presents results from the multilevel analysis on the second type of temporal violation: started on steady *don't walk*.

**Table 4.10 Bivariate model results for pedestrian temporal violations**

| *Association** | *Crossed with >5 seconds green* | *Started on steady don't walk* |
|---|---|---|
| Positive | • **Time of day: Overnight (00:00–05:59)**<br>• **Time of day: Morning (06:00–11:59)**<br>• Time of day: Evening (18:00–23:59)<br>• **Temperature (°F)**<br>• **Intersection type: 2-leg (mid-block)**<br>• Median width (ft)<br>• **Population of Hispanic or non-white race/ethnicity (%) (within 0.25mi)** | • **Other characteristics: Wheelchair, Skateboard, Scooter, or Bicycle**<br>• **Day of week: Weekend**<br>• **Time of day: Overnight (00:00–05:59)**<br>• Time of day: Morning (06:00–11:59)<br>• **Intersection type: 2-leg (mid-block)**<br>• Population of Hispanic or non-white race/ethnicity (%) (within 0.25mi) |
| Negative | • Age: Child<br>• # vehicles passing (average of past 10 sec and next 10 sec)<br>• **Waiting time (sec)**<br>• **# other people crossing (both directions)**<br>• AADT of street being crossed<br>• Distance to nearest marked crosswalk (ft) | • **Group size (# pedestrians)**<br>• **Age: Child**<br>• **Age: Teen**<br>• Gender: Female presenting<br>• # other people waiting<br>• # vehicles passing (average of past 10 sec and next 10 sec)<br>• **Waiting time (sec)**<br>• **Other people crossing (either direction)**<br>• **Crossing obstacles (any)**<br>• **Hourly precipitation (in)**<br>• AADT of street being crossed |

*All other variables (not shown) were not statistically significant ($p \geq 0.10$).
**Bold** relationships were the same in the multivariate model.

**Table 4.11 Multilevel logistic regression model results for crossed with >5 seconds green**

| *Variable* | *Estimate* | *Std. err.* | *z-score* | *p-value* |
|---|---|---|---|---|
| Intercept (std. dev. = 1.062) | -5.320 | 0.650 | -8.190 | <0.001 |
| Waiting time (sec – 60sec) | -1.893 | 0.239 | -7.937 | <0.001 |
| # other people crossing (both directions) | -0.286 | 0.090 | -3.171 | 0.002 |
| Time of day: Overnight (00:00–05:59) | 1.347 | 0.221 | 6.088 | <0.001 |
| Time of day: Morning (06:00–11:59) | 0.490 | 0.161 | 3.039 | 0.002 |
| Temperature (°F) | 0.015 | 0.005 | 2.898 | 0.004 |
| Intersection type: 2-leg (mid-block) | 2.774 | 1.168 | 2.375 | 0.018 |
| Population of Hispanic or non-white race/ethnicity (%) | 0.033 | 0.014 | 2.368 | 0.018 |

N (level 1) = 5,109; N (level 2) = 47.
Log-lik. (this model) = -846.7; log-lik. (intercept-only model) = -1,088.2; McFadden's pseudo-$R^2$ = 0.222.

**Table 4.12 Multilevel logistic regression model results for started on steady don't walk**

| *Variable* | *Estimate* | *Std. err.* | *z-score* | *p-value* |
|---|---|---|---|---|
| Intercept (std. dev. = 0.668) | -1.071 | 0.150 | -7.121 | <0.001 |
| Group size (# pedestrians) | -0.123 | 0.054 | -2.271 | 0.023 |
| Age: Child | -0.809 | 0.311 | -2.603 | 0.009 |
| Age: Teen | -0.362 | 0.205 | -1.763 | 0.078 |
| Other char.: Wheelchair, Skateboard, Scooter, or Bicycle | 0.467 | 0.097 | 4.828 | <0.001 |
| Waiting time (sec – 60sec) | -0.870 | 0.102 | -8.522 | <0.001 |
| Other people crossing (either direction) | -0.780 | 0.098 | -7.944 | <0.001 |
| Crossing obstacles (any) | -0.383 | 0.194 | -1.977 | 0.048 |
| Day of week: Weekend | 0.491 | 0.147 | 3.343 | 0.001 |
| Time of day: Overnight (00:00–05:59) | 1.701 | 0.173 | 9.861 | <0.001 |
| Hourly precipitation (in) | -9.604 | 3.102 | -3.096 | 0.002 |
| Intersection type: 2-leg (mid-block) | 2.788 | 0.760 | 3.669 | <0.001 |

N (level 1) = 5,112; N (level 2) = 47.
Log-lik. (this model) = --2,368; log-lik. (intercept-only model) = -2,669; McFadden's pseudo-$R^2$ = 0.113.

Several factors were significantly associated with the first pedestrian temporal violation behavior: crossing with 5+ seconds of green showing for a conflicting protected vehicle movement. As waiting time increased, and when there were other people crossing, pedestrians were less likely to cross against a conflicting green. Conversely, this behavior was more likely overnight (between midnight and 6am) and during the morning hours (between 6am and noon), and for warmer temperatures. Only two location characteristics were significant. Crossing against a conflicting green was more likely at a mid-block signal and in neighborhoods with higher shares of Hispanic or non-white populations.

Some similar yet other different factors were significantly associated with the second pedestrian temporal violation behavior: starting to cross on a steady *don't walk* indication. This behavior was less likely for children, teens, larger group sizes of pedestrians, and when there were other people crossing at the same time. People using a (micro)mobility device (bicycle, etc.) were more likely to start crossing on steady *don't walk*. As waiting time increased, people were less likely to cross on steady *don't walk*, and people facing a crossing obstacle (like a car, snow pile, or puddle) were also less likely to start crossing against the *don't walk* sign. Starting to cross on steady *don't walk* was more common on weekends and during overnight hours (midnight to 6am), but less common when it was raining. Only one location characteristic was significant. Crossing against the steady *don't walk* sign was more likely at a mid-block signal.

## 4.6 Example Locations

In the following subsections, we highlight a few specific locations that exemplify the results found from the bivariate and multivariate statistical analyses. These locations were all found to have significantly higher-than-average rates of pedestrian violation behaviors in the preceding Sections 4.4 and 4.5.

### 4.6.1 North Crosswalk, Signal 7086 (Redwood Rd & N Temple, Salt Lake City)

The north crosswalk at signal 7086—Figure 4.9—stood out as one location with higher-than-average rates of both spatial and temporal violations. Rates of crossing mid-block were more than twice the average (57, 6% vs. 2%), as were rates of crossing with some conflicting green time (137, 14% vs. 6%), and rates of crossing on steady *don't walk* were slightly higher than average (241, 25% vs. 22%). Figure 4.10 shows an example crossing instance with both a spatial and temporal violation. The pedestrian is crossing several car-lengths back from the intersection against oncoming traffic; in this instance, the pedestrian pauses once reaching the median and then runs across the rest of the street during a small gap in traffic. Many other pedestrians were observed to cross mid-block here, especially traveling between the two gas stations / convenience stores on either side of the crossing. Many of the temporal violations occurred at night, when traffic volumes were lower.


**Figure 4.9 Satellite view of camera angle for north crosswalk at signal 7086**


**Figure 4.10 Screenshot of example pedestrian crossing behavior at signal 7086**

This crossing contains some characteristics found to be significantly associated with pedestrian crossing behaviors that are considered violations. It is the location in the study with the highest percentage of people of Hispanic/non-white race/ethnicity living nearby, which was associated with higher rates of spatial and temporal violations. It also has a (small) median, which was associated with higher rates of crossing against a conflicting green. On the other hand, the crossing has a longer-than-average crosswalk length and higher-than-average traffic volumes, characteristics that were associated with lower rates of spatial and temporal violations. Other factors may be at play. This location is at the intersection of two major transit lines (TRAX Green Line and Bus Route 1) and has multiple convenience stores and fast food restaurants on either side (although these characteristics—transit stops, gas station/convenience store—were not significant in the regression models). According to members of the technical advisory committee, many of the pedestrians crossing at this location are homeless, which could explain some of the higher rates of violations seen here. Also, it should be noted that the pedestrian phase for the north crosswalk was not set to pedestrian recall at any time during the videos, although this intersection has a relatively high pedestrian volume (around 1,000 pedestrians per day) and volumes spread throughout the day and night.

If UDOT is strongly interested in discouraging mid-block crossings in locations like this (with small medians), one potential option is to harden the median for pedestrians by installing decorative fencing or other aesthetic objects that discourage pedestrians from crossing them. If UDOT is strongly interested in discouraging crossings against conflicting green vehicular movements and/or steady *don't walk* pedestrian indications at locations like this (with relatively high pedestrian volumes at all times of day), one potential option is to place the crossing on pedestrian recall rest-in-walk, so that the *walk* indication comes on every cycle without pedestrians having to press the push-button. Potential strategies like these will be discussed in more detail in Chapter 6.0.

### 4.6.2 Only Crosswalk, Signal 7475 (300 W & 50 S, Salt Lake City)

The pedestrian hybrid beacon signal 7475—Figure 4.11—was notable for its very high rates of temporal violations: crossing with some conflicting green time (32, 58% vs. 6%) and crossing on steady *don't walk* (43, 78% vs. 22%).


**Figure 4.11 Satellite view of camera angle for only crosswalk at signal 7475**


**Figure 4.12 Screenshot of example pedestrian crossing behavior at signal 7475**

Figure 4.12 shows an example event in which the pedestrian crosses in the crosswalk but without pressing the push-button and activating the signal. It should be noted that many observed crossing violations occurred under fairly low-traffic conditions, and pedestrians were able to wait on the wide median for an acceptable gap in traffic. So, violation behaviors may have not resulted in dangerous outcomes (like conflicts or crashes) for most pedestrians, at least during the observation period.

This was the only crosswalk studied that was a mid-block signalized crossing. Among other characteristics associated with higher rates of temporal violations, this crossing had a wider median and a higher share of people of Hispanic/non-white race/ethnicity living in the surrounding neighborhood. On the other hand, it had average traffic volumes (a factor associated with lower rates of temporal violations) that were close to the average among all study locations. This crossing likely did not have high rates of spatial violations in part because the wide median has fencing installed up to 50–140 ft back from the crossing, which encouraged crossings right at the crosswalk area. It is also instructive to note that this crosswalk connects a convention center with an indoor arena, so there are likely more non-resident pedestrians crossing here.

We are unsure what could be done by UDOT (based on the findings of this research) to discourage temporal violation pedestrian behaviors at mid-block signalized crossings such as these. We should note that findings for this single crossing may not be transferrable to other mid-block crossings, and more research on pedestrian behaviors at mid-block crossings is needed. There are other good reasons for there to be a crossing here (linking a major indoor arena and a convention center), a pedestrian hybrid beacon is a good choice for this location, and having a center median offers protection, especially for people who require more time to cross the street. Perhaps changes in push-button placement could increase compliance with the pedestrian signal. Right now, push buttons are placed on the signal poles, on one side of the fairly wide (~20 ft) crosswalk. Pedestrians approaching from the opposite side from the push-button may be more inclined to accept a gap in traffic rather than walking an extra 20 ft to press the button. Installing push-buttons on both sides of the crosswalk (or in the center) might increase their usage. Another option might be to allow the pedestrian signal to be placed in free (rather than coordinated) operation—this would require vehicle detection—which might reduce pedestrian delay and potentially improve pedestrian compliance.

#### 4.6.3 East Crosswalk, Signal 8302 (Main St & Center St, Moab)

The east crosswalk at signal 8302—Figure 4.13—is a good example of a location that had higher-than-average rates of spatial violations, but we considered those violations to be of a "less severe" variety. Specifically, a large minority of pedestrian events at this location involved crossing outside of the crosswalk markings (205, 37% vs. 7%); however, an average number of people (14, 2% vs. 2%) crossed mid-block at this location. Figure 4.14 is one example of these crossings outside of the crosswalk markings. Many people were observed crossing up to a car length away from the crosswalk markings; although, since this is a quiet side street, there was rarely any conflicting traffic waiting to leave or entering this leg of the intersection.

Considering factors associated with this weaker form of spatial violation, the crosswalk length was average. However, this crossing had one of the lowest AADTs and shortest distances to the nearest crosswalk of the locations in this study, both of which are factors that were associated with lower rates of this type of spatial violation. In other words, since these values were low, they would predict higher rates of crossing outside of the crosswalk markings, as was observed at this location. Investigating other site characteristics, it should be noted that this is one of the busiest intersections in Moab. It sees some of the highest pedestrian volumes at any signalized intersection in Utah, with upwards of 8,000 pedestrians per day during the summer months. It is also located immediately adjacent to the Moab Information Center and a park/plaza that is likely visited by many tourists. Anecdotally, many pedestrians were observed walking to/from the plaza, and one entrance to the plaza directs people at the street approximately 25 ft back from the crosswalk. Other people were observed walking to/from angled on-street parking.

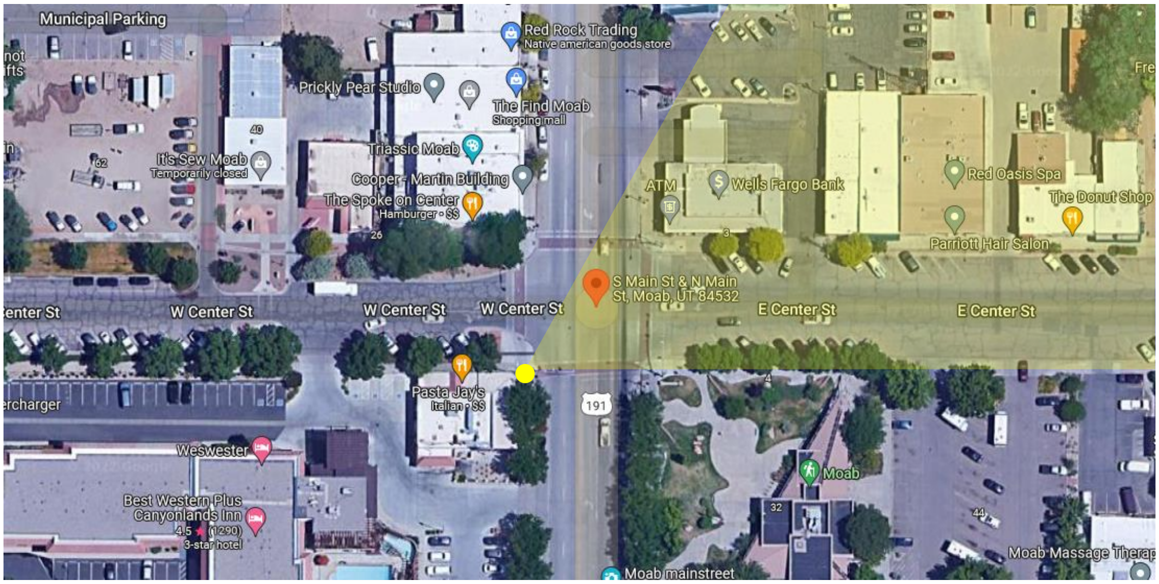



**Figure 4.13 Satellite view of camera angle for east crosswalk at signal 8302**


**Figure 4.14 Screenshot of example pedestrian crossing behavior at signal 8302**

Based on our observations, it is likely that the high rates of crossing outside of the crosswalk markings are not a huge pedestrian safety issue. Given this information, it is possible that some simple design changes could help to improve compliance. First, the crosswalk markings here are quite narrow: only ~8 ft, which may be too narrow to accommodate the large volumes of pedestrians crossing the street. Simply widening the crosswalk to be 15 ft or more could immediately improve the rate of pedestrians staying within the crosswalk. Second, the entrance to the plaza heading to/from the Moab Information Center could be redesigned to direct pedestrian traffic to the crosswalk itself, rather than upstream of the crosswalk. Both of these minor design changes would likely increase the number of people crossing the street within the crosswalk markings.

#### 4.6.4 North Crosswalk, Signal 7464 (5415 S & 4420 W, Kearns)

The north crosswalk at signal 7464—Figure 4.15—is another location with high rates of less severe spatial violations. Specifically, the majority of pedestrian events at this location involved crossing outside of the crosswalk markings (26, 72% vs. 7%); however, there was no significant overabundance of mid-block crossings here (2, 5% vs. 2%). Figure 4.16 is one example of these crossings outside of the crosswalk markings. The person bicycling on the sidewalk crosses the minor street using the curb ramps (targeted for the crosswalks across the main street), which are more in-line with the sidewalk than the crosswalk itself, which is set back from the major street.

For this crossing, we suspect intersection geometric design is playing a major role in the resulting pedestrian behaviors. As shown in Figure 4.15 and Figure 4.16, the north sidewalk along 5415 S is approximately 11 ft wide and is curb-tight, located between the curb and fences and yards with no buffer zone before the street. However, at the intersection, the crosswalk is pulled far back from the major street, so much so that the crosswalk starts approximately 21 ft back from where the curb would extend across the minor street. In other words, for pedestrians traveling along the major street to shift from the sidewalk to using the crosswalk markings, they have to shift laterally 15–20 ft, twice. Most pedestrians we observed were not willing to do this much out-of-direction travel.

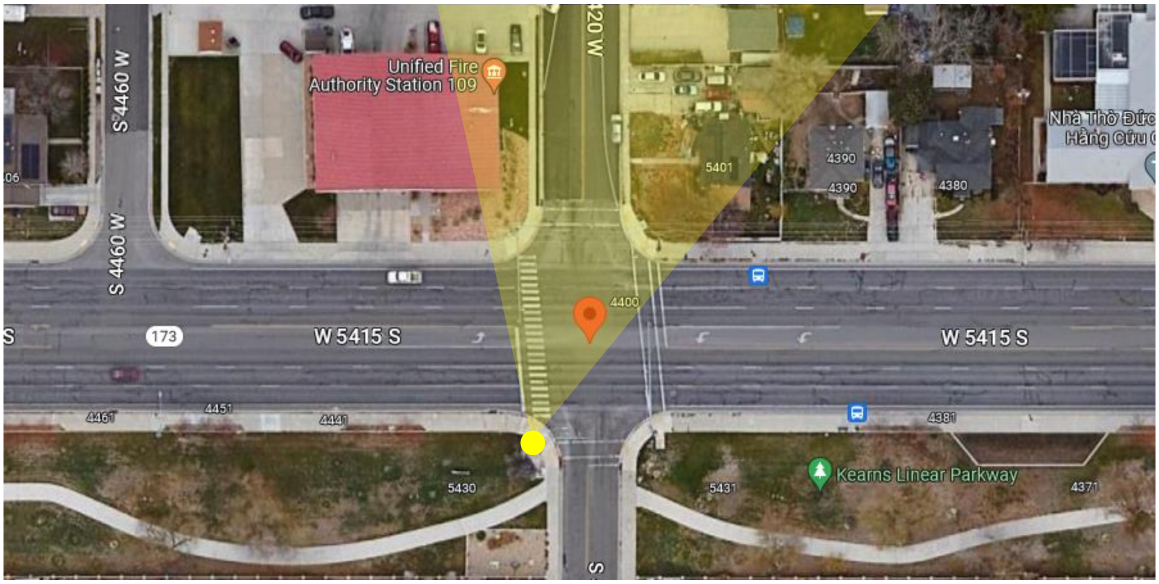



**Figure 4.15 Satellite view of camera angle for north crosswalk at signal 7464**


**Figure 4.16 Screenshot of example pedestrian crossing behavior at signal 7464**

Two other design factors complicate the situation and further encourage pedestrian spatial violations. First, the minor street being crossed (4420 W) is narrower than all other crossings in our study, so pedestrians have less of an incentive to shift their travel path to use the crosswalk markings. Second, there are two sets of curb ramps on each corner: One set of directional curb ramps is for use by users of the north crosswalk. However, the other set of curb ramps, for users of the east and west crosswalks, is designed and looks more like a diagonal (apex) curb ramp, which is typically used for multiple crosswalks. In fact, these curb ramps are located in a place where they would normally be used by someone traveling straight through on the sidewalks of 5415 S. We observed most sidewalk users (including people on bicycles) using these (more convenient) street-adjacent curb ramps rather than the ones further away. In short, the crossing design encourages pedestrians to cross outside of the crosswalk markings, and the crosswalk itself is in an inconvenient location for most pedestrians.

If UDOT is strongly interested in discouraging out-of-crosswalk crossings in locations like this (short crossing of a minor street that involves significant out-of-direction travel for pedestrians), a possible solution is to move the crosswalk closer to the desired and expected path of pedestrian travel. In this situation at signal 7646, this would mean moving the north crosswalk to be in-line with the sidewalks of 5415 S, and using the existing diagonal curb ramps. If there is a desire to have a shorter crossing (like that of the existing set-back crosswalk), then reducing the curb radius might be a more appropriate solution.

#### 4.6.5 Other Locations

High rates of spatial violations at a few other locations warrant some discussion as well. Since the topics are related, we are discussing them together in one subsection. The west crosswalk at signal 7099 (Redwood Rd & 2320 S, West Valley City) saw higher-than-average rates (11, 11% vs. 2%) of pedestrians crossing mid-block. Similarly, the south crosswalk at signal 8222 (200 N & 1225 W, Cedar City) saw higher-than-average rates of both mid-block crossings (7, 15% vs. 2%) and crossings outside of the crosswalk markings (10, 26% vs. 7%). Although the pedestrian volumes were relatively low at these crossings, the shares of pedestrian events with these spatial violations were statistically higher than average.


**Figure 4.17 Satellite view of camera angle for west crosswalk at signal 7099**


**Figure 4.18 Screenshot of example pedestrian crossing behavior at signal 7099**


**Figure 4.19 Satellite view of camera angle for south crosswalk at signal 8222**


**Figure 4.20 Screenshot of example pedestrian crossing behavior at signal 8222**

Figure 4.17 and Figure 4.18 show the layout and video view of the west crosswalk at signal 7099, while Figure 4.19 and Figure 4.20 show the layout and video view of the south crosswalk at signal 8222. Both of these crossings have characteristics in common that are directly linked with factors associated with spatial violations from the regression models. Specifically, these locations have shorter-than-average crossing lengths and very low AADTs. In other words, it is easier for pedestrians to cross mid-block or slightly outside of the crosswalk because they rarely experience conflicting motor vehicle traffic, and they can cross more quickly. Another defining characteristic that was not able to be included in the data collection and analysis is that both locations have driveways very close to the intersection (within 20 ft of the crosswalk). Many pedestrians (or people bicycling) were observed to cross from the driveways rather than walking down to cross in the crosswalk, when traveling between adjacent stores and fast food restaurants. Based on this information, if UDOT is strongly interested in discouraging mid-block and out-of-crosswalk crossings in locations like this (smaller minor streets with businesses and restaurants), one potential option is access management. Commercial driveways could be discouraged or prohibited within a certain distance from the intersection (e.g., 50, 100, or 150 ft), which would likely discourage pedestrians from using driveways to cross the street and encourage more crosswalk utilization.

## 4.7 Summary

This chapter presented results from the descriptive and statistical analyses of pedestrian crossing behaviors and violations. Two types of spatial violations were identified: crossing mid-block (2% of pedestrian events) and crossing outside of the crosswalk markings (7%). Two types of temporal violations were identified: crossing with >5 seconds against a conflicting protected green vehicle movement (6%) and starting to cross on a steady *don't walk* pedestrian indication (22%). Bivariate chi-square analyses and multivariate multilevel regression models identified factors associated with these spatial and temporal violation behaviors. Finally, example locations with high rates of pedestrian signal violations were examined in more detail, and explanations and possible recommendations were presented.

# 5.0 CONCLUSIONS

## 5.1 Summary

Pedestrian fatalities have been trending upward the past 10 years, especially on non-freeway arterials which are usually crossed at traffic signals (GHSA, 2020). This trend is also occurring in Utah (UDPS, n.d.). This study was proposed to determine what factors influence pedestrian crossing behaviors and what can be done to improve pedestrian safety at signalized intersections. Literature on pedestrian crossing behaviors were reviewed for key findings and relevance, as summarized in Chapter 2.0. Data were collected via video recordings of 47 crosswalks at 39 signals throughout Utah, which were then watched by trained students to gather data on pedestrians and pedestrian crossing behaviors. Other data about the conditions (day of week, time of day, weather) and location (crossing and intersection characteristics, land use and built environment characteristics, neighborhood sociodemographic characteristics) were also assembled. The data collection process was described in Chapter 3.0. Subsequently, the data were analyzed (in Chapter 4.0) using descriptive and statistical methods, including chi-square tests and multilevel regression models. The present chapter summarizes key findings from the research project and notes study limitations.

## 5.2 Findings

### 5.2.1 Who and How Are Pedestrians Crossing?

As part of this project, we recorded 5,589 pedestrian events across 47 crossings at 39 signals in 25 cities in Utah. From watching videos and transcribing information, we can summarize characteristics of pedestrians and their waiting and crossing situations, in general. The following bullet points summarize our key findings about who is crossing and other characteristics of the crossing situation:

- Data collectors identified that most pedestrians were young or middle-aged adults (37% and 33%, respectively), and they recorded more male (62%) than female (32%) pedestrians. (Roughly 20-25% of events involved people of unknown age and/or gender.)

However, these rates may not be entirely accurate, due to difficulties (and potential biases) involved with guessing age and gender from low-resolution videos.

- Most pedestrians were walking under their own power. However, bicycling in the crosswalk was fairly common, observed in 11% of events. The fairly high share of bicycles among crosswalk users suggests that many people bicycling do not feel comfortable riding in the street, perhaps due to a lack of protected bicycle facilities. People riding scooters, pushing strollers, on skateboards, or in wheelchairs were less common, observed in about 1% of events (each).

- Most pedestrians were walking alone, although about a quarter (26%) of events involved pedestrians traveling in a group of two or more people. About a quarter of the time (26%), there were other pedestrians (outside of the group) crossing at the same time.

- Regarding waiting behaviors:

    - Most pedestrians (56%) waited 20 seconds or less before starting to cross the street, with 5% of events involving no wait time; however, 12% of events involved a wait of longer than one minute.

    - Most of the time, there were vehicles passing the crossing location in the previous 10 seconds (70%) or the next 10 seconds (60%) from when a pedestrian arrived at the waiting area.

    - We observed people pressing the push-button about 50% of the time; although, this may be an underestimate of push-button use due to poor video quality. Also, not everyone has to press the button to get the walk indication: e.g., if the signal is on pedestrian recall or another person already pressed the push-button.

    - In about 6% of events, someone who was waiting left the area without crossing the street. (These observations were removed from later analysis.) It is uncertain why these people gave up and left.

- Regarding the crossing situation:

- Almost half (46%) of pedestrians took 15 seconds or less to fully cross the street (curb to curb), while 2% took more than 30 seconds.
- Since crossing time depends on crossing distance, we also calculated walking speeds. About 3% of crossings were slower than 3.5 ft/sec (FHWA MUTCD), but 8.5% of crossings were slower than 4.0 ft/sec (Utah MUTCD). This suggests that adopting the slower walking speed of 3.5 ft/sec for pedestrian clearance interval timing would accommodate the walking speeds of 5–6% more pedestrians.
    - We should also note that our results are without accounting for any adjustments or compensating behaviors that pedestrians might make in response to short crossing times, such as walking faster. It is possible that an even larger share of pedestrians than we measured have desired walking speeds slower than 3.5 ft/sec.
- About 4% of the time, a car was blocking the crosswalk when pedestrians were trying to cross. Less than 1% of pedestrians appeared to be distracted by their phone or something else, although this may be an under- or over-estimate, due to the video quality (and depending on what counts as being "distracted"). In other words, pedestrian distraction does not seem to be a pervasive safety issue, and a bigger concern is motor vehicles improperly stopping in and blocking the crosswalk when pedestrians are trying to cross.
- Key findings for other pedestrian crossing behaviors (including spatial and temporal violations) are summarized in the following subsections.

#### 5.2.2 How Common and What Factors Are Associated with Spatial Violations?

We considered and measured two types of spatial violations when classifying pedestrian crossing behaviors. The first (stronger) measure was crossing NOT in the crosswalk or crosswalk area, so crossing mid-block (away from the crosswalk) or in the middle of the intersection. The second (weaker) measure was crossing NOT within the crosswalk markings for most/all of the crossing (but still within the general crosswalk area). We then analyzed these measures of spatial violations for any associations with pedestrian information, waiting information, crossing information, temporal information, weather information, crossing and intersection characteristics, land use and built environment characteristics, or neighborhood sociodemographic characteristics. In the following bullet points, we summarize our key findings about pedestrian spatial violations and discuss potential causes and implications:

- Nearly all pedestrians (97–98%) crossed in or within a few feet of the crosswalk. Only 2–3% of crossing events happened mid-block, more than a car length away from the crosswalk. We recorded only four instances of pedestrians crossing in the middle of the intersection, so we could not do any subsequent statistical analysis of this behavior.

- Among pedestrians crossing in the crosswalk or crosswalk area, a large majority of people (85%) stayed within the crosswalk markings for all/most of the crossing, and 11% of events had someone both within and outside of the crosswalk markings for part of the time. Only 7% of crossing events involved pedestrians being outside of the crosswalk markings for most/all of the crossing. Crossing outside of the crosswalk markings could indicate a desire to cross mid-block, or a situation where the crosswalk is out of direction for most pedestrian paths (e.g., not aligned with adjacent sidewalks).

- In the bivariate analyses and subsequent multivariate multilevel analyses, we identified several factors that were associated with higher or lower chances of both types of spatial violations (crossing mid-block and crossing outside of the crosswalk markings):

    - People riding a bicycle, or using a scooter, skateboard, or wheelchair were less likely to cross mid-block or outside of the markings. This finding is likely due to the characteristics of these vehicles: because they have wheels, they usually cannot mount a curb. Therefore, bicycles and other micromobility devices usually must enter the roadway at a (crosswalk) curb ramp or driveway.

    - Interestingly, people who experienced a longer wait time were less likely to cross mid-block or outside of the markings. This is somewhat counterintuitive (and contrary to other literature reviewed in Section 2.2), since past research has found and one might expect a longer wait time to make for a more impatient pedestrian, thus increasing their chances of performing a crossing violation behavior.

However, we suspect that this finding is more a reflection of law-abiding behavior: people who are likely to cross away from or outside of the crosswalk are also less likely to wait longer to make that crossing and instead look for gaps in traffic.

  - Crossing events recorded at times with warmer temperatures were more likely to involve one of these spatial violations. We are unsure of the precise reasons for this finding. One potential explanation is that, on hot days, pedestrians may try to avoid spending time walking along arterials or waiting at large signalized intersections, where there are large expanses of paved surfaces which may exacerbate urban heat issues.

  - Both types of spatial violations were less common (less likely) at crosswalks with longer crossing distances and/or higher traffic volumes. We suspect that this is a result of strategic decision-making on the part of pedestrians. Longer crossing distances mean longer crossing times and more potential exposure to motor vehicles. Similarly, higher traffic volumes imply greater exposure and potentially fewer gaps in traffic. Thus, pedestrians may be considering their risk when choosing (not to) cross wider and busier streets away from the crosswalk.

- Although pedestrians crossing mid-block was rare, we did identify several unique factors that were associated with only this spatial violation behavior:

  - Events with pedestrians identified as female presenting were less likely to involve a mid-block crossing. This matches findings from the literature that male pedestrians are more likely to perform a traffic violation than female pedestrians.

  - The presence of other people crossing at the same time seemed to reduce the chance of a mid-block crossing. Perhaps there is a degree of peer pressure, by which pedestrians are less likely to perform a traffic violation if they could be observed by others. Or this could be related to the following finding.

  - Mid-block crossings were more likely overnight, between the hours of midnight and 6am. This is not surprising, since motor vehicle traffic tends to be much lower at this time of day, offering more gaps for pedestrians to cross and reducing the need to spend more time walking to and waiting for the signal.

  - Our analyses found that mid-block crossings were slightly more common in neighborhoods having higher percentages of the population of Hispanic or non-white race/ethnicity. We should be clear to note that this finding does not suggest that people of a certain race/ethnicity are more or less likely to perform a spatial violation, because we did not (and could not) measure the racial/ethnic identity of pedestrians. Instead, this could indicate that such populations are disproportionately located in neighborhoods with fewer safe crossing opportunities, such as along large arterials with poorly connected street grids and long distances between controlled crosswalks.

- We also identified several factors that were uniquely associated with crossing outside of the crosswalk markings (but not crossing mid-block):

  - Contrary to the finding for mid-block crossings, events with crossings outside of the crosswalk markings were actually more likely when there were (any or greater numbers of) other pedestrians crossing at the same time. Rather than peer pressure, we suspect this may reflect space limitations and crowding. In places with more pedestrians (moving in the same or opposite directions), some people or groups may need to cross outside of the crosswalk markings to make space for everyone or to maintain their walking pace. Perhaps these locations have crosswalk markings that are narrower than may be warranted by the pedestrian volume.

  - Another unique factor was the effect of the number of passing vehicles when the pedestrian arrived at the waiting area. Specifically, crossing outside of the markings was less likely where there had been more vehicles passing the crossing location. This finding could reflect there being high volumes of traffic also waiting at the stop bar when pedestrians are crossing, thus discouraging pedestrians from straying too far outside of the crosswalk itself.

### 5.2.3 How Common and What Factors Are Associated with Temporal Violations?

We considered and measured two types of temporal violations when classifying pedestrian crossing behaviors. The first (stronger) measure was crossing more than 5 seconds against a green indication for a conflicting protected vehicle movement. The second (weaker) measure was starting to cross on the steady *don't walk* pedestrian indication. We then analyzed these measures of temporal violations for any associations with pedestrian information, waiting information, crossing information, temporal information, weather information, crossing and intersection characteristics, land use and built environment characteristics, or neighborhood sociodemographic characteristics. In the following bullet points, we summarize our key findings about pedestrian temporal violations and discuss potential causes and implications:

- A large majority (89%) of pedestrian crossing events occurred without any time spent in the intersection against a conflicting green movement. (This rate is approximate, since there was sometimes a couple-second discrepancy between the signal controller time and the video timestamp.) However, about 5–6% of the time, there were pedestrians in the crosswalk for at least 5 seconds (again, plus or minus a couple seconds) while a conflicting protected vehicle movement had a green indication.

- Regarding just the pedestrian signal status itself, a large majority of pedestrians started crossing on the *walk* indication (58%) or the flashing *don't walk* indication (19%). A sizable share (22%) did start crossing when the walk signal showed steady *don't walk*. However, as previously noted, we consider this to be a less serious temporal violation, for a couple of reasons. First, they could be anticipating the *walk*, and starting to cross when the intersection is clear but a couple of seconds before the *walk* indication actually appears. Second, they could be crossing when the *walk* indication would have appeared, but no one pressed the push-button (for a crossing not on pedestrian recall). Anecdotally, we noticed many instances of pedestrians crossing on steady *don't walk* but at the same time as the parallel through vehicle movements. Although often less serious, this behavior could still result in a potentially dangerous situation, since the signal may not provide enough time for the pedestrian to clear the intersection before the start of a conflicting protected vehicle movement. Thus, this is why we prefer to look at the first measure of a temporal violation: crossing against a conflicting protected green vehicle movement.

- In the bivariate analyses and subsequent multivariate multilevel analyses, we identified several factors that were associated with higher or lower chances of both types of temporal violations (starting to cross against steady *don't walk*, and crossing >5 seconds against a conflicting green):

    - Pedestrian crossing events that included a child were less likely to involve a temporal violation. This may be because children were usually accompanied by an adult, and such events may involve more control or instruction about children's crossing behaviors.

    - As with spatial violations, the odds of performing a temporal violation also decreased with waiting time. Although somewhat contrary to previous research, again, we interpret this to be a reflection of law-abiding behavior: As wait time increases, the people who remain are more likely to be those who do not want to cross against the *don't walk* indication or against a conflicting protected motor vehicle movement. Those pedestrians who are more likely to make a temporal violation are likely to wait less to do so.

    - We also find some evidence to support peer pressure with respect to temporal violations, which were less likely when there were other pedestrians crossing at the same time. Alternatively, this could reflect the fact that with more pedestrians present, there was a greater chance that someone pressed the push-button to bring up the *walk* indication.

    - Temporal violations were also less likely for events where there were more vehicles passing when the pedestrian arrived in the waiting area, and in locations with higher traffic volumes (AADT). We suspect these two findings arise from the same reason, as was also discussed for spatial violations: More motor vehicle traffic implies greater exposure and fewer gaps to accept, thus leading risk-averse pedestrians to rely on the traffic signal more to get them safely across the street.

  - Unsurprisingly, temporal violations happened more often during less busy times of day, including in the morning (6am to noon) and especially overnight (midnight to 6am). As with our explanation for spatial violations, lower traffic volumes imply more gaps for safe crossings and less of a need to rely on the temporal protection offered by the pedestrian signal.

  - Pedestrian crossing events at the one signal (7475) that was a mid-block crossing (2-leg intersection)—controlled by a pedestrian hybrid beacon—were much more likely to involve a temporal violation. In fact, more than half of the crossings at this location involved some sort of temporal violation. It may be difficult to extrapolate this finding to other mid-block signalized crossings. This particular intersection had a center median refuge island, and traffic was not particularly busy during the times when the video was recorded, both of which likely helped pedestrians to find an adequate gap in traffic without having to wait for the signal.

  - As with mid-block crossing behavior, our analysis also found that temporal violations were slightly more common in neighborhoods having higher percentages of the population of Hispanic or non-white race/ethnicity. Again, we need to clarify that this is a finding about a neighborhood characteristic, not a pedestrian characteristic. Perhaps such populations tend to be located in areas with larger arterials and near signals with longer cycle lengths, which might encourage more crossing against the signal indications.

- We found a few unique factors that were associated with only the behavior of crossing against a conflicting green vehicle movement:

  - This temporal violation was more likely for pedestrian crossings on days and at times with warmer temperatures. Again, we are uncertain about the cause of this finding. We have a similar possible explanation as for spatial violations: In hot weather, pedestrians may want to minimize their time spent walking or waiting near hot paved surfaces.

    - Median width was positively associated with crossing against a green light, but only in the bivariate analysis (not in the multivariate regression model). This could reflect people being more willing to cross against the light if they have a (wider) median where they can wait, effectively performing a two-stage pedestrian crossing by only worrying about gaps in one direction of traffic.

- We also identified several factors that were uniquely associated with crossing on steady *don't walk* (but not crossing against a conflicting green):

    - Crossings events involving teens were less likely to have this temporal violation. This could be similar to the potential explanation for children, or it could be related to the next finding about group size.

    - Crossing against the steady *don't walk* was less likely for larger groups of pedestrians. Perhaps the peer pressure element reduces temporal violation behavior. Or perhaps the more people there are in a group, the greater variety of pedestrian capabilities, and the less likely it is for everyone in the group to agree to crossing against the steady *don't walk*.

    - Crossings involving people using a bicycle, scooter, skateboard, and/or wheelchair were more likely to start on steady *don't walk*. Interestingly, this is contrary to our findings about spatial violations being less likely for this group of crosswalk users. Perhaps this group (dominated by bicycle users, and more scooter/skateboard than wheelchair users) is able to travel faster, and thus more willing to accept a gap in traffic. Alternatively, it may be more difficult for these users to stop, reach, and press the push-button, which could result in more crossings against steady *don't walk* but with parallel motor vehicle movements.

    - Pedestrian crossings on weekends were more likely to start on steady *don't walk*. We suspect that this had to do with lower traffic volumes and perhaps more pedestrians walking at times of day (evening) when traffic volumes are lower.

    - The presence of obstacles—such as a car blocking the crosswalk, piles of snow, or puddles of water—seemed to deter people from crossing against the steady *don't walk*. This could simply reflect an additional deterrent or challenge for pedestrians to overcome, or the presence of an obstacle could mean longer crossing time and less ability to accept a gap in traffic.

- Finally, crossings during hours with more precipitation were less likely to start on steady *don't walk*. While one might expect pedestrians to want to cross as soon as possible to avoid waiting in the rain or snow, perhaps there is an element of risk perception happening. Perhaps pedestrians think that drivers will not be able to see them as well if it is raining or snowing, or that they themselves will not be able to cross as fast if the road surface is wet or slippery.

### 5.2.4 Crash Correlation

In our interpretation of the study results, we frequently concluded that some finding (about rates of spatial or temporal pedestrian crossing violations, or some factor associated with these behaviors) did not necessarily suggest that the behaviors or situations analyzed were inherently dangerous or unsafe. For example, some people crossing against a steady *don't walk* or outside of the crosswalk markings might have been perfectly safe, with no potentially conflicting motor vehicles in sight. However, it could be useful to compare the rates of pedestrian violations that we observed in this study with rates of pedestrian crashes at signalized intersections. The strength of any correlation obtained from such an analysis might indicate which pedestrian behaviors could be more likely to result in collisions or injuries, in aggregate.

Thus, we calculated the correlations between pedestrian crashes and pedestrian behaviors. The pedestrian crash data we used was borrowed from a recent UDOT research project on systemic safety analysis for pedestrians (Singleton et al., 2022). Three crash outcomes were examined: total observed crashes (over 10 years, 2010–2019), model-predicted crashes, and a mixture of observed and model predicted crashes (using a method called empirical Bayes). The four pedestrian behaviors examined were: spatial violations (crossed mid-block, crossed outside of markings) and temporal violations (crossed with >5 seconds green, started on steady *don't walk*). To be comparable, we converted all measures to rates per intersection: crashes per year, and violations per hour.

Table 5.1 reports the correlation between each of the pedestrian violation behaviors and the various measures of pedestrian crashes. All of the estimated correlations were positive, meaning that there did seem to be some associations between the frequency of pedestrian violation behaviors and pedestrian crashes. This suggests that places with more violations also seem to experience more crashes; although, most correlations are fairly weak (< 0.20). The pedestrian behavior most closely linked (largest correlation) to pedestrian crashes was starting to cross on steady *don't walk* (it was marginally significant). While this could suggest that this behavior is dangerous, this was also the most frequently observed behavior, so other behaviors might have been more strongly correlated if more observations were collected.

**Table 5.1 Correlations between pedestrian behaviors and pedestrian crashes**

| *Correlation* | *Pedestrian crashes (# / year)* | | |
|---|---|---|---|
| | *Observed* | *Model Predicted* | *Empirical Bayes* |
| Pedestrian behaviors (# / hour) | | | |
| Crossed mid-block | 0.071 | 0.102 | 0.143 |
| Crossed outside of markings | 0.050 | 0.161 | 0.134 |
| Crossed with >5 sec green | 0.036 | 0.158 | 0.196 |
| Started on steady don't walk | 0.191 | *0.349* | *0.319* |

*Italics* are marginally statistically significant at $p < 0.10$

## 5.3 Limitations and Challenges

This study was not without challenges that limited the findings and recommendations resulting from the research. The biggest limitation arose from the data collection method itself: The data we manually collected from the videos are subject to potential human errors and biases. We tried to eliminate biases and errors by using a standardized data collection form, training our data collectors (undergraduate students) beforehand, validating the collected data afterwards (both manually and using automatic checks/flags), and correcting any errors that were discovered. Yet, biases and errors may remain, especially for pieces of information that were more tedious and subjective to collect. For instance, the quality of the videos often did not allow for the determination of pedestrians' gender and age with high reliability, and these characteristics are also harder to determine through observation only (due to different ways of presenting oneself). Various data collectors may have interpreted cues for age and gender (dress, hair, walking speed) differently, leading to systematic differences between videos. Other pieces of information about pedestrian waiting or crossing behaviors—for example: "paced or otherwise seemed impatient," "changed speed (e.g., walk to run, or run to walk)," and "seemed distracted by phone or something else"—may have been interpreted slightly differently by various data collectors. We did spend more time checking and correcting the outcomes of interest (pedestrian behaviors resulting in spatial and temporal violations). Since timestamps were important for relating crossing behaviors to the traffic signal (pedestrian and vehicle) status, we did check and correct timestamps as well. However, errors may still remain. Using a computer vision software that automatically extracts trajectories, locations, and timestamps for different road users might aid in improving the quality and reliability of some (but not all) of the pieces of information that we manually transcribed from the videos in this study.

Some other limitations of this research relate to the study design itself. Compared to previous research on pedestrian crossing behaviors at intersections (Table 2.1), our study investigated more sites (47 crosswalks at 39 signals) and observed more pedestrians (5,589) than in most prior studies. We also tried to vary the types of locations that we studied, in order to identify any intersection design, operational, or neighborhood contextual factors affecting pedestrian crossing behaviors and signal violations. However, more variation in certain categories or levels of potential explanatory variables would help to make results from a study like this more generalizable to other locations. For instance, we studied only three crosswalks at 3-leg intersections and only one (pedestrian hybrid beacon) signalized mid-block crossing. We were unable to study some characteristics such as the lack (or quality) of street lighting, the presence of right-turn restrictions, and some pedestrian signal timing strategies (such as exclusive pedestrian phases and leading pedestrian intervals). Also, although we tried to capture data during different seasons, about half of the videos were recorded in March, so we may have not adequately represented the impact of different weather or seasonal factors on pedestrian crossing behaviors. Finally, most of the videos were recorded in 2019 for a different UDOT research project (Singleton et al., 2020). Although other research has found that some pedestrian behavior at signalized intersections—push-button use (Runa & Singleton, 2022)—did not change much before vs. during the COVID-19 pandemic, and traffic volumes today are back up to pre-COVID levels in many locations, it is possible that there has been some systematic change in pedestrian crossing behaviors due to the COVID-19 pandemic. Our initial hypothesis is that, if such changes have happened, they are likely small; but such a hypothesis could be studied in future research.

# 6.0 RECOMMENDATIONS AND IMPLEMENTATION

## 6.1 Recommendations

Based on findings from our data collection and analysis of pedestrian crossing behaviors at signalized intersections in Utah, we have several recommendations for UDOT to consider that may help to improve pedestrian safety. Each of these recommendations relies on results from our statistical models presented in Chapter 4.0, suggestions from inspecting locations with higher-than-average rates of temporal and/or spatial violations in Section 4.6, and/or our findings summarized in Section 5.2.

- Our analyses found that crossings with a (wider) median tended to see more pedestrian temporal violations, notably crossing against a conflicting green protected vehicle movement. This was especially noticeable from observations at signal 7086 (Redwood Rd & N Temple, Salt Lake City), which also saw a high rate of mid-block crossings. To discourage two-stage and mid-block crossings in locations such as these (with small medians not suitable for pedestrians to wait), one option could be to install obstacles to discourage pedestrians from crossing over them. These obstacles could include decorative fencing or artistic barriers. Care should be taken that any objects installed on the median are safe (in case of collision), do not obscure sight distances for all road users, and do not catch trash or other debris.

- By using two different measures to indicate temporal violations, we identified that a large share of pedestrian who started crossing on steady *don't walk* (against the pedestrian signal) did not actually spend much time crossing against a protected green vehicle movement. (22% started crossing on steady *don't walk*, but only 6% spent more than 5 seconds crossing against a conflicting green movement.) This implies that a sizable number of pedestrians are crossing at the same time as the parallel through vehicle movements, but without the *walk* indication, likely because they did not press the push-button. We noticed this behavior at several locations (see Table 4.9), including (but not exclusively) at signal 7086 (Redwood Rd & N Temple, Salt Lake City) which had high pedestrian volumes throughout the day and night.

- One strategy to increase pedestrian signal compliance could be to place these crossings on pedestrian recall and rest-in-walk, so that the *walk* indication appears every cycle without pedestrians having to press the push-button. This type of operation could be prioritized for locations and/or times of day with higher pedestrian volumes, as measured by pedestrian push-button use (Singleton et al., 2020). Such information is currently available through the ATSPM website (UDOT, n.d.) and another website (Singleton Transportation Lab, 2023).
- Another option could be to utilize the "ped recycle" (or "ped reservice") setting in the traffic signal controller. In this situation, if a pedestrian phase is called after the start of the associated green vehicle movement, the signal will display the *walk* indication immediately (rather than waiting to do this during the next cycle) as long as there is still time to serve the pedestrian intervals. By potentially reducing pedestrian delay, this setting might help to reduce temporal violations.
- Of course, changes to pedestrian signal timing and phasing might have some implications for intersection traffic operations. Specifically, applying pedestrian recall and/or rest-in-walk is likely to increase the duration of phases, which may increase overall cycle length. Longer cycle lengths tend to mean greater delay for all road users, including pedestrians, and potentially more temporal violations. Future behavioral or simulation research could quantify these tradeoffs between accommodating pedestrians who don't press the button or press it late and minimizing (pedestrian and other road user) delay, and help to identify where and when these pedestrian traffic signal operational treatments may be best applied.

- Another strategy that could reduce temporal violations and increase pedestrian signal compliance would be to place pedestrian push-buttons in locations that are convenient and accessible for all pedestrians (and sidewalk users). For instance, at signal 7475 (300 W & 50 S, Salt Lake City), we saw many pedestrians cross without pressing the button to activate the pedestrian hybrid beacon. This could have been in part because, depending on what direction someone was approaching, the push-button was up to 20 ft away on the other side of the wide crosswalk. In that instance, adding push-buttons on both sides of the crosswalk waiting area (or in the center) might increase push-button usage and thus signal compliance. In general, push-buttons should be located close to the curb ramp and in a location that minimizes how far out of their way pedestrians must walk to reach them, in accordance to guidelines in the MUTCD (FHWA, 2022) and PROWAG (US Access Board, 2013).

- Our analyses identified that locations with shorter crosswalks (crossings of narrower streets) saw more spatial violations, and crossings of lower volume streets (with lower AADT) had more spatial and temporal violations. We reiterate that this finding is not to suggest that wider and busier streets will improve pedestrian safety; indeed, such streets tend to see more pedestrian crashes (Singleton et al., 2022). Instead, this reflects that pedestrians can more easily (and safely) cross smaller and quieter streets in locations and at times when they may not be expected. Notably, we saw high rates of spatial violations for crossings at two signals with these factors (7099, Redwood Rd & 2320 S, West Valley City) (8222, 200 N & 1225 W, Cedar City) that were characterized by the presence of driveways very close to (within 20 ft of) the crosswalk, and adjacent auto-oriented businesses and fast food restaurants. One strategy to potentially reduce pedestrian spatial violations in locations like these (smaller side streets in commercial areas) is access management. Prohibiting or discouraging commercial driveways within some distance (say, 50, 100, or 150 ft) of the intersection might discourage pedestrians from crossing at driveways and encourage them to cross at the crosswalk instead. While UDOT's guidelines currently prohibit driveways within at least 150 ft from an intersection on state routes (depending on functional classification), such regulation for non-state routes is determined by local governments.

- In our inspection of locations with high rates of crossing in the crosswalk area but outside of the crosswalk markings—which, again, we considered to be less severe of a spatial violation than crossing mid-block—we also noticed some design considerations that might better align crosswalks with the paths that pedestrians want to or have to take.
    - At signal 8302 (Main St & Center St, Moab), a lot of people were crossing from a nearby destination (visitor center) and the path led them to start crossing slightly

before (not at) the intersection. Also, the crosswalk was quite narrow (8 ft) for an intersection with one of the highest pedestrian volumes in the entire state of Utah. Widening the crosswalk to 15 ft or more at high-volume crossings might increase the percentage of pedestrians who cross within the crosswalk markings.

  - At signal 7464 (5415 S & 4420 W, Kearns), a lot of people were crossing closer to the intersection than the crosswalk, which was set back ~20 ft and required substantial out-of-direction travel for pedestrians to utilize. In situations like this (where the crosswalk is located far from the desired straight pedestrian path), a possible solution is to move the crosswalk closer to the expected path where pedestrians will be using it (i.e., in line with the upstream and downstream sidewalks).

- In addition to crossing violations, our data collection found a sizable difference in the number of people walking slower than 4.0 ft/sec (8.5%) versus those walking slower than 3.5 ft/sec (3.0%). We recommend that Utah consider using a walking speed of 3.5 ft/sec for pedestrian signal (clearance interval) timing, as suggested in the federal MUTCD, at least in some locations. Our results suggest that 3.5 ft/sec might accommodate the walking speeds of 5–6% more pedestrians than a 4.0 ft/sec walking speed.

  - More than or approximately 15% of several population groups crossed at a speed slower than 4.0 ft/sec: older adults, wheelchair users, children, people pushing strollers, people carrying loads, and pedestrians in groups of 3 or more people. A slower walking speed could be considered in locations with more concentrations of these types of pedestrians. Another option could be to implement an extended press feature of push-buttons in these locations, whereby holding the button for a couple seconds enables a longer pedestrian clearance time.

- Also, our data collection found that a larger portion of pedestrian crossing events involved a car blocking the crosswalk (4%) than involved an obviously distracted pedestrian (1%). This suggests additional educational campaigns or driver training efforts about stopping before the crosswalk and not blocking the crosswalk at intersections.

Based on rates found in our study, this form of education could have a greater reach/impact than education about distracted walking.

We also have some ideas for additional analyses that could utilize the data collected or findings produced by this research project. Specifically:

- Overall, we found that a fairly high share of crosswalk users were people bicycling (11%). Future analysis could take our dataset and compare bicycle mode shares in the crosswalk with various other location characteristics. Places with high sidewalk bicycle mode shares might indicate a need for enhanced bicycling infrastructure (e.g., a protected bicycle lane or off-street path) because many people feel most comfortable riding on the sidewalk.

- Also, the multilevel regression models estimated in this study identified some locational factors (crossing, intersection, land use, built environment, and neighborhood sociodemographic characteristics) that were associated with higher or lower rates of specific types of pedestrian crossing violations. By applying the model results to all other signalized intersections in Utah, locations with high expected rates of these pedestrian behaviors could be identified for further study or prioritized for safety treatments. Such work would require the assembly of similar data as was assembled and presented in Table 4.3 to be collected for all signals, and the application of a simplified form of the models presented in Sections 4.4 and 4.5 (with only level-two variables).

Finally, based on some of the study's limitations and challenges, we have several suggestions for future research on pedestrian crossing behaviors and pedestrian safety:

- The one mid-block location we studied (signal 7475, 300 W & 50 S, Salt Lake City) had high rates of temporal violations, but not high rates of spatial violations. We do not know the degree to which these findings are transferrable or the result of factors specific to this particular location: a pedestrian hybrid beacon, with a center median island, and fencing along the median before/after the crossing. There is a need to investigate pedestrian behaviors at other mid-block signalized crossings (both with and without medians, and with varying design characteristics) to see if other mid-block crossings have high rates of temporal (or spatial) violations, and what design characteristics might reduce these rates.

- Overall, this study studied 47 separate locations; while this is more than in most previous research, it is less than may be desirable to ascertain the impacts of various design, operational, and locational factors on pedestrian crossing behaviors. It would be useful to expand this study to more locations, and study each location for longer and at different times of year. All of these techniques would help to increase the sample size (in terms of both level-one and level-two units) and, more importantly, result in more generalizable research findings.

- One way to potentially increase sample sizes, while also reducing some potential errors in data collection, would be to remove humans from much of the hands-on data collection process. Computer vision and machine learning approaches exist to extract information (user trajectories, timestamps, locations, etc.) from recorded videos in a more systematic way. Such methods may help collect some data—like timestamps or more subjective pedestrian behaviors—in a more accurate or at least standardized manner. Yet, such video-processing methods still require some degree of human interaction, including setting up the fields of view (angles, distances, zones) and telling the computer how to interpret and translate movements (of objects through a pixel grid) into meaningful information about pedestrian behaviors.

- Long term, it would be useful to continue to monitor the capabilities of technology used to automatically monitor traffic and capture surrogate safety measures (e.g., computer vision, machine learning, and artificial intelligence from videos or other sensors). At some point, technology costs may decrease and capabilities may increase enough such that many devices can be deployed in the field and track road user behaviors in real time. Networks of devices could monitor the situation and send alerts (to transportation agency managers, or even to road users themselves in the field) if there are too many or severe traffic violations of certain types.

## 6.2 Implementation Plan

There are a variety of ways in which our recommendations could be implemented. Many of the recommendations based on data analysis and study findings involve somewhat minor design or operational changes to intersections and crosswalks: installing decorative median obstacles, putting crossings on pedestrian recall and rest-in-walk or using the “ped recycle” setting, aligning push-buttons and crosswalks with desired pedestrian paths, and discouraging intersection-adjacent driveways. These treatments could be tested in a handful of locations, and their efficacy on reducing pedestrian crossing violation behaviors could be tested using observational before/after analyses (utilizing similar data collection methods as were used in this study). If successful, these treatments could then be considered for implementation more widely, based on guidelines determined through subsequent research. Such testing and implementation would require the coordination and buy-in of traffic signal operations and roadway design engineers from both state and local transportation agencies.

Our suggestion about changing the walking speed assumed for pedestrian clearance interval timing from 4.0 to 3.5 ft/sec would likely require the retiming of many traffic signals, as well as support from UDOT and local agencies’ traffic signal operations staff and managers. As previously discussed, implementing this change might also result in adverse operational impacts, potentially including longer cycle lengths and pedestrian delay. This change could be tested in a handful of locations first (perhaps those used by more older adults), to measure the operational impacts for all road users and any changes in pedestrian crossing behaviors.

The educational campaign to discourage motor vehicle drivers from blocking the crosswalk could take multiple approaches. There could be minor enhancements to the driver licensure process, including test questions or field exam to check for stopping behaviors. A marketing campaign could be designed to educate the broader public about crosswalk rules, not just at signalized intersections, but also the need to yield to pedestrians at uncontrolled and unmarked legal crossings. Additional signs or pavement markings could be placed at specific high-risk or high-pedestrian volume intersections to highlight the stop bar. Restricting right-turns-on-red could be a potential strategy at key locations.

We also identified several opportunities for further analysis and future research. Some of these efforts more locally—such as studying road user behaviors at mid-block crossings or testing the effectiveness of specific intersection treatments recommended above—could likely be accomplished via a research project funded through UDOT's "UTRAC" research prioritization process. For larger research efforts—studying more locations, over longer time periods, using computer vision and machine learning methods—requiring greater resources, a research project funded through the National Cooperative Highway Research Program (NCHRP) or Transportation Pooled Fund (TPF) programs would likely be more feasible.

# REFERENCES


Bendak, S., Alnaqbi, A. M., Alzarooni, M. Y., Aljanaahi, S. M., & Alsuwaidi, S. J. (2021). Factors affecting pedestrian behaviors at signalized crosswalks: an empirical study. *Journal of Safety Research, 76*, 269-275. https://doi.org/10.1016/j.jsr.2020.12.019

Brosseau, M., Zangenehpour, S., Saunier, N., & Miranda-Moreno, L. (2013). The impact of waiting time and other factors on dangerous pedestrian crossings and violations at signalized intersections: A case study in Montreal. *Transportation Research Part F: Traffic Psychology and Behaviour*, *21*, 159-172. https://doi.org/10.1016/j.trf.2013.09.010

Chai, C., Shi, X., Wong, Y. D., Er, M. J., & Gwee, E. T. M. (2016). Fuzzy logic-based observation and evaluation of pedestrians' behavioral patterns by age and gender. *Transportation Research Part F: Traffic Psychology and Behaviour*, *40*, 104-118. https://doi.org/10.1016/j.trf.2016.04.004

Chen, S., Xing, J., & Cao, Y. (2017). The impact of waiting time on pedestrian violations at signalized Intersections. *Civil Engineering and Urban Planning: An International Journal (CiVEJ)*, *4*(2). https://doi.org/10.5121/civej.2017.4201

Cinnamon, J., Schuurman, N., & Hameed, S. M. (2011). Pedestrian injury and human behaviour: observing road-rule violations at high-incident intersections. *PloS one*, *6*(6), e21063. https://doi.org/10.1371/journal.pone.0021063

Cooper, J. F., Schneider, R. J., Ryan, S., & Co, S. (2012). Documenting targeted behaviors associated with pedestrian safety. *Transportation Research Record: Journal of the Transportation Research Board*, *2299*(1), 1-10. https://doi.org/10.3141/2299-01

Day, C. M., Taylor, M., Mackey, J., Clayton, R., Patel, S. K., Xie, G., ... & Bullock, D. (2016). Implementation of Automated Traffic Signal Performance Measures. *ITE Journal*, *86*(8), 26–34.

de Lavalette, B. C., Tijus, C., Poitrenaud, S., Leproux, C., Bergeron, J., & Thouez, J. P. (2009). Pedestrian crossing decision-making: A situational and behavioral approach. *Safety Science*, *47*(9), 1248-1253. https://doi.org/10.1016/j.ssci.2009.03.016

Ding, T., Wang, S., Xi, J., Zheng, L., & Wang, Q. (2015). Psychology-based research on unsafe behavior by pedestrians when crossing the street. *Advances in Mechanical Engineering*, *7*(1), 203867. https://doi.org/10.1155/2014/203867

Dommes, A., Granié, M. A., Cloutier, M. S., Coquelet, C., & Huguenin-Richard, F. (2015). Red light violations by adult pedestrians and other safety-related behaviors at signalized crosswalks. *Accident Analysis & Prevention*, *80*, 67-75. https://doi.org/10.1016/j.aap.2015.04.002

Eustace, D. (2001). Pedestrian reaction to crossing signal delay. *Journal of the Transportation Research Forum*, *40*(1). Eno Transportation Foundation.

Federal Highway Administration (FHWA). (2022). *Manual on Uniform Traffic Control Devices (MUTCD)*. https://mutcd.fhwa.dot.gov/

Freeman, J., & Rakotonirainy, A. (2015). Mistakes or deliberate violations? A study into the origins of rule breaking at pedestrian train crossings. *Accident Analysis & Prevention*, *77*, 45-50. https://doi.org/10.1016/j.aap.2015.01.015

Governors Highway Safety Association (GHSA). (2020). *Pedestrian Traffic Fatalities by State: 2019 Preliminary Data*. https://www.ghsa.org/resources/Pedestrians20

Guéguen, N., & Pichot, N. (2001). The influence of status on pedestrians' failure to observe a road-safety rule. *Journal of Social Psychology*, *141*(3), 413-415. https://doi.org/10.1080/00224540109600562

Guo, H., Gao, Z., Yang, X., & Jiang, X. (2011). Modeling pedestrian violation behavior at signalized crosswalks in China: A hazards-based duration approach. *Traffic Injury Prevention*, *12*(1), 96-103. https://doi.org/10.1080/15389588.2010.518652

Jason, L. A., & Liotta, R. (1982). Pedestrian jaywalking under facilitating and nonfacilitating conditions. *Journal of Applied Behavior Analysis*, *15*(3), 469-473. https://doi.org/10.1901/jaba.1982.15-469

Koh, P. P., Wong, Y. D., & Chandrasekar, P. (2014). Safety evaluation of pedestrian behaviour and violations at signalised pedestrian crossings. *Safety Science*, *70*, 143-152. https://doi.org/10.1016/j.ssci.2014.05.010

Kruszyna, M., & Rychlewski, J. (2013). Influence of approaching tram on behaviour of pedestrians in signalised crosswalks in Poland. *Accident Analysis & Prevention*, *55*, 185-191. https://doi.org/10.1016/j.aap.2013.03.015

Lachapelle, U., & Cloutier, M. S. (2017). On the complexity of finishing a crossing on time: Elderly pedestrians, timing and cycling infrastructure. *Transportation Research Part A: Policy and Practice*, *96*, 54-63. https://doi.org/10.1016/j.tra.2016.12.005

Lefkowitz, M., Blake, R. R., & Mouton, J. S. (1955). Status factors in pedestrian violation of traffic signals. *The Journal of Abnormal and Social Psychology, 51*(3), 704–706. https://doi.org/10.1037/h0042000

Mukherjee, D., & Mitra, S. (2020). A comprehensive study on factors influencing pedestrian signal violation behaviour: Experience from Kolkata City, India. *Safety Science*, *124*, 104610. https://doi.org/10.1016/j.ssci.2020.104610

National Academies of Sciences, Engineering, and Medicine (NASEM). (2018). *Systemic Pedestrian Safety Analysis*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25255.

National Academies of Sciences, Engineering, and Medicine (NASEM). (2020). *Guidance to Improve Pedestrian and Bicyclist Safety at Intersections.* Washington, DC: The National Academies Press. https://doi.org/10.17226/25808.

National Highway Traffic Safety Administration (NHTSA). (2020.) *Traffic Safety Facts*. https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812850

Paschalidis, E., Politis, I., Basbas, S., & Lambrianidou, P. (2016). Pedestrian compliance and cross walking speed adaptation due to countdown timer installations: A self report study. *Transportation Research Part F: Traffic Psychology and Behaviour*, *42*, 456-467. https://doi.org/10.1016/j.trf.2015.07.010

Pelé, M., Bellut, C., Debergue, E., Gauvin, C., Jeanneret, A., Leclere, T., ... & Sueur, C. (2017). Cultural influence of social information use in pedestrian road-crossing behaviours. *Royal Society Open Science*, *4*(2), 160739. https://doi.org/10.1098/rsos.160739

Ren, G., Zhou, Z., Wang, W., Zhang, Y., & Wang, W. (2011). Crossing behaviors of pedestrians at signalized intersections: observational study and survey in China. *Transportation Research Record: Journal of the Transportation Research Board*, *2264*(1), 65-73. https://doi.org/10.3141/2264-08

Runa, F., & Singleton, P. A. (2022). Impacts of the COVID-19 pandemic on pedestrian push-button utilization and pedestrian volume model accuracy in Utah. *Transportation Research Record*, 03611981221089935. https://doi.org/10.1177/03611981221089935

Russo, B. J., James, E., Aguilar, C. Y., & Smaglik, E. J. (2018). Pedestrian behavior at signalized intersection crosswalks: observational study of factors associated with distracted walking, pedestrian violations, and walking speed. *Transportation Research Record: Journal of the Transportation Research Board*, *2672*(35), 1-12. https://doi.org/10.1177/0361198118759949

Schneider, R. J. (2020). United States pedestrian fatality trends, 1977 to 2016. *Transportation Research Record: Journal of the Transportation Research Board, 2674*(9), 1069-1083. https://doi.org/10.1177/0361198120933636

Schultz, G. G., Berrett, J. J., & Eggett, D. L. (2019). *Pedestrian walking speeds at signalized intersections in Utah* (Report UT-19.06). Utah Department of Transportation. https://rosap.ntl.bts.gov/view/dot/42385

Shaaban, K., Muley, D., & Mohammed, A. (2018). Analysis of illegal pedestrian crossing behavior on a major divided arterial road. *Transportation Research Part F: Traffic Psychology and Behaviour*, *54*, 124-137. https://doi.org/10.1016/j.trf.2018.01.012

Singleton, P. A., Rahman, M. R., & Burbidge, S. (2022). *Systemic analysis of bicycle and pedestrian safety in Utah* (Report UT-22.07). Utah Department of Transportation. https://rosap.ntl.bts.gov/view/dot/62355

Singleton, P. A., Runa, F., & Humagain, P. (2020). *Utilizing archived traffic signal performance measures for pedestrian planning and analysis* (Report UT-20.17). Utah Department of Transportation. https://trid.trb.org/view/1753523

Singleton Transportation Lab. (2023). *Utah pedestrian activity: Monitoring pedestrian activity in Utah*. https://singletonpa.shinyapps.io/ped-covid19/

Smaglik, E. J., Sharma, A., Bullock, D. M., Sturdevant, J. R., & Duncan, G. (2007). Event-based data collection for generating actuated controller performance measures. *Transportation Research Record: Journal of the Transportation Research Board, 2035*, 97–106. https://doi.org/10.3141/2035-11

Smith, S. A. (2015). The Cities of Zion? Mormon and non-Mormon town plans in the US Mountain West, 1847–1930. *Journal of Historical Geography, 50*, 1-13. https://doi.org/10.1016/j.jhg.2015.03.003

Sturdevant, J. R., Overman, T., Raamot, E., Deer, R., Miller, D., Bullock, D. M., ... & Remias, S. M. (2012). *Indiana traffic signal hi resolution data logger enumerations*. Purdue University. http://doi.org/10.4231/K4RN35SH

Taylor, M., & Mackey, J. (2018). *Automated Traffic Signal Performance Measures*. Presented at the 2018 UDOT Annual Conference, Sandy, UT.

Tiwari, G., Bangdiwala, S., Saraswat, A., & Gaurav, S. (2007). Survival analysis: Pedestrian risk exposure at signalized intersections. *Transportation Research Part F: Traffic Psychology and Behaviour, 10*(2), 77-89. https://doi.org/10.1016/j.trf.2006.06.002

Utah Department of Public Safety (UDPS). (n.d.). *2018 Utah Crash Facts: Pedestrians*. https://highwaysafety.utah.gov/crash-data/utah-crash-summaries/

Utah Department of Transportation (UDOT). (n.d.). *UDOT Automated Traffic Signal Performance Measures (ATSPM)*. https://udottraffic.utah.gov/atspm/

U.S. Access Board. (2013). *(Proposed) Public Rights-of-Way Accessibility Guidelines*. https://www.access-board.gov/prowag/

Vasudevan, V., Pulugurtha, S. S., Nambisan, S. S., & Dangeti, M. R. (2011). Effectiveness of signal-based countermeasures for pedestrian safety: Findings from pilot study. *Transportation Research Record: Journal of the Transportation Research Board*, *2264*(1), 44-53. https://doi.org/10.3141/2264-06

Yagil, D. (2000). Beliefs, motives and situational factors related to pedestrians' self-reported behavior at signal-controlled crossings. *Transportation Research Part F: Traffic Psychology and Behaviour*, *3*(1), 1-13. https://doi.org/10.1016/S1369-8478(00)00004-8

Yang, X., Abdel-Aty, M., Huan, M., Peng, Y., & Gao, Z. (2015). An accelerated failure time model for investigating pedestrian crossing behavior and waiting times at signalized intersections. *Accident Analysis & Prevention*, *82*, 154-162. https://doi.org/10.1016/j.aap.2015.04.036

Zhang, G., Tan, Y., & Jou, R. C. (2016). Factors influencing traffic signal violations by car drivers, cyclists, and pedestrians: A case study from Guangdong, China. *Transportation Research Part F: Traffic Psychology and Behaviour*, *42*, 205-216. https://doi.org/10.1016/j.trf.2016.08.001

Zhang, W., Wang, K., Wang, L., Feng, Z., & Du, Y. (2016). Exploring factors affecting pedestrians' red-light running behaviors at intersections in China. *Accident Analysis & Prevention*, *96*, 71-78. https://doi.org/10.1016/j.aap.2016.07.038

Zhou, H., Romero, S. B., & Qin, X. (2016). An extension of the theory of planned behavior to predict pedestrians' violating crossing behavior using structural equation modeling. *Accident Analysis & Prevention*, *95*, 417-424. https://doi.org/10.1016/j.aap.2015.09.009

Zhuang, X., Wu, C., & Ma, S. (2018). Cross or wait? Pedestrian decision making during clearance phase at signalized intersections. *Accident Analysis & Prevention*, *111*, 115-124. https://doi.org/10.1016/j.aap.2017.08.019