MAG Regional Bicycle Safety Analysis Guidance Document

June 2019

MARICOPA ASSOCIATION of GOVERNMENTS

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1.0 INTRODUCTION

The Maricopa Association of Governments (MAG) recently engaged a team consisting of Lee Engineering, LLC, Toole Design Group, LLC, and MaxGreen Transportation Engineers, LLC, to conduct a Regional Bicycle Safety Analysis of the MAG region. The study has the following goals:

- Conduct an extensive review of crash reports for crashes involving bicyclists in the MAG region.
- Develop of a series of summary sheets and matrices providing a statistical overview of the types and locations of crashes along with the characteristics of the site and travelers involved in the crashes. These deliverables have been provided to MAG under separate cover but are included in the appendix to this document.
- Develop a guidance document to provide assistance to MAG member agencies for planning and designing new active transportation facilities and improvements to existing facilities.

This Regional Bicycle Safety Analysis Guidance Document includes a literature review and a comprehensive summary of the findings of the crash report review. Many of the guidance document's conclusions and recommendations are drawn directly from the findings from the literature review and crash report review, so a thorough understanding of the findings is needed to appropriately implement the recommendations.

2.0 LITERATURE REVIEW

There are many ways to analyze crash data and integrate crash analyses into the countermeasure selection processes. The purpose of this chapter is to provide a review of different approaches to bicycle safety studies relevant to the regional scale.

This review is divided into two primary sections:

1. **Crash Analysis Methodology Review:** This section provides a summary of the different ways that state and regional planning bodies analyze their bicycle crash data.
2. **Countermeasure Selection Methodology Review:** This section summarizes the different ways that state and regional planning bodies decide which countermeasures to implement and where to implement them. It includes a discussion of systemic safety approaches to countermeasure selection and implementation and a summary of tools MAG and its member agencies can use to help select appropriate countermeasures for implementation.

The information presented in the Literature Review was used to guide the review of Bicycle Crash Reports and development of the Recommendations.

2.1 Safety Analysis Methodology Review

This section highlights how other state and regional planning bodies analyze their bicycle crash data. It is divided into two parts: trend identification and methods to account for severity.

2.1.1 Trend Identification

Each jurisdiction has its own unique approach to crash analysis; however, there are many similarities across communities. Nearly all agencies conduct frequency analyses to identify patterns in the types of crashes that have occurred, and many also use spatial analyses to identify geographic trends.

Frequency Analysis

Assessing crashes by the frequency of various crash attributes is the most basic type of crash analysis. This approach can be used on all crash databases with attribute information (e.g., demographic, environmental conditions, user conditions, roadway geometry, user movements). Regional agencies often comprehensively evaluate the number of crashes that have occurred for most variables present in their crash databases. Agencies will also sometimes separately tabulate the number of fatal/serious injury crashes within each category.

The Denver Regional Council of Government's (DRCOG) 2012 study, *Pedestrian and Bicycle Safety in the Denver Region* analyzed collisions in the Denver region between bicyclists and motor vehicles. This analysis examined long-term trends of total bicyclist fatalities, providing a review of the bicyclist fatalities, bicyclist injury crashes, and total bicyclist crashes from 1991 to 2007. To complement these long-term trends, DRCOG also performed a more detailed attribute frequency analysis for the most recent three years of data. They examined the total number of crashes and fatal crashes by roadway type (freeway, arterial, collector, local). For crashes that occurred on arterials and collectors/local roads, DRCOG further examined the details of the crashes, including an examination of speed, distance from an intersection, presence of driveway, and time of day (DRCOG, 2012). DRCOG also analyzed crashes by severity within each county. To contextualize the traffic safety problem in the region, DRCOG calculated a bicyclist fatality rate (0.14 fatalities per 100,000 population per year) and compared it to those of other metropolitan areas. Finally, DRCOG reviewed crash patterns associated with specific variables, including the mode of the at-fault user, citation (e.g., failure to yield, careless driving), vehicle movement preceding collision, alcohol impairment for bicyclist, age and gender of bicyclists involved in crashes, and temporal conditions (DRCOG, 2012).

Multiple Variable Frequency Analysis

While univariate frequency analysis, as described above, can provide a strong starting point for understanding the crash patterns in a community, it can also be useful to look at the co-occurrence of various crash characteristics to help link crash types to potential countermeasures. For instance, if a large number of bicyclist fatalities in a region occur due to wrong-way riding on collectors or arterials, it might point to the need for improved bicycle crossings on these roads. Crash trees and crash typologies are two useful approaches for analyzing crash frequencies for multiple variables simultaneously.

Crash Trees

The crash tree is a useful method for identifying crash patterns and looking at bigger picture crash findings. This approach can be used on all crash databases with crash attribute data (e.g., demographic, environmental conditions, user conditions, roadway geometry, or user movements).

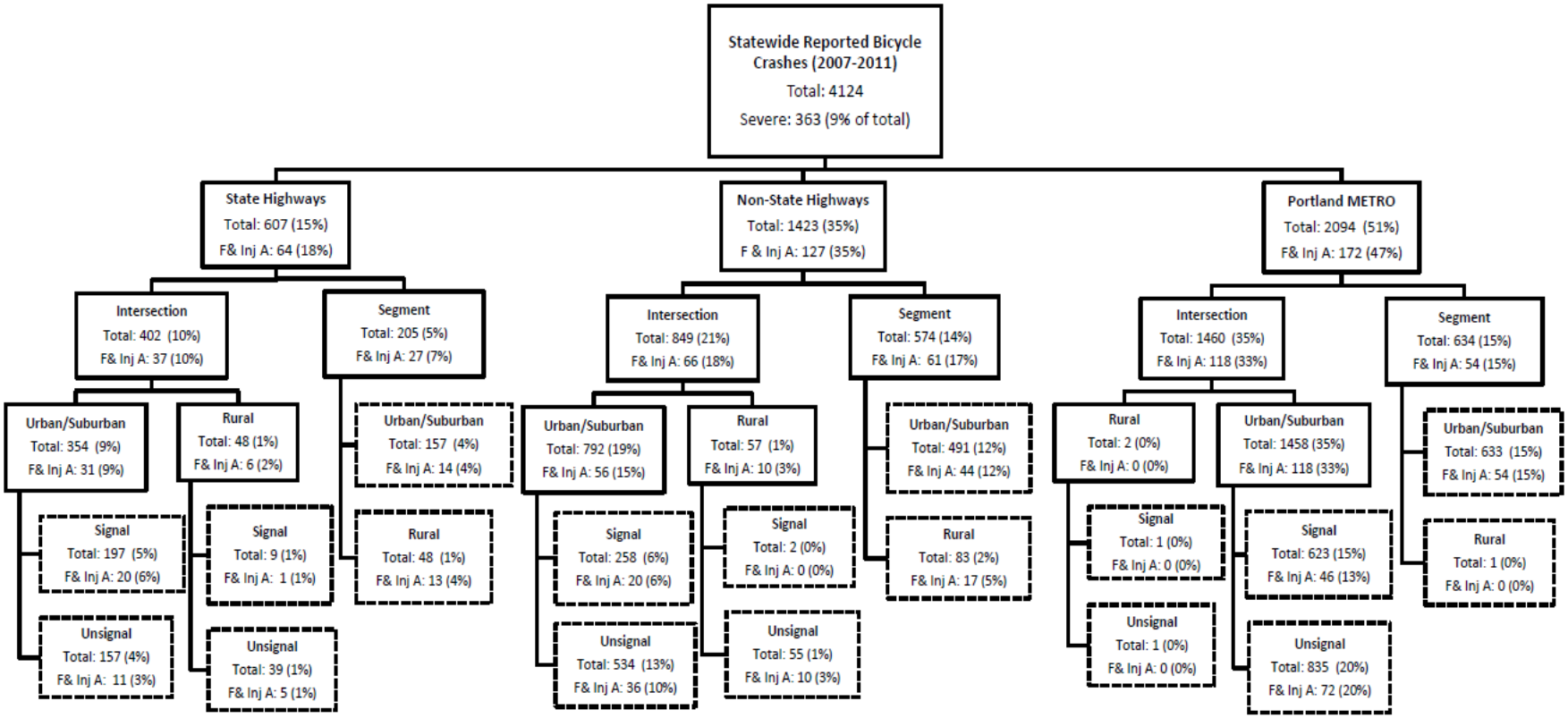
The Oregon Department of Transportation's (ODOT) 2014 *Pedestrian and Bicycle Safety Implementation Plan* sought to identify and prioritize candidate project corridors through a data-driven process to reduce fatal and severe-injury pedestrian and bicyclist crashes on public roads throughout Oregon. ODOT used crash frequency, crash severity, and other identified crash risk factors (e.g., intersection traffic control, number of intersection legs, presence of turn lanes) to identify locations throughout the state that would be good candidates for safety improvement projects. Their analysis included pedestrian and

bicyclist crashes that occurred during a five-year period (ODOT, 2014). Crash risk factors that were considered during the analysis included:

- Geometry – presence or absence of turn lanes, or number of intersection legs;
- Intersection traffic control – signalized, unsignalized, or all-way stop control; and
- Segment characteristics – number of access points per mile, presence of sidewalk or bike lane, and presence of illumination.

Figure 1 shows one of the crash trees ODOT used to examine crash trends across total and severe bicycle crashes. While ODOT considered several risk factors during their analysis, the crash trees were only completed for data that was available across the entire statewide dataset. For example, several crashes occurred at night, suggesting that darkness or lack of lighting is a risk factor. However, ODOT did not have access to a statewide streetlight dataset so lighting was not included in the crash tree. Similarly, roadway characteristics associated with very few crashes were also excluded from the crash tree. This crash tree helped ODOT review trends by roadway ownership and crash location (intersection vs. segment, urban vs. rural, and signalized vs. unsignalized intersection).

Figure 1: ODOT's Bicycle Crash-Tree Diagram



Source: ODOT, 2014, p.60

Crash Typologies[1]

Crash typing is another common and useful way to evaluate crash trends. It has been used for active transportation analyses since the 1970s (Snyder and Knoblauch, 1971). It requires a slightly more involved analysis process than calculating crash frequencies, but it provides a much more comprehensive understanding of the types of scenarios that are commonly associated with crashes in a community. This approach can be used on all crash datasets with pre-crash position and movement data for both drivers and bicyclists. If detailed location or facility data is available, crash types can be developed to highlight more specific crash trends.

In 2018, North Carolina's Department of Transportation (NCDOT) published a bicycle crash study evaluating over 4,000 crashes from six years of data. NCDOT used a crash typing approach and delineated crashes by the crash participant location and pre-crash events (NCDOT, 2018). NCDOT analyzed the bicyclist position prior to the crash (e.g., travel lane, bike lane/paved shoulder, sidewalk/crosswalk/driving crossing, multi-use path, driveway/alley, non-roadway) and bicyclist direction of travel (e.g., with traffic, facing traffic, not applicable, unknown). The same process was completed for driver positions in relation to bicyclists. The crash typing process yielded 78 different crash types; however, the study focused only on the most common crash types. NCDOT's top 10 crash types were associated with nearly 60 percent of all bicycle crashes (NCDOT, 2018). NCDOT used these crash types to identify countermeasures which have been known to address conditions that lead to the most common crash types.

[1] In the literature review, "crash type" refers to a variable that describes the events and crash participant maneuvers that led up to the crash.

Figure 2: NCDOT Top Bicycle Crash Types

Rank	Crash Type	Total	Percent of NC Total
1	Motorist Overtaking – Other / Unknown	513	10.8
2	Motorist Drive Out – Sign-Controlled Intersection	423	8.9
3	Motorist Left Turn - Opposite Direction	393	8.3
4	Motorist Drive Out - Commercial Driveway / Alley	300	6.3
5	Bicyclist Ride Through – Sign-Controlled Intersection	226	4.8
6	Motorist Right Turn – Same Direction	205	4.3
7	Non-Roadway	196	4.1
8	Motorist Overtaking – Undetected Bicyclist	183	3.8
9	Bicyclist Ride Through – Signalized Intersection	167	3.5
10	Bicyclist Left Turn – Same Direction	160	3.4
Subtotal for top ten types for frequency		2,766	58.2

Source: NCDOT, 2018, p.14

Spatial Analysis

Spatial analysis is a useful way to examine the distribution of crashes over the geographic extent of a region. Crashes are aggregated in various ways in studies of this type, including:

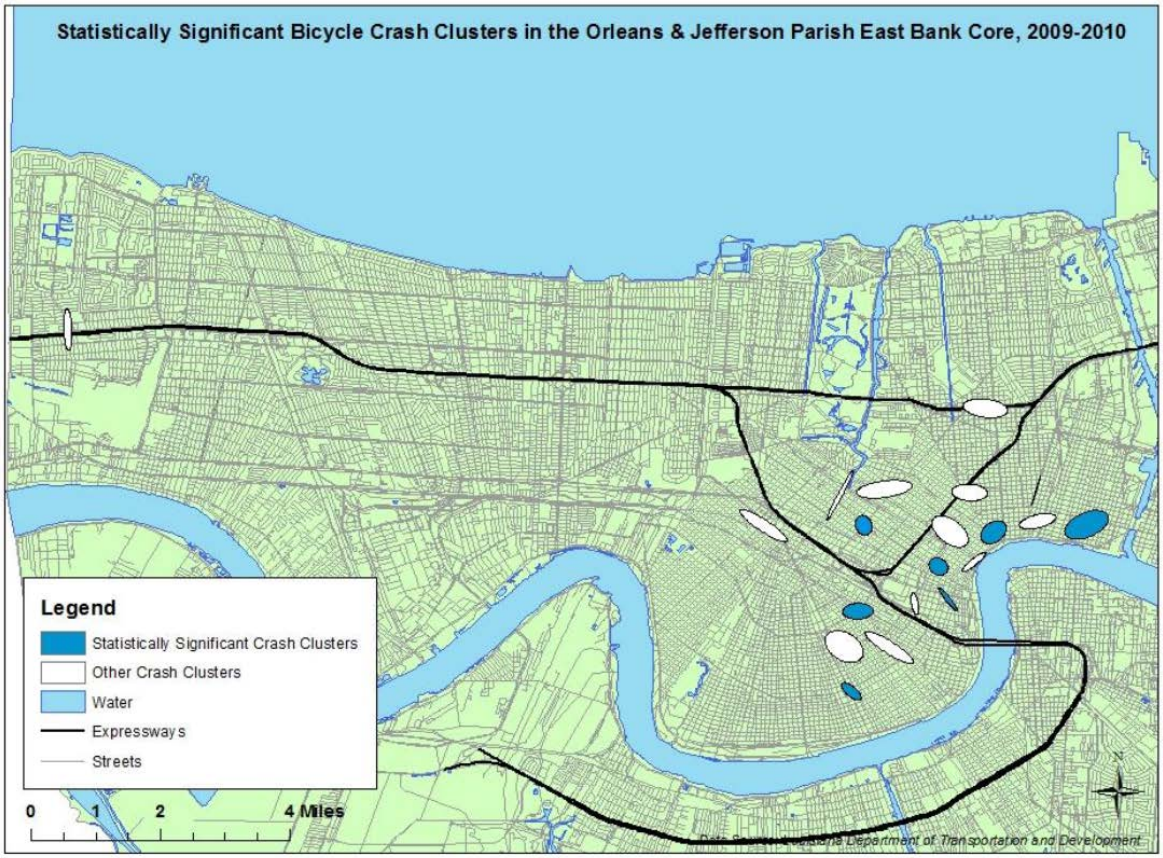
- Visual assessment of kernel density estimates ("heat maps")
- Spatial clustering of crashes
- Aggregation of crashes to the intersection or segment on which they occurred
- Aggregation of crashes along corridors using a "moving window"

The last of these techniques is typically the basis of developing "high-injury networks," which are often the basis for identifying priority locations for countermeasure implementation in Vision Zero communities.

DRCOG developed a high injury network map by calculating the number of crashes per mile for all road segments (DRCOG, 2012). The 11 high-crash corridors identified in the analysis represented 24 percent of all bicycle crashes. DRCOG also identified high crash intersections based on the total crashes and injury crashes.

A crash analysis completed for the New Orleans region included a crash cluster analysis of bicycle crashes (Tolford, 2012). Crash cluster analyses identify areas with a higher than average number of crashes**.** The analysis also identified statistically significant clusters of crashes which were used to provide guidance as to where crash-reduction resources should be targeted. Two parishes emerged as crash hotspots throughout the region and were selected for more in-depth analyses (Tolford, 2012). The analyses identified 10 high-crash corridors in both parishes and identified eight statistically significant clusters which will be further evaluated for appropriate safety interventions (see Figure 3).

Figure 3: Bicycle Crash Cluster Analysis: New Orleans Region.



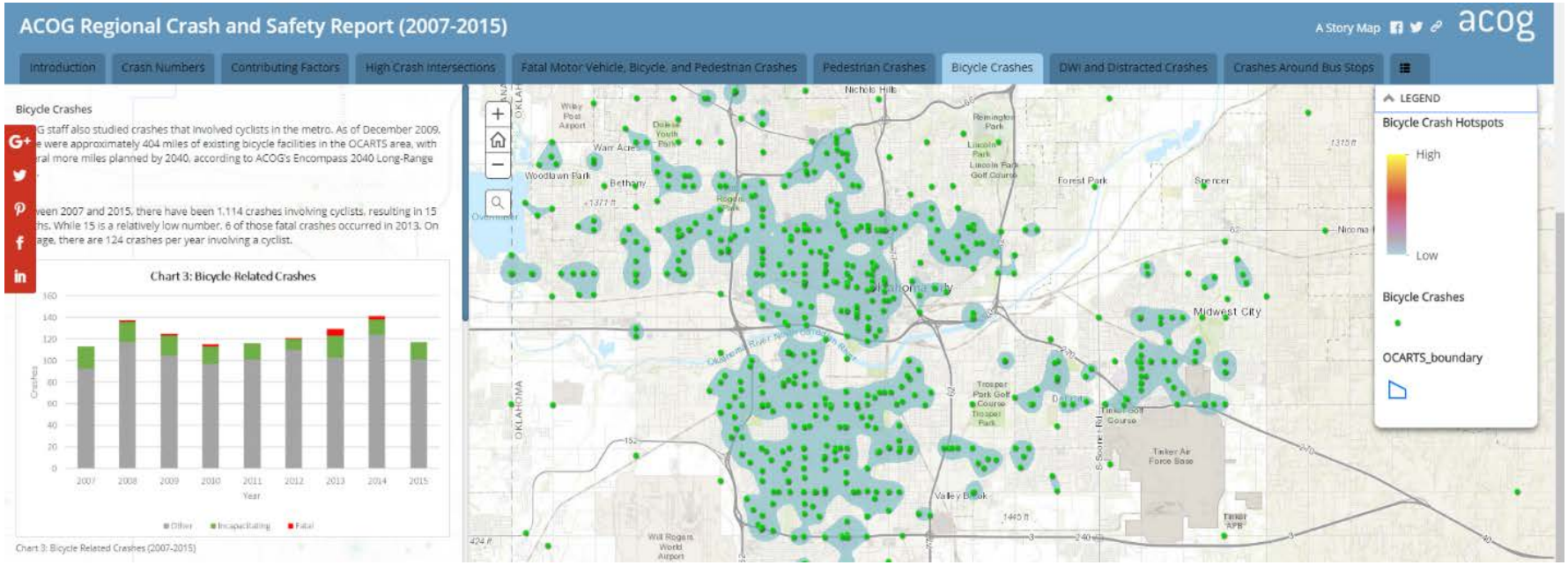
Source: Tolford, 2012, p.33

The Association of Central Oklahoma Governments' (ACOG) *Regional Crash and Safety Report* is based on an analysis of crashes that occurred between 2007 and 2015 on city streets across the region. The entire crash analysis report is presented online as a series of maps with accompanying tables (ACOG, 2017). The dataset included 1,114 bicycle crashes. Figure 4 shows a screenshot of one of the webpages.

While the crash data is presented in a more interactive format than a standard report, the level of detail for bicycle crashes is relatively scant. The information presented in data tables includes the total number of bicycle crashes and the severity level, and the number of bicycle crashes by year, top citation, location, time of day, and day of week (ACOG, 2017). The spatial analysis shows the total number of bicycle crashes, but at such a large scale, the only trend observed was that crashes tended to cluster near downtowns. A more detailed examination of the geographic distribution of crashes would be necessary to identify trends specific enough to help identify potential countermeasures. One interesting spatial statistic that ACOG calculated which no other agency in this review

completed was the number of bicyclist (and pedestrian) crashes that occurred within one-quarter-mile of a school (ACOG, 2017).

Figure 4: Screenshot of ACOG's Online Bicycle Crash Analysis



Source: *ACOG, 2017*

Systemic Safety Analysis

Systemic safety is an analysis approach that uses identified risk factors, or specific crash types, to proactively identify sites for safety improvements. A systemic safety approach influences both how crash data is analyzed and how locations are selected for countermeasure implementation. Thomas et al. (2018) defined a systemic approach as a "data-driven, network-wide (or system-level) approach to identifying and treating high risk roadway features correlated with specific or severe crash types. Systemic approaches seek not only to address locations with prior crash occurrence but also those locations with similar roadway or environmental crash risk characteristics." Systemic safety analysis is particularly well-suited to situations with low rates of exposure, and consequently low numbers of crashes at any given location, such as bicyclist crashes and crashes on rural roads.

Thomas et al. (2018) divide a systemic safety approach into the seven steps listed below. The first three steps relate to the process of collecting and analyzing data, whereas the remaining steps relate to the process of screening the roadway network and selecting countermeasures.

1. *Step 1 involves defining the area for analysis, identifying the facility or location type target or focus, and identifying subsets of target crash type(s) for systemic focus. This step sets the stage for all subsequent steps.*

2. *Step 2 involves compiling the roadway and other location characteristics and crash data that will be needed to identify risk factors in Step 3. All systemic processes require data, and the compiled data will serve as an important foundational database to identify potential treatment sites in Step 4.*

3. *Step 3 involves analyzing data to determine factors associated with the target pedestrian crash type or location of interest or using alternate approaches from research or local knowledge to identify key risk factors. Risk factors can be identified based on analysis of the existing dataset or by relying on existing research. Practitioners should be able to identify the strength and direction of each identified risk factor.*

4. *Step 4 involves identifying an optimal set of sites that have common risk and site characteristics that are suitable for similar packages of treatments, using various screening and ranking methods.*

5. *Step 5 involves identifying appropriate countermeasures or combinations of measures that could potentially address risks identified. In Step 5, there is also a chance to further refine and prioritize the locations identified in Step 4.*
6. *Step 6 involves considering additional priorities, performing diagnostics, performing economic assessments, allocating funding, and implementing a systemic treatment plan, including construction of pedestrian safety improvements.*
7. *Step 7 involves evaluating project and program impacts before starting the process anew.*

The Atlanta Regional Commission's (ARC) recent *Safe Streets for Walking and Bicycling: A regional action plan for reducing traffic fatalities in metropolitan Atlanta*, serves as an example of a systemic safety approach applied at the regional scale. ARC's plan suggests that systemic safety approaches are useful because they proactively tackle the fundamental causes of crashes that exist in a given roadway system and prevent dangerous roadway designs from being repeated (ARC, 2018).

ARC's analysis included a dataset of 15,500 bicyclist and pedestrian crashes and 10 years of data. As part of the methodology, the authors conducted an analysis of crash frequencies by temporal condition, contributing factors, roadway and environmental factors, and crash types (ARC, 2018). The frequency analysis compared trends among total bicyclist and pedestrian crashes to those of fatal and severe injury bicyclist and pedestrian crashes to identify major risk factors associated with fatal and serious crashes involving pedestrians and bicyclists. The number of crashes, along with weighted crash risk scores, were used to identify the final risk factors. The analysis yielded four major risk factors: speed, number of lanes, lighting, and crosswalks (ARC, 2018). Based on these risk factors, ARC developed a toolbox of countermeasures which can be installed to improve bicyclist safety. The countermeasures were selected based on existing research that documents the relationship between the countermeasure, risk factor, and increased safety for pedestrians and/or bicyclists.

ARC's approach is recommended as a best practice approach to the extent that time and budget allow. Following a systemic safety approach will help MAG to lead a more proactive approach to bicycle safety in the region, use resources more effectively, ensure that all decisions are data-driven, and make more informed decisions about bicycle safety and bicycle planning in the future. For additional information about how systemic safety analysis can be used for network screening and to identify countermeasures, see **Identifying Systemic Safety Issues** discussion below.

2.1.2 Methods to Account for Crash Severity

Because there can be different trends associated with different types of crashes, it is useful to conduct an analysis of all crashes and to examine trends among different injury severity levels. Typically, crash datasets make it possible to identify the number of injuries associated with a crash as well as the severity of the injuries incurred. Some communities choose to analyze trends among severe injuries and fatalities (referred to as KSI for "killed and serious injury") and compare those to trends among crashes of all injury severity levels (including no injury). If the share of a certain type of crashes resulting in fatalities or serious injuries is disproportionately high, it may be indicative of a particularly urgent safety issue.

Regional planning bodies choose to integrate crash severity into their analyses in different ways. Some communities calculate crash frequencies for crashes of all severity levels, treating crashes of different severity levels as if they were all the same type of crash. In the New Orleans regional bike crash analysis, aside from one or two analyses showing crashes by injury severity level, the frequency analyses were conducted only for total crashes, not injury or fatal crashes (Tolford, 2012). DRCOG's crash analysis examined total, fatal, and injury crashes. However, most of the frequency analyses focused on total crashes; the frequency of fatal crashes was not calculated for all crash attributes and there was limited emphasis on severe crashes (DRCOG, 2012). Another approach is to combine fatal and serious injury (or incapacitating injury) crashes and compare trends among fatal and serious injury crashes to those of total crashes (crashes of all injury levels). This approach is useful because fatal bicyclist crashes are typically very rare, which means there often are not enough fatal crashes in a database to identify trends. By combining fatal and serious injury crashes, an agency is increasing its sample size and is more likely to be able to identify trends.

Another method which some communities use to account for crash severity is Equivalent Property Damage Only (EPDO) weighting. This process involves establishing weighting factors for fatal, injury, and property damage only crashes and using these weights to develop a score for each crash. The weighting factors are calculated based on the societal costs of crashes of different severity levels relative to the cost of a property damage only crash (see Table 1 and Table 2). The weighting factors are then applied to each crash based on the most severe injury sustained. Note that some jurisdictions, including the California Department of Transportation, combine fatal and severe injury crash costs for a total cost of $1,833,179 (CalTrans, 2016).

> Equivalent Property Damage Only Score =
> *(Fatal Weighting Factor x Fatal Crashes) + (Injury Weighting Factor x Injury Crashes) + (PDO Weighting Factor x PDO Crashes)*

Sites with the highest total scores can then be selected for further investigation. EPDO weighting can also be used to identify the most impactful types of crashes by summing the associated weights. One drawback to this approach for network screening is that it may overemphasize locations with a small number of severe crashes (Herbel et al., 2010). This is especially a concern for bicyclist crashes, which are relatively rare at any given location. For more information about this approach, refer to the *Highway Safety Improvement Program Manual* (FHWA, 2010).

Table 1: Equivalent Property Damage Only (EPDO) Weighting Factors

Weighting Factor	Calculation
Fatality	$\frac{\text{Average fatal crash cost}}{\text{Average PDO crash cost}}$
Injury	$\frac{\text{Average injury crash cost}}{\text{Average PDO crash cost}}$
Property Damage Only (PDO)	1

Source: Highway Safety Improvement Program Manual

Table 2: Cost of Motor Vehicle Crashes by Injury Severity

Injury Severity	Cost*
Fatal	$5,674,894
Severe Injury	$305,764
Evident Injury	$111,830
Possible Injury	$63,559
Property Damage Only	$10,475

*Crash Costs presented in 2018 dollars.
Source: *Highway Safety Manual (FHWA, 2010)*

Depending on the number of fatal and serious injury crashes in MAG's dataset, it may be appropriate to combine crashes of these two injury levels when conducting analyses. If identifying countermeasures specifically to reduce fatal crashes is a priority for MAG, we recommend examining crash trends for fatal and severe injury crashes as well as total crashes to ensure that all important trends can be identified, especially those impacting the most serious crashes.

2.2 Countermeasure Selection Methodology Review

This section explores methods and tools for selecting countermeasures to improve bicyclist safety. It begins with a discussion of the two primary network screening approaches and ends with a review of national tools which MAG or its member agencies can use during its countermeasure selection process.

2.2.1 Network Screening

Network screening is used to identify either specific crash types to address with system-wide improvements or to identify specific sites in need of safety improvements (Herbel et al., 2010). These two approaches can be understood as the identification of sites in need of safety improvements versus the identification of systemic safety issues to address throughout a roadway network.

Identifying Sites for Safety Improvements

Identifying sites for safety improvements using primarily crash frequencies is the traditional approach to network screening. Typically, communities use the number of crashes or the number of crashes of a certain severity level (e.g., fatal or serious injury) to screen a roadway network and identify locations to prioritize for safety improvements. Once locations are identified, communities develop a custom set of countermeasures to implement at each location, typically following field review of the location to better understand existing conditions and behaviors.

Communities that follow this approach may develop a high injury network or use a hotspot analysis to identify locations where the highest number of crashes occurred. The areas with the highest number of crashes are then prioritized for safety improvements. Tolford's (2012) analysis of New Orleans regional bike crash data summarized in the **Spatial Analysis** discussion above serves as an example of a community following this approach. Tolford (2012) identified locations for safety improvements based on the number of bike crashes alone. The Oregon Department of Transportation (ODOT) used this approach as one component of its network screening process (ODOT, 2014). However, ODOT used both the number of bike crashes and the severity of bike crashes in its network screening process.

Identifying Systemic Safety Issues

As discussed above, systemic safety is a methodology used to assess crash data in a way that highlights system-wide risk factors. The risk factors are then used to select locations for countermeasure implementation. The approach focuses on identifying typically lower-cost countermeasures that can be implemented at many locations to reduce the probability that future crashes will occur. This approach is different from traditional, more reactive, approaches that identify sites for safety improvements based on the number of crashes that have historically occurred.

ODOT's 2014 *Pedestrian and Bicycle Safety Implementation Plan* summarizes the department's systemic approach to identifying sites for safety improvements. As part of this effort, a risk-based scoring method was developed to identify locations for bicycle and pedestrian safety improvements (ODOT, 2014). The method was developed to weight different risk factors and integrate data other than the number of crashes into the safety analysis process (see Figure 5). PMT Relative Weight refers to the weight assigned to each risk factor based on the project management team's (PMT's) opinion of the relative importance of each risk factor, the probability that the risk factor will lead to a crash, and the degree to which each risk factor meets or exceeds specific criteria set out by the PMT. The risk factor criteria are described in the column Risk Factor Scores. ODOT combined the traditional approach of using crash frequency and severity (see bottom three rows in Figure 5) with a systemic approach that integrated several other risk factors identified

during the crash analysis. ODOT's approach helped to identify specific, high-risk locations, and can be especially useful in larger networks such as those at the state or regional scale. The analysis was conducted using a spatial analysis model developed with ArcGIS 10.1 Model Builder (ODOT, 2014).

Figure 5: ODOT's Bicycle Risk Factor Scoring Criteria

Risk Factor	PMT Relative Weight	Risk Factor Scores
Proximity to Signal	1	• 1 point awarded if at least 1 signal is located on the segment or within 100' of the segment
Undivided, 4-lane Segment Characteristic	1	• 1 point awarded if the segment is an undivided 4-lane segment
Proximity to Transit Stop	1	• 1 point awarded for segments with 1 transit stop located on the segment or within 100' of the segment; • 2 points awarded for 2 or more transit stops
Lack of Bicycle Facility (Left side of road)	2	• 2 points awarded for the lack of a bicycle facility on the left side of the road
Lack of Bicycle Facility (Right side of road)	2	• 2 points awarded for the lack of a bicycle facility on the right side of the road
AADT	3	• 2 points awarded for AADT between 12,000 and 18,000; • 4 points awarded for AADT above 18,000
Posted Speed Limit	3	• 2 points awarded for a posted speed limit of 35 or 40 mph; • 4 points awarded for posted speed limits above 40 mph
Number of Driveways	4	• 2 points awarded for segments with 1 driveway; • 3 points for segments with 2 to 3 driveways; • 4 points for segments with 4 to 8 driveways; • 5 points for segments with more than 8 driveways
Number of Non-Severe Injuries and Bicyclists Involved but Not Injured	5	• 2 points for first occurrence • 1 additional point for each subsequent
Number of Severe Injuries Resulting from Bicyclist-Involved Crashes	6	• 4 points awarded if a severe injury was reported; • 2 additional points awarded for each additional severe injury
Number of Fatalities Resulting from Bicyclist Involved Crashes	6	• 4 points awarded if a fatality was reported

Source: ODOT, 2014, p. 71

ODOT used federal and academic resources, including the Crash Modification Factor (CMF) Clearinghouse and FHWA's *Guidance Memorandum on Promoting the Implementation of Proven Safety Countermeasures,* to develop a countermeasure toolbox which ODOT and local agency staff can use to implement countermeasures at locations identified by the risk-based scoring tool. The countermeasures were evaluated to identify documented effectiveness, ease of implementation, and relative construction costs (ODOT, 2014). A list of priority countermeasures was identified and a countermeasure toolbox was developed to assist in selecting the appropriate set of countermeasures for

each project corridor. Figure 6 presents a snapshot of ODOT's bicycle crash countermeasure toolbox.

Figure 6: ODOT's Bicycle Crash Countermeasure Toolbox

Crash Countermeasures by Area Type and Traffic Control	Relative Construction Cost	Relative Ease of Implementation	Countermeasure Effectiveness*	Relative Reliability of CMF
All Locations				
Signalized				
Bike detection	1	1	Accounts for human factors	N/A
Lighting	2	2	0.58	1
Pavement markings	1	1	Accounts for human factors	N/A
Right-turn channelization island	2	2	Reduces conflict points	N/A
Signal Timing - Leading pedestrian interval	1	1	0.59	2
Signal Timing - Modify left-turn phasing	1	1	Reduces conflict points	N/A
Vehicle turning movement restrictions	1	2	Reduces conflict points	N/A
Unsignalized				
Enhanced crossing treatment	1	2	0.58	2
Lighting	2	2	0.58	1
Reduce curb radii	2	2	Reduces speed	N/A
Skip Striping	1	1	Accounts for human factors	N/A
Supplemental signs and markings	1	1	Accounts for human factors	N/A
No Traffic Control				
Access control	3	3	0.75	1
Bicycle route signage	1	1	Accounts for human factors	N/A
Longitudinal bike stencil	1	1	Accounts for human factors	N/A

* When evaluating countermeasure effectiveness for a given countermeasure, ODOT refers to engineering judgment when a CMF is not available.

Source: Pedestrian and Bicycle Safety Implementation Plan, p. 82

While ODOT's process is somewhat complex and relies on knowledge of ArcGIS's Model Builder tool, the crash data used for the analysis is data MAG has access to and MAG may be able to access the appropriate roadway network data. This approach integrates crash and other roadway information into the countermeasure selection process and can be useful in locations with low numbers of bicycle crashes. This approach also presents a clear way to integrate *multiple* values into a countermeasure selection decision, including construction cost, ease of implementation, and countermeasure effectiveness. This approach highly prioritizes safety and follows a systemic safety approach by presenting a means for selecting locations for countermeasures based on risk factors, not only crash history. ODOT's approach could be replicated for MAG but a more simplified version may be more appropriate so that MAG staff can continue to revise and implement the methodology regardless of access to GIS tools like Model Builder.

2.2.2 Countermeasure Selection Resources

Three resources are designed to help communities select countermeasures to improve bicyclist safety:

- Crash Modification Factors,
- Speed and volume thresholds, and
- Systemic Safety Project Selection Tool.

Crash Modification Factors

Crash Modification Factors (CMFs) are multiplicative factors used to estimate the expected number of crashes after implementing a given countermeasure at a specific location. The lower the value of the CMF, the greater the expected reduction in crashes. Crash Reduction Factors (CRFs) are directly related to CMFs (CRF = 1 – CMF), but they measure the percentage of crashes a countermeasure is expected to reduce. For CRFs, the higher the value, the greater the expected reduction in crashes (CalTrans, 2016). CMFs (and CRFs) can be used to identify the most effective countermeasures for reducing specific types of crashes.

CMFs are typically derived from academic and state DOT studies on countermeasures. The Federal Highway Administration's (FHWA's) CMF Clearinghouse is a free, online database that provides CMFs for many countermeasures, bicycle-related and otherwise. The database was created in 2009 but it is frequently updated. A benefit of using the CMF Clearinghouse is that the site provides information about the study used to derive the CMF, including an overall quality rating. This information can help assess whether a given countermeasure's CMF is applicable to the location where an agency is considering implementing the countermeasure. In addition, this information can help an agency consider the impacts that a countermeasure may have on other road users. The CMF Clearinghouse makes it easy to identify whether the countermeasure is expected to reduce crashes for motorists as well as pedestrians/bicyclists, if data is available.

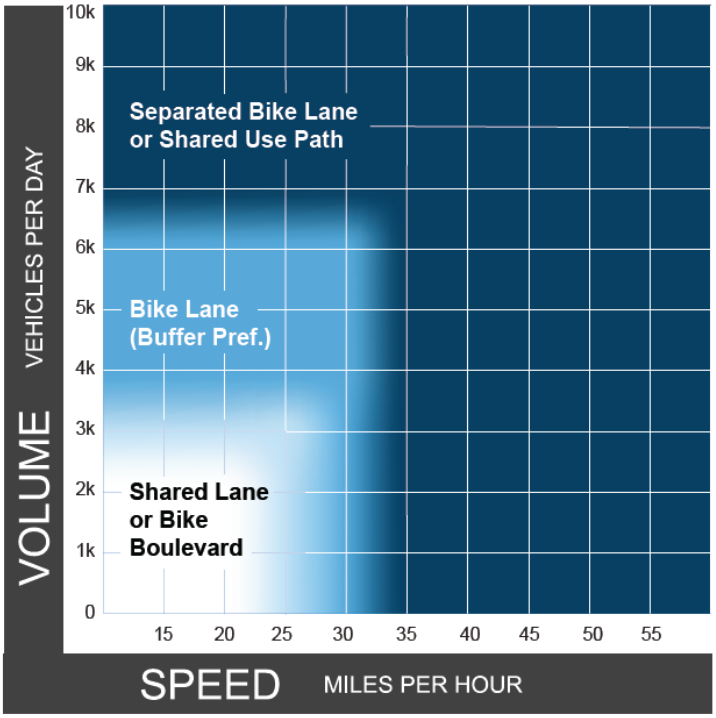
Currently, very few CMFs are available specifically for bicycle countermeasures or for the impacts of general roadway countermeasures on bicyclists. However, this is changing as bicycle safety becomes more researched. In addition, many communities consider CMFs for pedestrian safety when assessing bicycle countermeasures because in many cases, pedestrians and bicyclists face similar safety threats. To date, CMFs have been developed to estimate the effect on safety of installing bicycle boulevards, bike lanes, cycle tracks or separated bike lanes, bike lanes at signalized intersections, raised bicycle crossings, colored bike lanes at signalized intersections, and a few other categories.

Speed and Volume Thresholds

Communities that follow best practices for bikeway selection integrate roadway speed and motor vehicle volume data into their decisions about which types of bikeway to install in different locations. Several communities have adopted speed and volume charts to make it easy for agency planners and engineers to consider which bikeway is most appropriate in a given situation. FHWA's recently released *Bikeway Selection Guide* (2019) presents the speed and volume chart shown in Figure 7. MAG will be incorporating this chart as part of its Active Transportation Plan Toolbox. The facility guidance presented in the chart is based on an extensive literature review of speed and volume charts from around the world and studies of the safety (actual and perceived) of different bikeway

treatments in different contexts. The chart is designed to promote the implementation of bicycle facilities that are suitable for people of all ages and abilities and prioritizes the safety and comfort of bicyclists.

Figure 7: FHWA's Preferred Bikeway Selection Guidance



Notes

1 Chart assumes operating speeds are similar to posted speeds. If they differ, use operating speed rather than posted speed.

2 Advisory bike lanes may be an option where traffic volume is <3K ADT.

Source: FHWA, 2019, p. 23

FHWA's Systemic Safety Project Selection Tool

FHWA's *Systemic Safety Project Selection Tool* (2013) provides a step-by-step process for integrating systemic safety principles into safety planning processes. It includes considerations for determining whether to implement spot or systemic safety improvements and presents mechanisms for evaluating the safety benefits of treatments implemented using a systemic approach. Figure 8 shows the steps involved in the project selection tool. As noted in the figure, the tool includes a discussion of countermeasure selection. The process of selecting countermeasures includes three tasks:

1. Assemble a comprehensive list of countermeasures,
2. Evaluate/screen countermeasures, and
3. Select countermeasures for deployment.

Figure 8: Implementation Framework for the Systemic Safety Project Selection

Source: FHWA, 2013, p.1

The data needed to complete this phase of the process includes documentation of proven, effective, and tried countermeasures (e.g., those identified in the CMF Clearinghouse), effectiveness measures (e.g., CMFs), implementation costs for each countermeasure, and a review of countermeasure installation feasibility based on local and state policies and practices. Each of the aforementioned items should be used to evaluate and select appropriate countermeasures. It will also be important for MAG and its member agencies to consider the feasibility of installing countermeasures based on anticipated maintenance needs and political feasibility. As described in the tool, meetings, workshops, or other outreach efforts could be conducted to encourage a variety of stakeholders to participate in the countermeasure selection process. For example, MAG may wish to engage agency staff from engineering, enforcement, first responders, and public health departments in discussions about which countermeasures are most suitable for the region, understanding that this may vary from jurisdiction to jurisdiction.

2.3 Summary

This literature review summarized methodologies that state and regional agencies are using for bicycle safety studies, both to conduct analyses and select countermeasures. Every agency follows its own unique approach, including frequency analyses, crash typologies, spatial analyses and systemic analyses. Agencies like the Atlanta Regional Council, who are striving to address root factors associated with bicycle safety, are

choosing to follow a systemic safety approach. Safety study approaches that target root issues like roadway characteristics, common crash types, and high-injury networks are well-positioned to develop effective, data-driven processes for selecting and implementing countermeasures. Moving forward, we recommend that MAG and its member agencies follow a systemic safety approach to the best extent possible.

3.0 CRASH REPORT REVIEW

The analysis included a detailed review of MAG Region crash reports for bicycle crashes that occurred during the three-year period of 2015 through 2017. However, the study excludes crashes that occurred at the intersection of two arterial streets. The rational for excluding intersections was based on; 1) MAG and its member agencies analyze intersection crashes for all modes on a regular basis, 2) the existing gap of information on crashes occurring on arterial segments.

MAG provided a total of 874 crash reports for review, but 44 of the reports were excluded from the analysis, for the following reasons:

- 35 crash reports were excluded because the crashes described were located at arterial-arterial intersections.
- Three crash reports recounted incidents not involving a crash.
- Two crash reports were for crashes not involving a bicyclist.
- Two crash reports were for crashes occurring on private property.
- One reported crash involved a wheelchair improperly coded as a bicycle.
- One reported crash involved a bicycle that was struck while parked with no rider.

After removing these 44 crash reports, a total of 830 valid crashes were used for analysis, averaging about 277 crashes per year.

Tabular data from the Arizona Department of Transportation's (ADOT's) Safety DataMart was used to supplement the review of the crash reports. The use of ADOT data allowed the study to take advantage of ADOT's tabular coding of the data fields in each crash, helping to reduce errors caused by coding hard-copy data from the crash reports. However, during the crash report review, the study team did find several errors in the ADOT data coding, which were corrected to create a final complete database of information about each crash. Table 3 depicts the specific elements included in the study's crash database and identifies the source of each data element.

The study also included a review of the site characteristics of each crash, such as the number of lanes on the roadway, presence or absence of bike lanes and sidewalks, and other features. These elements were determined using aerial imagery from Google Earth and other sources. In general, aerial imagery was used as near as possible to the time of the particular crash to determine the roadway and site characteristics at that time.

Many elements desired for the study, such as crash type and fault, could not be determined from the crash report or the ADOT tabular data. Rather, these elements were determined by project team members after reviewing the circumstances of each crash from the officer's narrative, the site characteristics and traffic control, and information

from the ADOT tabular data. Project team members were carefully trained to ensure that judgments about crash type, fault, and other factors were consistent for all crashes reviewed.

Table 3: Crash Database Elements

General Information					
Incident ID	Incident Date	Incident Time	Total Units	Total Non Motorists	Total Injuries
Total Fatalities	Injury Severity	Hit and Run Flag			
Location Information					
Latitude	Longitude	City/Town	On Road	Crossing Figure	Direction from Crossing
Traffic Control					
Motor Vehicle Roadway Information					
Functional Classification	Number of Through Lanes	Roadway Configuration	Posted Speed Limit (mph)		
Bicyclist Roadway Information					
Functional Classification	Number of Through Lanes	Roadway Configuration	Posted Speed Limit (mph)	Bike Facility Present	Width
Facility Curb Lane > 16'?	Sidewalk Width	Paved Striped Shoulder			
Bicyclist Information					
Age	Gender	Alcohol Use	Drug Use	Influencing Condition	Injury Severity
Safety Device	Location	Direction of Travel	Maneuver	Violations	Citations
Driver Information					
Age	Gender	Alcohol Use	Drug Use	Influencing Condition	Injury Severity
Direction of Travel	Maneuver	Violations	Citations		
Weather Conditions					
Weather Conditions	Surface Conditions	Light Conditions	Site Change Since Crash?		
Crash Typing					
Fault	Crash Location	Crash Type			

	Data from ADOT Safety Data Mart
	Project Team Determination

3.1 General Crash Characteristics

Figure 9 shows the number of crashes that occurred each year from 2015 to 2017. In addition to the number of crashes per year, Figure 9 also shows injury severities. The six levels of injury severity, as defined by Arizona's Crash Report form, are:

- 1 - no injury
- 2 - possible injury
- 3 - non-incapacitating injury
- 4 - incapacitating injury
- 5 -fatal injury
- 99 - unknown injury

More crashes, just over 300, occurred in 2016 than in either of the other two years. Crashes dropped about 14 percent in 2017 when compared to 2016, but the volatility in the yearly crash data suggests that the drop may not be a significant change that could be expected to continue into the future. More fatal crashes also occurred in 2016 compared to 2015 and 2017.

Figure 9: Number of Bicyclist Crashes by Year and Injury Severity

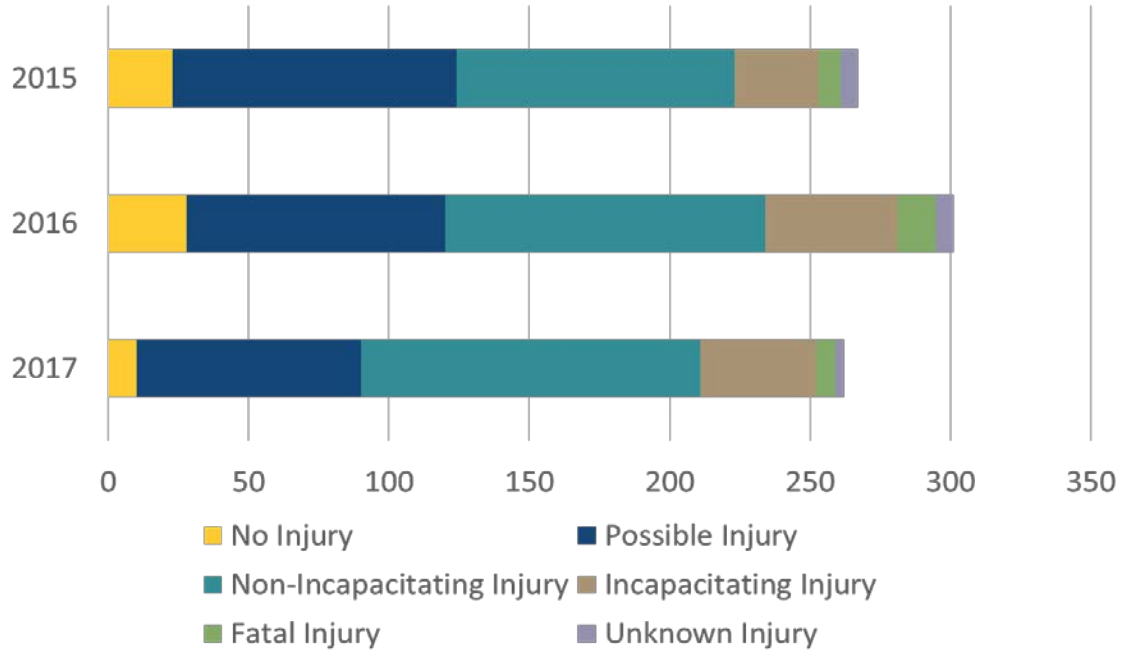


Figure 10 shows the number of units involved in each crash. A unit is usually either a bicyclist or a motor vehicle. The vast majority (98 percent) of the crashes involved only two units—one bicycle and one motor vehicle—laying the foundation for the subsequent crash analysis focusing on the single cyclist and the single motorist involved in each crash. Only two percent of the crashes analyzed involved three units, and less than one percent involved four units.

Figure 10: Number of Units Involved in Bicyclist Crashes

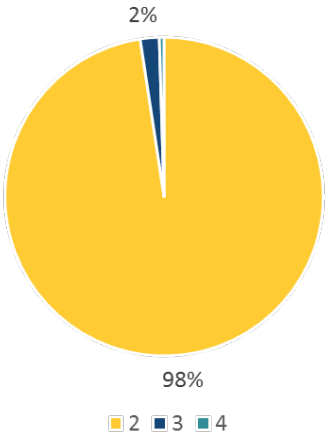


Figure 11 shows the number of crashes by month. April is the month with the highest number of crashes, with just over 90. This makes sense in the MAG region because the weather is warm but has not reached its summer extreme levels yet. As expected, the number of crashes dropped during the summer months (June and July) but there was an unexpected jump in August. August had the third highest number of crashes, just behind March. A potential cause for the jump in August could be the start of the school year during that month. The fact that December is the second-lowest month for crashes is also unexpected. A potential cause for the decline in December may be less bicycling due to work and school holidays.

Figure 11: Bicyclist Crashes by Month

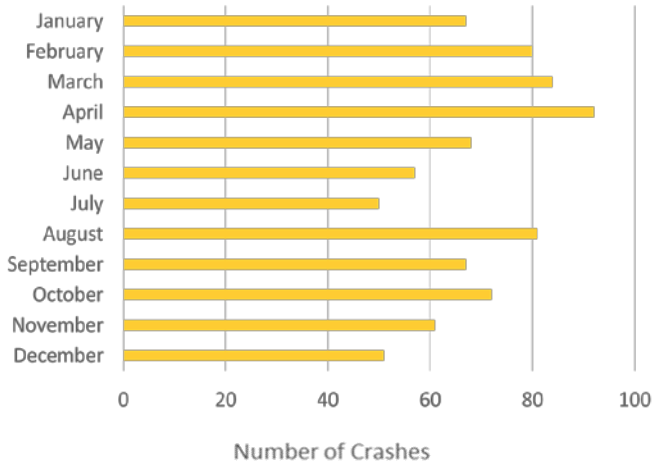


Figure 12 shows the number of crashes that occurred on each day of the week. Thursday experienced the most crashes; Sunday had the fewest crashes. Every weekday had a higher number of crashes than either Saturday or Sunday.

Figure 12: Bicyclist Crashes by Day

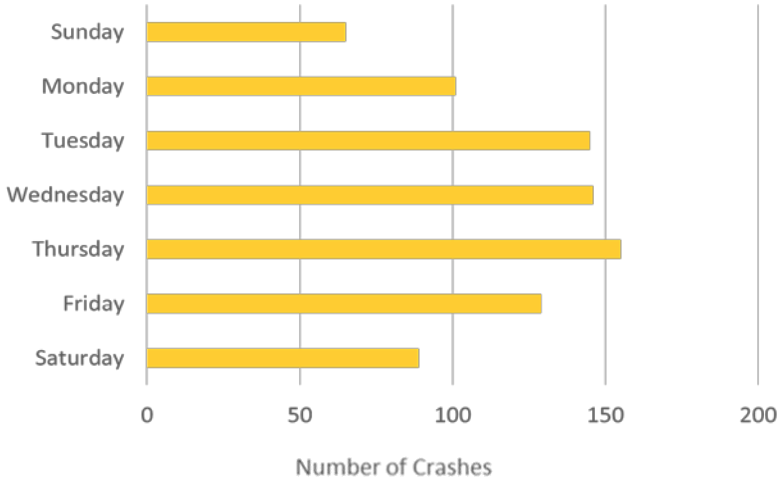


Figure 13 shows bicyclist crashes by time of day, in one-hour intervals. Bicyclist crashes occurred most commonly during the hour from 4:00 to 5:00 p.m., when about 11 percent of crashes occurred. Both hours between 4:00 and 6:00 p.m. accounted for more crashes than any other hour of day; about 20 percent of crashes occurred during one of these two hours. No similar spike exists during the morning peak traffic period; rather, the remaining daylight hours all had somewhat similar crash experience.

Figure 13: Bicyclist Crashes by Time of Day

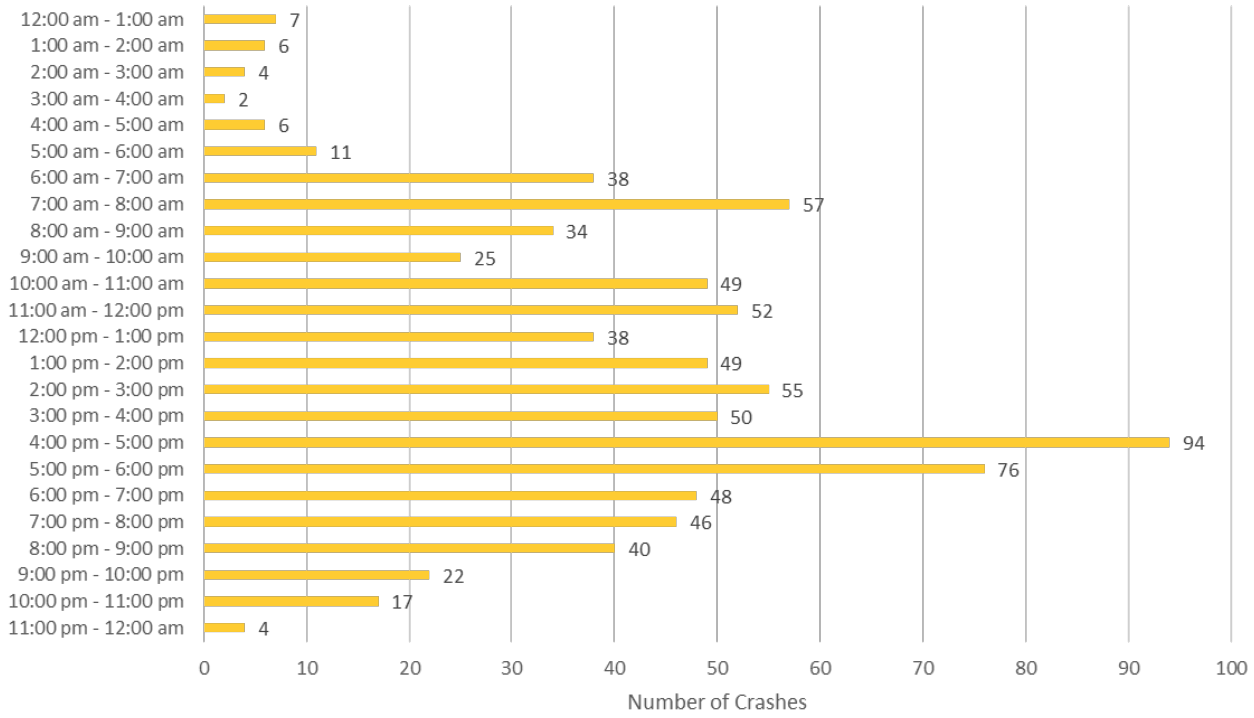


Figure 14 shows the lighting conditions when the crashes occurred. The majority of crashes (74 percent) occurred during daylight hours. The data controverts the perception that most crashes happen when cyclists are riding in the dark without lights. Only 18 percent of crashes happened in the dark when lighting (such as a streetlight) was available. This is higher than the number of crashes in the dark when there was no lighting available, which accounted for only 4 percent of crashes.

Figure 14: Bicyclist Crashes by Lighting Conditions

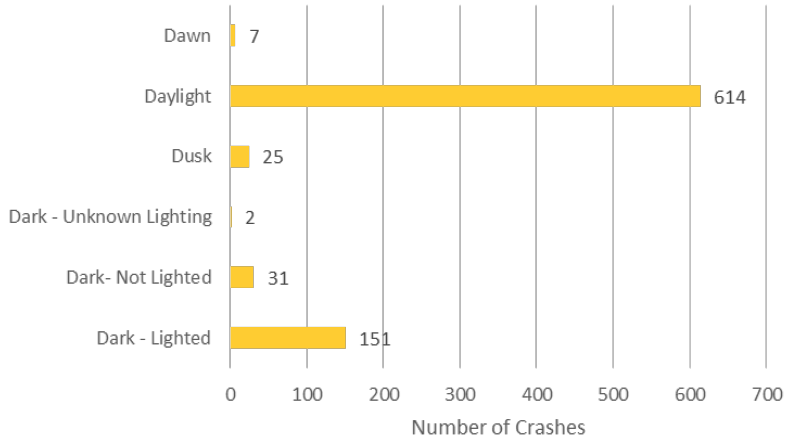
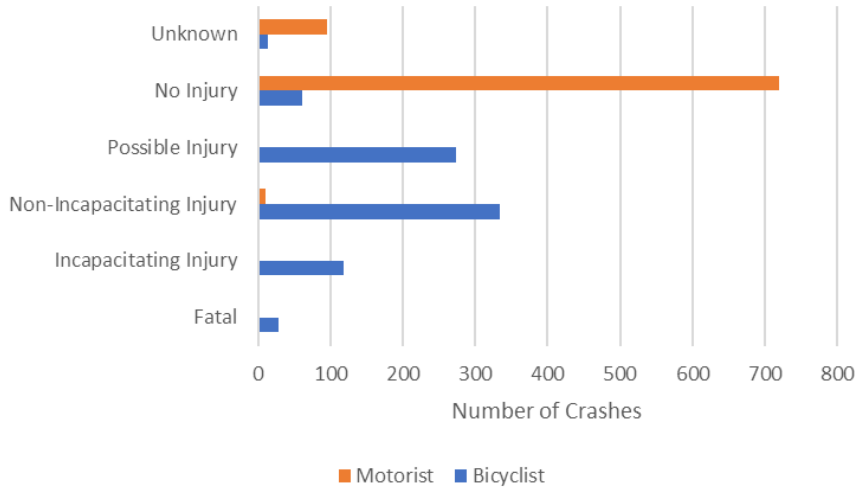


Figure 15 provides the injury severity of both bicyclists and motorists involved in the crashes. Cyclists were injured in about 93 percent of crashes where the injury severity is known. The most common cyclist injury severity level was a non-incapacitating injury (40 percent). A bicyclist was fatally injured in 29 of the crashes (9.7 fatal crashes per year). Motorists avoided injury in 98 percent of the crashes where the motorist's injury severity was known.

Figure 15: Injury Severity

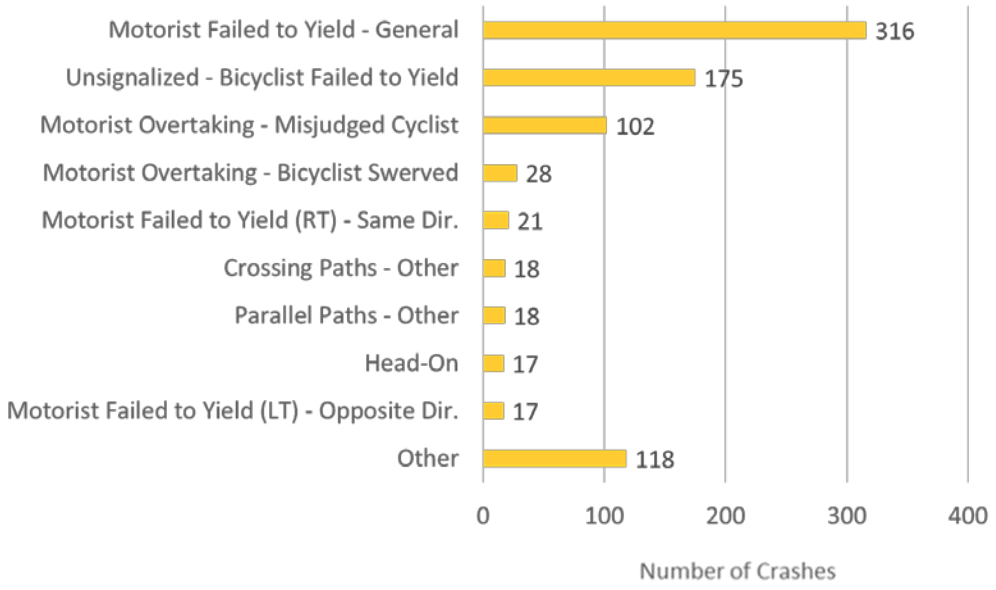


3.2 Crash Type

The study evaluated each crash against a list of crash types (shown in Table 4) that was created expressly for the MAG project based on information from prior studies of bicycle crashes and national literature, including the Pedestrian and Bicycle Crash Analysis Tool (PBCAT)[2].

Figure 16 illustrates which crash types were most common throughout the three-year period. The most common crash type was when a motorist failed to yield when entering the street from a driveway or side street, and when the bicyclist was riding on the sidewalk (or in the street) and was most often approaching from the driver's right. This occurred 316 times, or 38 percent of crashes. The second most common crash type was when a bicyclist failed to yield at an unsignalized location. This crash type occurred 175 times, or 21 percent of crashes. The third most common crash type was when a motorist was overtaking a bicyclist from behind and misjudged the space between the vehicle and the bicycle. This occurred 102 times, or around 12 percent of crashes. The top three crash types combined accounted for 72 percent of the bicyclist crashes. Illustrations of these three crash types are shown below.

Figure 16: Crash Type Frequency for Bicyclist Collisions



[2] See also: FHWA Pub. No. FHWA-HRT-06-090, June 2006.

Table 4: Crash Typing Structure for Bicyclist Collisions

MOTORIST FAILED TO YIELD - PARALLEL PATHS

Motorist Failed to Yield (Left-Turn) - Same Direction
Motorist Failed to Yield (Left-Turn) - Opposite Direction
Motorist Failed to Yield (Left-Turn) - Direction of Cyclist Unknown
Motorist Failed to Yield (Right-Turn) - Same Direction ("right hook")
Motorist Failed to Yield (Right-Turn) - Opposite Direction
Motorist Failed to Yield (Right-Turn) - Direction of Cyclist Unknown
Motorist Failed to Yield (Merge)
Other Motorist Failed to Yield - Signalized - Red Light Running
Other Motorist Failed to Yield - Unsignalized

MOTORIST FAILED TO YIELD - PERPENDICULAR PATH

Motorist Failed to Yield - Red Light Running
Motorist Failed to Yield - Right Turn on Red
Motorist Failed to Yield - Unsignalized - General
Motorist Failed to Yield - Unsignalized - Multiple Threat

BICYCLIST FAILED TO YIELD

Signalized Intersection (Red) - Bicyclist Ride Out (Stopped then Violated Signal)
Signalized Intersection (Red) - Bicyclist Ride Through (Violated Signal without Stopping)
Signalized Intersection - Bicyclist Failed to Clear
Signalized Intersection (Green) - Left-Turn Bicyclist Failed to Yield to Oncoming Traffic
Unsignalized - Bicyclist Failed to Yield

OVERTAKING

Motorist Overtaking - Undetected Bicyclist/Misjudged Space
Motorist Overtaking - Bicyclist Swerved
Bicyclist Overtaking - Extended Door (Dooring)
Bicyclist Overtaking - Other

LOSS OF CONTROL / TURNING ERROR

Motorist Lost Control/Turned into Opposing Lanes
Bicyclist Lost Control/Turned into Opposing Lanes

OTHER CRASH TYPES

Head-On
Parking/Bus Related
Backing Vehicle
Parallel Paths - Other/Unknown
Crossing Paths - Other/Unknown

Motorist Intentionally Caused Bicyclist Intentionally Caused Unusual Circumstances Non-Roadway Unknown Location Insufficient Information

Figure 17 shows the most common example of a general motorist failure to yield that was identified in this study. The specific instance depicted in the figure occurred 190 times, meaning that nearly 23 percent of the bicyclist crashes transpired this way. The figure depicts a motor vehicle exiting a driveway and a contraflow bicyclist on the sidewalk approaching from the motorist's right. The motorist fails to yield to the bicyclist, who is traveling against traffic on the sidewalk. (Note that cyclists may ride this way legally per Arizona state law, although the City of Tempe prohibits it and the City of Scottsdale requires cyclists on the sidewalk to yield to motorists on driveways.) Several other crash configurations involved a motorist's failure to yield, but this is the most common configuration.

Figure 17: Typical Bicyclist Crash Involving Motorist Failure to Yield

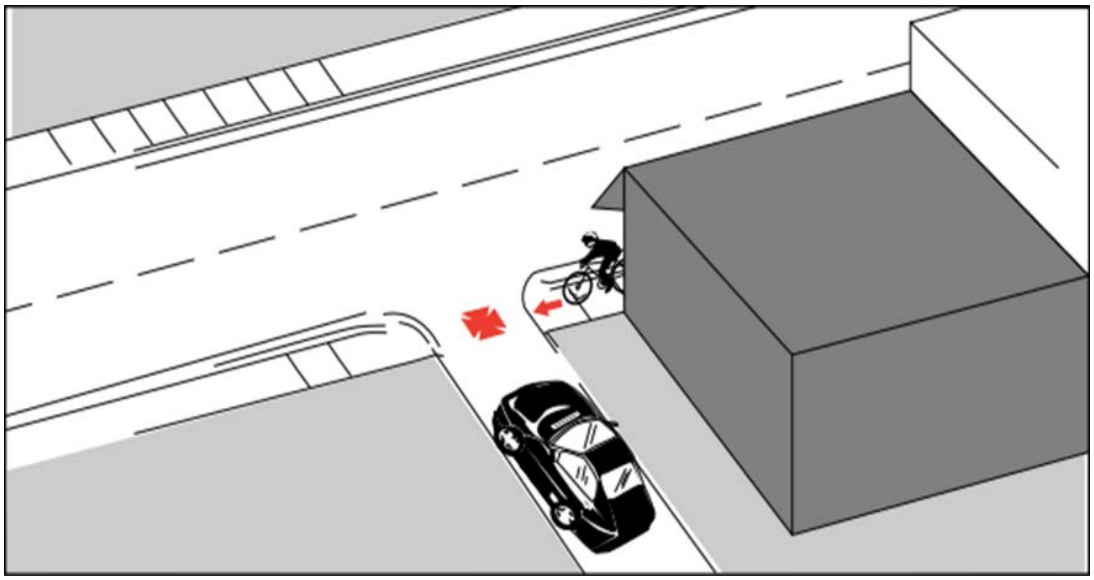


Image Source: Crash Type Manual for Cyclists, FHWA

Figure 18 illustrates an example of the second most common bicyclist crash type, where a bicyclist fails to yield to a motor vehicle. As seen in the image, a motor vehicle in a travel lane exhibiting no improper action collides with a bicyclist entering or crossing the street, and the bicyclist fails to yield to that vehicle. Most commonly this crash type involved a bicyclist attempting to cross an arterial, but the circumstances involved in bicycle fail-to-yield crashes varied considerably and are sometimes misreported. A typical scenario is a bicyclist attempting to cross a high speed and high volume arterial road. Because of the slower speed of bicyclists, they will often find it difficult to find gaps on these streets, will wait for a gap in traffic on the near side, proceed and get struck by drivers in the opposing lanes.

Figure 18: Typical Crash Involving Bicyclist Failure to Yield

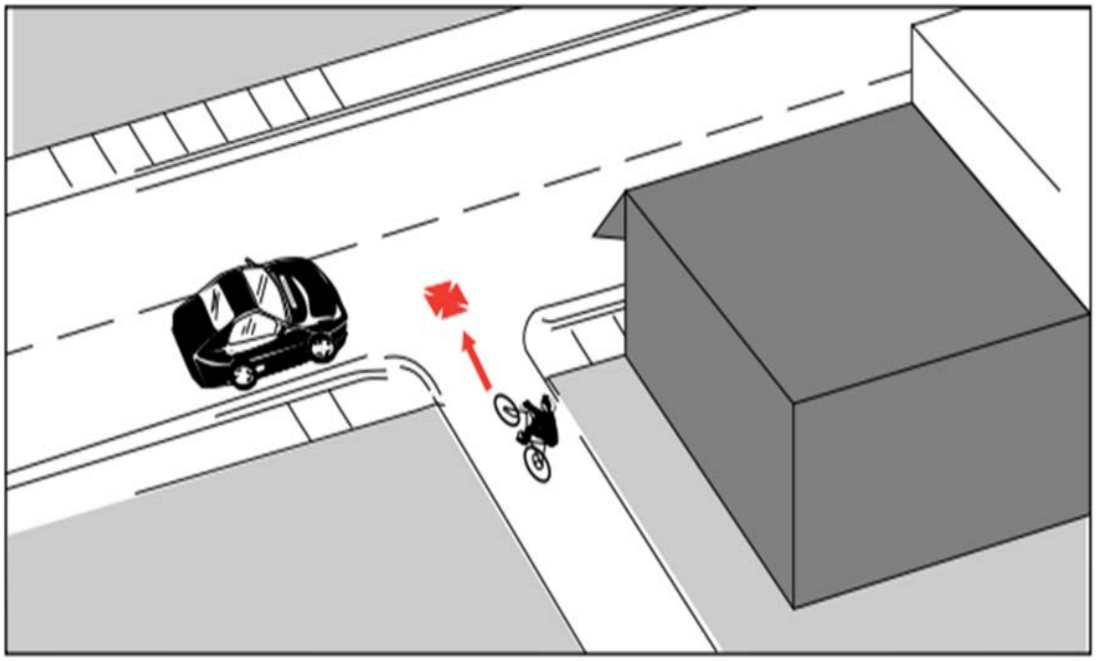


Image Source: Crash Type Manual for Cyclists, FHWA

Figure 19 illustrates a motorist overtaking a misjudged or undetected cyclist. This crash type occurs in one of two ways:

- A motorist wants to pass a bicyclist, assumes there is enough space adjacent to the bicyclist to pass, and misjudges the space, leading to the motorist colliding with the bicyclist.
- A motorist does not see a bicyclist ahead in the roadway and collides with the bicyclist from behind.

Figure 19: Typical Crash Involving a Motorist Overtaking a Cyclist

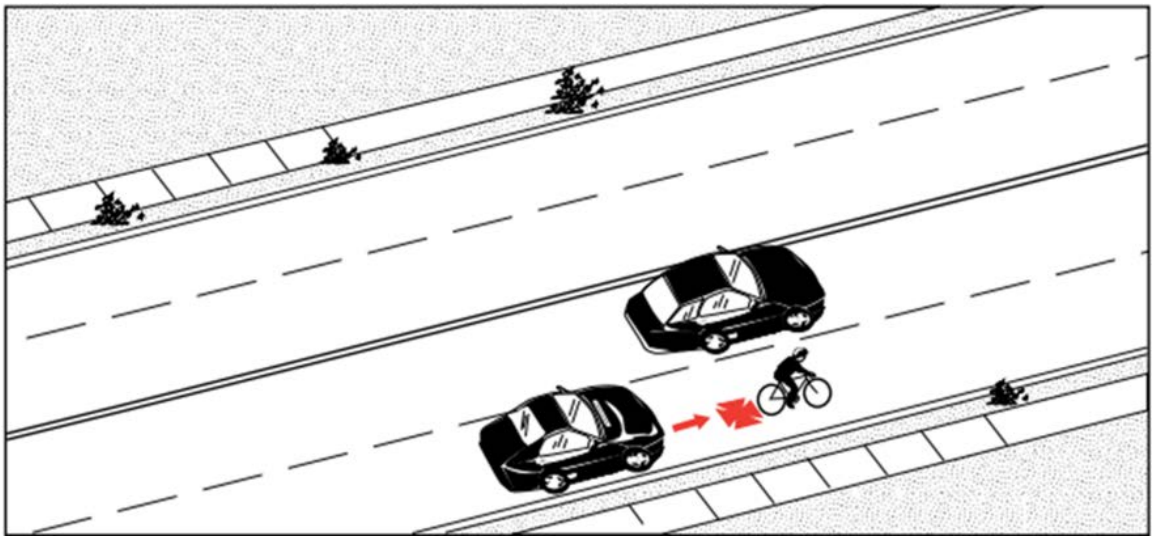
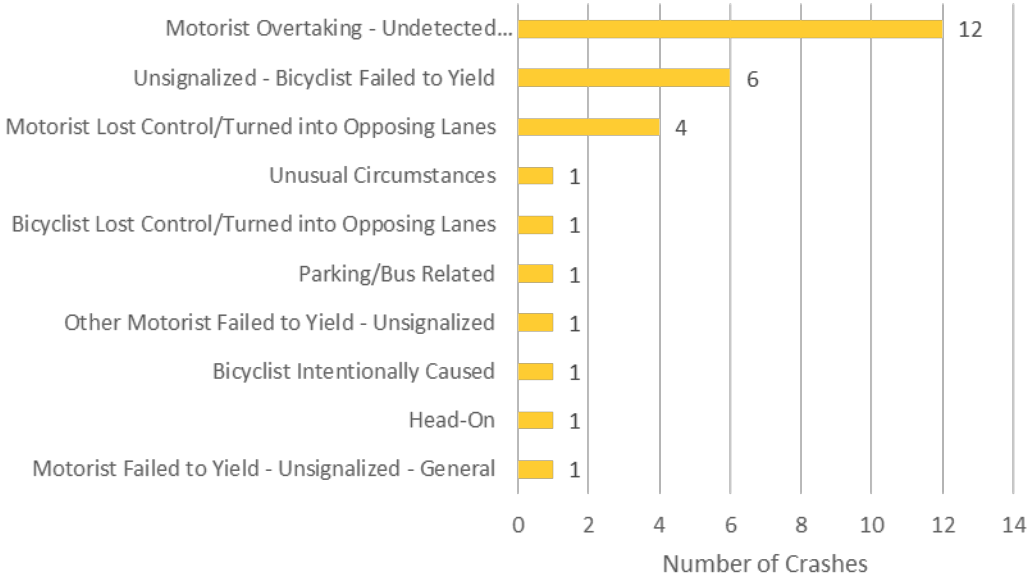


Image Source: Crash Type Manual for Cyclists, FHWA

Figure 20 shows the crash types in fatal bicyclist collisions. Of the 830 bicyclist crashes evaluated, 29 included a fatality, or about 3 percent of the total. Motorist overtaking crashes, as shown in Figure 19, are the most common crash type that results in a fatality, with 41 percent of fatal crashes of this type.

Figure 20: Crash Type Frequency for Fatal Bicyclist Collisions



3.3 Crash Site Characteristics

Figure 21 shows whether a bicycle facility was present along the path of the bicyclist when the crash took place. About 69 percent of crashes occurred where no bike facility was present. The remaining reports for 259 crashes (31 percent of all crashes) noted the presence of some type of bicycle facility. However, the presence of a bicycle facility does not necessarily mean that the bicyclist crash occurred in the bicycle facility. For example, a bike lane may be provided on a high speed, high volume road where a less confident bicyclist may not feel comfortable riding, so they may bike on the sidewalk and be struck while riding on the sidewalk. Figure 34 addresses where bicyclists were riding when crashes occurred.

Figure 21: Bicycle Facility along Path of Bicyclist

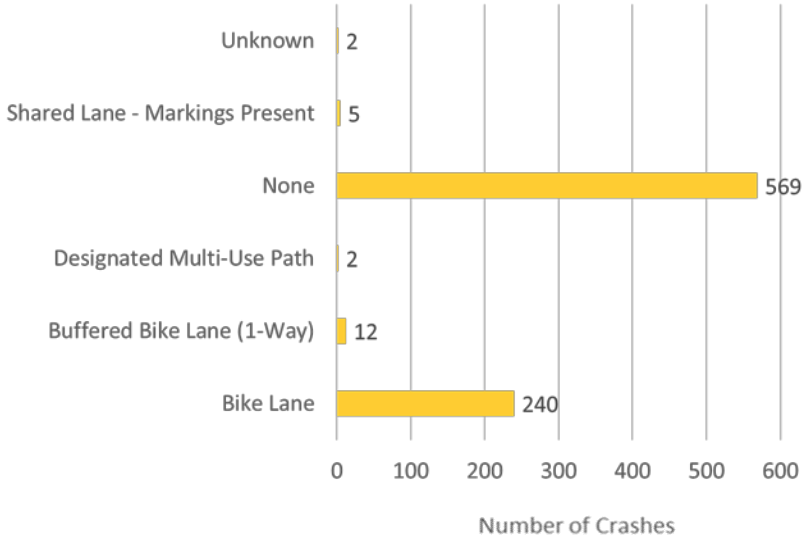
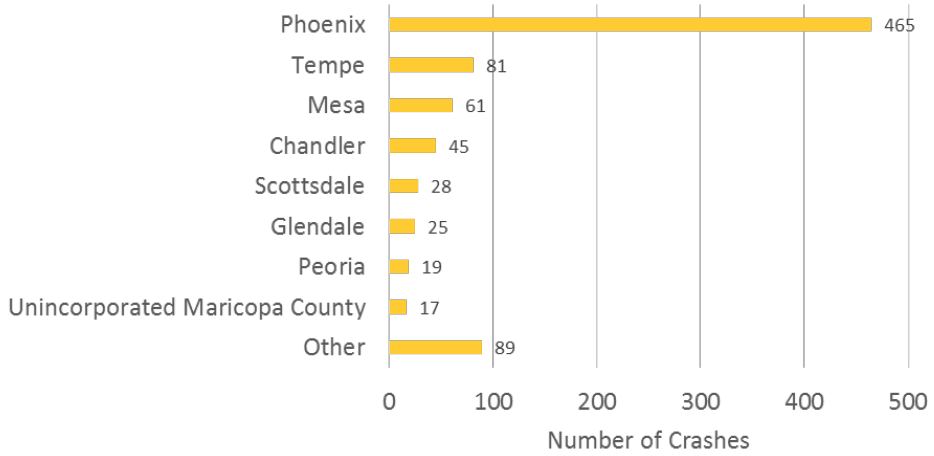


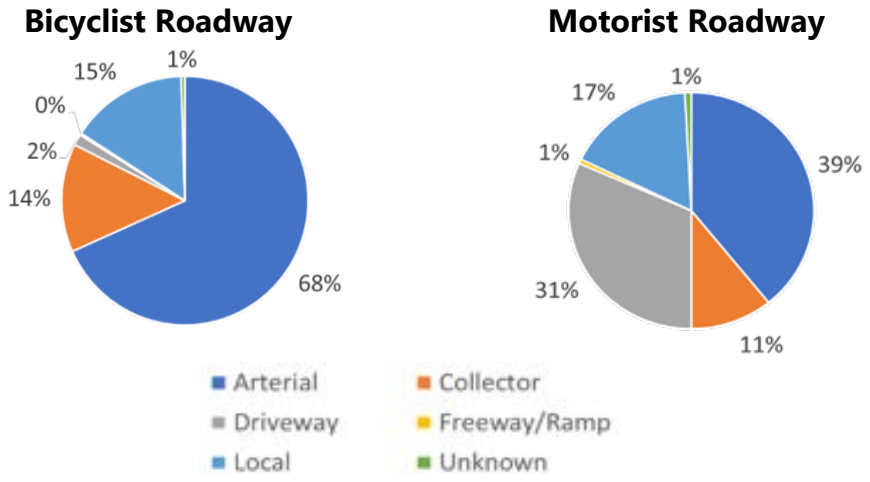
Figure 22 shows the number of bicyclist crashes happening across different jurisdictions in the MAG Region. Phoenix experienced the most crashes by far compared to other jurisdictions, with a total of 465 crashes, or 56 percent of the total. This is not surprising because Phoenix is the largest and the most populous city in Arizona. Tempe had the second most crashes, 81 crashes or nearly 10 percent of the total. Although Mesa, Chandler, Glendale, and Scottsdale all have larger populations than Tempe, bicycle ridership is higher in Tempe, notably because of the presence of Arizona State University's main campus.

Figure 22: Bicyclist Crashes by Jurisdiction



Because motorists and cyclists may be traveling on different types of roadways that intersect at the crash location, crash reports indicate what type of roadway each was on at the time of the crash. Figure 23 depicts the type of roadway each operator was traveling on when a crash occurred. Bicyclists were riding across or along arterials in 68 percent of the crashes. The second and third most common roadway for the bicycle during the crash was a local street (15 percent of crashes) and a collector (14 percent of crashes). The motorist was traveling on an arterial in 39 percent of crashes and in a driveway for 31 percent of crashes. As stated before, the most common crash was a motorist failing to yield from a driveway while crossing a sidewalk or entering the street, as shown in Figure 17.

Figure 23: Types of Roadways Where Bicyclist Crashes Occurred



Again, because motorists and cyclists may be traveling on roadways with different speed limits that intersect at the crash location, crash reports indicate the speed limit of the roadway each was on at the time of the crash. Figure 24 shows the speed limits on roadways where crashes occurred. Bicyclists were on or crossing a roadway with a speed limit of 40 mph most often, while motorists were most often on a roadway without a speed limit, such as a driveway.

Figure 24: Speed Limits Where Bicyclist Crashes Occurred

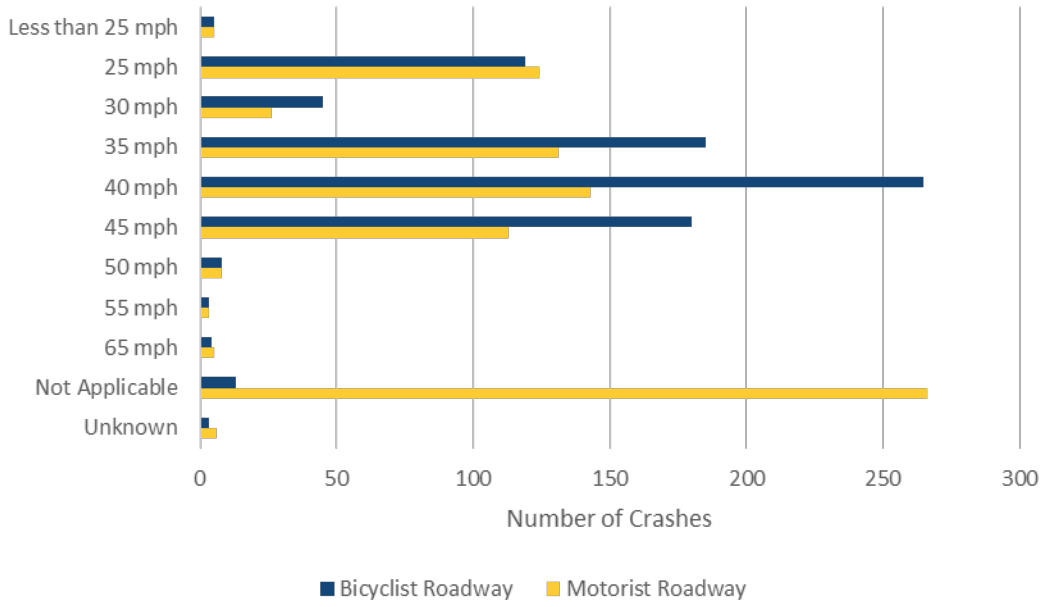


Figure 25 depicts whether the site conditions have changed since the crash. As seen in the figure, 95 percent of the sites have remained unchanged since the crash occurred.

Figure 25: Site Change since Crash

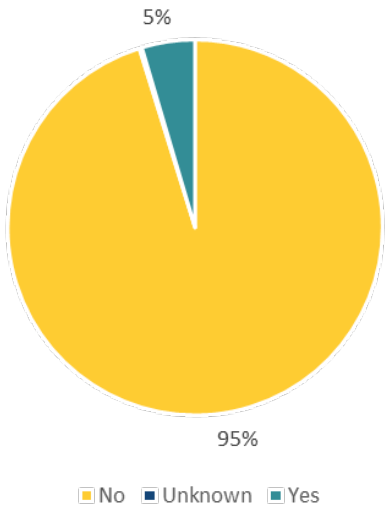
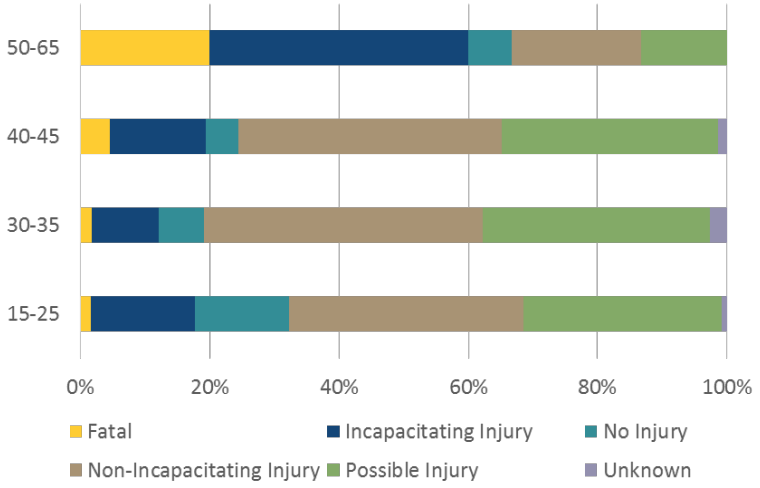


Figure 26 shows the percentage of crashes of each injury severity on streets with similar speed limits. Streets with the highest speed limits, over 45 mph, were much more likely to be the site of fatal and incapacitating injury crashes. About 60 percent of crashes on high speed roadways resulted in a fatality or incapacitating injury. Streets posted 30 or 35 mph were least likely to experience a severe crash; on these roadways fatalities or severe injuries occurred in about 12 percent of crashes.

Figure 26: Relationship Between Speed Limit and Injury Severity

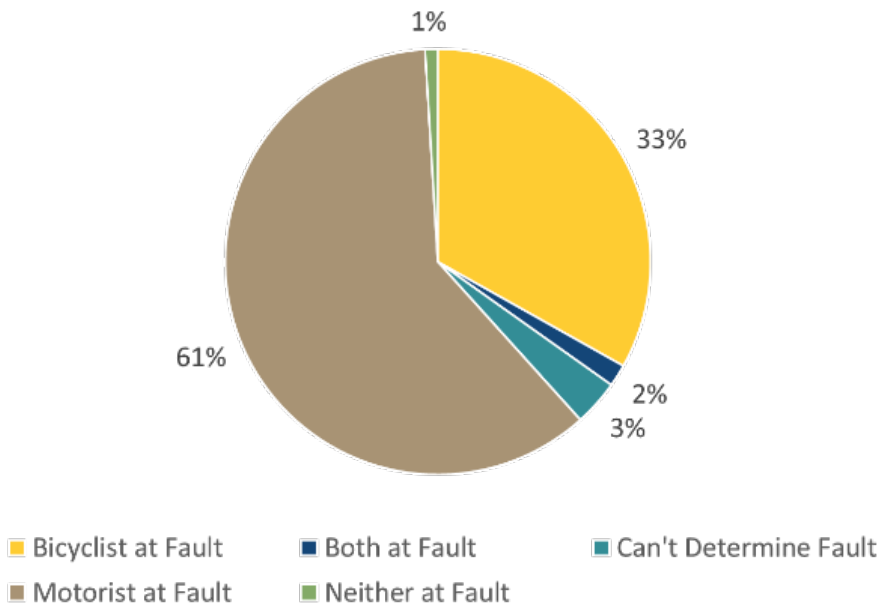


3.4 Fault

Assigning fault in a bicyclist collision was a subjective decision made by the project team. Officers responding to bike crashes do not always assign fault appropriately according to state and local laws. For instance, in several crashes, officers cited a cyclist for riding against traffic on the sidewalk even though it is not illegal. For the purposes of this study, fault was assigned consistently for all crashes based on state law, regardless of the findings of the responding officer.

While input provided by the investigating officer was used, it was not the sole deciding factor for fault assignment. Figure 27 depicts who was judged to be primarily at fault for causing the crash as determined by examining each individual crash report.

Figure 27: Fault in Bicyclist Crashes



The motorist was more often judged to be at fault than the bicyclist for the crashes reviewed as a part of this study. The motorist was at fault in 61 percent of crashes while the bicyclist was at fault in 33 percent of crashes. In a few crashes the fault could not be determined, or it was deemed that both the driver and bicyclist were equally at fault, or neither entity was at fault.[3]

[3] When neither the cyclist nor the motorist was at fault, usually a third party (such as another vehicle not involved in the collision) was determined to be the cause of the crash.

In many bike crashes, assessing fault is reasonably straightforward. However, a note is required about assignment of fault in crashes where a bicyclist on an arterial is struck by a motorist entering or exiting the arterial at a driveway or side street.

Arizona law (ARS 28-815.A) requires cyclists to stay to the right side of the roadway (with several exceptions). State law does not contain any such requirement for cyclists on sidewalks. As such, cyclists on sidewalks are generally permitted to ride in either direction and are thus not determined to be at fault in crashes even when they are traveling against traffic, on the left side of the street. Rather, state law requires motorists to yield before entering a roadway. While state law is not as clear as desirable for motorists crossing a sidewalk with respect to bicyclists on the sidewalk, for the purposes of this study, the motorist is designated at fault for failing to yield to a cyclist on a sidewalk, regardless of the cyclist's travel direction.

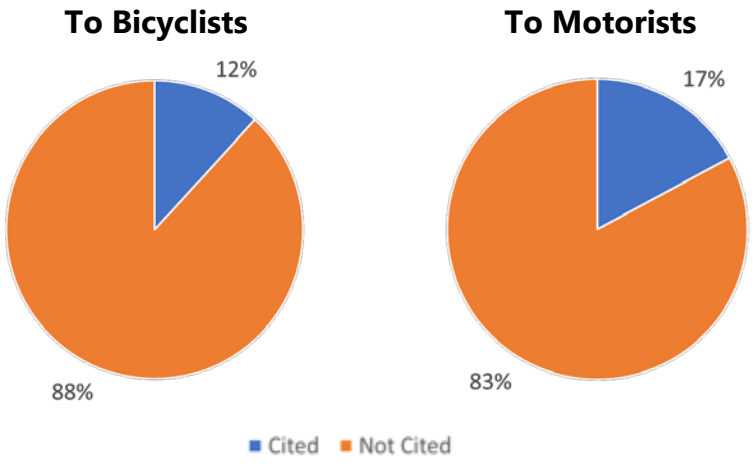
On the contrary, if a cyclist is traveling in the roadway, whether in a vehicle travel lane, bike lane, or on the shoulder, ARS 28-815 requires a bicyclist to ride with traffic. As such, the cyclist is generally determined to be at fault if involved in a crash while riding in a contraflow direction in the roadway and colliding with a motorist entering or exiting a driveway or side street.

The City of Tempe has a longstanding ordinance prohibiting cyclists from riding on sidewalks on the left side of the street (contraflow or against traffic). In this study, crashes in Tempe were assigned fault in the same way as the rest of the MAG region for consistency. The study found that 29 crashes (about 3 percent of all crashes) of this type occurred in Tempe over the 3-year analysis period (about 10 per year). These crashes were all designated in this study with the motorist at fault even though the cyclist was riding contraflow on the sidewalk in violation of Tempe's ordinance. In these 29 crashes, responding officers issued a citation to the cyclist on 23 occasions (79 percent of the time), mostly in violation of Tempe city ordinance 7-52.C.

An ordinance in the City of Scottsdale took effect on December 13, 2018, modifying the city code to require cyclists riding on the sidewalk to yield to motorists at conflicting driveways and side streets (17-82.C). This ordinance had not been adopted during the period from 2015 to 2017 when this study's crashes occurred, but it is mentioned here for completeness and context.

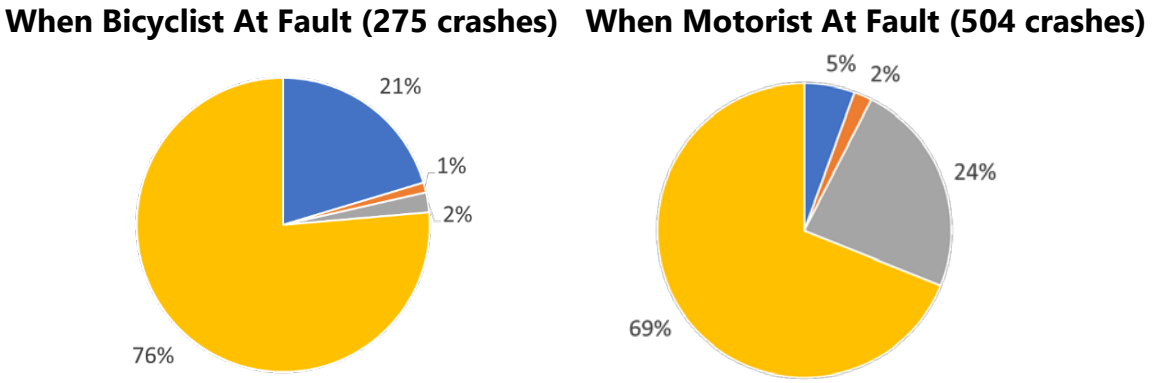
Figure 28 shows whether a citation was issued to the bicyclist or the motorist as a result of the collision. Citations were not typically issued to either the bicyclist or the motorist in these collisions, or this information was not recorded on the crash report. Bicyclists were cited in only 12 percent of crashes, and motorists were cited in 17 percent of crashes. (It should be noted that the crash reports may not capture the complete extent of citations given as a result of each crash, but the data here reflects the information available from the reports.)

Figure 28: Citations Given By Travel Mode in Bicyclist Crashes



Similar to the previous figure, Figure 29 deals with citations issued to either the bicyclist or driver resulting from the crashes. In this case, however, the figure shows whether a citation was issued when the bicyclist was judged to be at fault and when the motorist was judged to be at fault.

Figure 29: Citations Given By Fault



3.5 Road User Characteristics

Figure 30 shows the gender of the bicyclist and motorist involved in the bicyclist crashes. Men were involved in the majority of crashes, as both bicyclist and motorist. About 77 percent of bicyclists and 52 percent of motorists in crashes were male. Notably, 11 percent of motorists had an unknown gender, caused by crashes that are hit-and-run. The percentages are not surprising because male bicyclists far outnumber female bicyclists. Similarly, while male drivers represent less than 50 percent of all motorists by population, when accounting for average annual miles driven men make up 59 percent of roadway miles driven.

Figure 30: Gender of Those Involved in Crashes

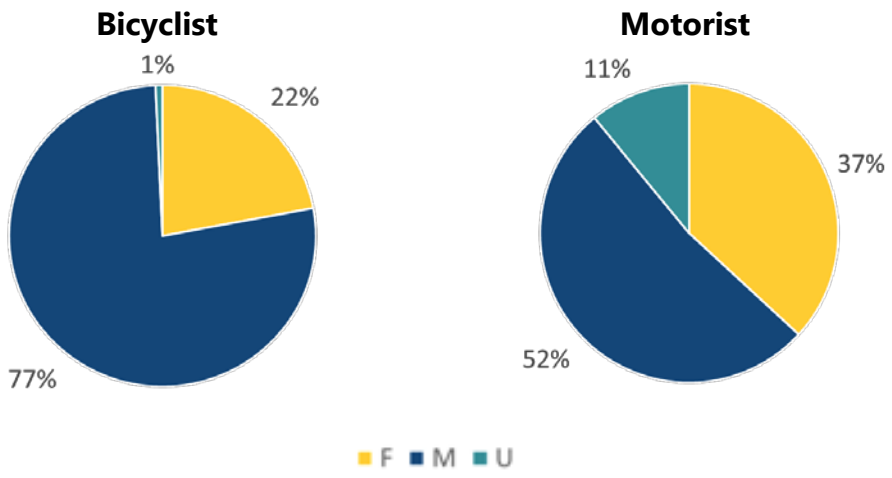
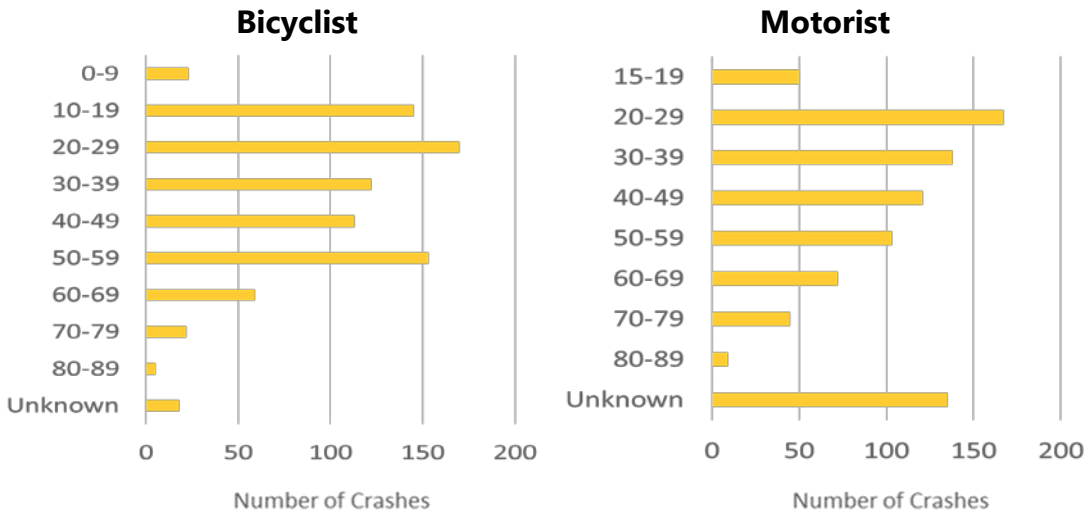


Figure 31 shows the ages of bicyclists and motorists involved in crashes, with ages grouped into 10-year intervals. The most common age for bicyclists in crashes is between 20-29 years old, followed closely by cyclists 50-59 years old. Both age groups experienced more than 150 crashes over the three-year study period. The most common age group for a motorist to be involved in a crash is also 20-29 years old. This age group also is associated with over 150 crashes. For motorists, after age 29 the number of crashes decreases roughly linearly with age group. As noted before, the large number of unknowns come from hit-and-run crashes.

Figure 31: Age of Those Involved in Crashes



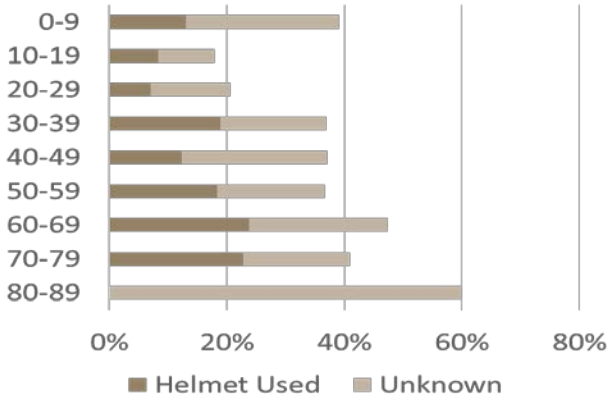
Arizona crash reports provide a space for the investigating officer to record whether the bicyclists were wearing a helmet. However, officers sometimes did not record the safety equipment information, presumably because they did not know what safety equipment was in use at the time of the crash.[4] Figure 32 shows the percent of riders wearing a helmet by age group. While there is a slightly greater tendency for helmet use by the very youngest and oldest age groups, there is a significant lack of helmet use among bicyclists.

The figure shows the portion of unknown helmet use, which may or may not include a situation where a helmet was used. Not including the "unknown" category, the age group most often wearing a helmet was cyclists in their 60s. The age group least often wearing a helmet at the time of the crash was cyclists between ages 20 and 29.

[4] A helmet is the only safety equipment applicable to cyclists that is specifically listed on the Arizona crash report form. If a cyclist were using other safety equipment, officers could choose "other" on the crash report. However, officers selected "other" for only four of the 830 crashes reviewed. The type of safety equipment the cyclist used in these four crashes is unknown.

Figure 33 shows helmet use of cyclists in crashes according to injury severity. Figure 33 shows the same levels of injury severity as in Figure 15. Just under 30 percent of bicyclists in fatal crashes were wearing a helmet. Less than 20 percent of bicyclists in incapacitating injury crashes were wearing a helmet.

Figure 32: Bicyclist Helmet Use for Cyclists in Crashes, by Age



It is somewhat counterintuitive that helmet use appears to be greater among cyclists in fatal crashes than cyclists involved in crashes of other severities. However, the most common fatal bicyclist crash type—motorist overtaking—also is associated with cyclists on higher-speed roadways who tend to be more confident road cyclists and who are also more likely to wear a helmet. A helmet is also not often likely sufficient protection to prevent a fatality or serious injury in high speed crashes. The small number of fatal crashes in the database (29) when compared to crashes of other severity levels also contributes to the skewed values for helmet use. However, the fact remains that use of a helmet does not necessarily result in less severe crashes for bicyclists and may point to the need for safer and more comfortable bicycle facilities to reduce crash risk and severity.

Figure 33: Helmet Use of Cyclists in Crashes, by Injury Severity

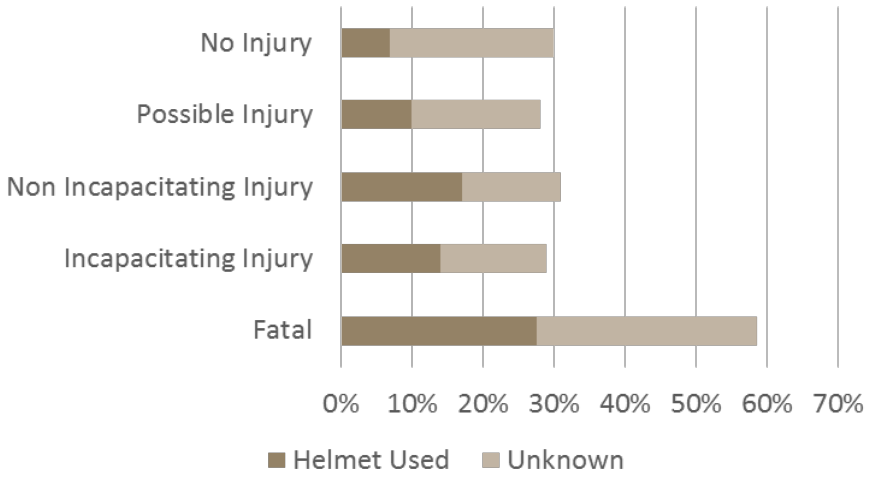


Figure 34 shows where the bicyclist was riding when the crash occurred. To provide more detail, the left chart shows the location of the bicyclist when a bike lane existed at the crash site, and the right chart shows the location of the bicyclist when a bike lane did not exist. When a bike lane was provided, only 44 percent of cyclists were using the bike lane when the crash occurred. Even though a bike lane was present, a bicyclist was on the sidewalk 23 percent of the time when a crash occurred. When no bike lane was provided, 37 percent of crashes occurred when the bicyclist was on the sidewalk. The bicyclist was in the travel lane 25 percent of the time when crashes occurred when a bike lane was not provided. It should be noted that crossing the road is an issue whether there are bike lanes or not (19 percent of crashes when a bike lane was present, 29 percent of crashes when a bike lane was not present). It should also be noted that the presence of a bike lane along a section of roadway may not reflect that bike lanes are sometimes not continuous along roadways; a cyclist may have started on the sidewalk in a section of roadway without bike lanes and not transitioned to the bike lane when it appeared along his or her route.

Figure 34: Bicyclist Riding Location

Streets with Bike Lanes (254 crashes) **Streets without Bike Lanes (569 crashes)**

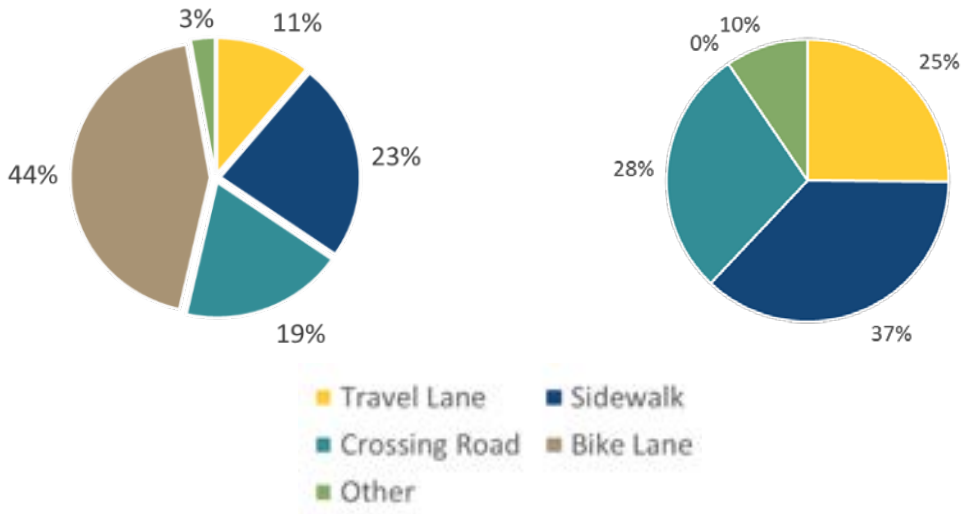


Figure 35 shows the riding location of bicyclists in crashes when the bicyclist is at fault, and Figure 36 shows the riding location of bicyclists in crashes where the motorist is at fault. When deemed to be at fault in a crash, cyclists are most often struck while crossing the roadway or
riding in a travel lane. These two cyclist riding locations accounted for about 82 percent of crashes where the bicyclist was at fault.

Conversely, in 51 percent of crashes where motorists were deemed to be at fault, cyclists were riding on the sidewalk. No other cyclist riding location was particularly prominent in cases where the motorist was at fault.

Figure 35: Bicyclist Riding Location when Bicyclist is at Fault (275 crashes)

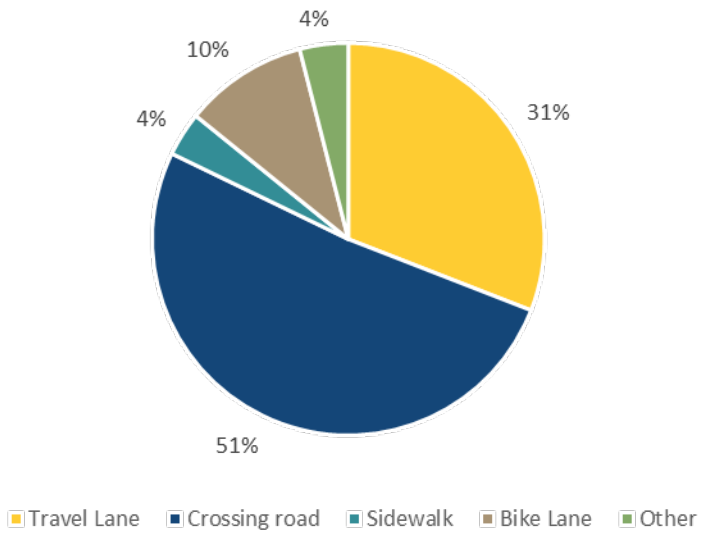


Figure 36: Bicyclist Riding Location when Motorist is at Fault (504 crashes)

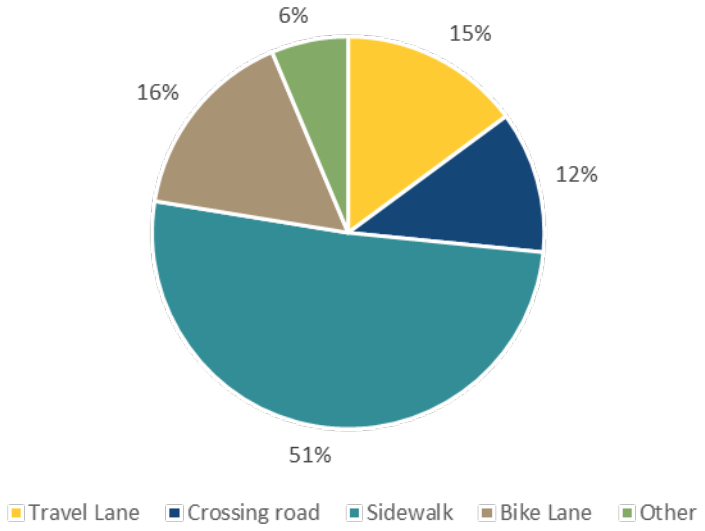


Figure 37 shows which direction the bicyclist was traveling at the time of the crash with respect to the motor vehicle traffic flow. The bicyclist could be riding against traffic (contraflow), with traffic, crossing the street, or unknown. Cyclists in crashes were about evenly distributed between riding with traffic and riding against traffic. About 20 percent of cyclists in crashes were crossing the roadway or making another movement that could not allow his or her travel direction to be categorized.

Figure 37: Bicyclist Travel Direction at Time of Crash

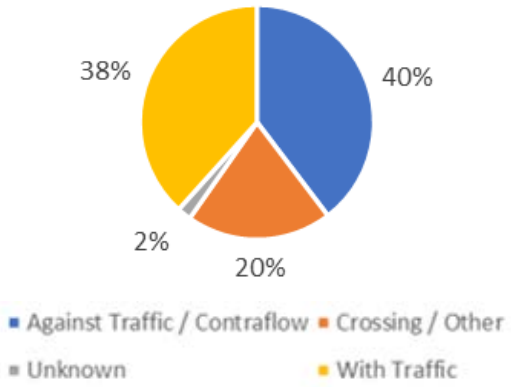


Figure 38 shows the direction of the bicyclist at the time of crash, adding information about fault to Figure 37. The left chart shows the bicyclist travel direction when the bicyclist was at fault, and the right chart shows the direction of the bicyclist when the motorist was at fault. When the bicyclist was at fault, the bicyclist was most often crossing a roadway. Other cyclists at fault were split about evenly between with- and against-traffic.

When the motorist was at fault, the direction of bicyclist travel was nearly equally divided between bicyclists traveling contraflow (50 percent) and with traffic (45 percent).

Figure 38: Bicyclist Travel Direction by Fault

When Bicyclist at Fault (275 crashes) **When Motorist at Fault (504 crashes)**

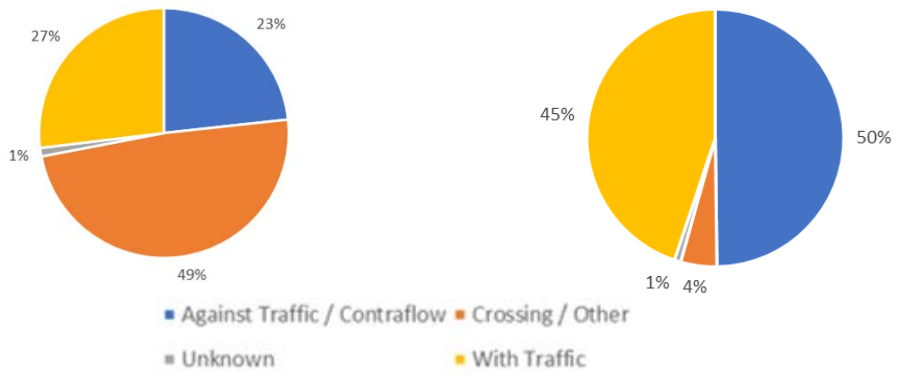


Figure 39 shows the relationship between cyclist travel direction (with or against traffic) and the presence of a bike lane at the site of each crash. Where a bike lane exists, cyclists involved in crashes traveled in the contraflow direction in 37 percent of crashes and with traffic in 50 percent of crashes. Where a bike lane does not exist, cyclists were slightly more likely to be riding contraflow. Crashes at sites without a bike lane were more likely to involve cyclists crossing the street, likely because streets with bike lanes in the MAG region are often narrower and have lower speeds and traffic volumes than sites without bike lanes. As previously discussed, in either case the bicyclist may have been riding on the sidewalk rather than in the bike lane.

Figure 39: Relationship Between Cyclist Travel Direction and Presence of Bike Lane

Streets with Bike Lanes (254 crashes) **Streets without Bike Lanes (569 crashes)**

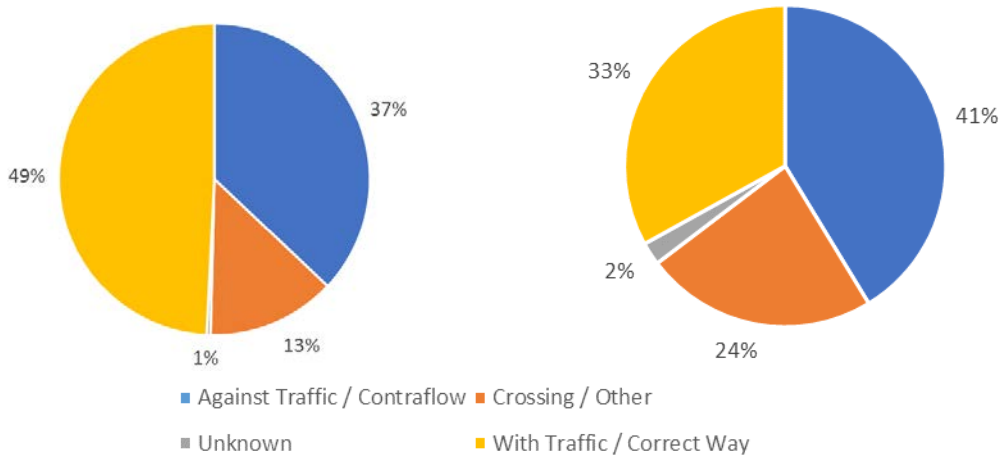


Figure 40 is similar to Figure 39, but rather than showing the presence of a bicycle facility, it focuses on the riding location of cyclists. Cyclists riding on the sidewalk are much more likely to be involved in a crash when traveling contraflow. Nearly 85 percent of cyclists riding on the sidewalk at the time of the crash were traveling contraflow. Cyclists in the travel lane and bike lanes are much less likely to be traveling contraflow when in crashes. Cyclists in bike lane crashes are traveling contraflow in 22 percent of crashes and cyclists in travel lane crashes are traveling contraflow in 16 percent of crashes. It is possible that cyclists are more likely to ride contraflow on sidewalks, but it is also possible that contraflow sidewalk riding carries so much risk that contraflow sidewalk riders are overrepresented in crashes.

Figure 40 also illustrates that "bicyclist on sidewalk" account for the largest number of crashes and the largest number of contraflow crashes. However, cyclists traveling on sidewalks in the same direction as adjacent motor vehicle traffic are involved in considerably fewer crashes than cyclists traveling with traffic in bike lanes or travel lanes. Cyclists riding with traffic were involved in 40 crashes on sidewalks, 88 crashes in bike lanes, and 159 crashes in travel lanes.

Data from Figure 40 are presented in tabular format in Table 5.

Figure 40: Relationship Between Cyclist Travel Direction and Cyclist Riding Location

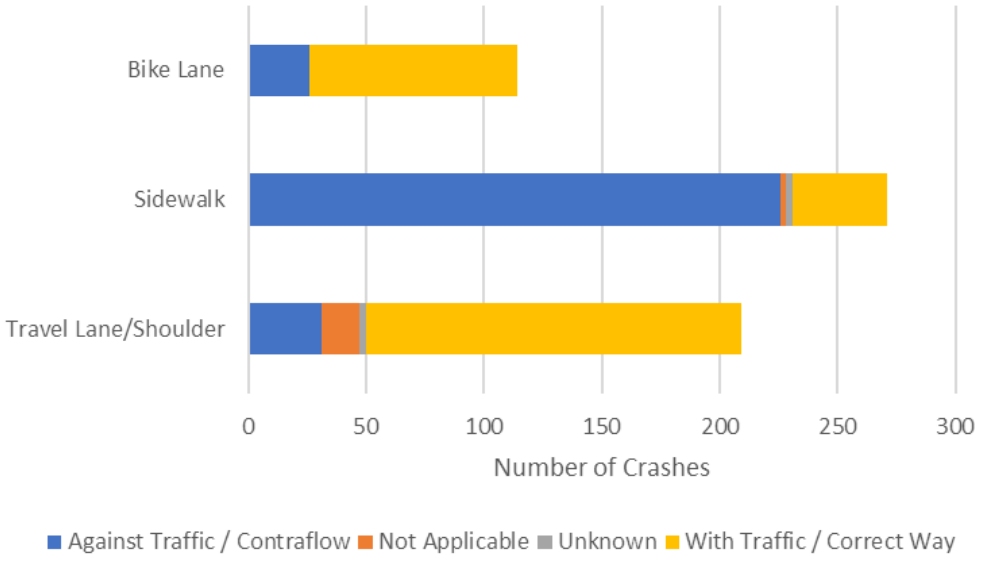


Table 5: Relationship Between Cyclist Travel Direction and Cyclist Riding Location

	Number of Crashes	Bicyclist Riding Direction				Total
		Against Traffic/ Contraflow	Crossing/Other	Unknown	With Traffic/ Correct Way	
Bike Lane (or other designated bike facility)	114	23%	0%	0%	77%	100%
Crossing Roadway Midblock	125	2%	95%	0%	3%	100%
Crosswalk Marked	47	38%	45%	0%	17%	100%
Crosswalk Unmarked	38	53%	18%	3%	26%	100%
Shoulder/Roadside - Paved	27	11%	0%	0%	89%	100%
Shoulder/Roadside - Unpaved	10	20%	20%	10%	50%	100%
Sidewalk - at Driveway Access	262	85%	1%	1%	13%	100%
Sidewalk - Midblock (not at driveway)	9	33%	0%	0%	67%	100%
Travel Lane	172	15%	8%	1%	76%	100%
Unknown	23	26%	0%	35%	39%	100%
Other	3	0%	67%	33%	0%	100%

4.0 GEOGRAPHIC ANALYSIS METHODS AND PROCEDURES

A Geographic Information System (GIS) can be used to plot and evaluate the location of the bicyclist crash sites. ArcMap is a good example of a powerful GIS engine that can used for such analysis.

4.1 Displaying Crashes, Hotspot Analysis,

Agencies can use location information from crash reports as most crash reports includes GPS coordinates that show where the collision occurred. Some crash reports may lack GPS coordinates, but the location could usually be determined using other information from the report, such as cross streets or addresses that might have been included. After the coordinate system information is extracted for all crashes, it can be imported into ArcMap and converted into a shapefile, which is then projected onto a base map of the local agency jurisdiction.

4.2 Bicyclist Hotspot Crash Analysis

Once the coordinate system data is projected, a hotspot analysis can be conducted using the *Optimized Hotspot Analysis* tool. This tool works by using the Getis-Ord Gi* to analyze

points and create a map of statistically significant hotspots. Before the analysis is run, a bounding polygon can be drawn excluding areas with lower crash density or areas where no crashes could occur due to lack of roads. This bounding polygon increases the precision of the analysis. In addition to using the automated hotspot analysis tool to identify areas of high crash density, local agencies can visually review to identify high crash roadway segments, with input from their staff.

4.3 Sites with Multiple Crashes

Locations can be identified where two or more bicyclist crashes occurred, with the expectation that sites experiencing multiple crashes may offer more potential for safety improvement than sites with a single crash. For the purposes of the analysis, crashes can be considered to be at the same location if they occurred within certain distance of each other, a distance that captures crashes that occur, for instance, at the same driveway, but excludes crashes that occur at adjacent driveways.

It should also be noted that a conventional bike lane may not be the most appropriate accommodation on some streets, particularly those with high speeds and traffic volumes. An appropriate bicycle facility selection process, such as the process identified in the *Bikeway Selection Guide* (FHWA, 2019), should be undertaken before deciding to mark a bike lane.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The following conclusions can be drawn from the MAG Regional Bicycle Safety Analysis:

- While location-specific patterns of bicycle crashes are rare, strong trends exist related to the most common types of bicycle crashes. Of about 30 crash types defined as part of the study, the following three crash types accounted for over 70 percent of crashes:
    - The most common crash type, accounting for 23 percent of all crashes, involves a motorist entering a street from a driveway and a bicyclist on the sidewalk approaching from the right (riding contraflow). This crash type increases to about 38 percent of the total when other similar bicyclist crash types are included; for instance, when bicyclists are traveling with traffic on the sidewalk instead of contraflow, and when motorists are on a side street instead of a driveway.
    - The second most common crash type involves a bicyclist failing to yield when entering or crossing a street, accounting for 21 percent of crashes. Cyclists may fail to yield in several situations, including when entering a

major street from a driveway or side street and when making left or right turns.
    - The third most common crash type involves a motorist overtaking a cyclist that the driver did not see or where the driver misjudged the distance to the cyclist. This crash type accounted for 12 percent of all crashes.

- Bicyclist crashes reviewed in this study are not generally concentrated at high-crash locations. The vast majority (98 percent) of bicycle crashes occurred at a location where no other bicycle crash had occurred. Only eight locations out of 830 crashes region-wide experienced more than one bicycle crash in the three year period from 2015 to 2017. It is possible that this may be a result of low bicyclist volume. It is also possible that intersections of arterial streets do exhibit patterns of high-crash locations, but these types of crashes were excluded from this study. Bicycle crashes tend to occur based on a circumstance or situation at the crash site rather than at particular locations.

- It appears that many cyclists feel safe when riding contraflow on a sidewalk, particularly if the alternative involves crossing or riding in a high-speed, high-volume roadway. However, cyclists riding contraflow on the sidewalk are involved in the most common bicyclist crash type. The presence of these crashes may be indicative of the lack of adequate bicycle facilities or many on-street bicycle facilities being unsuitable for bicyclists of all ages and abilities.

- Among cyclists in crashes, known helmet use ranges from about 10 to 30 percent. Cyclists in fatal crashes are more likely to be wearing helmets than those involved in crashes of other severities, likely because cyclists wearing helmets are more likely to be riding on the types of facilities where fatal crashes occur most often (higher speed streets).

- Bicyclists were riding along or crossing arterials in 68 percent of crashes.

- Most bicycle crashes, 74 percent, occurred during daylight hours.

- Over two-thirds of crashes occurred on streets with no bicycle accommodations, but streets with bike lanes were the site of about 29 percent of crashes.

- Among cyclists in crashes while traveling along a street with a bike lane, only 54 percent of cyclists in crashes were using the bike lane. Cyclists not using the bike lane are twice as likely to use the sidewalk as to use a motor vehicle travel lane. This again may be indicative of existing bicycle facilities being unsuitable for bicyclists of all ages and abilities.

- Bicyclists involved in crashes who were riding along the street (as opposed to crossing the street) were about evenly split between those riding with traffic and those riding contraflow. However, the travel direction of bicyclists in crashes is highly correlated to their riding location. Nearly 85 percent of bicyclists in crashes on sidewalks were riding contraflow, whereas only 22 percent of cyclists in travel lanes and 16 percent of cyclists in bike lanes were riding contraflow at the time of the crash.

- Officers responding to bicyclist crashes did not always complete crash reports consistently and correctly.

- Right-hook crashes—where a cyclist is struck by a motorist traveling in the same direction and making a right-turn across the cyclist's path—are not among the most common bicyclist crashes in the MAG region. This crash type accounted for less than 3 percent of crashes studied. This trend may differ at arterial/arterial street intersections that were excluded from this study.

- No "dooring" crashes—where a cyclist impacts the opened door of a parked motor vehicle—were observed in the study. While dooring crashes are a concern in some cities, dooring crashes are likely uncommon in the MAG region because of the rarity of on-street parking along most routes frequented by cyclists.

- About 4 percent of cyclists in crashes were noted as impaired by alcohol or drugs, about twice the level of impairment of motorists in bicyclist crashes, who were noted as impaired in about 2 percent of crashes. (The motorist impairment statistic might be different if data were available from hit-and-run motorists who left the scene). Bicyclist impairment levels in this study are far lower than typical impairment levels of pedestrians involved in crashes.[5]

5.2 Recommendations

The following recommendations are offered for the consideration of MAG and MAG member agencies:

- Frequent, comfortable opportunities to cross streets can help encourage bicyclists to travel on the right side of the street rather than contraflow. These types of

[5] An example of typical region pedestrian impairment levels can be found in the City of Phoenix *2016 Pedestrian Collision Summary* (December 2017). According to this document, 18 percent of pedestrians in crashes were noted as impaired. The same document noted that 2 percent of motorists were impaired.

crossing enhancements will also help address the frequent crash type where bicyclists are crossing the road.

- MAG member agencies should explore the BikeHAWK crossing application that was developed in Tucson, especially for canal or other trail crossings and bike boulevards.

- Access management techniques can help reduce driveway-crossing conflict points.

- Bicycle infrastructure needs to be continuous to be most effective, both along a road and throughout a bicycle network. For instance, gaps in bike lanes may cause some people to choose not to ride, avoid the facility entirely, or to ride contraflow on the sidewalk.

- More bicycle infrastructure comfortable for people of all ages and abilities is needed along arterials, considering the preponderance of bicycle crashes that occur on arterials. This will often mean that a conventional bike lane is not adequate on many arterial streets.

- The crash data supports the use of one-way separated bike lanes along both sides of the street. This would likely address motorist overtaking bicyclist crashes by having a physical barrier or a wider separation between the motor vehicle and the bicyclist, and would encourage more bicyclists to ride in the street where they are most predictable and visible to motorists.

- The crash data tends to discourage the use of contraflow bicycle facilities, including contraflow bike lanes and two-way separated bike lanes on one side of the street, where there are driveways and side street intersections along the corridor. There has been little success in encouraging drivers to look to the right for a bicyclist before entering a street from a driveway or side street to check for contraflow bicyclists. Contraflow facilities should be limited to corridors with few to no driveways or side streets.

- Bicycle boulevards are an effective, low-cost way to provide continuous bicycling accommodations away from arterial streets where the majority of bike crashes occur, and in particular the more severe crashes. Bicycle boulevards are rare in the MAG Region but are well suited to the region's grid network that often extends to local streets in addition to arterials. Bicycle boulevards rely on fundamental principles of managing motorist speeds and volumes along these routes and prioritizing bicyclist crossings of intersecting streets, especially arterial streets where safe and convenient crossing opportunities are essential.

- Agencies should review the list in Section 4.5 of this report to determine if the addition of bike lanes (or all-ages-and-abilities bicycle infrastructure) could improve safety or bicyclist comfort at any of these sites. Agencies may also want to identify other locations (that did not experience bicycle crashes from 2015 to 2017) where the curb lane may be wide enough to designate marked bike lanes or a more protective type of bicycle facility.

- Where high-comfort bicycle facilities are not present, agencies should consider driveway treatments that better manage the conflict between right-turning motorists and sidewalk cyclists. This includes providing driveway aprons that include a change in grade for motorists entering the driveway rather than constructing driveways with curb returns and crossings at street-level; this reinforces the pedestrian's (or bicyclist's) right-of-way at these conflict points.

- Sidewalks are not shared-use paths, but they have much in common with shared-use paths when they are used by bicyclists. The 2012 AASHTO *Guide for the Development of Bicycle Facilities* anticipates the conflict between cyclists on a shared-use path and motorists on driveways:

  > *"At intersections and driveways, motorists entering or crossing the roadway often will not notice bicyclists approaching from their right, as they do not expect wheeled traffic from this direction. Motorists turning from the roadway onto the cross street may likewise fail to notice bicyclists traveling the opposite direction from the norm."*

  AASHTO offers the following advice to help address the conflict, although AASHTO cautions that no design can fully resolve the conflict:

  > *"A wide separation should be provided between a two-way sidepath and the adjacent roadway to demonstrate to both the bicyclist and the motorist that the path functions as an independent facility for bicyclists and other users. The minimum recommended separation between a path and the roadway curb (i.e., face of curb) or edge of traveled way (where there is no curb) is 5 ft."*

- Officers responding to bicycle crashes may need additional tools, resources or training to more accurately complete crash reports to properly assess fault, correctly issue citations, and document helmet use. Bicycle-savvy officers may be a good source of training.

- The low helmet use among cyclists in crashes illustrates a need for better cyclist education and encouraging helmet use at a younger age so that wearing a bicycle safety helmet becomes second nature. Establishing role models who wear helmets may help encourage more bicycle helmet use.

- Drivers and bicyclists may benefit from education about frequent crash types so they can adjust their behavior to reduce common crashes.

- The number and severity of motorist overtaking bicyclist crashes suggests that improving cyclist visibility may reduce crashes. While some cyclists in overtaking crashes were noted in crash reports as being sufficiently visible, others were not. Greater bicyclist visibility can result from an improved rear reflector or flashing light and bright or reflective clothing or helmet. Bicyclists should also be encouraged to use a rear-view mirror.

- Since many of the motorist overtaking bicyclist crashes involved driver distraction, stronger education and enforcement of existing distracted driving laws is recommended, including illustrating the consequences of talking on a phone, texting or viewing a personal electronic device while driving. Improved information should be included in the Arizona Driver License Manual and included in drivers' education courses, especially regarding the new Statewide Law prohibiting talking on a phone, texting or using a personal electronic device while driving.[6]

- Bicyclist count studies should be conducted to identify and quantify typical bicyclist riding locations (sidewalk versus in the street) and direction of travel (with traffic versus contraflow) to obtain a better understanding of bicyclist exposure and riding locations along arterial streets within the MAG Region. These types of counts are currently being done at 40 locations in Phoenix as part of the city's T2050 evaluation program. The existing bicyclist count data can be mined to identify riding location and direction of travel at the 40 locations (33 of which are along arterial or collector streets in Phoenix) for 2018 and 2019.

- Strava data should be used to obtain bicycle exposure data throughout the region. Actual long-term bicyclist counts at key locations throughout the MAG Region may

[6] On April 22, 2019, the Governor signed into Arizona law HB 2318 that banned use of handheld portable wireless communication devices while driving. The law went into effect upon the Governor's signature, but drivers are only subject to warnings until January 1, 2021. After that date, any such distracted driver is subject to a citation between $75 and $149 for a first offense, and $150 to $250 for a second offense. This law does not apply to hands-free phones or CB radio operation, even though they can cause some degree of driver distraction as well.

be used to identify adjustment factors to existing Strava data to provide exposure information for all roads within the MAG Region. Exposure data is critical to accurately identify roadways where bicycle crashes are overrepresented.

- MAG should encourage a revision to Arizona State Law to clarify that motorists entering streets from private driveways are required to yield to bicyclists on sidewalks. Existing state law only requires that motorists yield to pedestrians (ARS 28-856.2) and "all closely approaching vehicles on the roadway" (ARS 28-856.3). A plain reading of the existing statute does not require motorists to yield to cyclists riding on sidewalks even where sidewalk riding is legal and more comfortable than riding in the street.

- MAG or MAG member agencies also may want to consider the benefits of a change to ARS 28-792 to require drivers to yield to a bicyclist crossing roadways in crosswalks, in addition to the current law that requires yielding "to a pedestrian crossing the roadway within a crosswalk."

- Considering the involvement of contraflow cyclists in crashes, local agencies may want to consider adopting an ordinance requiring cyclists riding contraflow on sidewalks to yield to vehicles at conflicting driveways and side streets.

6.0 REFERENCES

1. Association of Central Oklahoma Governments (ACOG), *Regional Crash and Safety Report*, 2017.
2. Atlanta Regional Council (ARC), *Safe Streets for Walking and Bicycling*, 2018.
3. California Department of Transportation (CalTrans), *Local Roadway Safety Manual*, 2016.
4. Denver Region Council of Governments (DRCOG), *Pedestrian and Bicycle Safety in the Denver Region,* 2012.
5. Federal Highway Administration (FHWA), *System Safety Project Selection Tool*, 2013.
6. Federal Highway Administration (FHWA), *Bikeway Selection Guide,* 2019.
7. Herbel, S., L. Lang, and C. McGovern, *Highway Safety Improvement Program Manual*, 2010.
8. North Carolina Department of Transportation (NCDOT), *North Carolina Bicycle Crash Types*, prepared by the University of North Carolina Highway Safety Research Center, 2018.
9. Oregon Department of Transportation (ODOT), *Pedestrian and Bicycle Safety Implementation Plan, 2014*.
10. Snyder, M.B. and Knoblauch, R.L. (1971). *Pedestrian Safety: The Identification of Precipitating Factors and Possible Countermeasures*. Vol. I and II – Appendices. DOT/ NHTSA. FH-11-7312, 1971.
11. Tara Tolford, *New Orleans Regional Pedestrian and Bicycle Crash Report,* 2012.
12. Thomas, L. et al., *NCHRP 893: Systemic Pedestrian Safety Analysis*, National Academies of Sciences, Engineering, and Medicine, Washington, DC, 2018.

APPENDIX: DELIVERABLES PROVIDED TO MAG

Relationship among posted speed limit, injury severity, roadway classifcation, and number of through lanes in MAG Region Bicycle Crashes

Posted Sped Limit (mph)	Injury Severity*	Arterial						Collector						Driveway						Freeway/Ramp						Local						Unknown Classification						Grand Total
		Number of Through Lanes						Number of Through Lanes						Number of Through Lanes						Number of Through Lanes						Number of Through Lanes						Number of Through Lanes						
		0-2	3	4	5	6+	Total	0-2	3	4	5	6+	Total	0-2	3	4	5	6+	Total	0-2	3	4	5	6+	Total	0-2	3	4	5	6+	Total	0-2	3	4	5	6+	Total	
15	2						0						0						0						0	1					1						0	1
	3						0	2					2						0						0						0						0	2
20	3						0						0						0						0	1					1						0	1
	4						0	1					1						0						0						0						0	1
25	1			1	1		2	5		1			6						0						0	9					9						0	17
	2	1		1	1		3	2	1				3						0						0	32	1				33						0	39
	3						0	3					3						0						0	46					46						0	49
	4	1					1	3					3						0						0	11					11						0	15
	5						0	1					1						0						0	1					1						0	2
	99						0	1					1						0						0	1					1						0	2
30	1			1			1	1					1						0						0						0						0	2
	2	1		1			2	4					4						0						0	1					1						0	7
	3	1		1			2	6	1				7						0						0	3					3						0	12
	4			1			1	1					1						0						0	3					3						0	5
35	1			2	3		5	3					3						0						0	1					1						0	9
	2	1		5	8	4	18	8	2	2	1		13						0						0	6		1			7						0	38
	3	3		13	10	9	35	10	1	6		1	18						0						0	4		2			6						0	59
	4	1	1	2	5	3	12	1		1			2						0						0			1			1						0	15
	5			1			1	2				1	3						0						0						0						0	4
	99			2	1	1	4					1	1						0						0	1					1						0	6
40	1			1	4	1	6						0						0						0						0						0	6
	2	1		11	12	10	34			1			1						0	2					2	1					1						0	38
	3	1		15	17	13	46			2			2						0						0	6					6						0	54
	4			10	9	10	29			1			1						0						0	1		1			2						0	32
	5	1		4	3	1	9						0						0						0	1					1						0	10
	99			1	1	1	3						0						0						0						0						0	3
45	1			2	1	2	5						0						0						0						0						0	5
	2	1		9	5	9	24	1					1						0						0						0						0	25
	3	5		13	10	14	42	2		1			3						0						0	2					2						0	47
	4	2	2	8	2	10	24			1			1						0						0						0						0	25
	5			4		4	8	2					2						0						0						0						0	10
	99					1	1						0						0						0						0						0	1
50	1						0						0						0	1					1						0						0	1
	2						0	2					2						0						0						0						0	2
	4		1	2			3	1					1						0						0						0						0	4
	5	1					1						0						0						0						0						0	1
55	4						0	1					1						0						0						0						0	1
	5	1					1			1			1						0						0						0						0	2
65	2						0						0						0	1					1						0						0	1
	3						0			1			1						0					1	1						0	1					1	3
	4	1					1						0						0						0						0						0	1
Not App	1						0						0	17	1				18						0	1					1						0	19
	2	1					1						0	117	2				119						0						0						0	120
	3						0						0	103			1		104	1					1	1					1						0	106
	4						0						0	18					18						0						0						0	18
	99						0						0	3					3						0						0						0	3
Unknown	1						0						0						0						0						0	2					2	2
	2						0						0						0						0						0	2					2	2
	3						0						0						0						0						0	1					1	1
	4						0						0						0						0						0	1					1	1
Grand Total		**24**	**4**	**111**	**93**	**93**	**325**	**63**	**5**	**18**	**1**	**3**	**90**	**258**	**3**	**0**	**1**	**0**	**262**	**5**	**0**	**0**	**0**	**1**	**6**	**134**	**1**	**5**	**0**	**0**	**140**	**7**	**0**	**0**	**0**	**0**	**7**	**830**

* Injury Severities:

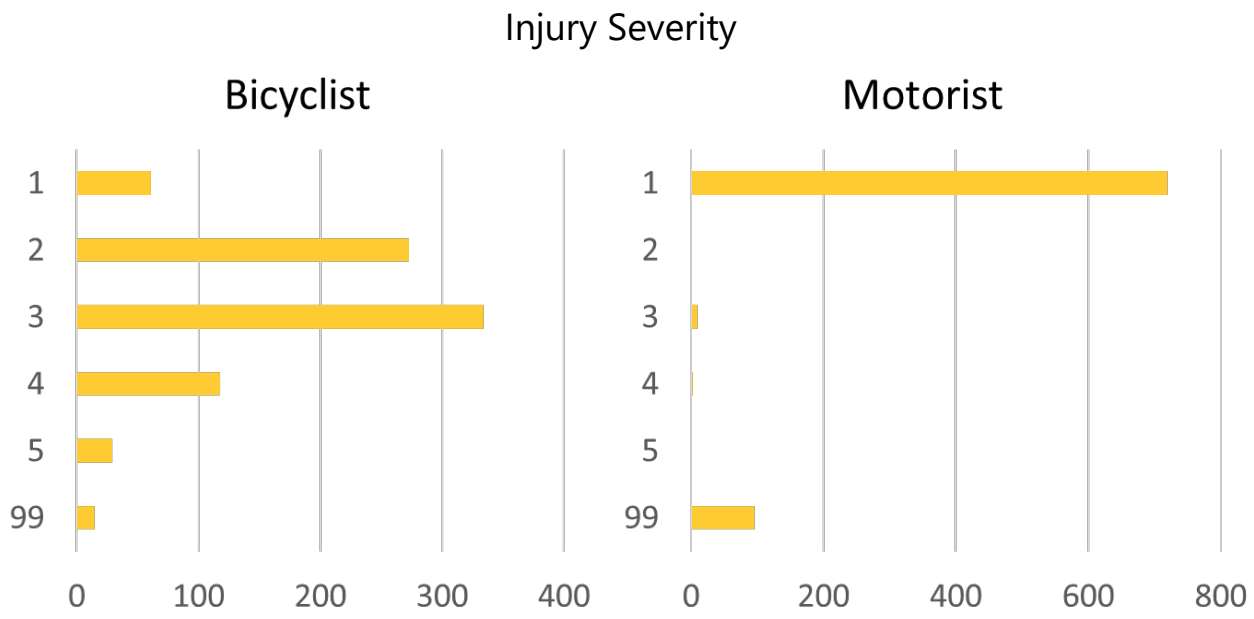
1	No injury
2	Possible Injury
3	Non-incapacitating injury
4	Incapacitating injury
5	Fatal injury
99	Unknown injury

Note: Classifications pertain to the roadway the motorist was on just prior to the crash.

MAG Regional Bicycle Safety Analysis

Fact sheet(s) on:

- Injury severity
- Manner of Collision
- Unit Actions
- At Fault
- Violations
- Time of Crashes
- Lighting Conditions
- Situations involving Serious or Fatal Injury

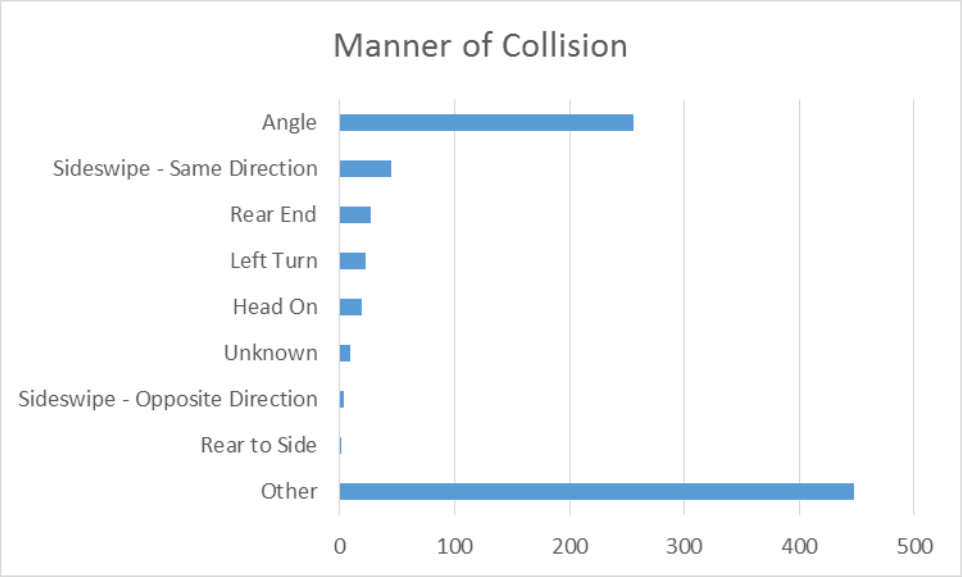


Injury Severities:

1. No injury
2. Possible injury.
3. Non-incapacitating injury
4. Incapacitating injury
5. Fatal injury
99. Unknown injury

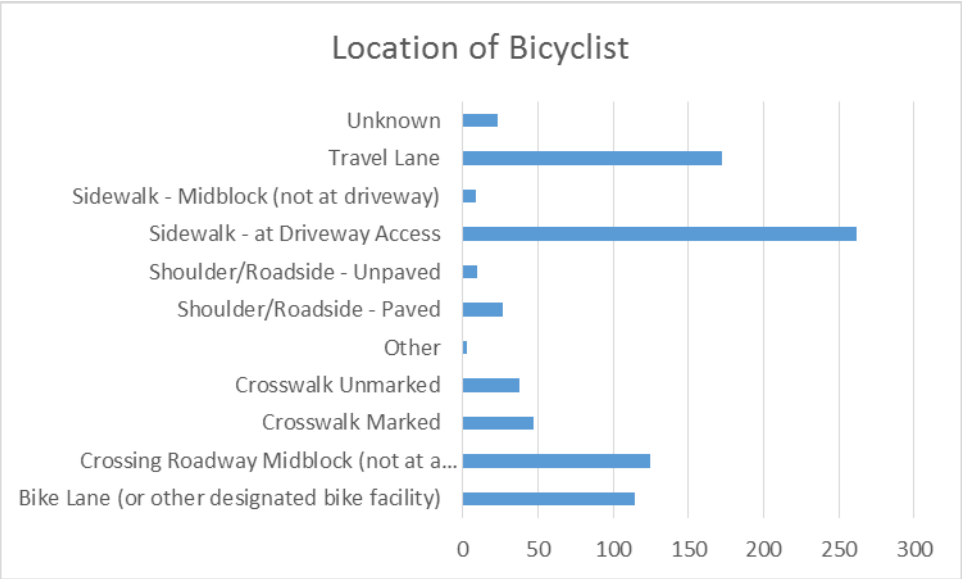
Bicyclists are much more likely to be injured in crashes than motorists. For crashes where the cyclist's injury level is known, about 7 percent of cyclists escaped a bike crash without any injury. The other 93 percent of cyclists were injured, with severity level 3 the most frequent. The study included 29 crashes in which cyclists experienced a fatal injury.
For crashes where the motorist's injury level is known, 98 percent of motorists were uninjured.

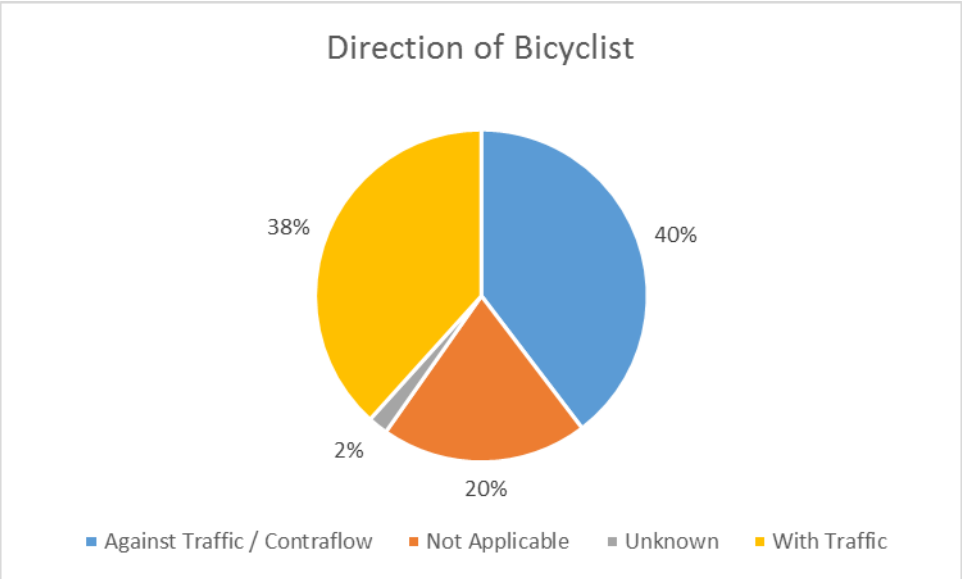
Manner of Collision



Angle crashes are the most common manner of collision among bike crashes evaluated, accounting for 31 percent of all crashes. However, the manner of collision was coded as "other" on 54 percent of crash reports, indicating the wide variety of bike crashes that occur and the lack of a clear crash type applicable to many bike crashes.

Unit Actions

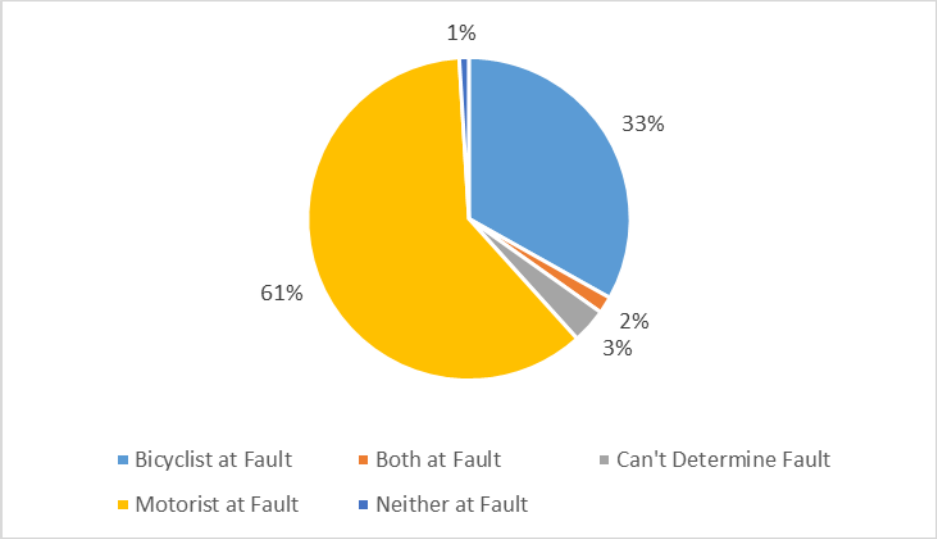




Cyclists involved in crashes are most commonly riding on a sidewalk where they are struck by a motorist entering or exiting a driveway. Cyclists in this location accounted for 31 percent of all bike crashes. The other most common locations for cyclists in crashes are in a travel lane (about 20 percent of crashes) and crossing a roadway midblock (about 15 percent of crashes). Cyclists in bike lanes were involved in about 14 percent of crashes.

Cyclists in crashes were about equally distributed between traveling with traffic and traveling against traffic. About 20 percent of bike crashes involved cyclists not traveling parallel to a roadway (such as crossing a road).

Fault



In many bike crashes, assessing fault is reasonably straightforward. However, a note is required about assignment of fault in crashes where a bicyclist on an arterial is struck by a motorist entering or exiting the arterial at a driveway or side street.

Arizona law (ARS 28-815.A) requires cyclists to stay to the right side of the roadway (with several exceptions). State law does not contain any such requirement for cyclists on sidewalks. As such, cyclists on sidewalks are generally permitted to ride in either direction and are thus not determined to be at fault in crashes even when they are traveling against traffic, on the left side of the street. Rather, state law requires motorists to yield before entering a roadway. While state law is not as clear as desirable, for the purposes of this study, the motorist is designated at fault for failing to yield to a cyclist on a sidewalk, regardless of the cyclist's travel direction.

On the contrary, if a cyclist is traveling in the roadway, whether in a travel lane or bike lane, ARS-28-815 applies, and the cyclist is generally determined to be at fault if involved in a crash with a motorist entering or exiting a driveway or side street.

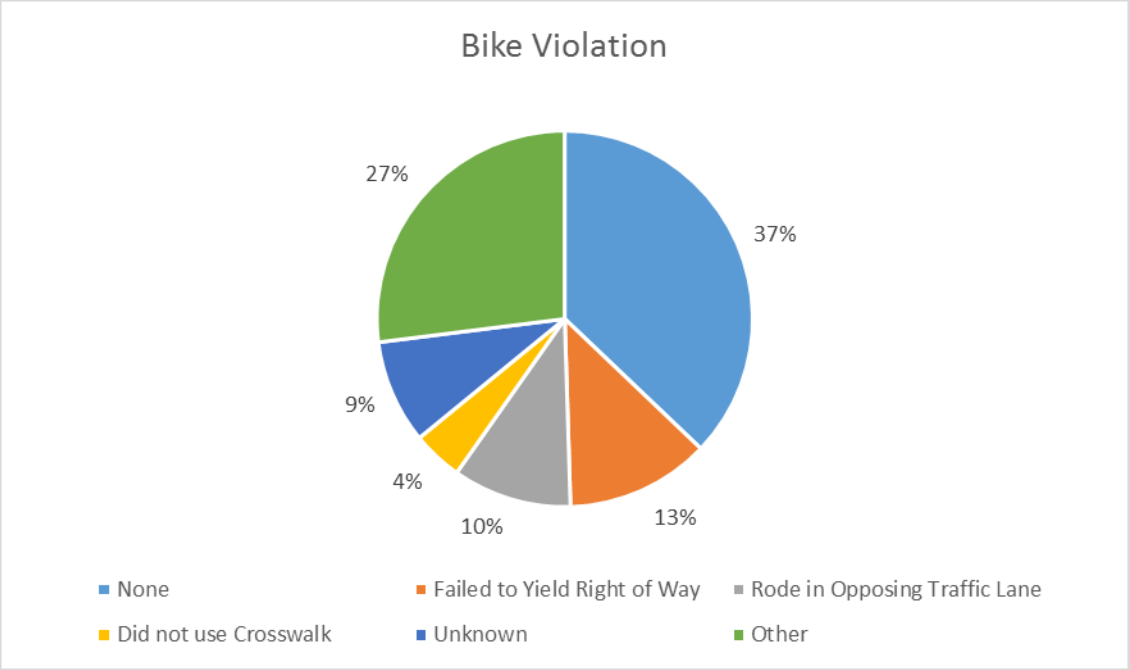
The City of Tempe has a longstanding ordinance prohibiting cyclists from riding on sidewalks on the left side of the street (against traffic). In this study, crashes in Tempe were assigned fault in the same way as the rest of the MAG region for consistency. The study found that 29 crashes (about 3 percent of all crashes) of this type occurred in Tempe over the 3-year analysis period. These crashes were all designated in this study with the motorist at fault even though the cyclist was at fault in accordance with Tempe's

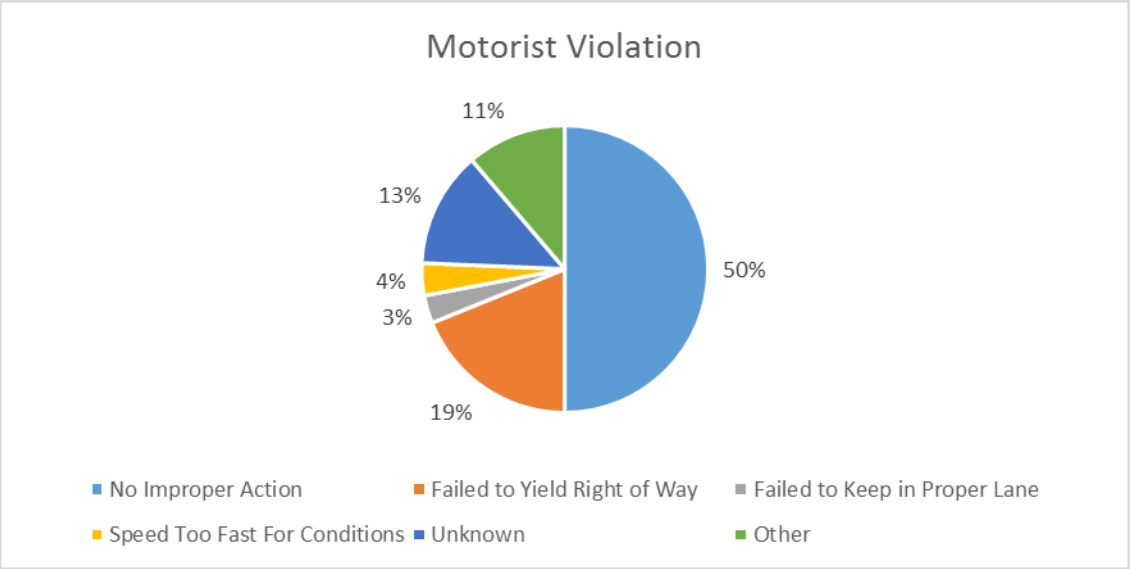
ordinance. In these 29 crashes, responding officers issued a citation to the cyclist on 23 occasions, mostly in violation of city ordinance 7-52.C.

An ordinance in the City of Scottsdale took effect on December 13, 2018, modifying the city code to require cyclists riding on the sidewalk to yield to motorists on conflicting driveways and side streets (17-82.c). This ordinance had not been adopted during the period from 2015 to 2017 when this study's crashes occurred, but it is mentioned here for completeness and context.

Officers responding to bike crashes do not always assign fault appropriately according to state and local laws. For instance, several crash reports were identified where officers cited a cyclist for riding against traffic on the sidewalk even though it is not illegal. For the purposes of this study, fault was assigned consistently for all crashes based on the methodology above, regardless of the findings of the responding officer.

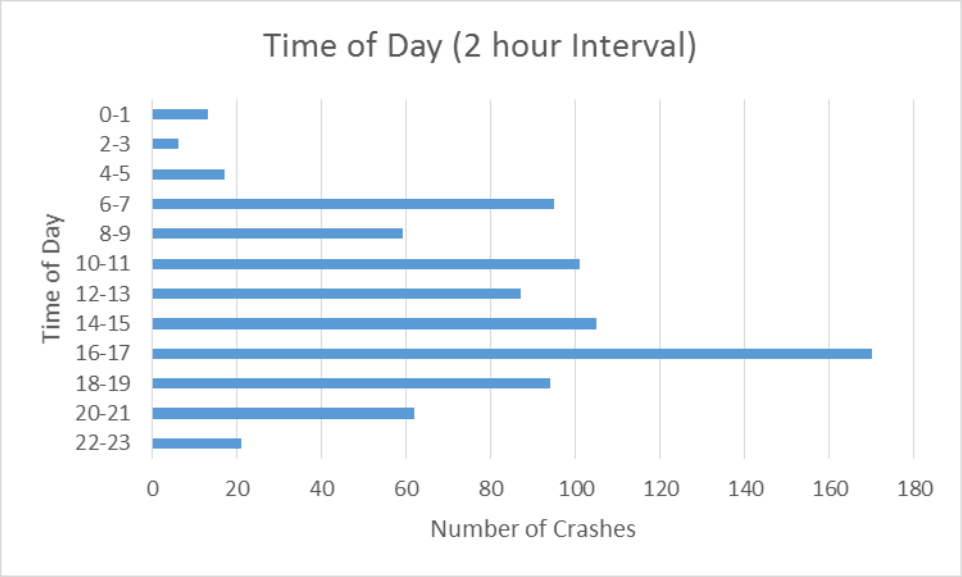
Violation





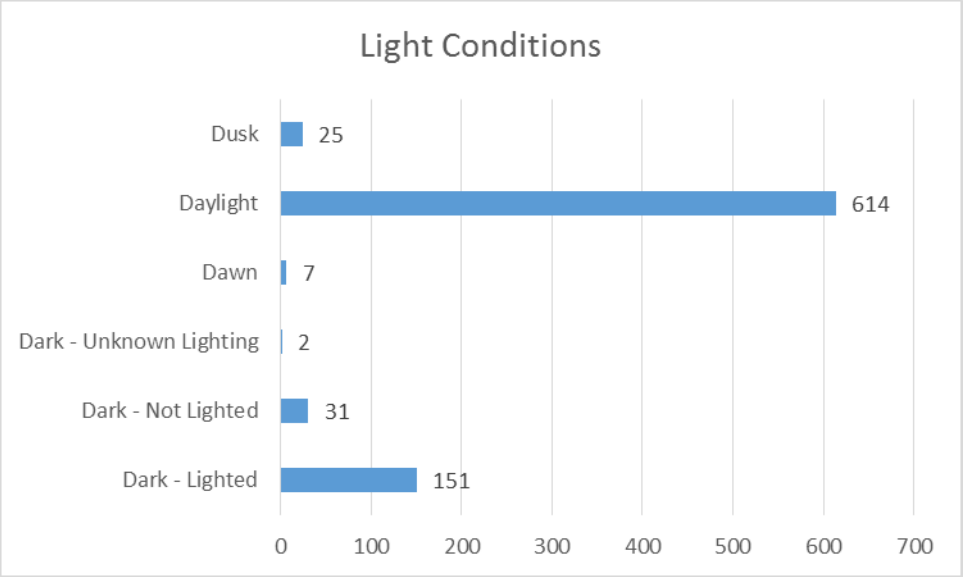
Responding officers found that about 37 percent of cyclists and 50 percent of motorists involved in crashes did not commit a violation. The most common violation for both cyclists and motorists was a failure to yield right-of-way, an issue for cyclists in 13 percent of crashes and for motorists in 19 percent of crashes.

Time of Day



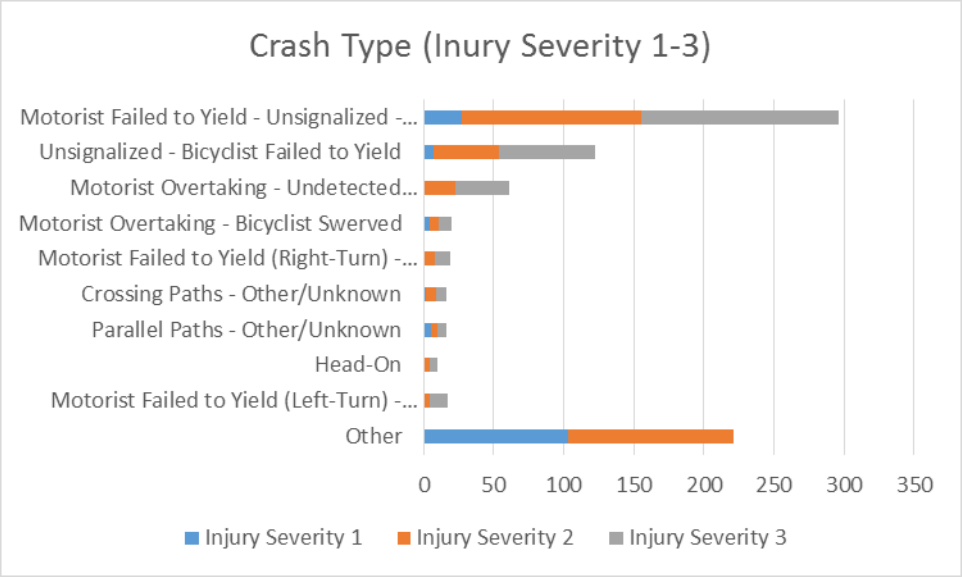
The most common time of day when bike crashes occur is the two-hour period between 4:00 and 6:00 p.m., when about 20 percent of crashes occur. No similar spike exists during the morning peak traffic period; rather, the remaining daylight hours all have somewhat similar crash experience.

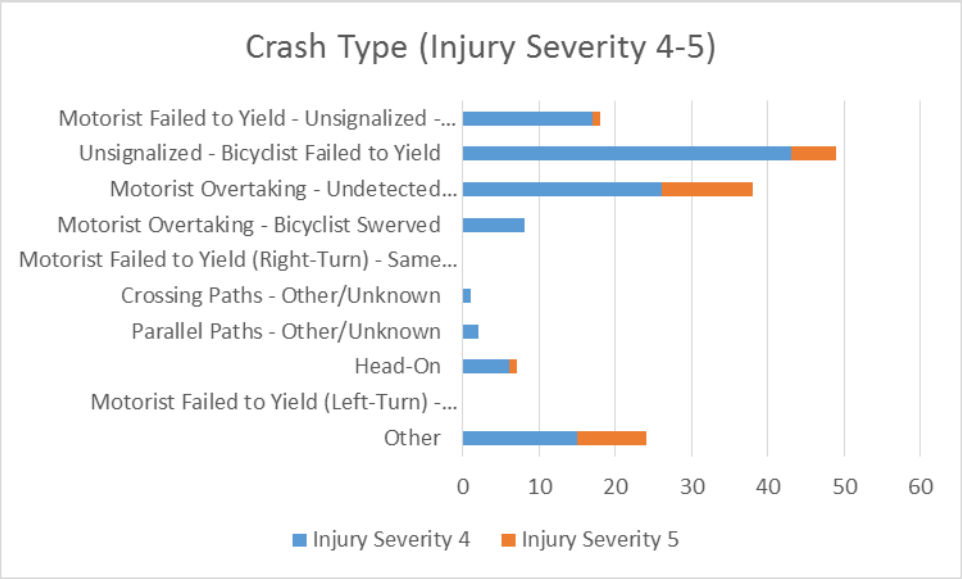
Light Conditions



In the MAG region, the vast majority of crashes, about 74 percent, occur during daylight hours. Among crashes during hours of darkness, far more occurred on roadways with lighting than on roadways without lighting.

Situations involving serious or fatal injury





Types of crashes involving fatal and incapacitating injury are largely similar to those causing no injury or lesser injury. However, a major area of difference is in the crash type involving motorists overtaking an undetected cyclist. This crash type is much more likely to cause fatal or serious injury than other crash types. It is the most common cause of fatal injuries among cyclists; this crash type alone accounts for 41 percent of cyclist fatalities. Likewise, 37 percent of crashes of this type result in incapacitating or fatal injury, a greater percentage than any other crash type.

The crash type next most likely to cause an incapacitating or fatal injury is cyclists' failure to yield at unsignalized locations. This crash type leads to injury severity 4 or 5 in 28 percent of crashes.

Relationship between presence and type of bicycle facility in crash and injury severity

Bicycle Facility Type	Injury Severity *						Grand Total
	1	2	3	4	5	99	
Bike Lane	19	67	115	29	9	1	240
Buffered Bike Lane (1-Way)	2	3	4	3			12
Designated Multi-Use Path		2					2
None	39	199	212	86	20	13	569
Shared Lane - Markings Present		1	3			1	5
Unknown	1	1					2
Grand Total	**61**	**273**	**334**	**118**	**29**	**15**	**830**

* Injury Severities:

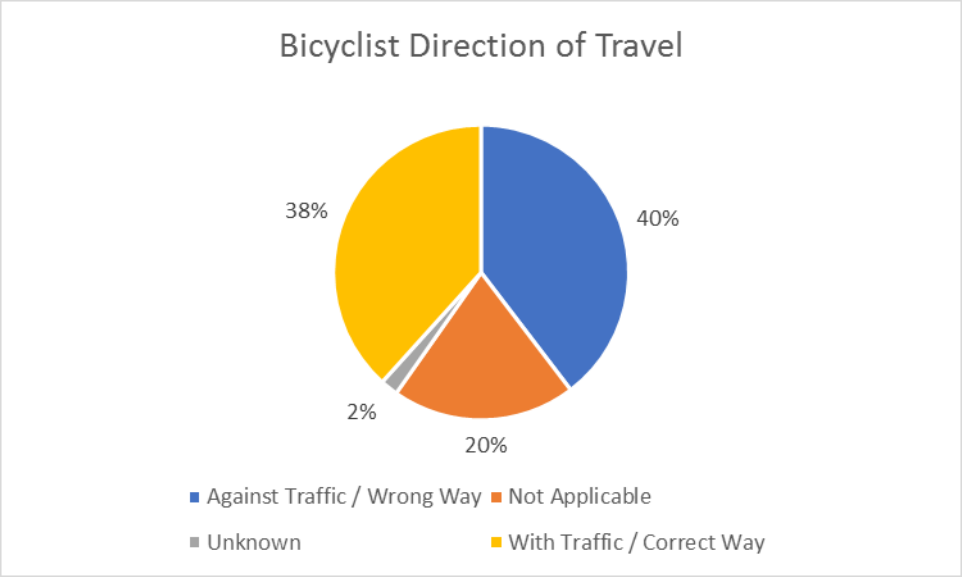
1	No injury
2	Possible Injury
3	Non-incapacitating injury
4	Incapacitating injury
5	Fatal injury
99	Unknown injury

MAG Regional Bicycle Safety Analysis

Fact sheet(s) on:

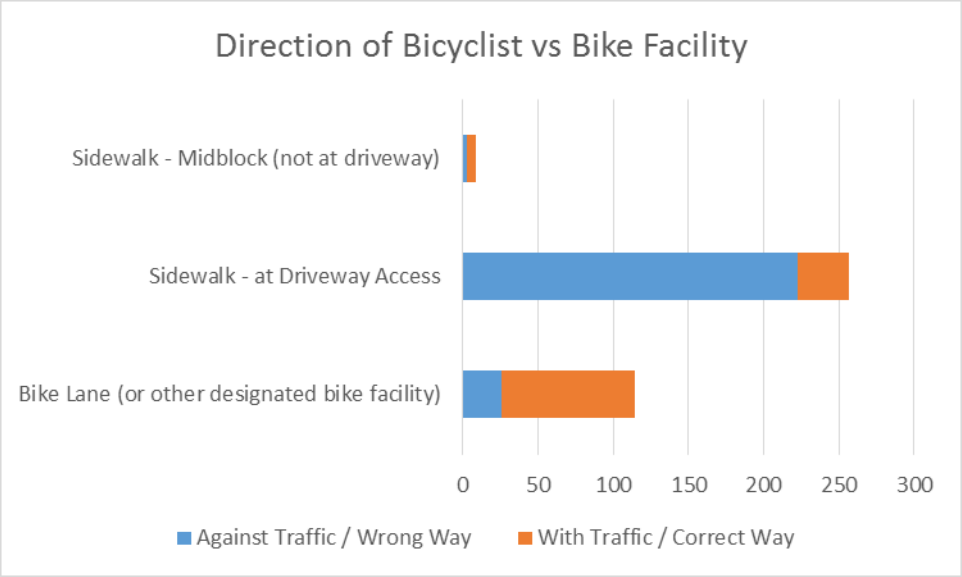
- Direction of travel
- Direction of travel vs. bike facility
- If bicyclist used existing facility
- Fault
- Relationship: Riding behavior/location and severity

Direction of Travel



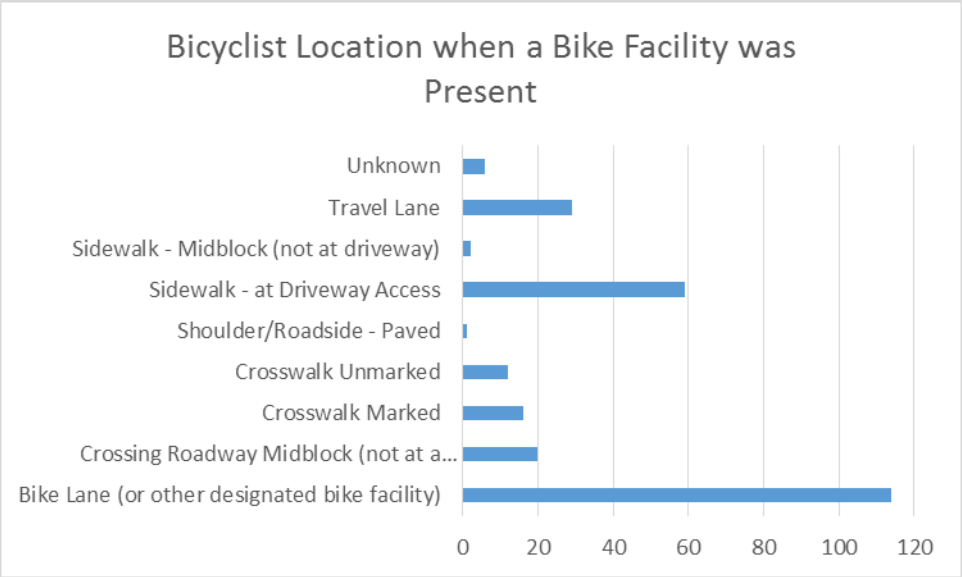
It was found that 38 percent of the time, bicyclists traveled with traffic and 40 percent of the time they traveled against traffic. In 20 percent of crashes, the direction of travel was coded as "Not Applicable," which signifies the bicyclist crossing the street or initiating some other turning movement. Two percent of the time the bicyclist's direction of travel was unknown.

Direction of Bicyclist vs. Bike Facility



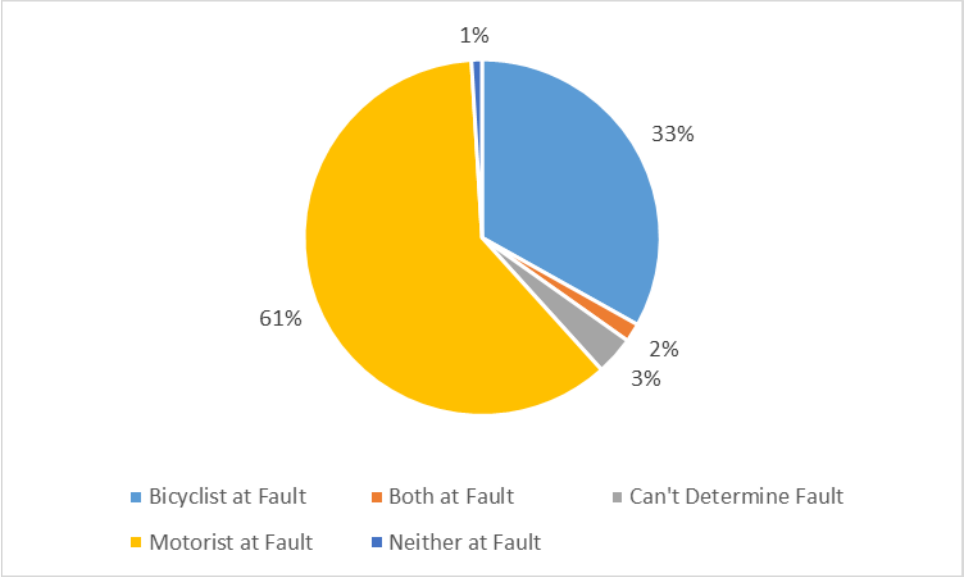
Most crashes occurred when the bicyclist was riding on the sidewalk. 87 percent of these were against traffic and the remaining percent was with traffic. The most common reason for this type of crash is a driver exiting a driveway, typically waiting to make a right turn. The driver will be looking to their left, waiting for a break in traffic to enter the roadway. They will usually not look to their right, which is the direction an against-traffic bicyclist would be coming from. Bicyclists who were riding in the bike lane when a crash occurred were riding with traffic 77 percent of the time and against traffic 23 percent of the time. A very small percentage of crashes occurred on the sidewalk not at a driveway. 67 percent were with traffic and 33 percent were against traffic.

Bicyclist Location when a Bike Facility was Present



When bike lane is present, the bicyclist would use the bike lane only 44 percent of the time. The bicyclist would use the sidewalk 25 percent of the time, even though a bike lane was present. Four percent of the time the bicyclist rode in the travel lane.

Fault



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Relationship among bicylist riding behavior, riding location, and injury severity							
Bicyclist Riding Behavior and Location	Injury Severity *						Grand Total
	1	2	3	4	5	99	
Bicyclist riding Against Traffic / Wrong Way	**25**	**143**	**130**	**26**	**3**	**2**	**329**
Bike Lane (or other designated bike facility)	2	9	11	3	1		26
Crossing Roadway Midblock (not at a crosswalk)		1			1		2
Crosswalk Marked	3	12	3				18
Crosswalk Unmarked	3	7	10				20
Shoulder/Roadside - Paved			2	1			3
Shoulder/Roadside - Unpaved			2				2
Sidewalk - at Driveway Access	16	100	92	13		2	223
Sidewalk - Midblock (not at driveway)		1	1	1			3
Travel Lane		11	8	6	1		26
Unknown	1	2	1	2			6
Bicyclist riding With Traffic / Correct Way	**22**	**85**	**137**	**46**	**20**	**8**	**318**
Bike Lane (or other designated bike facility)	4	14	48	16	5	1	88
Crossing Roadway Midblock (not at a crosswalk)	1		2	1			4
Crosswalk Marked	1	3	4				8
Crosswalk Unmarked	1	1	7	1			10
Shoulder/Roadside - Paved		9	8	3	2	2	24
Shoulder/Roadside - Unpaved			4		1		5
Sidewalk - at Driveway Access	2	11	17	3		1	34
Sidewalk - Midblock (not at driveway)	1	2	1		2		6
Travel Lane	10	42	44	21	10	3	130
Unknown	2	3	2	1		1	9
Bicyclist side of street Not Applicable (tpyically when the cyclist is crossing a street)	**10**	**39**	**63**	**44**	**6**	**5**	**167**
Crossing Roadway Midblock (not at a crosswalk)	3	29	40	38	5	4	119
Crosswalk Marked	3	5	11	2			21
Crosswalk Unmarked		1	3	2		1	7
Other			2				2
Shoulder/Roadside - Unpaved	1		1				2
Sidewalk - at Driveway Access		1	1				2
Travel Lane	3	3	5	2	1		14
Bicyclist side of street unknown	**4**	**6**	**4**	**2**			**16**
Crosswalk Unmarked	1						1
Other				1			1
Shoulder/Roadside - Unpaved		1					1
Sidewalk - at Driveway Access		2	1				3
Travel Lane		1	1				2
Unknown	3	2	2	1			8
Grand Total	**61**	**273**	**334**	**118**	**29**	**15**	**830**