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MEASURING SYSTEMIC IMPACTS OF BIKE INFRASTRUCTURE PROJECTS

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RESEARCH

UDOT Keeping Utah Moving
Utah Department of Transportation - Research Division
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DISCLAIMER

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16. Abstract:

This paper qualitatively identifies the impacts of bicycle infrastructure on all roadway users, including safety, operations, and travel route choice. Bicycle infrastructure includes shared lanes, conventional bike lanes, and separated bike lanes. The treatment of bicycle infrastructure at intersections is of particular interest, as the management of bike lanes through intersections varies considerably, even along the same bicycle corridor. The paper identifies different bicycle infrastructure treatments along roadways and at intersections, and provides a qualitative analysis of the effects of those treatments. Geometric features, traffic characteristics, and bicycle lanes in Utah are used for a before and after comparison. No evidence was found indicating a negative effect of bicycle infrastructure on the overall roadway operations. Meanwhile, evidence indicates that bicyclists perceive an increase in safety the more other bicyclists there are around them. Providing separated bicycle lanes along segments and at intersections is expected to increase perceived safety and reduce bicycle crash frequency. The findings appear to reflect some of the complex relationship between roadway users, geometric design, and operations. The paper provides qualitative tools for making informed bicycle infrastructure decisions when designing roadway and bicycle segments and intersections.

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LIST OF ACRONYMS

AADT	Average Annual Daily Traffic
FHWA	Federal Highway Administration
FYA	Flashing Yellow Arrow
HPMS	Highway Performance Monitoring System
KML	Keyhole Markup Language
LiDAR	Light Detection and Ranging
NACTO	National Association of City Transportation Officials
NB	Northbound
NTPP	Non-Motorized Transportation Pilot Program
PSR	Present Serviceability Rating
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2009)
SB	Southbound
UDOT	Utah Department of Transportation
USDOT	United States Department of Transportation
UTA	Utah Transit Authority
VMT	Vehicle Miles Traveled

EXECUTIVE SUMMARY

Over the past decade, there has been a heavy push for incorporating bicycle infrastructure along urban roadways. Research has repeatedly shown that increasing opportunities for bicycle transportation can reduce overall VMT and auto trips, improve environmental quality, promote economic development, and improve public health and physical activity. In Utah, 0.9% of commuters bike to work, which is an increase of 0.2% from 2007-2013. As mode share split continues to include more bicycle riders, transportation agencies are responding by adding more bicycle infrastructure. A cultural paradigm shift has created an environment where agencies are looking to integrate bicycle infrastructure along routes that were previously solely motorized corridors. This study seeks to compare a sample of different bicycle facility types planned or installed on UDOT roadways in 2015 and 2016 and examines the potential impacts of bicycle infrastructure on roadway and traffic dynamics by: identifying the impacts of the various types of bicycle infrastructure that may be installed along UDOT roadways; and identifying recommendations and strategies for mitigating any negative impacts, through relocation, planning, and design tactics. This study was limited as the project team anticipated having a set of specific corridors that were going to have bicycle infrastructure installed, but a majority of the projects were delayed or cancelled after the "before" data was collected. Because bicycle infrastructure construction projects are not widespread along the Wasatch Front it was difficult to make up for the lost projects.

Six data collection corridors containing 62 intersections along Utah's Wasatch Front (Davis, Salt Lake, and Utah Counties) were chosen where installations of bicycle infrastructure were planned for implementation in 2016 or 2017. Sites were also identified near these corridors where bicycle infrastructure is installed, is going to be installed, or will not be installed based upon city adopted bicycle master plans. These sites were used for comparison as control sites. Video data collection was conducted using a GoPro HERO Session 4 camera mounted to the handlebars of a commuter road bike. The video provided an in-lane view of a typical user experience. Video data also captured the pavement conditions, roadway hazards, and automobile and bicycle interactions at intersections. Geometric data including the number of lanes, lane widths, shoulder widths, storm drain covers, and pavement type and conditions were also collected using a combination of on-site and electronic data collection. AADT data was gathered from the open source KML file published by UDOT to show the amount of traffic present on roadway segments and at intersections along the study corridors. Crash data was gathered from the UDOT Safemap crash data website by applying a bicycle-related filter to study corridors.

Video observations suggest that the presence of a bike lane does not change driver behavior, but the presence of a cyclist does. The time frame and scope of this study did not allow an extended consideration for changes to the AADT as a result of bicycle infrastructure, and it is recommended that additional research be conducted to focus specifically on changes in AADT. Crash statistics revealed that in this sample a large percentage of bicycle-involved crashes at study sites took place at intersections (83%) rather than along linear segments. This finding is consistent with the frequency of motorist-cyclist interactions that occur at intersections where many turning movements are being made on and off of roads.

A review of several case studies from across the country found that drivers on roadways with bicycle lanes were less likely to encroach into all adjacent lanes, pass, or queue when interacting with cyclists, and that bike lanes are more effective at protecting cyclists than using sharrows or signs designating shared lanes. Also, the type of bicycle infrastructure may be associated with vehicular passing distance and frequency of encroachments. One study found that roads with buffered and bollard-protected bike lanes were correlated with larger passing distances and the lowest chance of encroachment. That same study found that roads with other types of bike facilities exhibited passing distances of 14-18 inches less than roads with protected or buffered bike lanes.

This research confirmed that a majority of incidents between vehicles and bicycles occur at intersections, it is recommended that designs for intersections along corridors with bicycle facilities aim to reduce conflict between bicyclists and other vulnerable road users by improving visibility, identifying a specific right-of-way, and promoting heightened awareness with competing modes. This can include employing treatments such as bike boxes, intersection crossing markings, two-stage turn queue boxes, median refuge islands, through bike lanes, combined bike lane/turn lanes, and protected bike lane intersection approaches.

1.0 INTRODUCTION

1.1 Problem Statement

Over the past decade, there has been a heavy push for incorporating bicycle infrastructure along urban roadways. The five-year Green Lane Project, for example, helped to quadruple the number of protected bike lanes in the United States between 2011 and 2016 (People for Bikes, 2017).

Research has shown that increasing opportunities for bicycle transportation can reduce overall VMT and auto trips, improve environmental quality, promote economic development, and improve public health and physical activity. According to the 2016 Benchmark Report from the Alliance for Biking and Walking, bicycle mode share among commuters has increased over the past decade, from 0.7% to 1.2%. In Utah, 0.9% of commuters bike to work, which is an increase of 0.2% from 2007-2013. As mode share split continues to include more bicycle riders, transportation agencies are responding by adding more bicycle infrastructure. A cultural paradigm shift has created an environment where agencies are looking to better accommodate active transportation to create a more balanced transportation network.

The bicycle infrastructure toolbox has a variety of ways to implement bike lanes. The Urban Bikeway Design Guide (NACTO, 2014) outlines four different bike lane types:

1. Conventional bike lanes
2. Buffered bike lanes
3. Contra-flow bike lanes
4. Left-side bike lanes

A bike lane is designated by striping, signage, and pavement markings to give preferential or exclusive right-of-way to bicycles (NACTO, 2014). Bicycle infrastructure is regularly added to existing infrastructure by adding lane striping to an outside shoulder or automobile travel lane but can also be part of complete street rebuilds or new roadways. This research focuses mainly on the system impacts of conventional bike lanes, leaving other bike lane options for additional research.

1.2 **Objectives**

This research seeks to identify the systemic impacts of bike infrastructure projects in Utah, specifically in UDOT Regions 2 and 3. This study compares a sample of different bicycle facility types planned or installed on UDOT roadways in 2015 and 2016 and examines the potential impacts of bicycle infrastructure on roadway and traffic dynamics. The two main objectives of this research are:

1. Identify the impacts of the various types of bicycle infrastructure that may be installed along UDOT roadways.

2. Create recommendations and strategies for mitigating any negative impacts, through relocation, planning, and design tactics.

1.3 **Scope**

Impacts of conventional bike lanes are different for roadway segments than for intersections. Bike lanes reduce interaction between automobiles and bicycles, allowing the cyclist to travel at self-paced speeds, without disrupting traffic flow. Bicycle behavior is more predictable using bike lanes, guiding the interaction between bicycles and automobiles, where bicyclists remain inside the lane unless turning, passing, or avoiding hazards within the bike lane. Reducing hazards within the bike lanes reduces erratic bicycle behavior and has greater opportunity to facilitate the overall network benefits from the bike lane. Interactions between automobiles and bicycles are much more frequent at intersections where travel paths cross and behavior is less predictable for both drivers and bicyclists. Intersections with continuous bike lanes facilitate bicycle and automobile interaction and provide visual guidance for all roadway users.

This study utilizes data collected along five roadways in Utah, totaling more than 50 directional miles of roadway and 61 controlled intersections. Each study corridor has both automobile and bicycle traffic. However, the bicycle lane characteristics vary between corridors. The study areas were in Weber, Davis, Salt Lake, and Utah Counties. The recommendations from the report will allow UDOT to draft policies and procedures to mitigate any negative impacts of bicycle infrastructure, providing the highest efficiency and operating network possible for all users.

1.4 **Outline of Report**

The report is organized into six chapters. Chapter 2 provides a brief literature review examining the impact of bicycle infrastructure on mode choice and automobile traffic. Chapter 2 also includes the research methods and justifications employed in this work. Chapter 3 presents the collected data and provides summary characteristics for the geometric data and bicycle crash reports. Chapter 4 presents analysis of the non-motorized travel behavior observed in the sample and identifies case studies of impacts from other locations. Chapter 5 provides conclusions based upon the data provided in the previous chapters and Chapter 6 outlines the authors' recommendations for mitigating bicycle infrastructure impacts.

2.0 RESEARCH METHODS

2.1 **Overview**

A literature review was performed identifying known effects of bicycle infrastructure, and a synopsis is included in this section. The literature review has two subsections that provide needed background information: 1) the effect of perception of bicycle infrastructure on both the cyclist and the driver and the impact on mode choice, and 2) the known systemic traffic impacts of bicycle infrastructure. This section also includes a discussion of the research methods employed and the justification for each.

2.2 **Background**

Research indicates that building bicycle infrastructure induces cycling demand. Research by Dill and Carr indicate that cities with more bike lanes and paths per square mile have higher percentage of bicycle commuters (2003). Their study included commuter data from 64 U.S. cities with populations greater than 250,000 from the 2000 Census, and 43 of those cities provided specific information about bike facilities. The top four cities ranked for the percent of bicycle commuters were all within the top five highest cities ranked for the number of bike lanes and paths per square mile. St. Paul, MN was the anomaly and ranked second for bike lanes and paths but 19th in percent commuters. Providing bicycle infrastructure supports the current demand while also persuading additional users to commute by bicycle.

2.2.1 Influence of Individual Perception of Bicycle Infrastructure.

Monsere, McNeil, and Dill conducted intercept surveys along bicycle lane test facilities in Portland, OR (2012). The survey of cyclists, motorists, pedestrians, and adjacent businesses showed an improved perceived safety and comfort among cyclists, particularly women, but among motorists who never rode a bicycle, the perceived effect was increased travel time and feeling inconvenienced by the facility. Pedestrians expressed concern about interactions with cyclists when crossing the bike lane. Perceptions were stronger in relation to the buffered bike lane facility as compared to the protected bike lane facility. User perception is a continued obstacle to overcome when installing bicycle infrastructure.

User perception is different for every person, as each person places a different subjective value on a variety of factors. Pucher, Komanoff and Schimek (1999) identified eight factors that affect the decision to bicycle. They include: public attitude and cultural differences, public image, city size and density, cost of car use and public transport, income, climate, danger, and cycling infrastructure. The reason to choose bicycling will differ from person to person as they weight each of these items differently.

Travel time is a huge factor in mode choice. People are particularly more aware of travel time when using non-motorized modes such as the bicycle (Akar and Clifton, 2009). Overcoming the stigma of an extended travel time is difficult but may be accomplished when the biking or walking is perceived as a form of exercise or when comfortable bicycle infrastructure allows for an easier trip. Akar and Clifton (2009) identified that people who see non-motorized travel as exercise, and have flexibility in departure time, are more likely to ride a bicycle. Dill and Carr showed that cities with higher levels of bicycle infrastructure have higher levels of bicycle commuting (2003).

2.2.2 Known Systemic Impacts of Bicycle Infrastructure

Bikes lanes with both left and right side lane markings improve bicycle behavior at intersections by encouraging consistent lane positioning, which improves bicycle and automobile interactions (NACTO, 2014).

Concern over shared lanes surfaced in the literature search due to the apparent differences in speed between bicycles and automobiles in the same lane. Shared lanes are often designated using painted markings within the lane, called sharrows. Duhn et al. looked at the traffic impacts of bicycle facilities and the impact of sharrows (Duhn, Lehrke, Hourdos and Lindsey, 2017). They determined that roadways with bike lanes reduced the occurrence of automobiles encroaching on adjacent lanes, or queuing behind cyclists, compared to roadways with sharrows, or no bicycle facilities. The presence of the sharrows alerts drivers to the presence of bicyclists, but the impact of the bicycle infrastructure may not differ significantly from roadways with no facilities (Duhn, Lehrke, Hourdos and Lindsey, 2017). Similarly, posted signs also alert automobiles, but Duhn, et al. (2017) could find no evidence the roadways with bicycle lanes operated differently than roadways with no facilities.

2.3 **Study Methods**

This section describes the qualitative and quantitative analysis methods used to determine any operational, functional, and safety impacts of the given bicycle infrastructure types.

2.3.1 Consideration for Differences in AADT

Historic Average Annual Daily Traffic (AADT) counts establish growth trends along a corridor. Comparisons can be made of AADT on given roads before and after installation of bike lanes to determine whether such installations significantly affect AADT. However, the limited after data available for this research limits potential conclusions about long-term changes to the AADT from installing bike infrastructure. Bicycle facility maps and city bicycle master plans were consulted to identify locations of existing and future bicycle infrastructure for comparison sites.

2.3.2 Bicycle Crash Frequency

Interactions between automobiles and bicycles are much more frequent at intersections (than between then) where travel paths cross and behavior is less predictable for both drivers and bicyclists. Intersections with continuous bike lanes (i.e. lanes that don't drop on the approach to the intersection) simplify bicycle and automobile interaction by providing visual guidance for all roadway users. A comparison will be made of bicycle crash frequency along segments with and without bike lanes, and with different types of bike lanes. An additional comparison of bicycle crash counts will be made of intersections with continuous bike lanes, shared bike lanes with right turning automobiles, and the absence of bike lanes.

2.3.3 Case Study Demonstrating Bicycle Infrastructure Application

A case study comparison aids in the conceptual understanding of the impact of bicycle infrastructure on all roadway users. The case study depicts a two-mile stretch of roadway that also has a signalized intersection dividing the stretch into two segments. The case study roadway portrays a conventional bike lane painted alongside the outside travel lanes of a five-lane roadway. The intersection is a three-lane side street that crosses the five-lane roadway.

2.3.4 Summary Statistics

Summary statistics are used to provide a quick and simple description of the data without any predictive component or significance testing. Summary statistics can include mean (average), median (center point of data), mode (most frequently occurring value), minimum value, maximum value, value range, standard deviation, and frequency percentages. Summary statistics will be used in this analysis to provide context for the bike infrastructure changes. Specifically, this type of analysis will be used to describe changes that occurred when construction took place.

2.4 **Summary**

Chapter 2 provides the methodology for a qualitative analysis of the impacts of bicycle infrastructure. In future chapters, comparisons will be made of facilities with and without bike lanes.

3.0 DATA COLLECTION

3.1 Overview

Six data collection corridors containing 62 intersections in Utah were chosen where installations of bicycle infrastructure were planned for implementation in 2016 or 2017. The selected bicycle lanes are located throughout the Wasatch Front region of Utah in Davis, Salt Lake and Weber Counties. Additional sites were identified where bicycle infrastructure is installed, is going to be installed, or will not be installed based upon city adopted bicycle master plans. These sites were used as controls within the study.

3.2 Video Data

Videotaping of bicycle infrastructure was performed using a GoPro HERO Session 4 camera mounted to the handlebars of a commuter road bike. Videotapes provide an in-lane view of how the bicycle lanes are utilized, providing a “feel” for the actual bike lane. Videotapes captured the pavement conditions, roadway hazards, and automobile and bicycle interaction at intersections. The video data also verified other collected geometric data.

3.3 Geometric Data

Geometric data of the number of lanes, lane widths, shoulder widths, storm drain covers, and pavement type and conditions were collected using a combination of various tools and resources. Digital mapping and satellite imaging applications, primarily Google Earth and Google Maps, were used prominently for this research. They are high-resolution displays of the Earth created from satellite imagery. Google Earth and Google Maps allow users to pan to a desired street view and location, and use a variety of content, including map and terrain data, imagery, business listings, traffic, reviews, and other related information provided by Google, its licensors, and users (Google, 2015). Street view images are available at frequent spacing in urban areas but are not continuous. Google Earth also allows for data overlays, saved in the form of Keyhole Markup Language (KML) files.

The Utah Department of Transportation (UDOT) Data Portal provides open access to available data overlays, including the AADT traffic statistics collected by the Transportation Monitoring Unit and developed and analyzed by the Traffic Analysis Section of the Systems Planning and Programming Division within UDOT (UDOT, 2017b). Data collected from Google Earth, Google Maps, and attached KML files included the roadway and intersection geometric configurations and measurements, the intersection left turn phasing, and the AADT data, which also includes the proportion of truck traffic.

The Online Virtual Navigator, available through UDOT, is part of the Right of Way Photolog Viewer (UDOT, 2017a). The Right of Way Photolog is a collection of images that were taken facing forward using light detection and ranging (LiDAR). LiDAR collects 2,000 points of data per second using 40 different sensors mounted to a vehicle, and images are captured as the vehicle drives across the State highways. The Virtual Navigator has much more frequent images than Google Earth/Maps and allows for higher accuracy in data collection. The images are tied to UDOT mileposts and also contain latitude and longitude coordinates. The Virtual Navigator viewer allows for a person to input the route and milepost to zoom to an approximate location on the highway. It was used to verify mile markers along the roadways and at intersections, as well as verify geometric data when data from Google Maps was not frequent enough.

Video logs collected as part of this research provide continuous data while traveling inside the bicycle lanes. A review of the videos allowed documentation of the exact type and location of hazards in and around the bicycle lane, as well as characterizing and documenting automobile behavior near a bicyclist. The video logs also show the path chosen by a cyclist while navigating intersections without continuous bicycle lanes.

Geometric data is used in comparing and analyzing the different corridors and intersections. Table 1 provides a notation, description, and data range for each of the geometric features collected as part of the data collection.

Table 1. Geometric and Bicycle Infrastructure Characteristics on Research Corridors

Notation	Description	Range
Number of lanes	Motor vehicle travel lanes, excluding bike lanes and turn pockets	2-5 lanes
Roadway width	Average roadway width along each segment taken as an average of several measurements (feet)	60-96 ft, 82 ft average
Lane width	Average lane width along each segment and at each intersection (feet)	12 ft
Dedicated turn lane	Measurement indicating the presence of any turn lanes, either as a continuous center turn lane or as left turn or right turn pockets	TWLTL, LT, RT
Shoulder width	Measurement of the paved shoulder width from the outside painted line to the edge of pavement or face of curb	3-15 ft, 10.7 ft average
On-street parking	Indication if on-street parking is present	Y/N
Pavement material	Roadway material type	Asphalt/concrete
Debris	Indication of presence of debris inside the bike lane	Y/N, minor rocks
Drainage grate	Indication if storm drain grates are bicycle friendly, flush to roadway, and/or within the bicycle lane	Bicycle safe, transverse grate, longitudinal grate
Manhole cover	Indication if a manhole cover is located within a bicycle lane	Y/N
Rumble strip	Indication of the presence of rumble strips along the shoulder or within the bicycle lane	None observed
Potholes	Indication of potholes or cracks within the bicycle lane that would be hazardous to a bicyclist	Y/N
AADT	Two-way average annual daily traffic along the mainline roadway as reported by UDOT in the year 2014, taken as an average if a roadway segment extended into multiple count stations	11,775-35,975, average 22,024
Freight/Truck	Measured percent of AADT as reported by UDOT in the year 2014, taken as an average percent if a roadway segment extended into multiple count stations	5.8%-42%, average 22.82%*

*AADT data based on UDOT model output for each location

3.3.1 Number of Lanes

The number of lanes identifies the number of continuous travel lanes along roadway segments as well as the number of through, left, and right-hand turn lanes at intersections and lists the number of lanes along each data collection corridor. Data collection corridors consisted of 2, 3, 4, and 5 lane roadways, where the 3 and 5 lane roadways included a center two way left turn lane (TWLTL). Table 3 provides the number and type of lanes at each intersection, including the number and type of lanes for the minor cross street. The type of lane includes whether it is a through, left, or right turn lane.

Table 2. Directional Through Lanes at Study Segment Locations

Corridor	State System Mile Marker	Through Lanes in Each Travel Direction	Continuous LT Lane
SR-126 (Main St/State St) in Davis and Weber Counties	0.00 to 12.72	2	Yes
US-189 (University Ave) Provo; 800 N to 5200 N in Provo	2.64 to 6.71	2	Yes
2050 W and SR-114 (Geneva Road); 600 S (Provo) to 400 N (Orem)	1.56 to 7.08	1-2	No
US-89 (300 S); US-189 (University Ave) to 700 E in Provo	333.46 to 334.11	2	No
100 S; US-189 (University Ave) to 700 E	n/a	1	No

Table 3. Number and Type of Intersection Lanes (UDOT Region 1)

Location	Major Approach				Minor Approach		
	Mile Marker	Thru lanes	LT Lane	RT Lane	Thru lanes	LT Lane	RT Lane
Region 1-							
Intersections with SR-126 (Main St/State St) through Davis and Weber Counties							
I-15 Interchange	0.15	2	2	1	0	2	1; 2
Main St (Layton)	0.29	2	0	1	0	2	1
Gentile St	0.61	2	1	1	1	1	1
Church St	0.77	2	1	0	1	0	0
500 N (Layton)	1.21	2	1	1	1	1	1
Hill Field Rd/Industrial Park	1.70	3	0	1	3	0	1
Gordon Ave/1000 N	1.86	2	1	1	1	1	1
Angel St/1200 W	2.37	2	1	0	1	1	0
1600 N (Layton)	2.84	2	1	0	0	1	0
Antelope Dr/2000 N	3.10	2	1	1	3	1	0
1000 E (Clearfield)	3.83	2	1	1	2	1	1
SR-193 (700 S)	4.55	2	1	1	2	1	1
200 S (Clearfield)	5.20	2	1	0	1	0	1
Center St (Clearfield)	5.44	2	1	1	2	1	1
SR-107 (300 N)	5.73	2	1	1	1	1	0
SR-103 (650 N)	6.08	2	1	1	2	1	1
800 N (Clearfield/Sunset)	6.23	2	1	-	0	1	1
1300 N (Sunset)	6.73	2	1	-	0	1	1
SR-37 (1800 N)	7.23	2	1	-	0	1	1
2300 N (Sunset)	7.73	2	1	-	0	2	1
6000 S	8.23	2	1	-	0	2	1
5700 S	8.59	2	1	-	0	2	1
SR-97/5600 S	8.73	2	1	1	2	2	1
5400 S	8.97	2	1	0	1	0	0
SR-26 (Riverdale Rd)/5300 S	9.12	2	1	1	1	2	1
4800 S	9.71	2	1	1	1	1	1
4400 S	10.22	2	1	1	1	1	0
4000 S	10.72	2	1	1	1	0	0
SR-79 (Hinckley Dr)	11.24	2	1	1	2	1	1
SR-108 (Midland Dr)/3300 S	11.74	2	1	1	1	1	1
2550 S	12.72	2	1	1	1	1	1

Table 4. Number and Type of Intersection Lanes (UDOT Regions 2-3)

Location	Major Approach			Minor Approach		
	Thru	LT	RT	Thru	LT	RT
Region 2-						
South Jordan Pkwy/Mtn. View Corridor	2	1	1	1	0	1
600 W Interchange/Bangerter Hwy.	2	2	1	0	2	1
South Jordan Pkwy/Redwood Rd	2	2	1	2	2	1
Bangerter Hwy/Redwood Rd	2	1	1	0	2	1
Region 3-						
Intersections with US-189 (University Ave) in Provo						
800 N	2	1	1	1	1	1
960 N	2	1	0	0	1	0
Canyon Rd	2	0	0	0	2	1
Bulldog Blvd/1230 N	2	1	1	3	1	0
Paul Ream Ave	2	1	1	1	1	0
University Pkwy	2	1	1	2	1	1
2230 N	2	1	1	2	1	1
2680 N	2	1	1	1	1	0
3300 N	2	1	1	1	1	1
3700 N	2	1	1	2	1	1
4200 N	2	1	1	1	1	1
4400 N	2	1	0	0	1	1
4800 N	2	1	1	1	1	1
5200 N	2	1	0	1	1	1
Intersections with 2050 W and SR-114 (Geneva Rd) in Provo/Orem						
600 S	0	1	1	1	0	0
Center St (Provo)	1	1	1	1	1	1
SR-265 (University Pkwy)	2	1	1	1	2	2
1000 S (Orem)	2	1	1	1	1	1
800 S (Orem)	2	1	1	1	0	0
400 S (Orem)	2	1	1	1	1,2	1
Center St (Orem)	2	1	1	2	1	1
400 N (Orem)	2	1	0	0	1	1
Intersections with US-89 (300 S) in Provo						
US-189 (University Ave)	2	2	1	2	2	1
200 E	2	0	0	0	0	1
400 E	2	0	0	1	0	0
700 E	1	1	2	1	2	1
100 S/University Ave in Provo	2	1	1	0	1	1

3.3.2 Lane Width

Automobile and bicycle lane widths were gathered for comparison to determine any systemic influence from encroaching on adjacent lanes. All automobile travel lanes were measured to be a standard 12-ft wide. Bicycle lanes were also a standard 5-ft width where they were installed. Bicycle lanes were not present along many segments of the study roadways. In locations where they were present, some of them were not continuous through intersections.

Table 5 identifies the percent of each study corridor that had a bike lane installed, as well as if the right turn lane onto minor side streets shared the bike lane.

Table 5. Percent Bike Lane and Combined Right Turn Lane

Corridor	Mile Marker	Right Shoulder	% Bike Lanes	Shared Bike/RT Lane
SR-126 (Main St/State St) in Davis and Weber Counties	0.00 -12.72	Yes	39%	Yes
US-189 (University Ave) in Provo; 800 N to 5200 N	2.64 - 6.71	Yes	100%	Yes
2050 W and SR-114 (Geneva Rd); Center St (Provo) to 400 N (Orem)	1.56 - 7.08	Limited	0%	N/A
US-89 (300 S) in Provo; US-189 (University Ave) to 700 E	333.46 - 334.11	No	100%	No
100 S in Provo; US-189 (University Ave) to 700 E	-	Yes	17%	Yes

Tables 6 and 7 below, identify the number of bike lanes through major and minor intersections as well as where those intersections are located.

Table 6. Bike Lanes through Major and Minor Intersection Approaches (Region 1)

Location	Mile Marker	Bike Lane Thru Major	Bike Lane Thru Minor
Region 1-			
Intersections with SR-126 (Main St/State St) through Davis and Weber Counties			
I-15 Interchange	0.15	0	0
Main St (Layton)	0.29	0	0
Gentile St	0.61	0	0
Church St	0.77	0	0
500 N (Layton)	1.21	0	0
Hill Field Rd/Industrial Park	1.7	0	0
Gordon Ave/1000 N	1.86	0	0
Angel St/1200 W	2.37	0	0
1600 N (Layton)	2.84	0	0
Antelope Dr/2000 N	3.1	0	0
1000 E (Clearfield)	3.83	0	0
SR-193 (700 S)	4.55	0	0
200 S (Clearfield)	5.2	0	0
Center St (Clearfield)	5.44	0	0
SR-107 (300 N)	5.73	0	0
SR-103 (650 N)	6.08	1	0
800 N (Clearfield/Sunset)	6.23	1	0
1300 N (Sunset)	6.73	1	0
SR-37 (1800 N)	7.23	1	0
2300 N (Sunset)	7.73	1	0
6000 S	8.23	1	0
5700 S	8.59	1	0
SR-97/5600 S	8.73	0	0
5400 S	8.97	0	0
SR-26 (Riverdale Rd)/5300 S	9.12	0	0
4800 S	9.71	1	0
4400 S	10.22	1	0
4000 S	10.72	0	0
SR-79 (Hinckley Dr)	11.24	0	0
SR-108 (Midland Dr)/3300 S	11.74	0	0
2550 S	12.72	0	0

Table 7. Bike Lanes through Major and Minor Intersection Approaches (Regions 2-3)

Location	Mile Marker	Bike Lane Thru Major	Bike Lane Thru Minor
Region 2-			
South Jordan Pkwy/Mtn. View Corridor	11.32	1	1
600 W Interchange/Bangerter Hwy.	1.00	0	-
South Jordan Pkwy/Redwood Rd	2 / 45.06	1	1
Bangerter Hwy/Redwood Rd	40.84	1	-
Region 3-			
Intersections with US-189 (University Ave) in Provo			
800 N	2.64	1	1
960 N	2.79	1	0
Canyon Rd	2.94	1	0
Bulldog Blvd/1230 N	3.06	1	0
Paul Ream Ave	3.26	1	0
University Pkwy	3.43	1	1
2230 N	3.95	1	0
2680 N	4.32	1	0
3300 N	4.93	1	0
3700 N	5.31	1	0
4200 N	5.73	1	0
4400 N	5.95	1	0
4800 N	6.35	1	1
5200 N	6.71	1	0
Intersections with 2050 W and SR-114 (Geneva Rd) in Provo/Orem			
600 S (Provo)	-	1	0
Center St (Provo)	1.56	1	0
SR-265 (University Pkwy)	4.96	1	0
1000 S (Orem)	5.28	0	0
800 S (Orem)	5.40	0	0
400 S (Orem)	6.05	0	0
Center St (Orem)	6.55	0	0
400 N (Orem)	7.08	0	0
Intersections with US-89 (300 S) in Provo			
US-189 (University Ave)	334.11	1	0
200 E	333.92	1	1
400 E	333.73	1	0
700 E	333.46	0	0
100 S/University Ave in Provo	0	0	1

3.3.3 Right Shoulder Width

Right shoulder width was measured from the edge of the automobile travel lane to the edge of pavement or to the face of the curb. Several measurements were taken along the corridor and an average established. The right shoulder width would often be incorporated into a bike lane, however larger shoulders sometimes allowed for on-street parking in addition to the bike lane. Table 8 provides the measured right shoulder widths including bike lane widths where applicable.

Table 8. Right Shoulder Width

Location	Shoulder Width (ft)
Region 1-	
SR-126 (Main St/State St) in Davis and Weber Counties	
Layton	15
Clearfield	5
Roy	8
Ogden	12
Region 2-	
South Jordan Pkwy/Mtn. View Corridor	3
600 W Interchange/Bangerter Hwy	12
South Jordan Pkwy/Redwood Rd	12
Bangerter Hwy/Redwood Rd	12
Region 3-	
US-189 (University Ave) in Provo; 800 N to 5200 N	12
2050 W and SR-114 (Geneva Rd); 600 S (Provo) to 400 N (Orem)	12
US-89 (300 S) Provo; US-189 (University Ave) to 700 E	5
100 S/University Ave (Provo)	12

3.3.4 Storm Drain and Manhole Covers

The location and type of storm drains and manhole covers were identified using the video logs. Bicycle friendly storm drains, with smaller drainage grates, are safer for bicyclists. Erratic behavior from the cyclist can sometimes be attributed to maneuvering to avoid hazards, such as uneven manhole covers or storm drains. Manhole covers go mostly unnoticed by automobiles due to the speeds and suspension, however the bicycle travels at lower speeds and most often does not have suspension. Bicyclists are likely to avoid manholes, even when they are flush to the rest of the pavement.

Figure 1. Manhole cover inside the bike lane

3.3.5 Pavement Type and Condition

Pavement type and condition were collected from video logs as a possible correlation to ridership counts, erratic bicycle behavior, or to indicate any safety issues. Pavement type relates to the construction material for flexible asphalt or rigid concrete construction, while condition relates to the rideability and comfort to the cyclist. Pavements with lots of cracking or uneven surfaces are difficult to ride on and may potentially result in less ridership, erratic cyclist behavior, or utilizing other parts of the roadway outside of the bike lane (Landis, Vattikuti and Brannick, 1997). Figure 2 shows a pothole hazard within a bike lane. The pothole is near the outside edge of the bike lane where bicyclists usually travel in order to stay farther from automobiles. The presence of the pothole will likely result in many cyclists moving left (closer to car traffic) to avoid the hazard.

Figure 2. Video log showing a pothole hazard inside the bike lane

The Highway Performance Monitoring System (HPMS) Field Manual, produced by the Federal Highway Administration (FHWA), provides a 5-point pavement surface condition rating scale referred to as the Present Serviceability Rating (PSR) (USDOT, 2016). The PSR is used in the Highway Capacity Manual (HCM) to calculate Bicycle Level of Service (BLOS) (Landis, Vattikuti and Brannick, 1997; TRB, 2010).

Table 9 provides a synopsis of the different PSR values, their qualitative rating scale, and a description of each value as used in the HCM and HPMS field manual (USDOT, 2016; TRB, 2010)

Table 9.Present Serviceability Rating

PSR Value	Rating	Description
5	Very good	New, or nearly new, superior pavements that are smooth, distress free (no cracks or patches).
4	Good	Good riding surface with few surface deteriorations. Little evidence of rutting, or fine cracking/spalling.
3	Fair	Riding is noticeably inferior, difficult for high-speed traffic. Surface defects are rutting, map cracking, multiple patches, joint failures, faulting/cracking, or pumping.
2	Poor	Pavement condition affecting speed. Distress over 50% of surface with potholes, deep cracks, raveling, spalling, patching, scaling, pumping, or faulting.
1	Very poor	Extremely deteriorated. Passable only at reduced speed with great ride discomfort. Distress over 75% of surface with large potholes, deep cracks, raveling, spalling, patching, scaling, pumping, or faulting.

3.4 Traffic and AADT Data

AADT data was gathered from the open source KML file published by UDOT to show the amount of traffic present on roadway segments and at intersections along the study corridors. The full AADT data collection is provided in the appendix. Table 10 displays this data at the corridor level. A standard K factor of 0.09 for urban planning and design was used to calculate a Directional Design Hourly Volume (DDHV) (McLeod and Pisczatoski, 2011).

Table 10. AADT Data for Study Roadway Segments

Location	2014 AADT	DDHV
Region 1-		
SR-126 (Main St/State St) in Davis and Weber Counties		
Layton	22,100	1,989
Clearfield	22,300	2,007
Roy	24,000	2,160
Ogden	16,000	1,440
Region 2-		
South Jordan Pkwy/Mtn. View Corridor	11,980	1,078
600 W Interchange/Bangerter Hwy	10,000	900
South Jordan Pkwy/Redwood Rd	35,975	3,238
Bangerter Hwy/Redwood Rd	29,155	2,624
Region 3-		
US-189 (University Ave) in Provo; 800 N to 5200 N	35,000	3,150
2050 W and SR-114 (Geneva Rd); 600 S (Provo) to 400 N (Orem)	12,000	1,080
US-89 (300 S) Provo; US-189 (University Ave) to 700 E	14,585	1,313
100 S/University Ave (Provo)	25,370	2,283

Tables 11 and 12 below show the AADT for each of the intersections included in the study. This includes data relative to major and minor AADT, and DDHV.

Table 11.AADT Data for Study Intersections (Region 1)

Location	**Major AADT**	**DDHV**	**Minor AADT**
Region 1-			
SR-126 (Main St/State St) in Davis and Weber Counties			
I-15 Interchange	20,415	1,837	Ramp
Main St (Layton)	20,415	1,837	965
Gentile St	23,735	2,136	13,325
Church St	23,735	2,136	3,900
500 N (Layton)	23,735	2,136	-
Hill Field Rd/Industrial Park	23,735	2,136	25,050
Gordon Ave/1000 N	22,045	1,984	1,925
Angel St/1200 W	22,045	1,984	-
1600 N (Layton)	22,045	1,984	-
Antelope Dr/2000 N	22,045	1,984	41,160
1000 E (Clearfield)	15,695	1,413	-
SR-193 (700 S)	20,925	1,883	18,765
200 S (Clearfield)	20,925	1,883	-
Center St (Clearfield)	20,925	1,883	6,595
SR-107 (300 N)	20,925	1,883	14,490
SR-103 (650 N)	26,670	2,400	15,800
800 N (Clearfield/Sunset)	26,670	2,400	9,895
1300 N (Sunset)	21,615	1,945	-
SR-37 (1800 N)	24,160	2,174	13,960
2300 N (Sunset)	24,160	2,174	5,005
6000 S	24,160	2,174	4,255
5700 S	24,160	2,174	-
SR-97/5600 S	37,025	3,332	31,255
5400 S	37,025	3,332	-
SR-26 (Riverdale Rd)/5300 S	37,025	3,332	20,135
4800 S	23,475	2,113	13,135
4400 S	23,475	2,113	9,720
4000 S	21,810	1,963	9,255
SR-79 (Hinckley Dr)	20,960	1,886	14,675
SR-108 (Midland Dr)/3300 S	22,260	2,003	11,845
2550 S	22,260	2,003	10,000

Table 12. AADT Data for Study Intersections (Regions 2-3)

Location	**Major AADT**	**DDHV**	**Minor AADT**
Region 2-			
South Jordan Pkwy/Mtn. View Corridor	11,980	1,078	-
600 W Interchange/Bangerter Hwy	-	-	-
South Jordan Pkwy/Redwood Rd	35,975	3,238	25,600
Bangerter Hwy/Redwood Rd	29,155	2,624	Ramp
Region 3-			
Intersections with US-189 (University Ave) in Provo			
800 N	40,365	3,633	8,105
960 N	40,365	3,633	-
Canyon Rd	40,365	3,633	10,440
Bulldog Blvd/1230 N	32,315	2,908	17,845
Paul Ream Ave	30,960	2,786	-
University Pkwy	30,960	2,786	38,960
2230 N	32,480	2,923	15,325
2680 N	32,480	2,923	-
3300 N	32,480	2,923	-
3700 N	30,115	2,710	12,885
4200 N	26,940	2,425	-
4400 N	26,940	2,425	-
4800 N	26,940	2,425	12,325
5200 N	26,940	2,425	-
Intersections with 2050 W and SR-114 (Geneva Rd) in Provo/Orem			
600 S (Provo)	2,585	233	905
Center St (Provo)	10,000	900	25,000
SR-265 (University Pkwy)	11,775	1,060	21,085
1000 S (Orem)	11,775	1,060	-
800 S (Orem)	11,775	1,060	-
400 S (Orem)	11,775	1,060	4,535
Center St (Orem)	17,170	1,545	9,420
400 N (Orem)	17,170	1,545	5,345
Intersections with US-89 (300 S) in Provo			
US-189 (University Ave)	27,755	2,498	30,535
200 E	14,585	1,313	-
400 E	14,585	1,313	-
700 E	14,585	1,313	3,580
100 S/University Ave in Provo	25,370	2,283	<5,000

3.5 Intersection Left Turn Control

The type of left turn control for each approach at each signalized intersection was gathered. Some study intersections did not have signals. Approaches at those intersections are labeled as “stop” or “yield” to denote the type of control present. Left turning crashes are the most common type of intersection crash, some of which include bicycles. The left turn operations were a point of interest to consider in determining the effects related to bicycle infrastructure. The options for left turn control include permissive-only, protected-only, combined permissive with protected, and flashing yellow arrows (FYA). Tables 13 and 14 provide the left turn control for the major and minor intersection approaches.

Table 13. Intersection Left Turn Control (Region 1)

Intersection Site	Left Turn Phasing	
	Major	**Minor**
Region 1-		
SR-126 (Main St/State St) in Davis and Weber Counties		
I-15 Interchange	Protected	Protected
Main St (Layton)	N/A	Protected
Gentile St	Permissive Protected	Permissive Protected
Church St	Yield	Stop
500 N (Layton)	Permissive Protected	Permissive
Hill Field Rd/Industrial Park	Prohibited	Prohibited
Gordon Ave/1000 N	Protected (NB), FYA (SB)	Permissive
Angel St/1200 W	Permissive	Permissive
1600 N (Layton)	Permissive	Protected
Antelope Dr/2000 N	Permissive Protected	Permissive Protected
1000 E (Clearfield)	Permissive	FYA (NB), Permissive (SB)
SR-193 (700 S)	FYA	FYA
200 S (Clearfield)	Permissive	Permissive
Center St (Clearfield)	Permissive	Permissive
SR-107 (300 N)	Permissive Protected	Permissive Protected
SR-103 (650 N)	Permissive Protected	Protected
800 N (Clearfield/Sunset)	Permissive Protected	Protected
1300 N (Sunset)	FYA	Protected
SR-37 (1800 N)	Permissive Protected	Protected
2300 N (Sunset)	Permissive	Protected
6000 S	Permissive	Protected
5700 S	Permissive	Protected
SR-97/5600 S	Permissive Protected	Protected
5400 S	Permissive	Permissive
SR-26 (Riverdale Rd)/5300 S	Protected	Protected
4800 S	Permissive Protected	Permissive Protected
4400 S	Permissive Protected	Permissive Protected
4000 S	Permissive Protected	Permissive Protected
SR-79 (Hinckley Dr)	FYA	FYA
SR-108 (Midland Dr)/3300 S	Permissive Protected	Permissive Protected
2550 S	Permissive Protected	Permissive

Table 14. Intersection Left Turn Control (Regions 2-3)

Intersection Site	LT Phasing	
	Major	**Minor**
Region 2-		
South Jordan Pkwy/Mtn. View Corridor	Protected	Protected
600 W Interchange/Bangerter Hwy	Protected	Protected
South Jordan Pkwy/Redwood Rd	Protected	Protected
Bangerter Hwy/Redwood Rd	Protected	Protected
Region 3-		
Intersections with US-189 (University Ave) in Provo		
800 N	Permissive Protected	Permissive Protected
960 N	Permissive	Protected
Canyon Rd	-	Protected
Bulldog Blvd/1230 N	FYA	FYA
Paul Ream Ave	Permissive	Permissive
University Pkwy	FYA	FYA
2230 N	Protected	Protected
2680 N	Permissive	Permissive
3300 N	Permissive	Permissive
3700 N	Protected	Permissive Protected
4200 N	Permissive	Permissive
4400 N	Permissive	Protected
4800 N	Protected	Permissive
5200 N	Permissive	Permissive
Intersections with 2050 W and SR-114 (Geneva Rd) in Provo/Orem		
600 S (Provo)	Yield	Stop
Center St (Provo)	Permissive	Permissive
SR-265 (University Pkwy)	FYA	Protected
1000 S (Orem)	FYA	FYA
800 S (Orem)	Permissive	Permissive
400 S (Orem)	FYA	Protected (WB), FYA (EB)
Center St (Orem)	FYA	FYA
400 N (Orem)	Yield	Stop
Intersections with US-89 (300 S) in Provo		
US-189 (University Ave)	Protected (WB), FYA (EB)	Protected
200 E	Prohibited	Prohibited
400 E	Permissive	Permissive
700 E	Permissive	Protected
100 S/University Ave in Provo	Protected	Protected

3.6 **Bicycle Crash Data**

Crash data was gathered from the UDOT Safemap crash data website by applying a bicycle-related filter to study corridors. Data for bicycle-automobile crashes was gathered along each corridor from 2010 to 2017, noting the proximity of each crash to an intersection. Crash history can be used to identify problematic interactions between bicycles and automobiles.

3.6.1 Intersection Crash Data

For purposes of this research, intersection crash data includes any automobile-bicycle crash within 250 ft of a study intersection, or if the investigating officer indicated it was intersection-related (Johansson and Rumar, 1971; Stover and Koepke, 1988). Bicycle crash frequency was determined for each of the 62 study intersections and an additional crash frequency measurement was gathered for intersection-related crashes that occurred within the study area at non-study intersections. An example of the latter category would be an automobile-bicycle crash occurring at a stop-controlled minor side street. Figure 3 shows UDOT Safemap's automobile-bicycle crash mapping at the intersection of University Parkway and University Avenue during the study period. Five bicycle crashes occurred within the physical area of the study intersection and another five occurred within 250 ft of it. Tables 15 and 16 show bicycle crash frequency for all intersections within each corridor.

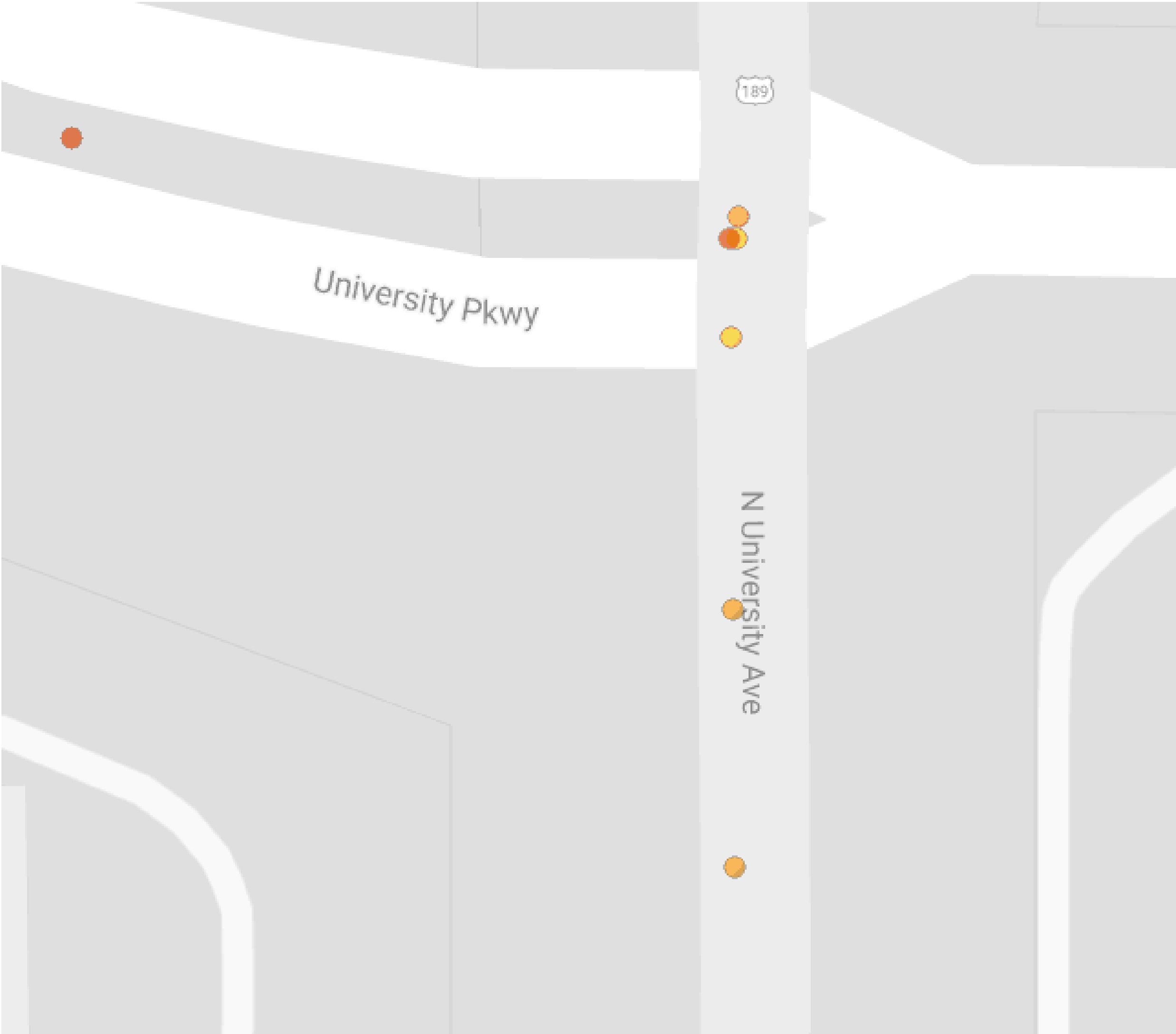


Figure 3. Example of UDOT Safemap Corridor Data (University Pkwy/University Ave)

Table 15. Intersection-Related Automobile-Bicycle Crashes (Region 1)

Intersection Site	**Bike Crashes 2016-2017**
Region 1-	
SR-126 (Main St/State St) in Davis and Weber Counties	
I-15 Interchange	0
Main St (Layton)	0
Gentile St	4
Church St	1
500 N (Layton)	2
Hill Field Rd/Industrial Park	1
Gordon Ave/1000 N	2
Angel St/1200 W	2
1600 N (Layton)	0
Antelope Dr/2000 N	5
1000 E (Clearfield)	1
SR-193 (700 S)	3
200 S (Clearfield)	3
Center St (Clearfield)	2
SR-107 (300 N)	4
SR-103 (650 N)	1
800 N (Clearfield/Sunset)	2
1300 N (Sunset)	0
SR-37 (1800 N)	1
2300 N (Sunset)	1
6000 S	1
5700 S	1
SR-97/5600 S	5
5400 S	1
SR-26 (Riverdale Rd)/5300 S	0
4800 S	2
4400 S	6
4000 S	0
SR-79 (Hinckley Dr)	0
SR-108 (Midland Dr)/3300 S	0
2550 S	0
Intersection-related but not at study site	14
Total	**65**

Table 16. Intersection-Related Automobile-Bicycle Crashes (Regions 2-3)

Intersection	**Bike Crashes 2016-2017**
Region 2-	
South Jordan Pkwy/Mtn. View Corridor	0
600 W Interchange/Bangerter Hwy	0
South Jordan Pkwy/Redwood Rd	4
Bangerter Hwy/Redwood Rd	1
Total	**5**
Region 3-	
Intersections with US-189 (University Ave) in Provo	
800 N	4
960 N	2
Canyon Rd	0
Bulldog Blvd/1230 N	14
Paul Ream Ave	0
University Pkwy	10
2230 N	2
2680 N	0
3300 N	1
3700 N	3
4200 N	2
4400 N	0
4800 N	6
5200 N	2
Intersection-related but not at study site	7
Total	**53**
Intersections with 2050 W and SR-114 (Geneva Rd) in Provo/Orem	
600 S (Provo)	0
Center St (Provo)	1
SR-265 (University Pkwy)	0
1000 S (Orem)	0
800 S (Orem)	0
400 S (Orem)	0
Center St (Orem)	2
400 N (Orem)	0
Intersection-related but not at study site	0
Total	**3**
Intersections with US-89 (300 S) in Provo	
US-189 (University Ave)	2
200 E	2
400 E	0
700 E	0
Intersection-related but not at study site	3
100 S/University Ave in Provo	2
Total	**9**

3.6.2 Segment Crash Data

Segment crash data includes any automobile-bicycle crash not classified as intersection related or occurring within 250 ft of an intersection. Crashes were assigned to entire corridors rather than small segments between intersections. Table 17 provides a synopsis of the overall frequency of bicycle crashes for segments along each corridor.

Table 17. Segment-Related Automobile-Bicycle Crashes

Corridor	Crash Frequency
SR-126 (Main St/State St) Davis/Weber Counties	11
US-189 (University Ave); 800 N to 5200 N in Provo	10
2050 W and SR-114 (Geneva Rd); Center St (Provo) to 400 N (Orem)	6
US-89 (300 S); US-189 (University Ave) to 700 E in Provo	0
100 S; US-189 (University Ave) to 700 E in Provo	0

Main Street/State Street (in Davis and Weber Counties) and University Avenue (in Provo) displayed the highest number of segment-related crashes. 300 South and 100 South in Provo did not experience any.

3.7 **Summary**

Data collection efforts included obtaining AADT, left turn control type, and crash history for six study corridors and 62 intersections. Gathering the data included the use of databases and aerial maps as well as site visits that included video recording of bike lane use. Crash data was obtained through UDOT’s Safemap tool, which allowed the research team to distinguish crashes occurring at or near intersections from those that were not intersection-related.

4.0 DATA EVALUATION

4.1 Overview

For many bicyclists, bike lanes improve riding comfort by removing them from vehicle lanes and allocating space specific for them to ride. Bike lanes provide visual guidance for both drivers and bicyclists by delineating the expected path of bicyclists. Automobile travel lanes were first used to distinguish the direction between opposing vehicles along River Road in Oscoda, Michigan (Cranson, 2011). Painted lane markings delineate space for opposing and same-direction vehicles. This chapter explores the relationship between bike lane installations and human behavior, AADT, and crash frequency. Case studies from around the United States with bearing on these subjects are then described. Information learned in this research may help guide recommendations and strategies for bikeway planning and design.

4.2 Bicyclist and Driver Behavior Analysis

Human behavior is a topic of interest in transportation engineering. In the context of this research, bike lanes influence the behavior of both bicyclists and drivers. As noted in the Section 2.2.1, Monsere, et al (2012) identified a perceived effect among drivers of an increased travel time and feeling of inconvenience by the installation of a bike lane facility. A perceived increase in travel time can result in driver frustration and aggressive behavior around bicyclists and other drivers.

Figure 4 shows a driver going around a bicyclist that is utilizing a shared right turn pocket. The video log of this bicycle-automobile interaction demonstrates an instance where a driver's behavior changes as the result of a bicyclist being present. The video showed that the overtaking car went out of the lane, into the gore area, and around the bicyclist before re-entering the lane in front of the cyclist and proceeding to the signal. The video leading up to this interaction showed other vehicles entering the right turn lane upstream of the gore area as the roadway striping intended, indicating that the presence of a bicyclist did change driver behavior. Interactions between bicyclists and drivers are more frequent at intersections and their approaches because of the turning movements that occur there.

Figure 4. Vehicle Going Around a Bicycle in a Shared Right Turn Lane

4.3 Consideration for Differences in AADT

Historic AADT counts establish traffic trends and growth. Removing cyclists from automobile lanes removes delay associated with queuing behind slow-moving cyclists. Higher AADTs indicate potential for bike lanes to improve operations of the entire system in situations where bicycles are expected to be present and automobile lanes don't need to be removed in order to make room for the bike lanes. The time frame and scope of this study do not allow an extended consideration for changes to AADT as a result of bicycle infrastructure. That level of study would be recommended for additional research.

4.4 Crash Frequency

Intersection-related bicycle crashes accounted for 83% of all crashes along the study corridors. This high percentage is indicative of the large number of interactions between drivers and bicyclists near intersections. Table 18 compares the different intersections and segment-related crashes for each of the study corridors. Past UDOT research has also shown that more bicycle crashes can be expected at intersections than along linear road segments.

Table 18. Bicycle Crash Data of Intersection Related and Segment Totals

Corridor	Intersection-Related Totals	Segment-Related Totals	Corridor Totals	% Intersection Related	% Segment Related
SR-126 (Main St/State St) in Davis and Weber Counties	65	11	76	86%	14%
US-189 (University Ave); 800 N to 5200 N in Provo	53	10	63	84%	16%
2050 W and SR-114 (Geneva Rd); Center St (Provo) to 400 N (Orem)	3	6	9	33%	67%
US-89 (300 S); US-189 (University Ave) to 700 E in Provo	7	0	7	100%	0%
100 S; US-189 (University Ave) to 700 E in Provo	2	0	2	100%	0%
Total	**130**	**27**	**157**	**83%**	**17%**

4.5 Case Studies

Because of the data limitations inherent in this project, a survey of existing case studies was conducted relative to the impact of bicycle infrastructure on total roadway function. Those studies are described in the next few subsections.

Folsom Street, Boulder, CO

In July 2015 the city of Boulder, Colorado – one of the most bicycle friendly communities in the country – installed protected bike lanes along one of the busier vehicle corridors in the city. This was a project that had been identified in their 2014 Transportation Master Plan and the project was named the “Folsom Street Living Lab” and sought to “rightsize” city streets to accommodate all modes. This project was intended to “test and evaluate whether a new street configuration and design treatments would enhance multi-modal access and travel safety” (Roberts, 2015). Throughout the project the city sought and received a large amount of community feedback about the impact the pilot project was having on household travel and the ability to get around Boulder. A single southbound traffic lane was eliminated to create the protected bike lane (Figure 5 – photo courtesy of Scripps Media).

Figure 5. Folsom Protected Bike Lane

A before and after analysis determined that automobile travel times along that stretch of Folsom increased substantially. Figure 6 shows the travel times (high, average, and low) during the PM peak for the seven weeks following the installation of the protected bike lane. By Week 7, travel time during the PM peak had doubled for drivers. Both cyclists and motorists voiced their dissatisfaction with the new facility, which they deemed an attempt to "fix something that wasn't broken" [18]. Major complaints included: an increase in dangerous interactions between cyclists and motorists, congestion blocking the intersections and backing up traffic for blocks in all directions, inconsistent spacing of the bollards, and increased danger for cyclists wanting to turn left.

By October of 2015 (3 months after installation), the Boulder City Council reversed their decision on the "rightsizing" project and crews began removing the protected lane. It should be noted that Boulder is only the 4th city in the nation to remove a protected bike lane once installed. Others include Memphis, Boise, and Portland.

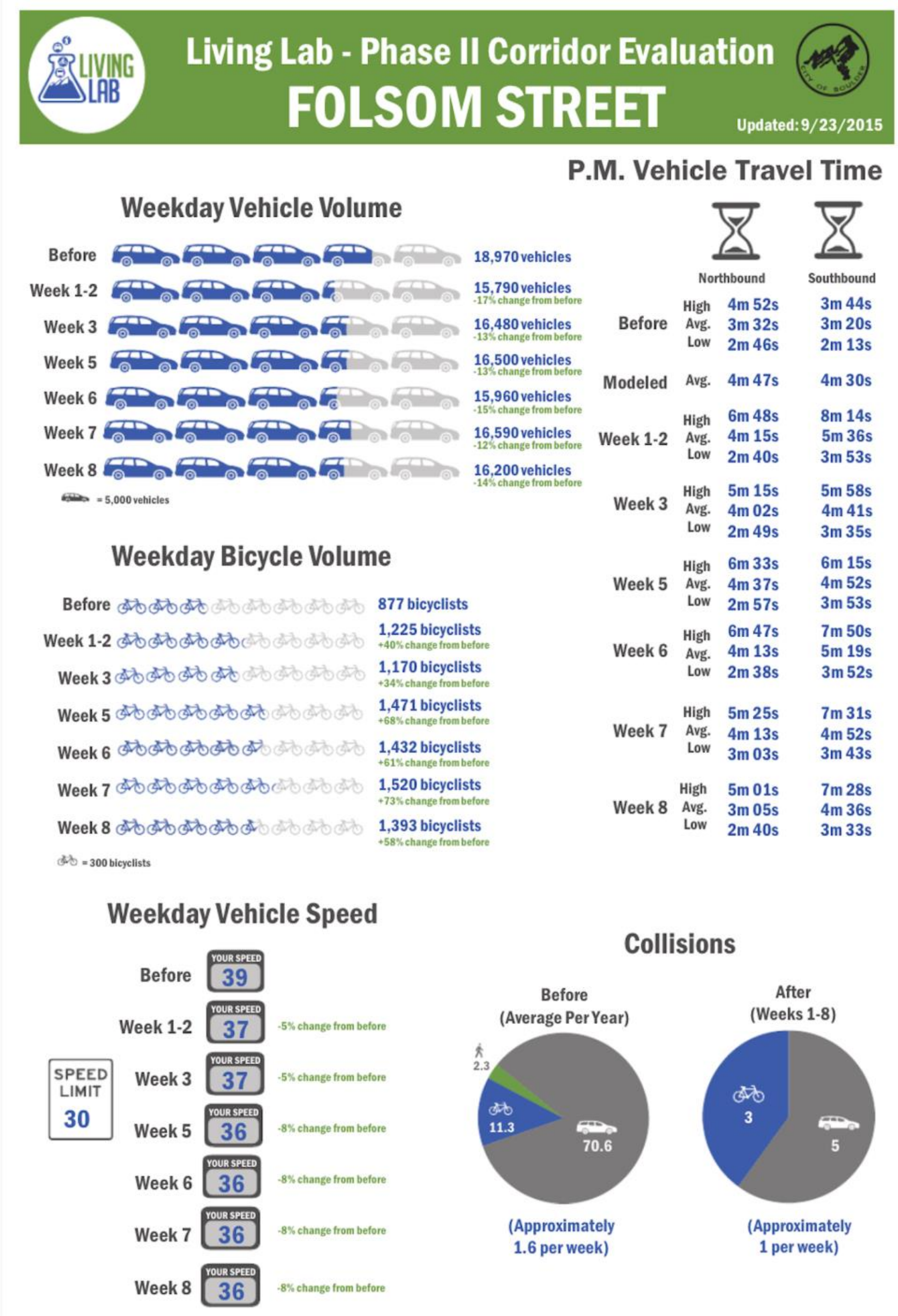


Figure 6. Folsom Street Corridor Statistics

While the public voiced concerns over the corridor project, Figure 6 shows the statistics of its actual impacts on traffic and safety. Although travel times for vehicles did significantly increase and total vehicle volumes fell by 14%, weekday bicycle volumes increased by about

60% and total collisions decreased by 40% (per week). Daily vehicle speeds only decreased by 3 mph and remained 20% above the posted speed limit.

Non-Motorized Transportation Evaluation Study

The Non-Motorized Transportation Pilot Program (NTPP) is a congressionally mandated program (SAFETEA-LU Section 1807) that, since 2006, has provided roughly $25 million each to four communities in Missouri, California, Minnesota, and Wisconsin to spur levels of walking and cycling via a variety of planning measures and enhancements. As a part of the pilot program, each community implemented its own strategy:

- Columbia: GetAbout Columbia encouraged walking and bicycling with more than 125 miles of new bikeways, pedestrian walkways, and sidewalks. Safety and convenience were improved via striped bicycle lanes, better signage, and new bicycle parking downtown.
- Marin County: WalkBikeMarin incorporated more than a dozen infrastructure improvements with education and outreach programs ranging from bicycle repair classes to community walking maps.
- Minneapolis Area: Bike Walk Twin Cities focused on strategic infrastructure planning through a fair and transparent process, with an emphasis on increasing walking and bicycling among women, immigrants, and underserved communities.
- Sheboygan County: NOMO, short for Nonmotorized Initiative, led to more sidewalks and bicycle lanes, bicycle racks near county buildings and buses, new urban and rural recreation trails, and volunteer-driven outreach programs (Volpe, 2018).

To evaluate the impacts of these infrastructure investments, community-wide before and after surveys were conducted. Phase 1 (before) yielded 1,279 complete surveys and 1,807 were received for Phase 2 (after). The surveys addressed a wide range of transportation-related questions and consisted of 54 variables including trip distance and mode choice. The study found no significant difference in travel behavior from before the investments were made to after. However, the researchers noted that "the inability to detect significant patterns of change is not synonymous to no change occurring (Krizek, 2011)". Challenges in adequately measuring behavior change included: the design of the research program, short evaluation period, limited resources allocated to data collection and evaluation, no traffic counts to monitor behavior, and reliance on self-reported behavior data. This evaluation also did not specifically look at impacts on vehicular traffic but focused on changes in non-motorist behavior.

Traffic Impacts of Bicycle Facilities in Minnesota

The University of Minnesota in cooperation with the Minnesota Department of Transportation conducted a research study in 2017 to increase understanding of the effects of bicycle facilities on driver behavior and traffic flows. The objectives of their study were to "identify needs for evaluation of facilities, select facilities to be evaluated, complete field evaluations, and summarize the implications for design (Lindsey, 2017)". Rather than conduct before and after evaluations, they simply observed driver behavior along corridors with existing facilities. Facilities observed included buffered and striped bicycle lanes, sharrows, signed shared lanes, and shoulders of various widths.

Their analysis classified driver behaviors as "no change in trajectory", "deviation within lane", "encroachment into adjacent lane", "completion of a passing maneuver", and "queuing behind cyclists". Researchers determined that drivers on roadways with bicycle lanes were less likely to encroach into adjacent lanes, pass, or queue when interacting with cyclists than drivers on roadways with sharrows, signs designating shared lanes, or no bicycle facilities. Additionally, the analysis showed that queuing behind cyclists, the most significant impact on vehicular traffic flows, generally was highest on roads with no facilities or shared facilities without marked lanes. A statistical analysis confirmed that buffered or striped bicycle lanes offer advantages over other facilities. Sharrows may alert drivers to the presence of cyclists, but traffic impacts on roadways with sharrows do not differ significantly from roadways without facilities. Signs indicating bicyclists may occupy lanes also may alert drivers to the presence of cyclists, but interactions on roadways marked only with signs did not differ from roadways without facilities (Lindsey, 2017).

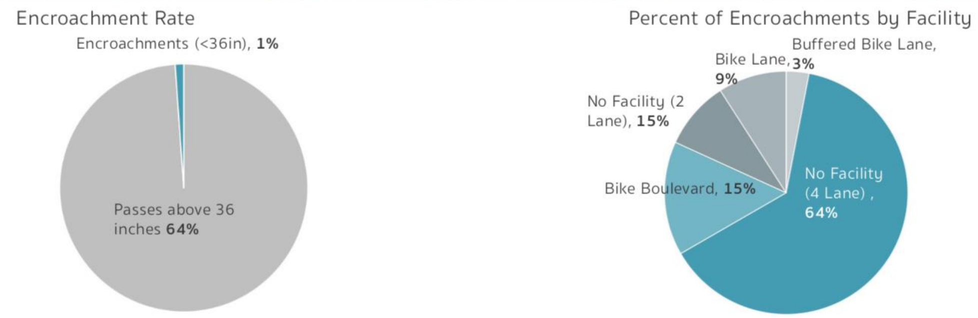
Motorist Passing of Cyclists

A separate study in Hennepin County, Minnesota explored the impacts that bicycle facility, automobile type, and other variables have on two measures of safety – vehicle passing distance (VPD) and encroachment (Evans, Pansch, Singer-Berk and Lindsey, 2017). Using a bike-mounted radar and camera, researchers recorded and analyzed 2,949 motorist passes on seven roads with four different types of bicycle facilities (Figure 7).

According to their analysis the average passing distance was 70 inches, and overall encroachment rate was only 1.12%. A statistical analysis further determined that roads with buffered and bollard-protected bike lanes are correlated with larger passing distances and the lowest chance of vehicles encroaching within 3 feet of a cyclist. Compared to roads with protected or buffered bike lanes, passing distances on roads with other types of bike facilities were 14-18 inches closer on average. However, despite having a lower average passing distance, standard bike lane and shoulder facilities (unmarked but wide enough to accommodate cyclists) did not significantly differ in chance of encroachment. Figure 7 shows details of this study (Evans, Pansch, Singer-Berk and Lindsey, 2017).

*Average Passing Distance

Encroachment Summary



Vehicle Type Summary (FHWA Categories)

	Total Passes	Vehicle Percent	Average Passing Distance	Encroachments	Encroachment Percent of All Passes	Percent of All Encroachments
Category 1	13	0%	89	0	0%	0%
Category 2	1844	63%	72	17	1%	52%
Category 3	984	33%	67	12	1%	36%
Category 4	65	2%	60	2	3%	6%
Category 5-8	38	1%	67	2	5%	6%

Passing Distance by Gender

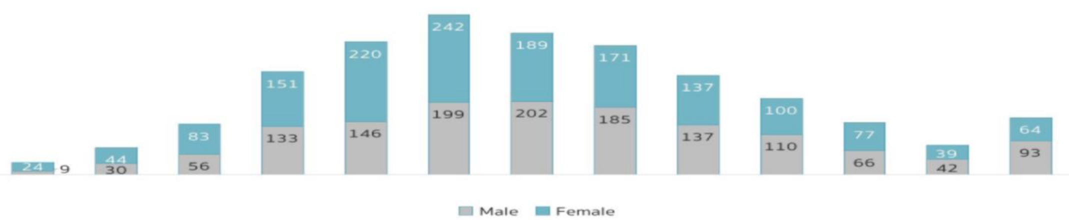


Figure 7. Hennepin Encroachment Study

The analysis also examined more complex bicycle infrastructure and found that bicycle boulevards had the highest chance of encroachment among all facility types, despite having only the second lowest average passing distance.

4.6 **Summary**

Video observations suggest that the presence of a bike lane does not change driver behavior, but the presence of a cyclist does. The time frame and scope of this study did not allow an extended consideration for changes to the AADT as a result of bicycle infrastructure, and it is recommended that additional research be conducted to focus specifically on changes in AADT. Crash statistics revealed that in this sample a large percentage of bicycle-involved crashes at study sites took place at intersections (83%) rather than along linear segments. This finding is consistent with the frequency of motorist-cyclist interactions that occur at intersections where many turning movements are being made on and off of roads.

A review of several case studies from across the country found that drivers on roadways with bicycle lanes were less likely to encroach into all adjacent lanes, pass, or queue when interacting with cyclists, and that bike lanes are more effective at protecting cyclists than using sharrows or signs designating shared lanes. Also, the type of bicycle infrastructure may be associated with vehicular passing distance and frequency of encroachments. One study found that roads with buffered and bollard-protected bike lanes were correlated with larger passing distances and the lowest chance of encroachment. That same study found that roads with other types of bike facilities exhibited passing distances of 14-18 inches less than roads with protected or buffered bike lanes.

The Folsom Street case study measured delay caused by installing bicycle infrastructure and found that the installation of a protected bike lane doubled travel time for vehicles along the corridor a Colorado. In this case a general purpose lane was removed, which likely caused the change in delay. There is no evidence that protected bicycle lanes would inherently cause delay in situations where general purpose lane space is not significantly reduced.

5.0 CONCLUSIONS

5.1 Summary

The objective of this paper was to quantify the effects of bicycle infrastructure on all roadway users. Providing dedicated roadway space for bicycle facilities may increase perceived and actual bicycle safety as well as mode share but lack of data and the presence of other significant variables makes conclusions about correlation and causation difficult. The original intent of this research was to collect data before and after construction of bicycle facilities and compare variables such as AADT. However, challenges with construction schedules and cancelled projects made these comparisons impossible. The available analysis and case study review is nevertheless useful.

5.1.1 Crash Risk at Intersections

Interactions between bicyclists and drivers were found to be most frequent at and near intersections. Intersection-related bicycle crashes accounted for 83% of all crashes along the study corridors. This finding is not surprising given the opportunity for conflicts among all roadway users at intersections.

5.1.2 Case Study Review

One case study found that while installing a protected bike lane resulted in a significant increase in peak period travel time and reduction in vehicle volume (14%), weekday bicycle volumes increased by about 60% and total collisions decreased by 40% (per week). Daily vehicle speeds decreased by 3 mph but remained 20% above the posted speed limit.

Other case studies found that drivers on roadways with bicycle lanes were less likely to encroach into adjacent lanes, pass, or queue when interacting with cyclists, and that bike lanes were more effective at increasing passing distance than sharrows or signs designating shared lanes. Additionally, roads with buffered and bollard-protected bike lanes were correlated with larger passing distances (14-18 inches on average) and the lowest chance of encroachment when compared to conventional bike lanes or shared roadways.

5.2 **Limitations and Challenges**

The impacts of non-motorized transportation interventions are difficult to demonstrate scientifically unless adequate means, resources, and time are allocated. In particular, before–after evaluations are extremely challenging without the availability of routinely collected data, such as regularly conducted household travel surveys and traffic counts. For this research, we anticipated having a set of specific corridors that were going to have bicycle infrastructure installed, but a majority of the projects were delayed or cancelled after the "before" data was collected.

Because bicycle infrastructure construction projects are not widespread along the Wasatch Front it was difficult to make up for the lost projects. Additional efforts to supplement the limited sample by analyzing existing infrastructure fell short due to budget and time constraints. Future research should include specific locations where construction is confirmed and appropriate traffic components can be measured before and within an appropriate time frame after construction. Lastly, key staff changes occurred within UDOT during the project lifespan and that led to additional challenges in delivering the intended project scope.

6.0 RECOMMENDATIONS

6.1 **Recommendations**

This research confirmed that a majority of incidents between vehicles and bicycles occur at intersections. It is recommended that designs for intersections along corridors with bicycle facilities aim to reduce conflict between bicyclists and other vulnerable road users by improving visibility, identifying a specific right-of-way, and promoting heightened awareness with competing modes. According NACTO, this can include employing treatments such as bike boxes, intersections crossing markings, two-state turn queue boxes, median refuge islands, through bike lanes, combined bike lane/turn lane, and protected bike lane intersection approaches (NACTO, 2014).

Figure 8. Intersection Bike Box

Bike boxes provide a designated area ahead of a travel lane at an intersection giving cyclists a safe and visible way to proceed ahead of traffic during a red signal phase (Figure 8). This allows them increased visibility not only by adjacent vehicle traffic, but also cross traffic which may not be as apt to see bicycle traffic coming when mixed with automobiles. Bike boxes can reduce signal delay, facilitate left turns for cyclists, prevent common right-hook conflicts, and allow groups of bicyclists to cross an intersection together more quickly.

Intersection crossing markings provide pavement marking through the intersection informing the cyclist which path to follow, while also providing automobiles with a visual clue to increase awareness and remind drivers to expect cyclists in that location (Figure 9). Crossing markings can also be used in difficult-to-navigate areas such as across driveways or ramps where cyclists may not be able to easily identify the safest path to travel.

Figure 9. Intersection Crossing Marking: Berlin, Germany

Two-stage turn queue boxes are a relatively new concept in the United States and are not widely employed. However, they are effective at providing cyclists with a safe way to make left turns at multi-lane signalized intersections when they must transition from a bicycle lane or protected bike lane on the right shoulder of the roadway (Figure 10: NACTO, 2014). The queue box allows a cyclist to cross adjacent traffic and then stop in a location ahead of stopped automobiles, similar to a bike box, and wait for the signal to change before proceeding straight ahead. These queue boxes allow cyclists to comfortably make left turns, provide a formal queuing space for cyclists, reduce conflicts arising from cyclists attempting to cross oncoming traffic to turn, and separate turning bicyclists from through cyclists.

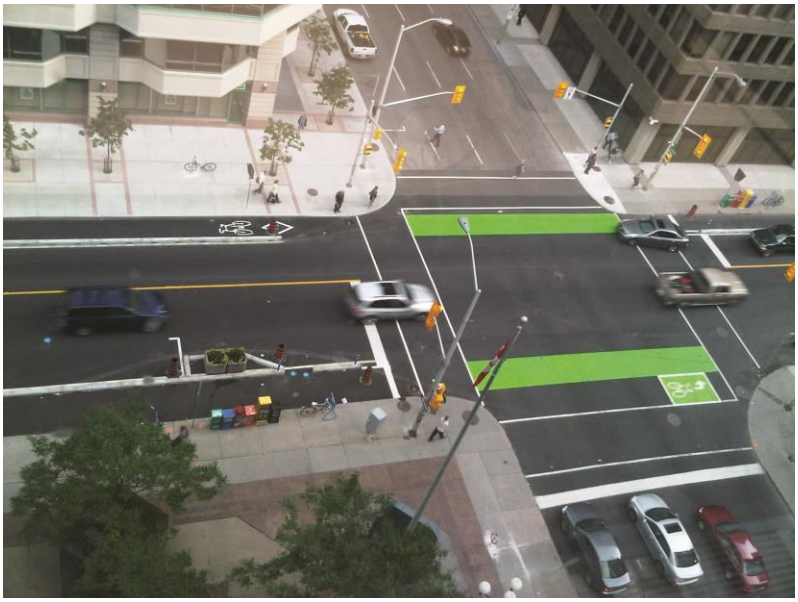


Figure 10. Two Stage Turn Queue Box: Ottawa, Canada

A median refuge island provides a protected space in the center of a street, which can facilitate bicycle and pedestrian crossings (Figure 11). This allows cyclists to only cross one direction of traffic at a time and avoid being stranded if a signal changes mid-crossing. Median refuges improve cyclist visibility and reduce the overall exposure to traffic. They also provide traffic calming and can slow automobile travel speeds.

Figure 11. Refuge Island

Through bike lanes allow cyclists to approach an intersection in a correct position to avoid conflicts with right turning vehicles (Figure 12). They also reduce vehicular conflict by alerting drivers approaching a turn that there could be cyclists present and they should yield to cyclists traveling straight. Additionally, this provides a somewhat protected bicycle pocket at the intersection. Through lanes can be combined with a bicycle box or other through intersection treatment to increase visibility.

Figure 12. Through Bike Lane

When right-of-way or road space is limited, a bike lane can be combined with a turn lane. This allows a bike lane to continue where it would otherwise be dropped. Sharrows or other pavement markings are included within the turn lane to alert drivers of the presence of bicycles and to inform cyclists of the appropriate location to ride to navigate the intersection. Signage can also be used to inform drivers and cyclists that the lane is a shared space, as shown in Figure 13. These shared lanes maintain cyclists' comfort and priority and reduce the potential of right-hook conflicts at the intersection.

Figure 13. Combined Bike Lane/Turn Lane: Bend, OR

Lastly, in locations where a protected bike lane is provided along a corridor, the crossing should be designed to reduce turn conflicts and provide connections to intersecting bicycle facilities. Typically, this is achieved by removing the protected bike lane barrier or parking lane and shifting the bicycle traffic closer to adjacent motor vehicle traffic. The crossing can then be treated the same as a conventional bike lane.

Figure 14. Protected Bike Lane Intersection Approach

A separate bicycle signal phase can also be employed to reduce conflicts with motor vehicles in heavy traffic locations. If the right-of way is large enough, a protected bike lane can be continued on either side of the intersection with the buffer as shown in Figure 14. When a protected bike lane must be dropped due to space constraints at the intersection, some form of bicycle accommodation should be made to ensure that cyclists are not unexpectedly merged directly into automobile traffic. The key is to improve visibility and provide cyclists with the safest possible area to navigate the intersection.

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APPENDIX A: Signal Details for Sample Corridors

Table 15. Left Turn Signal Phasing for Coupled Approach at Study Intersections

Intersection Site	Major Approaches	Minor Approaches
	LT Phasing	**LT Phasing**
Region 1-		
-SR-126 Main St/State St. through Davis County		
SR-126 and I-15 Interchange	Protected	Protected
SR-126 and Main St Layton	N/A	Protected
SR-126 and Gentile	Perm Protected	Perm Protected
SR-126 and Church St	Yield	Stop
SR-126 and 500 North	Perm Protected	Permissive
SR-126 and Hill Field Rd/Industrial Park	Prohibited	Prohibited
SR-126 and Gordon Ave/1000 North	Protected and FYA	Permissive
SR-126 and Angel St/1200 W	Permissive	Permissive
SR-126 and 1600 North	Permissive	Protected
SR-126 and Antelope Dr/2000 North	Perm Protected	Perm Protected
SR-126 and 1000 East	Permissive	Permissive, FYA
SR-126 and 700 S/SR-193	FYA	FYA
SR-126 and 200 S	Permissive	Permissive
SR-126 and Center St Clearfield	Permissive	Permissive
SR-126 and 300 N Clearfield	Perm Protected	Perm Protected
SR-126 and 650 North Clearfield	Perm Protected	Protected
SR-126 and 800 N Clearfield	Perm Protected	Protected
SR-126 and 1300 North Clearfield	FYA	Protected
SR-126 and 1800 N Clearfield	Perm Protected	Protected
SR-126 and 2300 N Clearfield	Permissive	Protected
SR-126 and 6000 S Roy	Permissive	Protected
SR-126 and 5700 South Roy	Permissive	Protected
SR-126 and 5600 South Roy	Perm Protected	Protected

SR-126 and 5400 South Roy	Permissive	Permissive
SR-126 and Riverdale Rd/5300 S Roy	Protected	Protected
SR-126 and 4800 South	Perm Protected	Perm Protected
SR-126 and 4400 South	Perm Protected	Perm Protected
SR-126 and 4000 South	Perm Protected	Perm Protected
SR-126 and Hinckley Dr	FYA	FYA
SR-126 and Midland Dr/3300 South	Perm Protected	Perm Protected
SR-126 and 2550 South	Perm Protected	Permissive
Region 2-		
South Jordan Parkway and Mountain View Corridor	Protected	Protected
600 West and Bangerter Hwy	Protected	Protected
South Jordan Parkway and Redwood Road	Protected	Protected
Bangerter Highway and Redwood Road	Protected	Protected
Region 3-		
US-189 from 800 North to 5200 North Provo		
US-189 and 800 North	Perm Protected	Perm Protected
US-189 and 960 North	Permissive	Protected
US-189 and Provo Canyon Road	-	Protected
US-189 and Bulldog/1230 North	FYA	FYA
US-189 and Paul Ream Ave	Permissive	Permissive
US-189/Univ Ave and University Parkway	FYA	FYA
US-189 and 2230 North	Protected	Protected
US-189 and 2680 North	Permissive	Permissive
US-189 and 3300 North	Permissive	Permissive
US-189 and 3700 North	Protected	Perm Protected
US-189 and 4200 North	Permissive	Permissive
US-189 and 4400 North	Permissive	Protected
US-189 and 4800 North	Protected	Permissive
US-189 and 5200 North	Permissive	Permissive
-600 South Provo to 400 North in Orem along Geneva Rd.		
2050 W 600 South Provo	Stop	Unprotected
SR-114 and Provo Center St	Permissive	Permissive
SR-114 and University Parkway	FYA	Protected
SR-114 and 1000 South	FYA	FYA
SR-114 and 800 South	Permissive	Permissive

SR-114 and 400 South	FYA	Protected/FYA
SR-114 and Orem Center St	FYA	FYA
SR-114 and 400 North	Uncontrolled	Stop
-Bike lanes on US-89 along 300 South Provo - between University Ave (US-189) and 700 East in Provo		
300 South and University Ave	Protected/FYA	Protected
300 South and 200 East	Prohibited	Prohibited
300 South and 400 East	Permissive	Permissive
300 South and 700 East	Permissive	Protected
- 100 South (University Ave to 700 East) in Provo		
100 South and University Ave	Protected	Protected