Patterns of Disparity in Cycling Infrastructure:
A Comparison of Neighborhood Access in Denver

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Environmental Design Honors Thesis

University of Colorado at Boulder

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Topic:
Social Equity and Active Transportation

Research Question:
How does the quality and safety of cycling infrastructure vary between low- and high-income neighborhoods in Denver?

Contribution:
Provide an analysis of bicycle crash locations and current infrastructure with neighborhood income levels to determine if a disparity exists in the type, quality, and safety of cycling infrastructure.

ACKNOWLEDGMENTS

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ABSTRACT

Background: Bicycling has the potential to improve fitness, reduce emissions and air pollution, boost the local economy and attract tourism, and cycling activity is booming in Denver. Between 2005 and 2016, cycling grew by 54%, with an estimated 8,181 cyclists in 2016. Over 607 miles of bicycle lanes have been installed in Denver as of last year, providing residents with the option of a more sustainable and active mode of transportation.

This study finds three issues on how the development of new infrastructure has proceeded over the last few years, including:

- The lack of cycling infrastructure in low-income communities
- The vulnerability (crash statistics) of current infrastructure
- The unjust process of implementing cycling infrastructure improvements

Methods: This thesis investigated three realms of the transportation planning process - infrastructure data, transportation policy, and implementation. The data process included a GIS analysis of current infrastructure, crash data, and commuting information. The policy and implementation process included extensive literature analysis and interviews with bicycle advocacy leaders.

Results: Low-income neighborhoods have less access to cycling infrastructure, at roughly 34% or 209 miles, yet these neighborhoods account for 48% of all bicycle-vehicle crashes in Denver. Of the 2285 crashes that have occurred between 2012 -2018, 85% have occurred at an intersection. Recent policies changes have increased available funding for bicycle infrastructure, yet Denver is only allocating 16% of its total budget to improving at-risk intersections. Denver's implementation process is two-fold - data collection and public outreach, with the former being the city's primary method for building new bike facilities. Public outreach is limited to (affluent) communities who have the time and resources to advocate for bike facilities.

Recommendations: Denver's approach to expanding its bicycle network is limited to the available data, infrastructure policies and funding, and public outreach. Based on infrastructure and crash data, Denver should focus its attention on improving intersection safety, yet limited funding is being directed to these areas. Furthermore, Denver should embrace inclusive strategies in its public outreach process that incorporate more diverse neighborhood groups.

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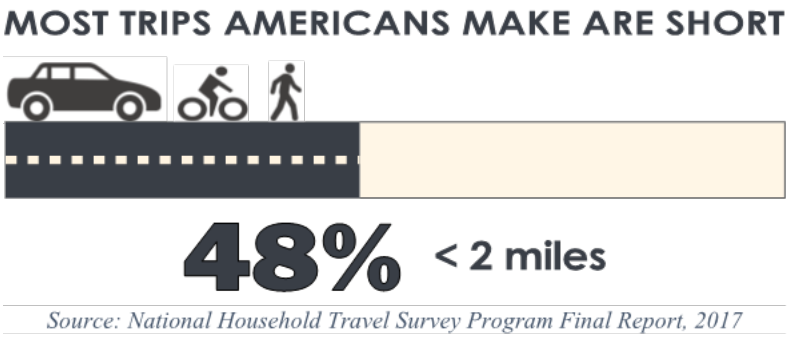
INTRODUCTION

Bicycling is an active mode of transportation that can effortlessly combine physical activity and commuting into daily life. Those who have ridden in a good biking city would agree that cycling is an enjoyable form of transportation (Speck 2012, pg. 190). On top of its ease of use and versatility, bicycling is an appealing alternative to the automobile as it is associated with a range of individual environmental benefits, including improved physical and mental health, decreased obesity and risk of cardiovascular diseases, reduced air pollution, noise, and greenhouse gases.

In terms of average daily trip distances, bicycles are one of the most efficient modes of transportation. In a given day, 48% of all trips taken in American cities are shorter than two miles (Chajka-Cadin et al. 2017; Pucher and Buehler 2006). Using the same amount of energy as it takes to walk, bicycles can transport you three times the distance in half the time (Gehl 2010, pg. 105).



Planning for Bicycles in Denver: Growth and Justice

Cycling is booming in Denver. According to official counts, commuter cycling increased by 54% between 2005 and 2016, with an estimated 8,181 cyclists in 2016 (The League of American Bicyclists 2018). Over 607 miles of bicycle lanes have been installed in Denver as of 2016, providing residents with the option of a more sustainable and active mode of transportation

(City of Denver 2018). Despite the growing popularity of commuter cycling, two problems related to the development of infrastructure have emerged; an increase in population and transportation needs and infrastructure inequality.

Mobility is directed correlated to opportunities, such as employment, social activities, health care, and consumer needs. Throughout the last decade, transportation infrastructure and demand in Denver, CO has grown considerably, yet there are significant disparities in access. Using literature on transportation equity, bicycling trends, active transportation research, federal and state policies, and interviews, this research looked to understand why access to cycling infrastructure differed between demographic boundaries. First, new bike lanes are primarily concentrated in the Lower Downtown (LODO), Cherry Creek, and Stapleton neighborhoods. This concentration directs cyclists to the central business district, which excludes a large number of cyclists in the surrounding neighborhoods, particularly low-income communities who might regularly use their bike to commute around town. Second, these neighborhoods are more expensive to live in, which means that most of the cycling infrastructure caters to high/mid-income level residents. People living in these districts, hypothetically, can afford to own personal vehicles and may not regularly commute by bike. Third, most funding is being directed toward improving or constructing new cycling infrastructure in high/mid-income neighborhoods. Using an in-depth literature review and GIS analysis of Denver's bicycle network, this research seeks to understand why cycling levels vary between demographic boundaries, asking the questions: *Are low-income communities more susceptible to poor quality and unsafe cycling infrastructure?*

BACKGROUND

The Bicycle as a Commuting Option

With 48% of daily commuting trips being under three miles, bicycling has the potential to be a dominant mode of travel. Reasons for its lack acceptance as a utilitarian transportation option, however, fall into the general categories of *public attitude and cultural differences, public image,* and *climate and topography* (Pucher, Komanoff, and Schimek 1999).

Public Attitude and Cultural Differences

Bicycling, both as a tool for commuting and recreation, varies across socio-demographic boundaries and can come with significant cultural stigmas depending on the context of research. Cultural norms and transportation trends indicate that bicycling is considered an expensive activity. In a focus group of African, African American, and Hispanic Portland residents, over 60% of the participants said that the biggest obstacle to cycling was buying the bicycle (Community Cycling Report 2012). The study also found that 35% of the participants did not own a bicycle because they did not have a safe place to store it (Community Cycling Report 2012). The connection is that bicycling, whether in Portland or Denver, is not seen as a universal activity, mainly when looking at socio-demographic boundaries.

In cities across Northern Europe, the Netherlands and Denmark mainly, bicycling is a necessity across age groups, economic backgrounds, and ethnicities (Pucher and Buehler 2016). Nearly 27 percent of all trips are made on the bicycle (Mapes 2009, pg. 65), with 95 percent of all students ages ten-to-twelve cycling to school every day (Walljasper 2010). Women, on average, make more daily bike trips than men, and roughly a quarter of all bikes trips are made by person ages 65 or older (Pucher and Dijkstra 2000).

While these statistics are reflective, it is important to remember that the bicycle was adopted early-on in response to increased population and congestion concerns. Like many cities in the 1960s, Amsterdam was on its way to becoming car-friendly (Shorto 2011). Rather than widening streets to accommodate the automobile, like nearly every American city, Amsterdam saw an opportunity to increase capacity without increasing congestion - i.e., the bicycle (Speck 2012, pg. 193).

For many American cities, bicycling is seen as on the fringes of acceptable transportation (Pucher and Buehler 2016, pg. 21). The majority of people on bikes are using them as recreation tools rather than an alternative to vehicular commuting; cycling only accounted for 0.9% of all trips taken in 2016 (*see Table 1*) (Denver Streets Partnership 2018; The League of American Bicyclists 2016).

Location	Bike-Ped Funding	% Bike Commuters	# Bike Commuters	Population
United States	*$1.5 B*	*0.9%*	*2,940,900*	*326,766,748*
Seattle, WA	$30 M	3.50%	14,801	704,358
Oklahoma City, OK	$25 M	0.30%	1,005	638,311
Cleveland, OH	$19 M	1.10%	1,621	385,810
Columbus, OH	$15 M	0.60%	2,523	862,643
El Paso, TX	$15 M	0.40%	1,098	683,088
San Jose, CA	$11 M	0.80%	3,900	1,406,622
San Antonio, TX	$9.5 M	0.10%	949	1,492,494
Denver, CO	$5 M	2.20%	8,181	693,060

Table 1: A Comparison of Bike-Ped Funding and Ridership
Source: Denver Streets Partnership 2018; League of American Bicyclist 2016

Public Image

Bicycling in America is not bound to a single image but takes on multiple perceptions dependent on the type and context. Recreational cycling, for instance, invokes a youthful and vigorous image as it relates to sport and fitness. Bicycling also boosts a positive environmental image with its zero-net carbon emissions, low noise pollution, and minimal energy use. Despite

this positive image, the cyclist is seen as the renegade commuter weaving in-and-out of traffic lanes, running red lights, and bumping pedestrians off the sidewalk (Pucher and Dijkstra 2000). Cyclist in these situations are often associated with the "anti-car" or "deviant" rhetoric, just lying outside the mainstream American life that encourages automobile use (Pucher, Dill, and Handy 2010).

One of the reasons why this renegade behavior is so prevalent in cities is the idea of vehicular cycling - a technique where the rider treats the bike as if it were another car on the road. In the words of its founder, John Forester: "The vehicular-style cyclist not only acts outwardly like a driver, he knows inwardly that he is one. Instead of feeling like a trespasser on roads owned by cars he feels like just another driver with a slightly different vehicle" (Forester 2001, pg. 3). For Forester, this issue of safety stems from the belief that cyclists are considered 'second-class citizens' compared to other forms on the road. He has even gone so far as to discredit separated bike lanes because they make cyclists inferior (Speck 2012, pg. 200).

While this tactic addresses the more significant systemic issue of universal safety on the street, there are two issues with this approach. The first is that cycling is not appropriate for all types of roads, such as state highways (Denver's I-25) and large-capacity arterial streets (Speer Blvd), based on their sheer size and capacity. The second, and more importantly concerning equity, is that vehicular cycling appeals to a small window of the cycling population. In this scenario, cyclists must continually evaluate traffic, signal and adjust speeds, and blocking lanes as if they were another car. Most people, particularly children and the elderly, find this 'dance with traffic' as an extremely stressful and unpleasant experience (Pucher and Buehler 2016, pg. 62). Even if vehicular cycling forces the cyclist to be recognized on the street, it does little for increasing his/her safety and overall acceptance as a mode of travel. If the goal of increasing

ridership is to improve safety, more emphasis should be put to creating bike facilities in appropriate locations that bolster a shared sense of the road.

Climate and Topography

Climate and topography are often factors that govern the adaptability of outdoor activities, such as winter sports in a mountainous region or surfing along a coastal area. This is true for bicycling as well, yet transportation trends indicate that they have less influence on particular regions, mainly for regions with already strong cycling culture. Cities in Canada, which tend to have extreme winters, have twice the amount of bicycle commuters compared to similarly sized American cities (*see Figure 1*) (Pucher and Buehler 2006, pg. 273). Canada's high rates of bicycle commuting are due to the prevalence of increased urban densities, mixed-use development strategies, and the prominence of safe cycling infrastructure (Speck 2012, pg.192)

Population size	USA			Canada		
	Metropolitan area	Kilometres of bike paths and lanes per 100,000 pop.	Bike modal share (%)	Metropolitan area	Km of bike paths and lanes per 100,000 pop.	Bike modal share (%)
Over 5 million						
	Los Angeles	7.3	0.6			
	Philadelphia	23.1	0.3			
	Chicago	4.6	0.3			
	New York	4.1	0.4			
	Average	9.8	0.4			
3–5 Million						
	Washington DC	14.0	0.3			
	Houston	21.4	0.3	Toronto	8.7	0.8
	Boston	3.8	0.6	Montreal	29.3	1.3
	Average	13.1	0.4		19.0	1.1
1 Million–2,999,999						
	Minneapolis	34.5	0.4			
	St Louis	26.4	0.1			
	Seattle	14.5	0.7	Vancouver	29.0	1.9
	Pittsburgh	10.0	0.1	Ottawa	65.9	1.9
	Denver	28.6	0.4			
	Portland	60.9	0.8			
	San Francisco	8.7	1.4			
	Milwaukee	7.0	0.2			
	New Orleans	3.4	0.6			
	Average	21.6	0.5		47.5	1.9
500,000–999,999						
	Madison	37.6	1.7	Calgary	68.3	1.5
	Fresno	5.4	0.7	Edmonton	64.6	1.2
	Raleigh	14.4	0.4	Quebec	54.0	1.3
	Average	19.1	0.9		62.3	1.3
National average		17.4	0.5		45.7	1.4

Figure 1: Cycling Facilities in Selected Canadian and American Cities
Source: Pucher and Buehler 2006, pg. 273

Why Infrastructure Matters: Reducing Fatalities

The Center for Disease Control and Prevention injury statistics website (WISQARS) reports that in 2017 there were 1,024 cyclist fatalities and 329,831 nonfatal injuries in the United States (Center for Disease Control and Prevention 2017). Compared to other high-income countries, the United States has much higher rates of fatal and nonfatal injuries per kilometer cycled (Pucher and Buehler 2016, pg.2089). Cyclists (per 100 million kilometers cycled) are 4.7 times more likely to be killed or seriously injured in the United States than in the Netherlands, Denmark, or Germany (Buehler and Pucher 2017, pg.285) (*see Table 2)*.

Country	No. of Cyclists Fatalities	No. of Cyclists Serious Injuries
United States	1,024	329,831
The Netherlands	206	1,049
Denmark	27	766
Germany	382	79,000

Table 2: Number of Cyclists Fatalities/Serious Injuries in 2017
Source: Buehler and Pucher 2017; Center for Disease Control and Prevention 2019

The issue of road safety in the United States has led to several movements organized around the goal of eliminating all traffic deaths and serious injuries, otherwise known as Vision Zero (Cushing et al. 2016; The League of American Bicyclists 2018, pg.57). Based on the data, safety for cyclists in the United States has a long way to go to achieve this goal. One of the critical intentions behind Vision Zero is that all traffic fatalities and serious injuries are preventable. Rather than seeing these incidences as the cause of human error, system-level policies can be implemented to improve infrastructure and technology (Cushing et al. 2016; Vision Zero Network 2018). This shift is also representative of the current terminology. Experts in safety now use the term “crash” instead of “accident” to emphasize that design is the main contributor to most traffic fatalities and injuries (Pucher and Buehler 2016, pg.2089).

Infrastructure and Accessibility

In the urban context, infrastructure and accessibility research focuses on several realms, including access (or proximity) to affordable housing, nutritious food, health services, and employment (Delmelle and Casas 2012; Glaeser, Kahn, and Rappaport 2008). The unifying thread in this research is that efficient transportation and neighborhood arrangement can dictate how people access these opportunities. Neighborhoods with limited sidewalk, cycling, or transit infrastructure, for instance, limit mobility to residents with access to a vehicle (McLafferty and Preston 1996). Studies show that minority groups consistently have longer commute times, which reflects greater reliance on a walk, bike, and public transit infrastructure (Carlson and Theodore 1997).

Within cities, fatality and injury rates resulting from motor vehicles collisions vary according to individual and neighborhood socioeconomic characteristics, with higher rates among vulnerable communities (Cubbin and Smith 2002; C. Cubbin, LeClere, and Smith 2000). Although many factors contribute to creating social inequalities, the thesis focuses on two broad categories of factors - the individual and the context - as directly contributing to inequalities in road traffic injury statistics.

Both income and education are well-documented individual factors; however, a cross-sectional study found that socioeconomic characteristics of individuals also exert independent effects on road traffic injuries (Cubbin, LeClere, and Smith 2000). Residents from low-income neighborhoods tend to cross more roads, confront more motor vehicles per day, and have a higher risk of injury (DeWeese et al. 2013; Zhu et al. 2011).

Low-income communities are also using more active transportation methods than in previous years. Residents who make between $10,000 - $25,000 annually have the highest rates

of walking and biking (McKenzie 2014) (see *Figure* 2). African Americans and Asian Americans have the highest growth rates of bicycling to work while Caucasians show the lowest rates (McKenzie 2014) (see *Figure* 3). On average, families and children living in low-income communities tend to bike or walk to school twice as much compared to their counterparts (McDonald et al. 2011). Studies in bicycle ridership show that Latinos and Native Americans are the fastest growing population to use bikes as a primary source of transportation. Between 2001 and 2009, these ridership numbers grew from 16% to 23% of all bicycle trips in the United States (Sierra Club Foundation 2013).

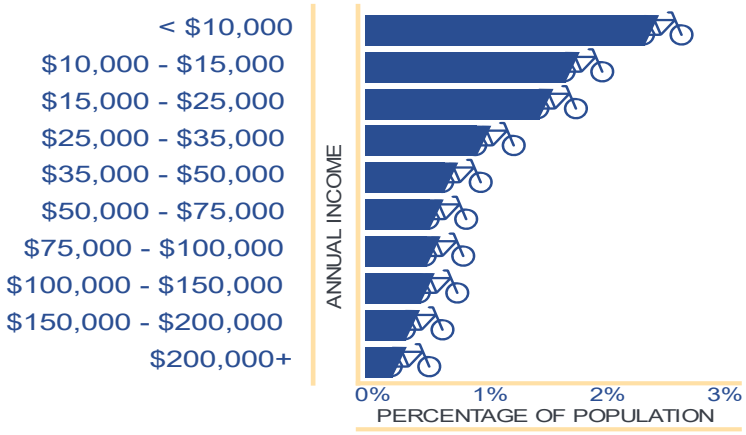


Figure 2: Bicycling to Work by Household Income
Source: U.S. Census Bureau, 2008-2012

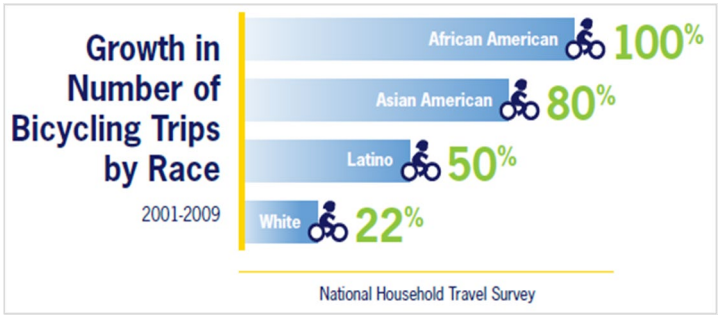


Figure 3: Growth in Number of Bicycling Trips by Race
Source: McKenzie 2014

According to McKenzie's report, bicycling rates do not vary much by income level, yet trip purposes made on a bicycle do. A study by John Pucher found that low-income residents (those making less than $10,000 annually) primarily bike for utilitarian purposes while high-income residents bike more for recreation and exercise (Pucher and Buehler 2016).

Although walking and bicycling rates have increased, the car is still the primary mode of transport in our society (Zimmerman et al. 2015). More than 10 million households, roughly 10% of the population, have no access to an automobile (American Association of State Highway and Transportation Officials (AASHTO) 2013; Babb 2016; Newman and Kenworthy 2015). Access to private vehicles across different ethnic communities is limited as well, with 13% in Latino, 20% in African American, and 12% in Asian American communities (Bell, Cohen, and Malekafzali 2006) (see *Figure* 4).

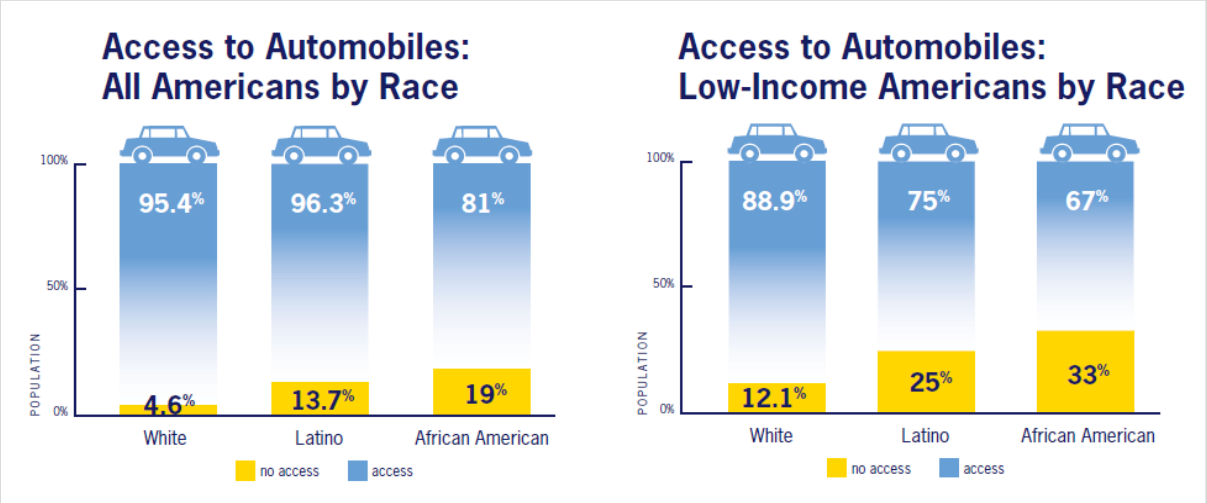


Figure 4: Access to Automobiles by Income & Race
Source: Bell et al.2006.

Travel Behavior and the Built Environment

Travel behavior is a function of three factors: density, diversity, and design. First, community density is measured by the number of buildings per land unit and is a distinct urban form characteristic that affects travel behavior (Cervero 1996; Cervero and Kockelman 1997; Ewing and Cervero 2010; Handy 1996). Higher densities and mixed land-use areas equate to shortened daily trips, further increasing the neighborhood's accessibility. Second, community diversity measures how different types of land uses influence travel behavior. Research suggests that by having different zoning types (commercial, residential, and open space) closer to residents, the probability of auto-dependent travel decreases (Cervero 1996). Finally, community design refers to the walkability of a neighborhood based on pedestrian rights-of-way, parking, and street layouts. If sidewalks are widened to accommodate more pedestrians and if parking is set to the rear of a building, the overall walkability and safety of that area are increased (Cervero 1996).

Does a Higher Income Equal Better Infrastructure?

The safety concerns discussed earlier are primarily the result of low-quality infrastructure. While 90% of all high-income neighborhoods have sidewalks on one or both sides of the street, that number drops to 49% in low-income neighborhoods (Gibbs et al. 2012). Street lighting differs as well, with over 75% in high-income neighborhoods and 51% in low-income neighborhoods (Gibbs et al. 2012). Traffic calming features, such as traffic islands and curb bulb-outs, are found three times as often in high-income areas compared to low-income areas (Gibbs et al. 2012) (*see Figure 5*).

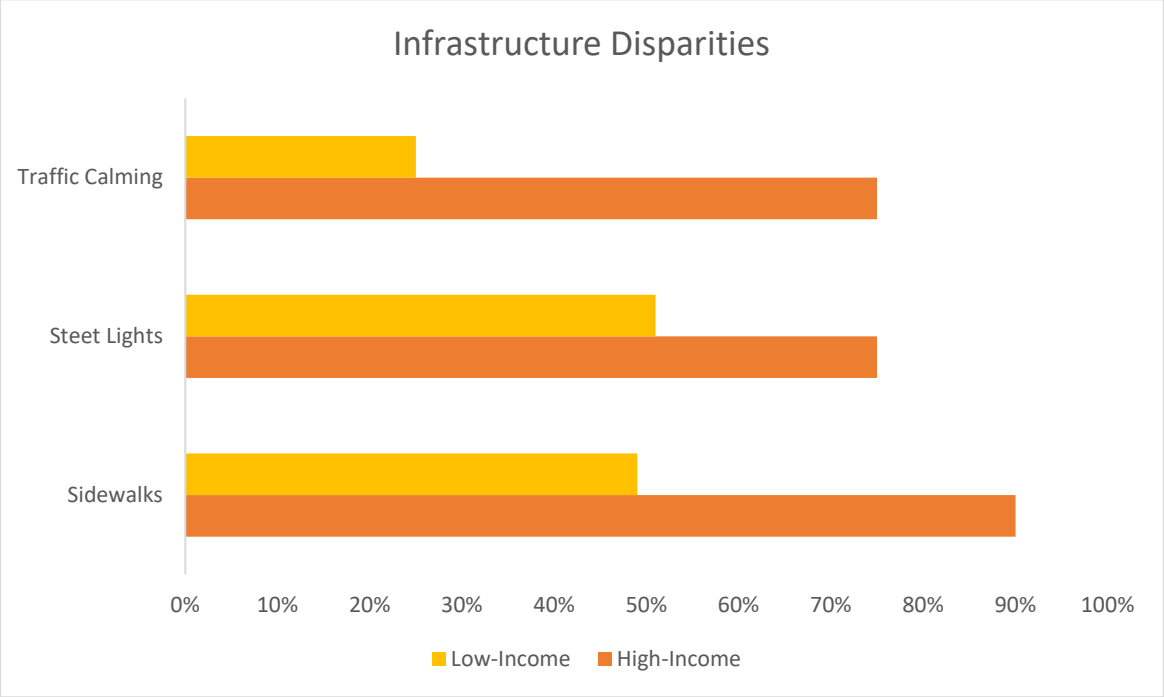


Figure 5: Infrastructure disparities between low- and high-income areas
Source: Gibbs et al.2002.

Is Urban Safety Universal?

Within the United States, vulnerable communities are walking and bicycling more than the national average, but their infrastructure remains unsafe. A five-year study by the Safe Kids Worldwide Organization found that children living in low-income communities were at a higher risk of being injured or killed while walking and bicycling than residents in upper-income communities (Dukehart et al. 2007). Fatality rates in Latino and African American communities are higher than white communities, with pedestrian fatalities at 50%, bicyclist at 30%, and vehicle occupant fatalities at 24% greater in (Dukehart et al. 2007) (*see Figure 6*).

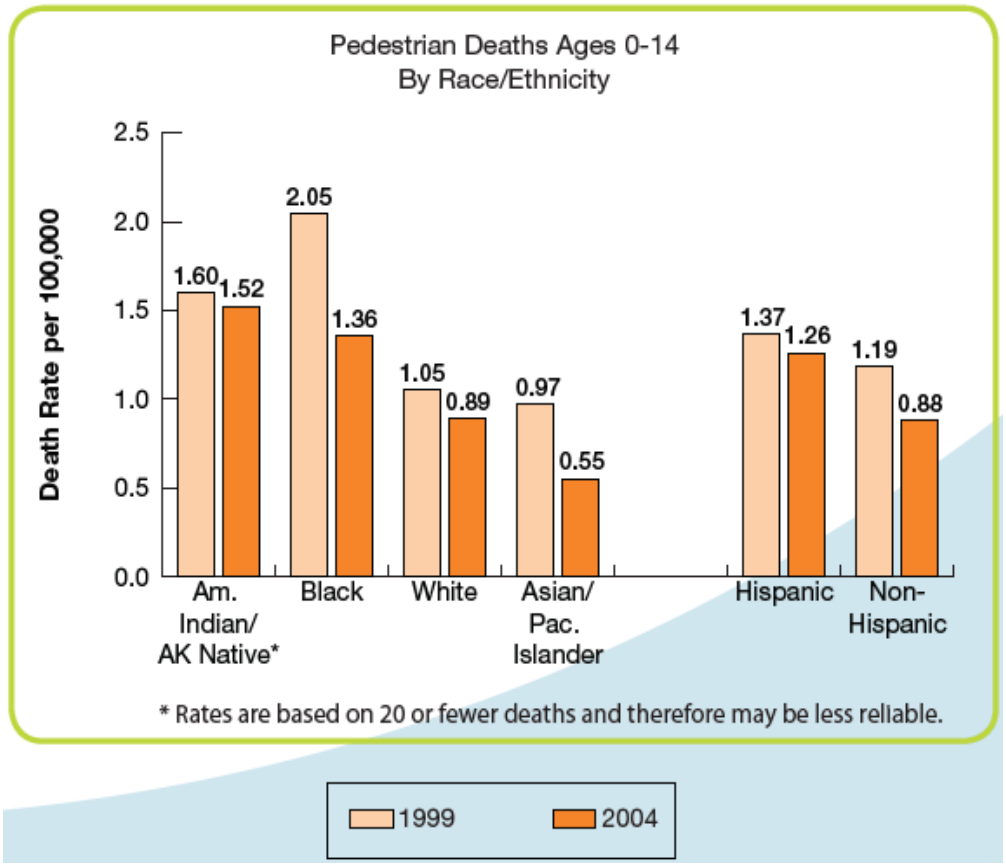


Figure 6: Pedestrian Deaths Ages 0-14 by Race/Ethnicity
Source: Dukehart et al.2007.

Degrees of Separation in Infrastructure

Multiple studies have shown that an increase in cycling infrastructure can effectively improve the number of people cycling while also reducing fatalities and injuries (Aziz et al. 2018; Gotschi 2011; Dill and Howe 2011; Parker, Gustat, and Rice 2011; Pedroso et al. 2016; Pucher, Dill, and Handy 2010; Schramm and Rakotonirainy 2009). While better infrastructure leads to higher rates of cycling, the cyclists' perception of safety can vary with different types of infrastructure.

Most roads in the United States are designed without cycling infrastructure. If it exists, it is often badly designed, poorly maintained and disconnected from a practical network (Pucher and Buehler 2016). For a cycling route to be effective, infrastructure should provide sufficient separation from traffic and support a range of intercity connections (Furth 2012, pg.108). According to Furth and Pucher et al., cycling infrastructure is classified by four degrees of separation from traffic lanes: *shared streets, bike lanes, separated lanes, and standalone paths (see Table 3).*

Degree of Separation	Description
Shared Street	Light traffic; no dedicated bike space
Bike Lane	Moderate traffic; separated by roadway striping
Separated Lane	Cycle track or shared-use path along a road; physically separated from traffic with a barrier, curb, or parked car
Standalone (multi-use)	An independent right-of-way path typically in a park or abandoned rail corridor

Table 3: Degrees of Separation for Bicycle Infrastructure

Higher degrees of separation are typically more expensive and involve a more significant amount of space to create. Therefore, the natural tendency in transportation planning is to design lower levels of separation (Furth 2012). While this approach makes sense from a city budget

perspective, separation from traffic, or lack thereof, can significantly influence the perception of safety. Increasing the amount of cycling infrastructure improves safety, yet the type and quality of infrastructure significantly influence how often people use it. Physical separation from vehicular traffic, for instance, dramatically enhances the ease of use for any bicycle route (Furth 2012).

Within the last decade, infrastructure improvements in several American cities have led to significant increases in cycling safety (Pucher and Buehler 2016, pg.2090). *Figure 7* summarizes data from 10 American cities that have successfully increased cycling safety through infrastructure expansion projects. Between 2000 and 2015, all ten cities significantly increased their cycling infrastructure, including on-road bike lanes, multi-use paths, separated bike lanes, and shared streets. As the data shows, all cities with available information have reduced the number of fatalities, and serious injuries compared to the total number of bicycle trips.

City	Years	Growth in Bikeway Network,[a] %	Growth in Bicycle Trips, %	Change in Crashes per 100 000 Trips, %	Change in Fatalities and Severe Injuries per 100 000 Trips,%
Portland, OR	2000–2015	53	391	−62	−72
Washington, DC	2000–2015	101	384	−46	−50
New York, NY	2000–2015	381	207	NA	−72
Minneapolis, MN	2000–2015	113	203	−75	−79
San Francisco, CA	2000–2015	172	167	−36	NA
Cambridge, MA	2000–2015	27	134	−57	NA
Chicago, IL	2005–2015	135	167	−54	−60
Seattle, WA	2005–2015	236	123	−25	−53
Los Angeles, CA	2005–2015	130	114	NA	−43
Philadelphia, PA	2008–2015	17	51	NA	−49

Figure 7: Improved Bicycle Infrastructure and Safety
Source: Pucher and Buehler 2016, pg.2090 (NA: no data available)

Level of Traffic Stress (LTS) Framework

Along with the availability of infrastructure, the most fundamental attribute of a thriving cycling network is its ability to provide low-stress connections between a cyclist's origin and destination (Mekuria et al. 2012, pg.3). Research shows that cyclists have varying levels of tolerance for traffic stress, which is a combination of perceivable danger, noise, air quality, and route connectivity (Mekuria, Furth, and Nixon 2012, pg. 3). While a small percentage of the (American) population can tolerate riding alongside vehicular traffic, most riders will only tolerate a small degree of interaction (Mekuria et al. 2017, pg.1). Most cities in the United States have pockets of low-stress connectivity options for bicycles, but highways and high-speed arterials often separate these routes, which further discourages bicycling for most people (Mekuria et al. 2017; Alta Planning + Design 2017). Taking these barriers into account, the LTS method classifies streets into four categories of stress, ranging from LTS 1 (suitable for children) to LTS 4 (suitable for vehicular cyclists) (*see Table 4).*

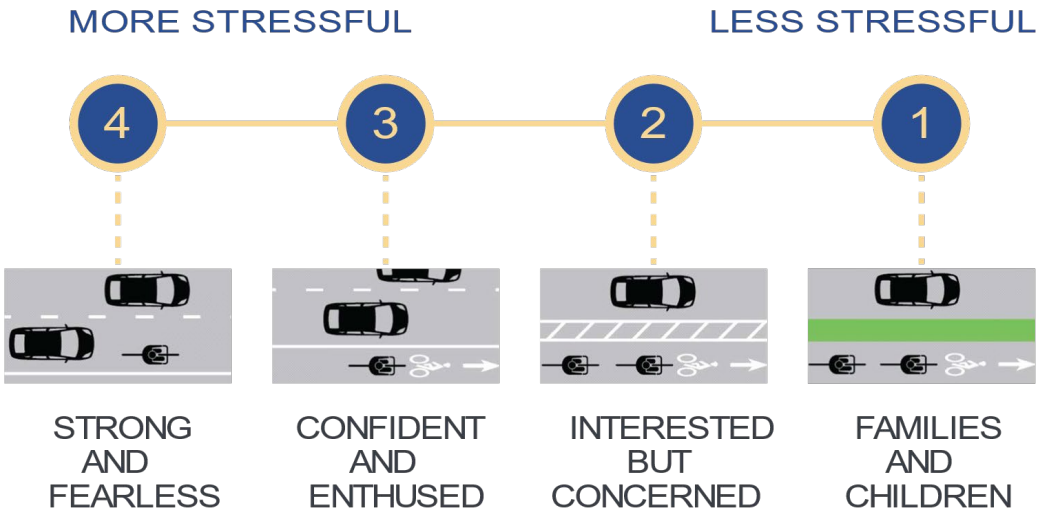


Figure 8: Level of Traffic Stress Rating
Source: Alta Planning + Design 2017

LTS 1	LTS 2	LTS 3	LTS 4
Presents minor traffic stress and demands little attention/negotiation from cyclists	Presents little traffic stress but demands more attention/negotiation from cyclists	Presents a fair amount of interaction with traffic and demands increased attention/ negotiation from cyclists	Presents high levels of traffic stress and demands attention/negotiation from cyclists
Suitable for most cyclists, including children trained to safety cross intersections	Suitable for interested but concerned cyclists, including experienced children with adults	Suitable for confident and enthused cyclists, including adult riders with experience	Suitable for strong and fearless cyclists with experience riding with moderately high-speed traffic (35 mph or more)
Cyclists are either physically separated from traffic (25 mph or less) or are in an exclusive bicycling zone	Cyclists are either physically separated from traffic (25 mph - 30 mph) or in an exclusive bicycling zone next to slow moving traffic	Cyclists are separated from traffic (30 mph - 35 mph) with painted marking	On road sections, cyclists share the road with vehicular traffic
Dedicated space = 6ft or more	Dedicated space = 4ft - 6ft	Dedicated space = 4ft or less	No dedicated space
Standalone (multi-use path)	Separated (on-road) Lane	Bike Lane (painted separation)	No separation
Intersections/crossings are easy to approach and cross for most cyclists	Intersections/crossings are easy to approach and cross for most adults or experienced cyclists	Intersections/crossings may be stressful but are considered acceptably safe to most adult cyclists	Intersections/crossings are stressful and involve variable negotiation with traffic

Table 4: Standards for Level of Traffic Stress
Source: Low-Stress Bicycling and Network Connectivity, 2012

METHODS

In order to provide a reliable assessment of Denver's bicycle network, this thesis followed an iterative process to investigate two realms of the transportation planning process - infrastructure data and transportation policy (*see Figure 9)*. The first section discusses the site selection criteria, background on city-wide crash data, and traffic counts. The second part discusses the goals of the Denver Moves plan (Connectivity, Equity, and Safety) and summarizes the success and pitfalls of these goals using GIS and transportation planning literature. The third portion examines how federal and state bicycle policies and funding contribute to the development of cycling infrastructure in Denver. The final section explores how Denver implements new cycling infrastructure, which is a combination of data inventory and public outreach.

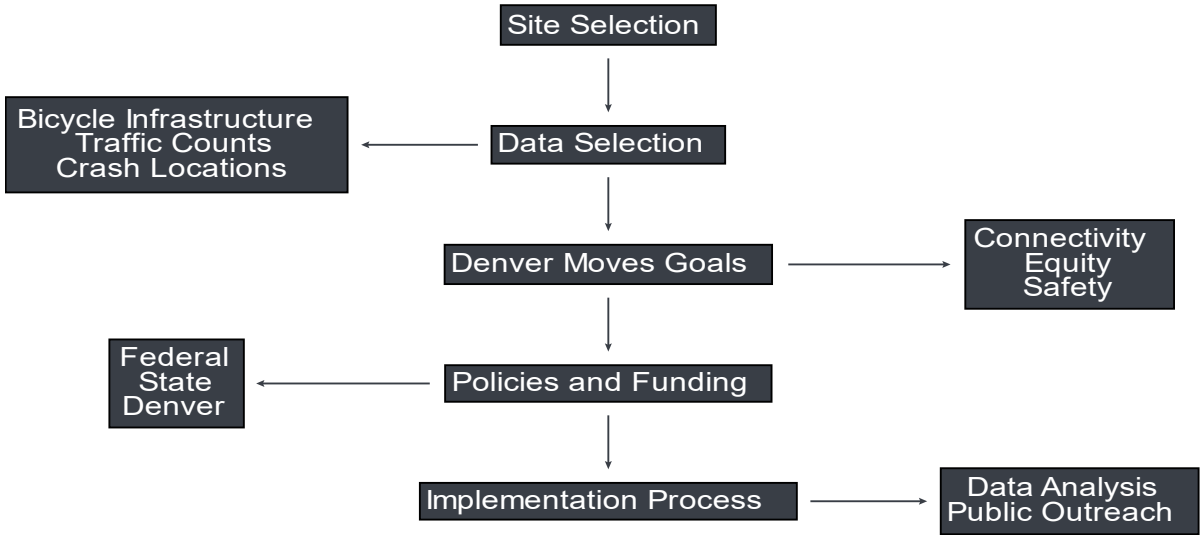


Figure 9: Research Methodology Flowchart

Site Selection

Located on the eastern plains of Colorado, the city of Denver, has roughly 700,000 inhabitants as of 2018. Approximately 372,000 people live within a radius of 10 miles from the city center, meaning that roughly 54% of Denver's population live within cycling distance (< 3 miles) of this area,

Transportation patterns in Denver have primarily been the result of regional development. Throughout the City's evolution, population growth has become more apparent with the increase in traffic congestion (City and County of Denver 2002). In 1982, Denver residents were driving an average of 18 miles a day. By 1999, that distance had increased to 24 miles per day, a 25% increase in less than ten years (Schrank and Lomax 2002). In 2014, that distance had risen to 33 miles, but current traffic records show that this number is starting to plateau (Schrank et al. 2015). This increase in total miles driven also affected the average number of delayed hours Denverites experienced. Between 1982 and 2014, the average commute time doubled, from 20 hours to 51 hours/year (Schrank et al. 2015) *(see Figure 10*).

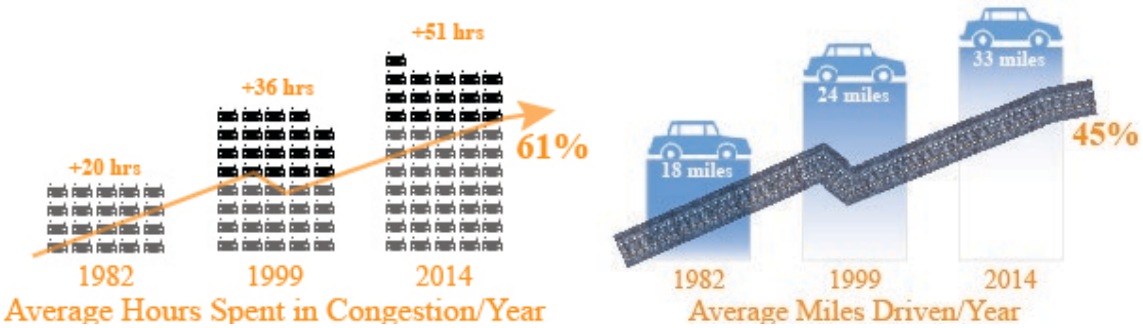


Figure 10: Congestion Trends from 1982-2014
Source: Texas A&M Transportation Institute

The road network in Denver, which is legally applicable for bicycle traffic, has a total length of 2,469 miles. Within the city, there are a total of 607.21 miles of cycling infrastructure ranging from painted off-street bike paths to shared streets with no separation. According to the latest figures, 8,181 people (2.3% of the total mode split) use a bike for commuting purposes (The League of American Bicyclists 2018, pg.285-287). Reasons for the popularity of cycling as a utilitarian option vary, however, some significant attractors include Denver's relatively flat topography, its contemporary bicycle infrastructure, short distances between neighborhoods, and good accessibility to central facilities.

Data Selection

Bicycle Infrastructure

Several studies have used the Level of Traffic Stress (LTS) method to measure network connectivity (Mekuria et al. 2017 and Fitch et al. 2016), yet few have compared crash locations and demographic characteristics with the LTS criteria to understand how cycling infrastructure affects the prevalence of crashes. This thesis uses the LTS method to measure network connectivity and stress tolerance levels for cycling routes in Denver on accident-prone locations.

In order to provide a reliable cycling risk analysis in Denver, while considering the issues discussed in the previous sections, this thesis followed an iterative workflow which identified adequate reference units to test the robustness of crash rates at various locations. The method demonstrated the applicability of the workflow in a case study from Denver, CO. Site-specific data was collected and aggregated via Geographic Information System (GIS). *Table 5* displays the datasets used in the process.

File Name	Description	Last Updated
Census Neighborhood Demographics (2010)	Demographic information from the 2010 census	January 2018
HUD Income Levels	Percentage of the 2014 population that is low-to-moderate income as calculated by the US Department of Housing and Urban Development	February 2019
Denver Bicycle Facilities	Existing and proposed bicycle facilities in the City and County of Denver	December 2017
Traffic Counts	Traffic volume data between 2010-2018	June 2018
Traffic Accidents	Traffic accident locations collected from the Denver Police Department	February 2019

Table 5: GIS Datasets
Source: Denver Open Data Source

Traffic Volume Data

The traffic volume data used for this study consists of 10,403 total traffic counts and covers a period between April 2008 to September 2016. Data comes from the Colorado Department of Transportation (CDOT), local governments, and toll road authorities and is made available to DRCOG (Denver Regional Council of Governments).

Crash Data

The crash data used for this study consists of 159,970 police crash reports and covers a period of 6 years (2012-2018). The Denver Police Department is responsible for crash data collection and conducts reports based on the National Incident-Based Reporting System (NIBRS). Reports are only included if; accidents total $1,000 or higher in damage, injuries or fatalities are recorded, or accidents involve drugs or alcohol. If an accident is classified as a counter report (no injury, under $500 in damage, or a hit and run), the report is sent to the State of Colorado without being entered into the database. This authoritative dataset is exclusively fed by police reports. Hence, hospital records, insurance claims, crowdsourced information, or other alternative data sources are not included.

For this study, crash reports that involved at least one bicycle and valid location information were extracted from the database. A total of 2285 geolocated crash reports between January 2012 and December 2018 met both criteria and were considered for further analysis; zero crash reports involving a bicycle were excluded. For this study, only location information for the risk calculation was relevant. Associated data about involved parties, liabilities and crash details were not considered.

Policies, Funding, and Implementation

The policies, funding, and implementation information was collected from several bicycle planning initiatives introduced by Denver. These include the 2015 Denver Moves Initiative, the 2015 Denver Bicycle Safety Action Plan, the 2017 Denver Mobility Action Plan, and the 2019 Denver Moves: Pedestrian & Trails Plan. Overall funding information was extracted from the Mayor's 2019 Budget Proposal which provides a detailed account of all city-wide projects and proposed budget.

RESULTS

The Denver Moves Plan

The 2019 Denver Moves: Pedestrians & Trails (DM) plan expands on the vision for increasing non-motorized transportation in Denver. Through a joint effort between Denver Public Works (DPW), Parks & Recreation, Community Planning, and Public Health & Environment Departments, the DM plan develops a high degree of integration between pedestrian and cycling facilities (Denver Right 2019, pg. 2). For cyclists specifically, the DM plan identifies existing/new bicycle lanes, shared roads, and street crossings to create a safe and comprehensive bicycle network (Denver Right 2019, pg. 1). The cyclist-related goals of the DM plan are divided into three realms: Connectivity, Equity, and Safety. Based on the literature and current GIS data, this thesis summarizes the success and pitfalls of these goals in detail.

Goal 1: Connectivity

As previously mentioned, a complete bicycle network is defined as the existing off-street and on-street routes that connect neighborhoods throughout a city. Gaps in this network, however, prove to be significant barriers for bike riders because they present stressful situations. For Denver, there are many gaps in the bicycle network, specifically as one gets farther away from off-street trail corridors. *Figure 11* is a map of Denver's complete bicycle network where the orange lines represent on-street corridors, and the thick yellow lines represent the major off-street corridors. The distinction is made between the two types because they represent detectable levels of stress for cyclists - off-street corridors are less stressful than on-street corridors. Differences in the mileage for each corridor are significant as well, with 96.8 miles of off-street facilities compared to 510.4 miles of on-street facilities. Based on traffic stress level information,

this means that less than 16% of all cycling infrastructure in Denver meets the criteria for low stress.

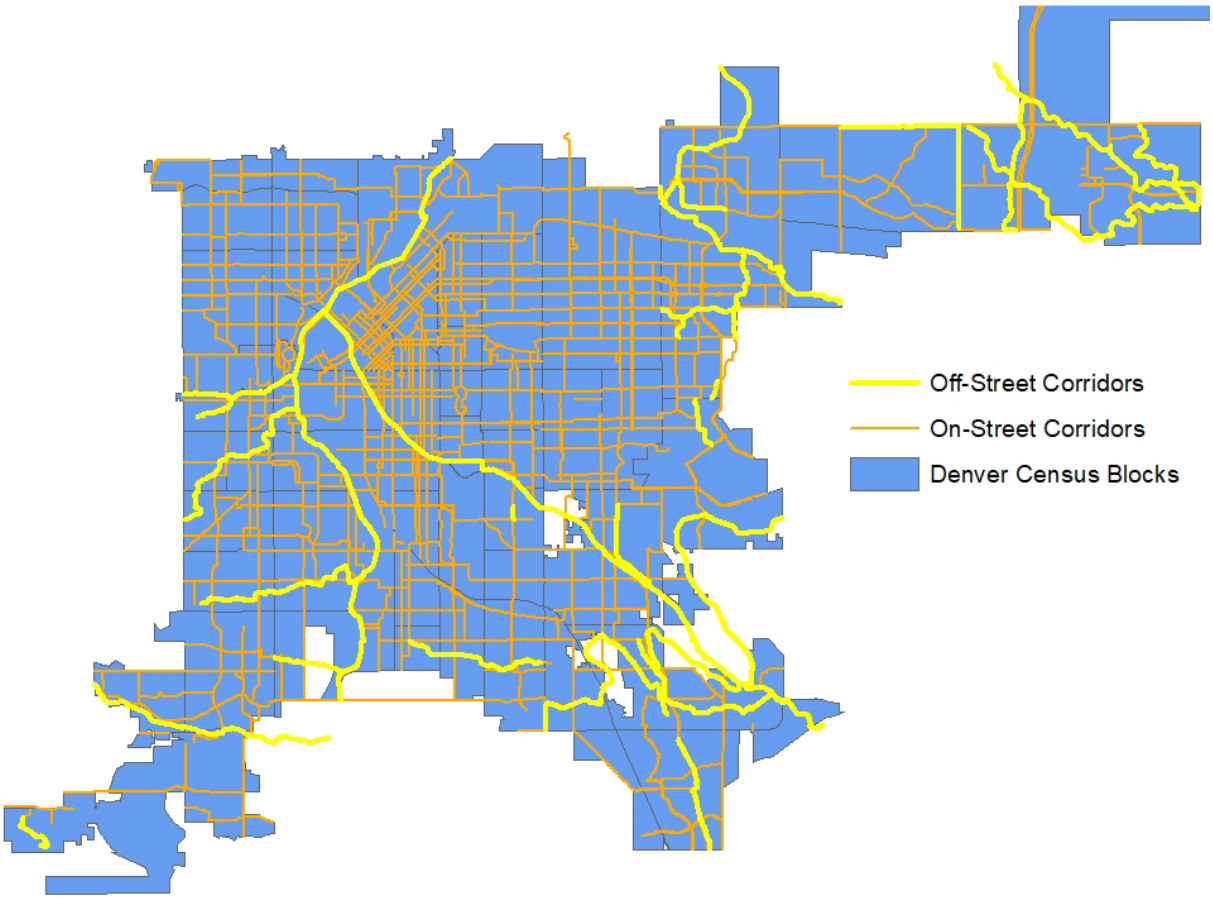


Figure 11: Denver Complete Bicycle Network

When on-road bike facilities are separated by level of traffic stress, it becomes clear that most cycling routes in Denver are stressful to ride. *Figure 12* and the table below show the percentage of separation and associated stress levels based on the most current bicycle facilities GIS data. As mentioned in earlier literature, Stress Level 2 is the optimal rating for on-road bicycle facilities or the facility that would be most comfortable for families and children. Results indicate that less than 3% (19.5 miles) of total on-road facilities meet the criteria for low-stress and 64% (391.2 miles) of on-road facilities are very stressful (Stress Level 4).

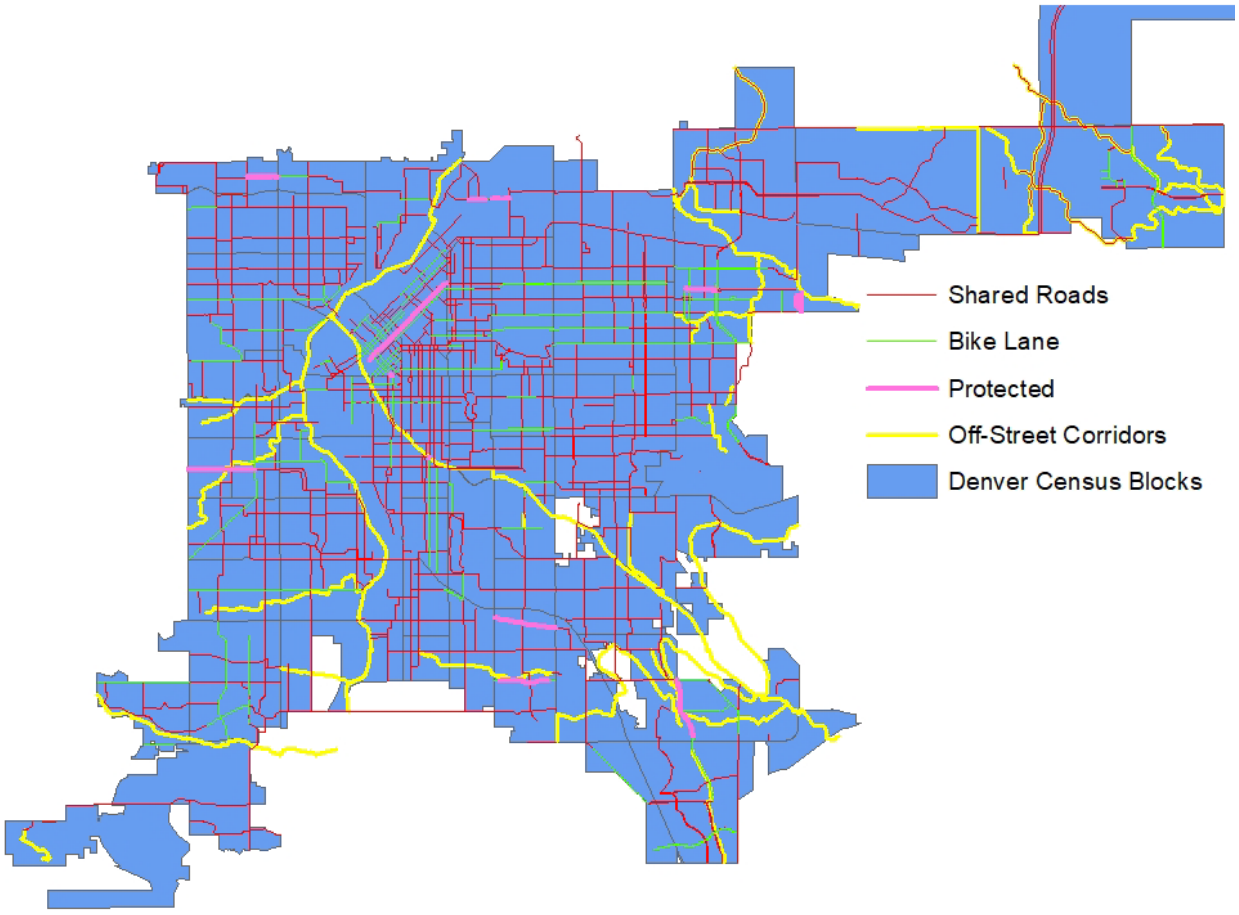


Figure 12: Separated Facilities

BICYCLE FACILITIES

Type	Miles	Level of Separation	Stress Level	Cyclists Comfortability	Traffic Speed
Shared road	391.2	no dedicated space	4	Strong and Fearless	25-40 mph
Bike lane	100.4	3ft - 4ft no barrier	3	Confident and Enthused	20-30 mph
Protected	19.5	4ft - 6ft with barrier	2	Interested but Concerned	25-30 mph
Off-street path	96.6	6ft - 10ft on-street	1	Families and Children	N/A
TOTAL	607.7				

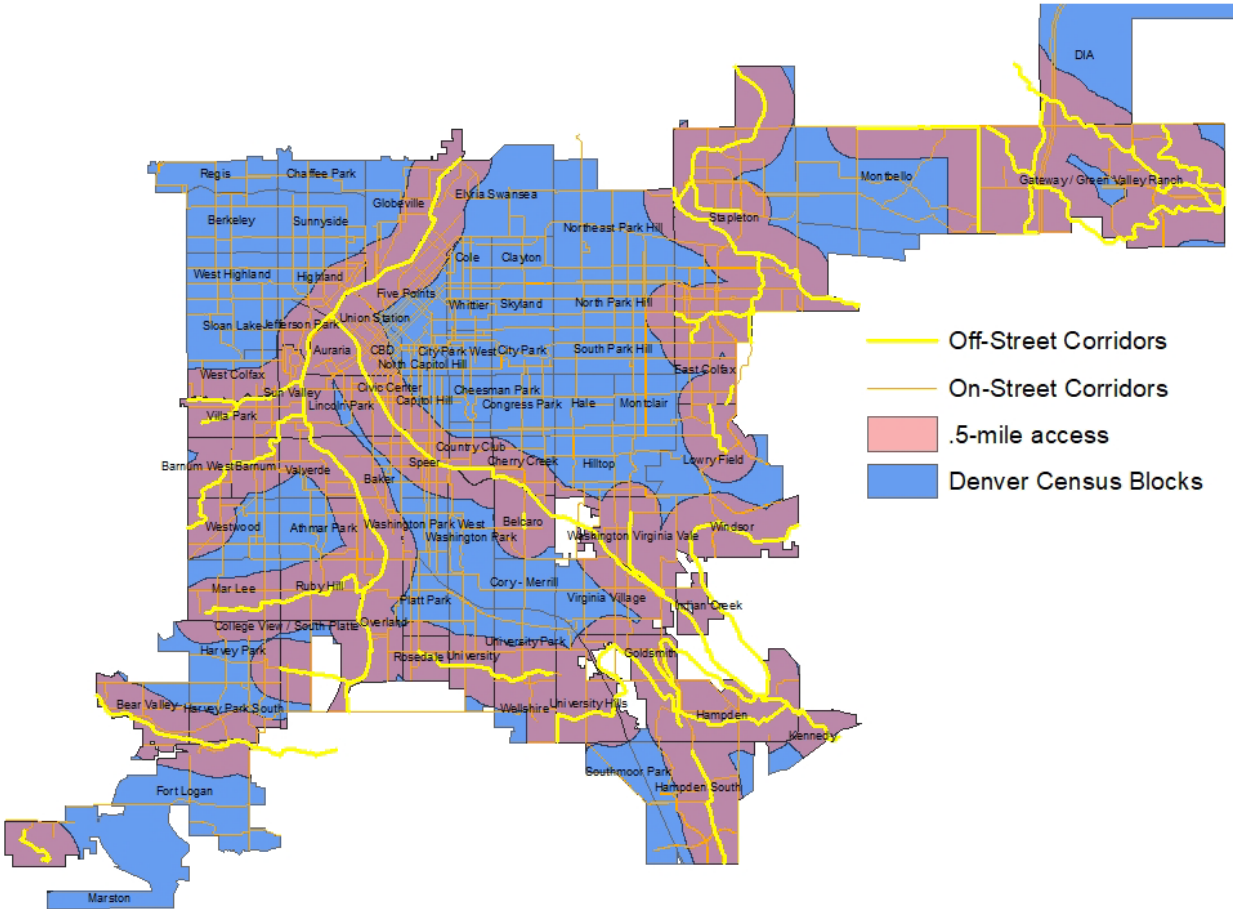


Figure 13: Bicycle Network with Off-Street .5-mile Buffer

Another significant component of this goal is to evaluate and establish access points within a .5-mile of low-stress off-street corridors. A .5-mile is considered the average distance a person is comfortable walking or biking to a destination (Speck 2012). *Figure 13* is a map of Denver's bicycle network showing a .5-mile buffer around the off-street corridors. According to the data, approximately 74% of Denver's population lives within .5-mile of a major off-street corridor.

Goal 2: Equity

While the majority of Denver's population may have sufficient access to off-street bicycle trails, it is worth to investigate how wealth plays into this scenario. When controlling for neighborhood income levels, this research found that 54% of Denver's population is considered low-income (*see Figure 14)*. This percentage describes the number of residents per census block who make less than $10,000 annually, which is essential considering that these residents have the highest rate of bicycling per income class (McKenzie 2014).

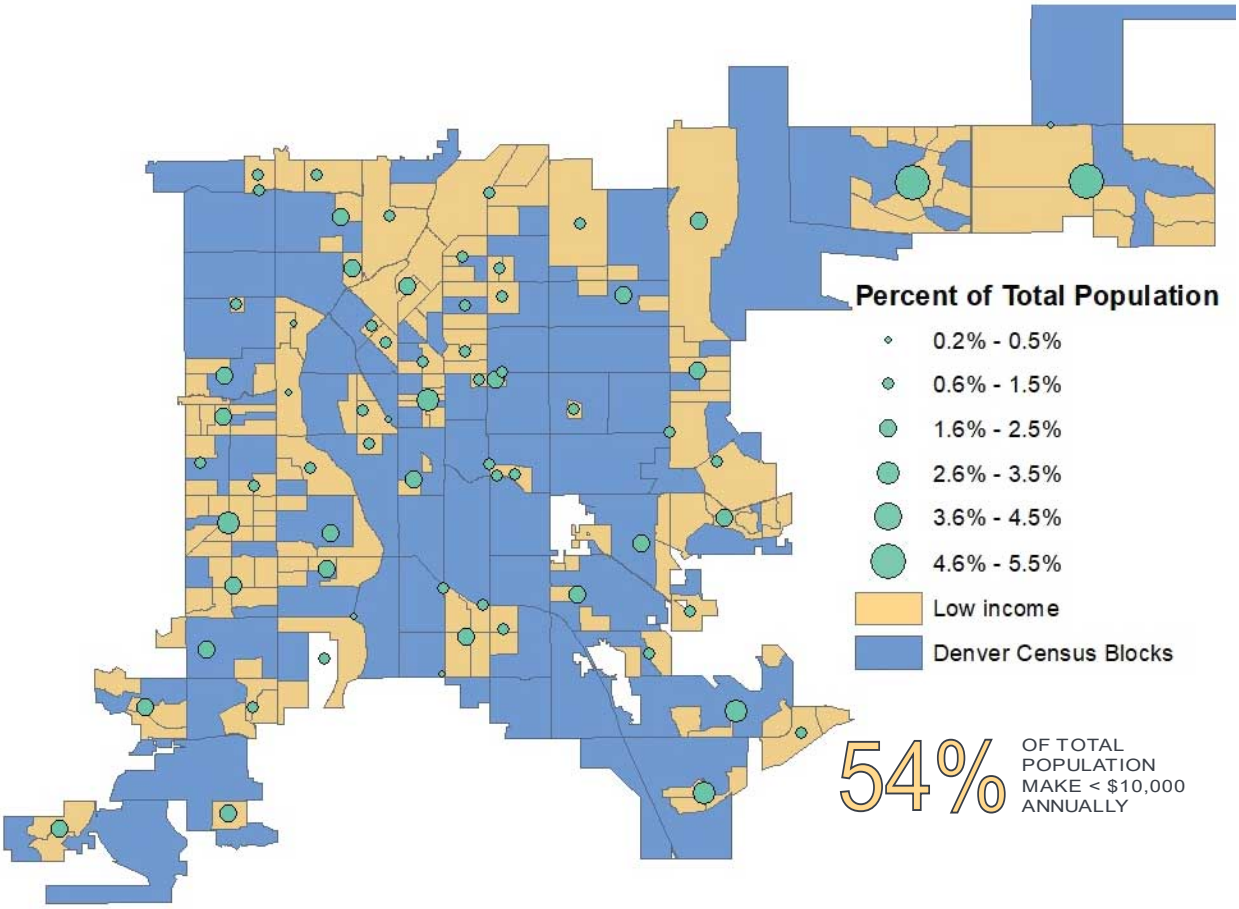


Figure 14: Denver Low Income Map

Controlling for neighborhood income, results show that low-income communities have access to roughly 209.2 miles of the bicycle network. Below is a map (*Figure 15)* of the bicycle network with a .5-mile buffer around the off-street corridors. According to the data, approximately 78% of the population in low-income communities live within .5-mile of an off-street corridor.

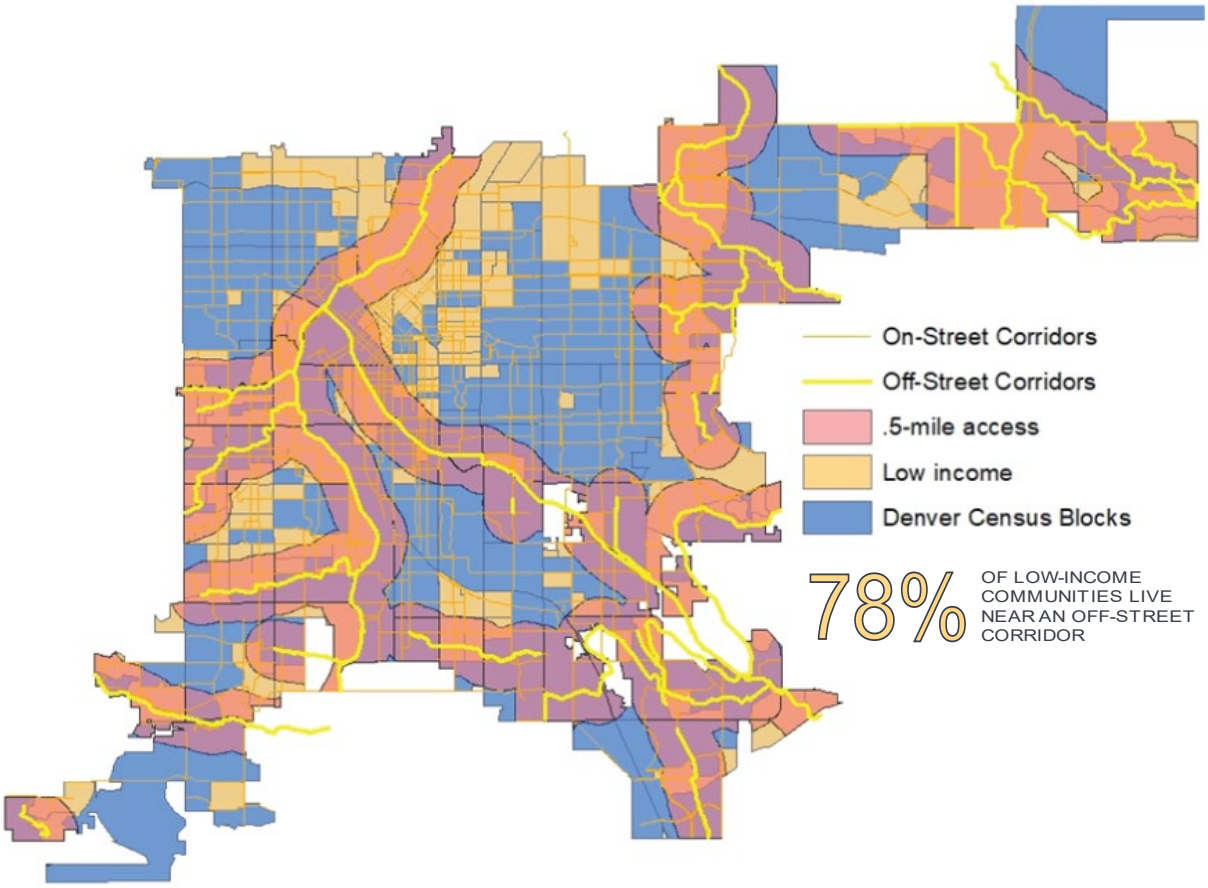


Figure 15: Low Income with Off-Street .5-mile Buffer

When on-road bike facilities are separated by level of traffic stress for low-income communities, most cycling routes are stressful. *Figure 16* and the table below show the percentage of separation and associated stress levels for these communities. Results indicate that 62% (172.3 miles) of total on-road facilities in low-income communities fall into the Stress Level 4 category or the facility that would be most comfortable for strong and fearless riders.

Overall, the findings suggest that low-income communities are subjected to higher rates of stress in their bicycle network.

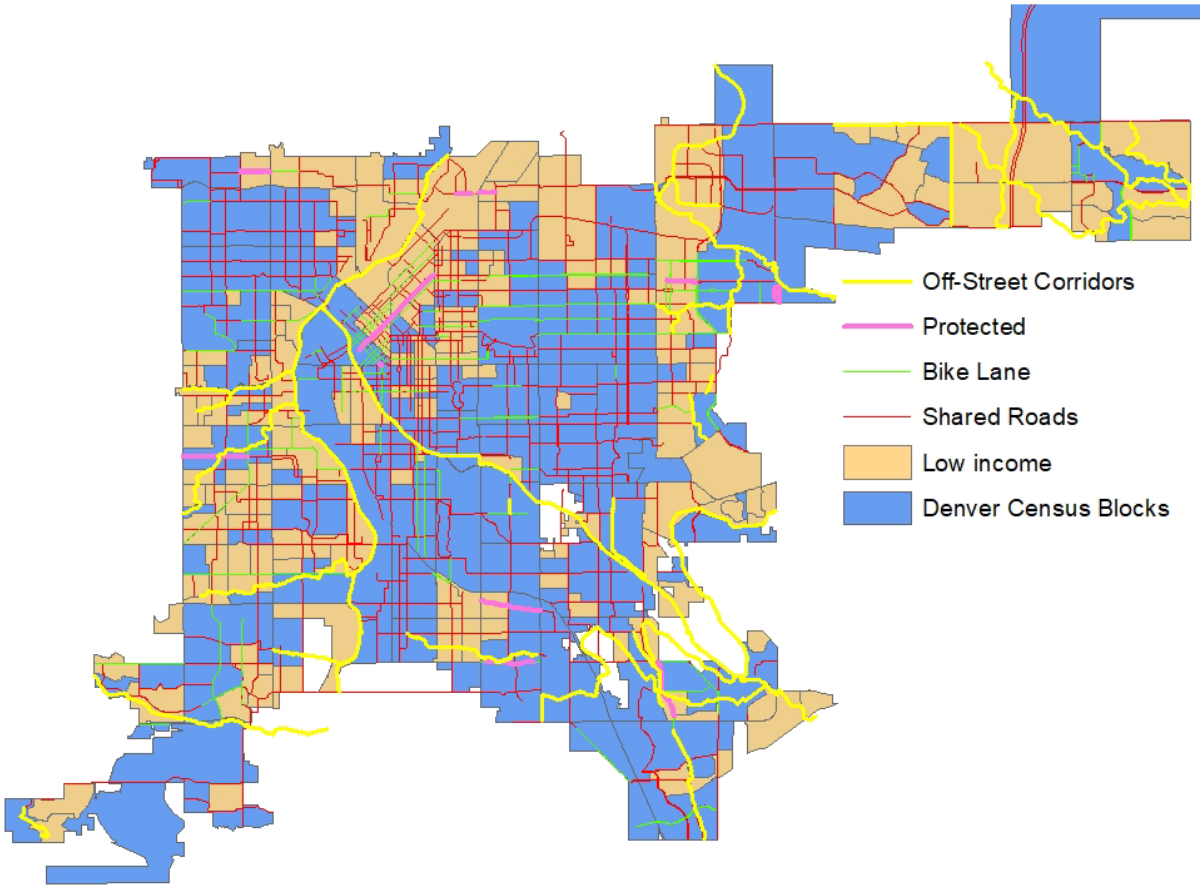


Figure 16: Low Income with Separated Facilities

BICYCLE FACILITIES IN LOW-INCOME COMMUNITIES

Type	Miles	Level of Separation	Stress Level	Cyclists Comfortability	Traffic Speed
Shared road	121.4	no dedicated space	4	Strong and Fearless	25-40 mph
Bike lane	23.1	3ft - 4ft no barrier	3	Confident and Enthused	20-30 mph
Protected	5.5	4ft - 6ft with barrier	2	Interested but Concerned	25-30 mph
Off-street path	59.2	6ft - 10ft on-street	1	Families and Children	N/A
TOTAL	209.2				

Goal 3: Safety

The final goal of the DM plan seeks to develop a well-maintained network that fosters high levels of personal safety and minimal conflicts between cyclists and vehicles. To measure safety in Denver's bicycle network, this thesis mapped 2012-2018 traffic crash data locations with current bicycle infrastructure. The map below (*Figure 17)* represents the total number of crashes involving a vehicle and bicycle. Within the six years of available data, 2285 crashes were reported in Denver. Findings indicate that roughly 85% of these crashes occurred at an intersection and that the majority of crashes occur within one mile of the downtown region. This is likely the result of two factors; there are increased bicycle use and a higher frequency of vehicular traffic in this region. Both of these factors lead to more interactions between cyclists and vehicles which significantly impacts the level of stress for a bicycle route.

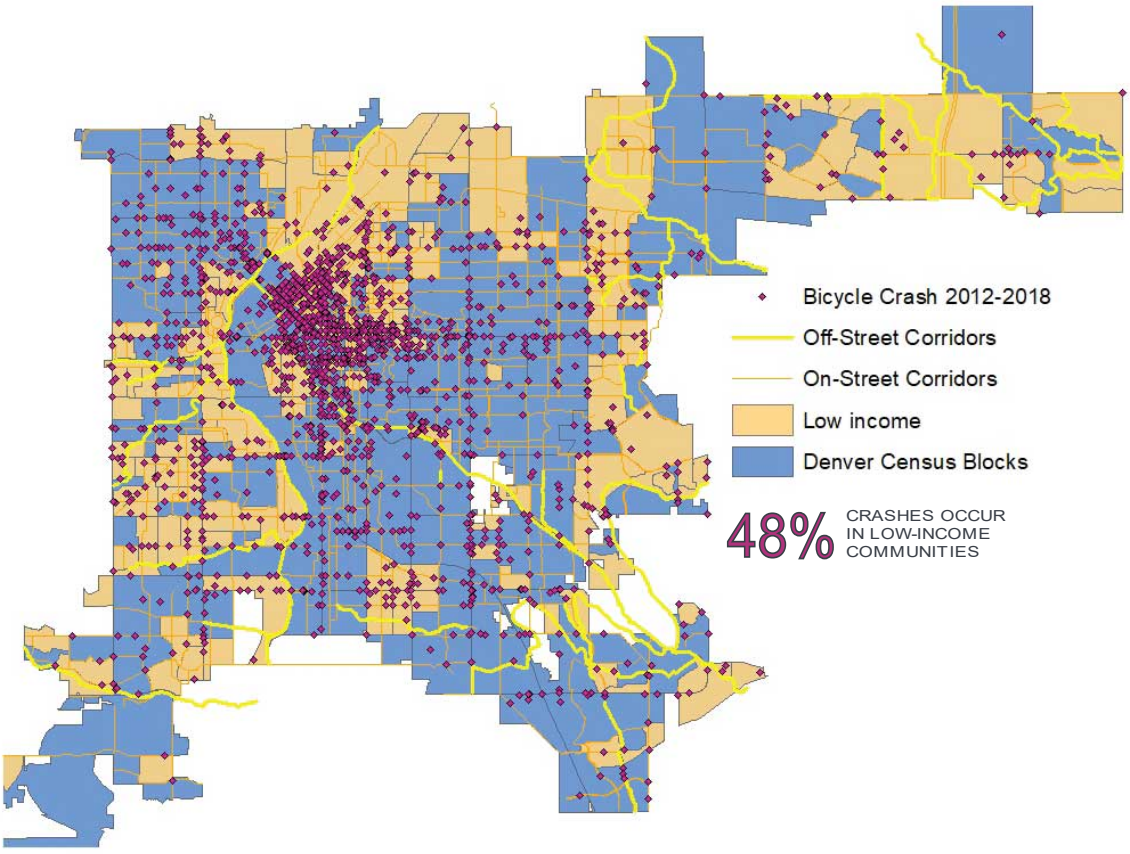


Figure 17: Low Income with Crash Locations

Controlling for neighborhood income levels, findings indicate that roughly 48% of all crashes involving a bicycle and vehicle occur in a low-income community. While this percentage is not surprising, as roughly half of Denver's population lives within a low-income community, the frequency at which these crashes are happening is worth investigating. Looking at the top ten crash sites revealed that crashes are occurring more frequently in low-income neighborhoods. *Figures 18* and the table below display these percentage concerning the location and frequency of crash. Highlighted rows in the table indicate crashes that occurred in low-income communities. Photos of each location can be found in *Appendix D: Bicycle/Vehicle Crash Locations.*

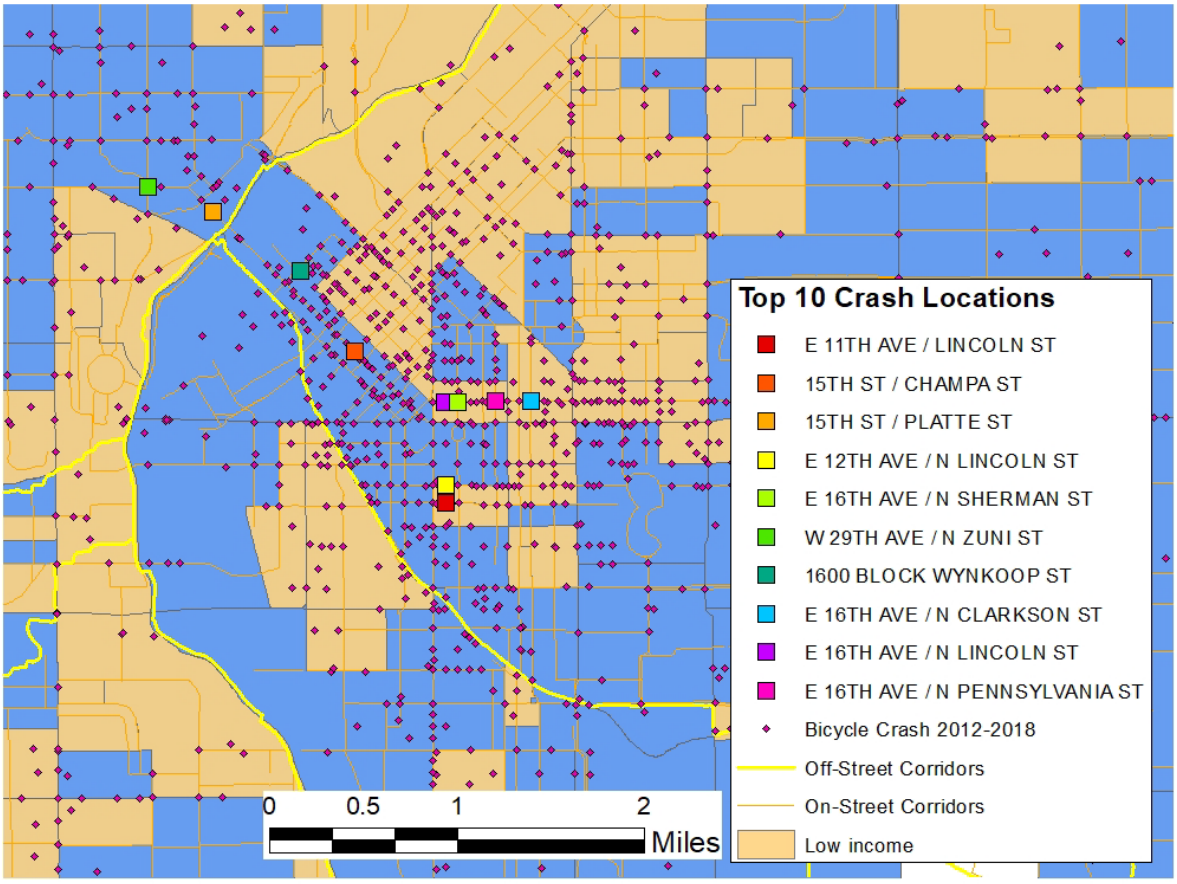


Figure 18: Top 10 Crash Locations

TOP 10 BICYCLE CRASH LOCATIONS

Crash location	Frequency of Crash	Level of Traffic Stress	Type	Bike Lane Width (ft)	Vehicle Traffic Count (24hr)
E 11th Ave / N Lincoln St	12	3	striped bike lane	3	8745
15th St / Champa St	10	2	buffered bike lane	4	12902
15th St / Platte St	6	4	shared street	0	16831
E 12th Ave / N Lincoln St	6	4	shared street	0	31976
E 16th Ave / N Sherman St	6	3	striped bike lane	3	2986
W 29th Ave / N Zuni St	6	3	striped bike lane	5	13140
1600 Block Wynkoop St	5	2	buffered bike lane	3	1421
E 16th Ave / N Clarkson St	5	3	striped bike lane	3	4701
E 16th Ave / N Lincoln St	5	3	striped bike lane	3	2973
E 16th Ave / N Pennsylvania St	5	3	striped bike lane	3	7582

Denver Moves Goals Discussion

Overall, the results indicate some disparities in the current bicycle network. First, the majority of cycling facilities are rated as high-stress routes. Over 64% (391.2 miles) of the on-road facilities meet the criteria for Stress Level 4, involve a significant amount of interaction with vehicles, and are considered extremely stressful cycling environments. Of the entire network, less than half (34%) of all cycling routes exist in low-income communities, yet the majority of these communities (78%) are within .5-mile of an off-street corridor. Despite having a moderate amount of access to both on-street and off-street facilities, crashes occur more frequently in low-income communities. Roughly 48%, or 1127, of all crashes, occurred in a low-income community.

Policies, Funding, and Implementation

As discussed previously, infrastructure, traffic stress, and the perception of safety significantly impact cycling levels in the United States. From a planning perspective, however, the process by which cities develop infrastructure and create safer streets for cyclists should be examined more closely. This process can be understood in three parts: bicycle policy, funding, and implementation (*see Figure 19)*. The following section describes how each of these components factors into the broader context of Denver's bicycling network, focusing on federal and state-level policies and funding initiatives before describing policies specific to Denver. The last portion of this section describes the implementation process used in Denver, which is a combination of data analysis and public outreach.

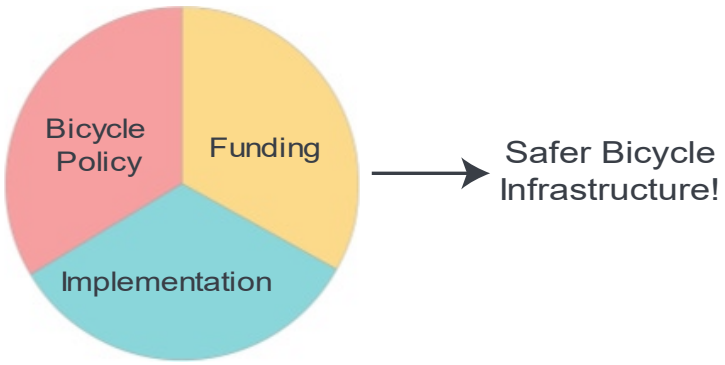


Figure 19: Process for Building Infrastructure

Federal Cycling Policies and Funding

The United States federal government has had a crucial role in improving bicycling conditions, mainly by increasing funding for infrastructure and passing laws that require state departments to integrate cycling into their transportation planning procedures (Pucher and Buehler 2006). One of the most influential pro-cycling laws was the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) (U.S. Department of Transportation 2018).

Before the 1990s, total federal funding for bicycle and walking projects averaged just $2 million a year. After the ISTEA passed, annual funding rose to $239 million per year by 1997. The ISTEA was later transferred to the Transportation Equity Act (TEA21) in 1998 and increased federal funding to $413 million in 2004 (U.S. Department of Transportation 2018).

The federal government not only increased funding for bicycling and walking projects, but it also reversed the years of neglect put on non-motorized travel. In 1990 and 1994, the US Department of Transportation set a new tone in transportation planning with the publications "Moving America" and the "National Bicycling and Walking Study" (U.S. Department of Transportation 1990, 1994). Both emphasized the importance of walking and cycling; however, the 1994 article set a new goal to double the current modal share of bicycling and walking in the United States. With help from the ISTEA, these articles required all states to produce short- and long-term transportation plans that included walking and bicycling design guidelines (Clarke 2003). The ISTEA also required each state to have a pedestrian/bicycling coordinator to facilitate non-motorized transport policies and planning. After passing the TEA21 in 1998, the USDOT issued another policy statement that required all federally-funded highway and transit projects include pedestrian/bicycle design guidelines (U.S. Department of Transportation 2000).

Overall, the federal government is a crucial element in securing more funding for bicycling and its integration into transportation planning. This funding, however, pales in comparison to the exorbitant amount dedicated to other transportation initiatives. In 2017, the United States Department of Transportation directed more than $175 billion to highway and road improvements (Urban Institute 2017) Although automobile infrastructure costs more to build than sidewalks or bicycle lanes per mile, $6 million and $133,000 per mile respectively, deaths and injuries caused by automobile crashes far exceed that amount for bicycles (Bushell et al.

2013; Proctor 2019). In 2017, automobile crashes accounted for more than 38,000 deaths and 2.5 million non-fatal injuries in the United States (Center for Disease Control and Prevention 2017). These crashes add up to more than $43 billion in medical and work loss expenses (Center for Disease Control and Prevention 2015). These numbers not only signify a lack of safe and comprehensive infrastructure but they illustrate the unbalanced nature of authority given to the automobile industry.

State Bicycle Funding

Despite the strides made at the national scale, projects are ultimately at the mercy of individual states, who have considerable discretion as to how these funds are used. Most states devote a significant portion of their federal budget to improving vehicular infrastructure (highways, parking), typically assigning a small portion to alternative transportation projects (Clarke 2003).

Since 2015, the FAST Act (Fixing America's Surface Transportation) has required all states to provide data reports on their alternative transportation projects. Each report must include the number and cost of each application submitted, as well as the number and cost of each project funded. Since this data was first reported, back in 2016, the percentage and cost of unfunded alternative transportation projects have increased (Douwes 2017). This means that the majority of funding states receive is not being allocated for bike or pedestrian projects.

For Colorado, only 16% of all transportation projects included bicycle or pedestrian facilities, and these facilities account for a mere 1.4% of the total project cost. In 2017, $12.2 billion was allocated to Colorado for its transportation spending, yet only $174 million was allocated for projects with bike/ped facilities (McLeod 2017, pg. 68). Considering other states,

Colorado has above-average spending directed to bicycle/pedestrian projects, yet the percent of costs associated with those facilities is well below the average.

Currently, nineteen states, including Colorado, have funding sources dedicated specifically for bicycle infrastructure. Colorado's primary funding source comes from the Funding Advancement for Surface Transportation and Economic Recovery (FASTER) program (McLeod 2017a). The FASTER program generates over $200 million every year for state transportation projects throughout Colorado by collecting revenue from vehicle registration fees, fines, supplemental surcharges on oversize/overweight vehicles, and vehicle rental fees, ranging between six and ten dollars per month for the average vehicle owner (Colorado Department of Transportation 2009). Colorado also has an impact fee which collects a one-time charge from developers for financing new infrastructure. These fees help fund growth-related pubic service costs and off-site services such as roads and other transportation improvements. Impact fees also generate revenue for local communities which they can use for street network improvements, transit facilities, and bicycle or pedestrian upgrades (McLeod 2017a, pg. 8).

Denver's Bicycle Policy

As discussed earlier, many cities throughout the United States, including Denver, have adopted the principles of Vision Zero policy to eliminate traffic deaths and severe injuries (Vision Zero Network 2018). Along with this goal, Denver also incorporated equity as a critical aspect in its 2016 Vision Zero policy, which ensured that efforts to improve traffic safety did not unintentionally exacerbate other social tensions (The City of Denver 2017). Within Denver's scope of equity, two major themes are recognized. The first is that streets should be designed for everyone. The second is that the overall transportation system should be safe for all users. These themes not only represent a shift in traditional transportation philosophy, one that prioritized

vehicular mobility over human needs, but it also emphasizes the need for community-led decision-making processes.

One crucial aspect of Denver's Vision Zero policy is that it was developed in collaboration with various city departments, including; law enforcement, public and environmental health, sustainability, transportation, community planning, emergency services, schools, parks and recreation, and social justice (The City of Denver 2017, pg. 13). Denver also incorporated thousands of resident participation feedback surveys to get a better sense of city-wide safety concerns. Throughout this process, Denver's Vision Zero Task Force developed five important themes, incorporating medium-term (2018-2023) actions and goals (*see Table 7*).

Theme	(2018-2023) Actions	Goal
Enhance City Processes and Collaboration	Establish a dedicated funding source for Vision Zero implementation and coordination	Dedicate $2 M/year to Vision Zero projects and programs over next five years
Build Safe Streets for Everyone	Update Transportation and Mobility Policies and Procedures to include street treatments with proven safety benefits	Update policies and procedures to prioritize the reduction of serious crashes
Create Safe Speeds	Create a speed management program to evaluate and promote safe speeds systematically	Provide consistency in the speed data collection methodology
Promote a Culture of Safety	Implement a multimodal safety education campaign	Educate Denverites about safe traffic behavior to reduce crashes
Improve Data and Transparency	Establish an official crash data reporting system to be used by all City agencies	Maintain consistency in data management to enhance monitoring techniques

Table 7: Major Themes and Actions of Denver's Vision Zero Policy
Source: The City of Denver 2017

Examples of Vision Zero Achievements in Denver

Multimodal Street Design Guidelines

Street design guidelines are used to inform street width, intersection geometry, crossing treatments, and bikeway/sidewalk designs (The City of Denver 2017, pg. 25). By incorporating a multimodal design lens, planners can ensure that their streets prioritize walking and biking, create context-sensitive typology, and help promote traffic safety. Denver's multimodal guidebook is the Living Streets Initiative (LSI), a city-building philosophy created in 2007 that equally accommodates the needs of pedestrians, bicyclists, transit users, and car owners while creating safe and comfortable spaces (Denver Living Streets Initiative 2014, pg. 4). Over five years (2007-2012), the LSI successfully enhanced streetscapes, encouraged diverse modes of travel, created a sense of high-quality spaces, attracted local investment, encouraged active lifestyles, and reduced air emissions. The LSI also helped to establish partnerships between public, private, and government sectors (Denver Living Streets Initiative 2014, pg.30).

Parking Restrictions

Vehicles parked too close to intersections, or midblock crossings contribute to crashes because they block sight lines for pedestrians and bicyclists (The City of Denver 2017, pg. 25). Through Denver's Vision Zero Initiative, the city was able to eliminate on-street parking near crossings by instituting no-parking zones within 20-50 feet of intersections. These spaces are then filled with bike parking, curb extensions, and green infrastructure (Park Smart Denver 2019).

Slow Zones

Slow zones are streets, typically in residential areas, that promote safety through reduced speeds. Speeds are often set at 20 mph and are applied through signage, enhanced signaling, pavement markings, and traffic-calming measures (The City of Denver 2017, pg. 26). Research suggests that 20 mph speed zones significantly increase the chances of crash survival by 35 percent (Cairns et al. 2015). The most recent and successful example of a slow zone initiative in Denver took place on Montbello Street in December 2018. Denver Public Works installed a Rapid Flashing Beacon and a pedestrian refuge island to increase crossing visibility (News Desk, News Partner 2018).

Overall, Denver's Vision Zero Initiative has been successful at promoting safer streets for pedestrians, bicyclists, and motorists by implementing a variety of policy-level strategies. Despite these improvements to bicycle policy measures, physical infrastructure improvements require two crucial resources in order to be successful: aggregated funding and public support.

Denver's Bicycle Funding

Figure 20: Funding Flowchart

In September of 2018, Denver released its 2019 budget proposal, which appropriates more than $2.4 billion for a host of city-wide initiatives. These include funding for affordable housing, homeless and vulnerable population services, mobility options and traffic congestion, community-supported projects, and overall city crime and safety concerns (City of Denver 2018). Of the $2.4 billion investment, $32.7 million is being directed into the city's Mobility Action Plan (MAP), which addresses transportation, mobility, and equity needs (City of Denver 2018). Roughly half of the $32.7 million investment, ($15.5 million), specifically goes to expanding the Denver Moves Plan. (*see Table 8 & Figure 21*) (City of Denver 2018, pg. 177).

Mobility Action Plan $32.7 M	
$17.2M	Other Funding Priorities
$15.5M	**Total Funding for Denver Moves Plan**
- $7.1M	Increase bicycle network (125 miles of bicycle lanes)
- $3.8M	Pedestrian crossing improvements
- $2.6M	Address high crash locations and Vision Zero
- $1M	Transit improvements and TOD
- $800,000	Bike Share Programs
- $200,000	Safe Routes to School Program

Table 8: Denver 2019 Budget Allocated for Mobility Action Plan
Source: City of Denver Budget Summary Report 2018

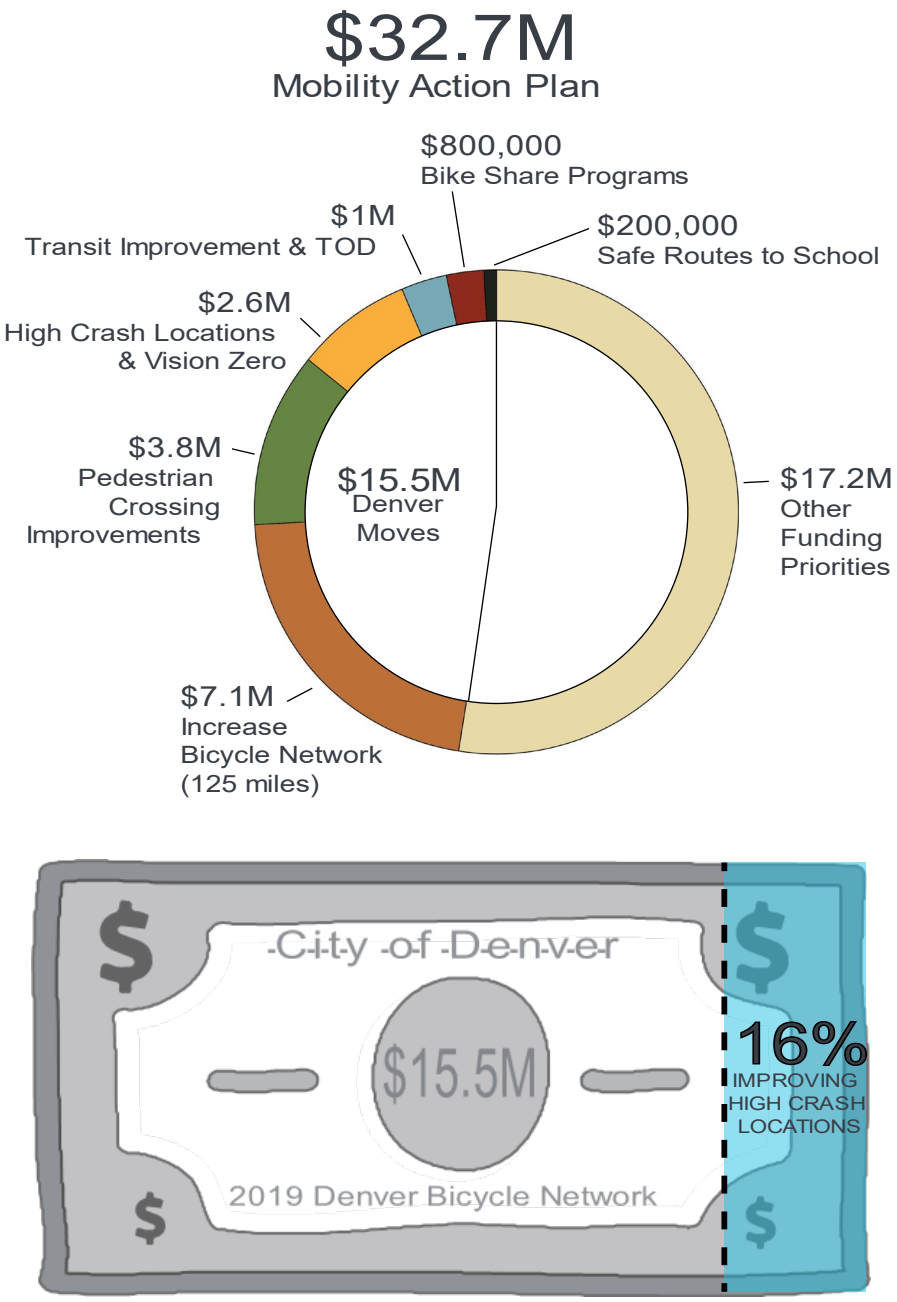


Figure 21: Funding Directed to Intersection Improvements
Source: Denver 2019 Budget Plan

Funding Issues

Despite having a significant increase in available funding, Denver's primary infrastructure budget holds some pitfalls. First, only 16%, or $2.6 million, is being allocated for intersection improvements. According to the 2008-2012 crash data and Denver's Bicycle Safety

Action Plan, 85% of all bicycle crashes occur in or near intersections. This high number suggests that there is a lack of clarity regarding how motorists and bicyclists should interact at intersections. This confusion is most likely due to the absence of proper bicycle facilities, such as bike signals, separated lanes, intersection crossings, and detection sensors. Without technology specific to bike users, cyclists are unsure of their place on the road, which confuses other users. The resulting interaction is unpredictable for both the motorists and cyclists as they try to navigate through a volatile intersection. Conflicts like this create significant barriers for new cyclists, especially vulnerable users, and younger riders.

Implementation Process

At the administrative level, policies and funding play a significant role in developing new bike lanes, yet these are only two slices of the development pie. The third is the implementation process, divided between data analysis and public outreach. These methods provide Denver with a picture of the gaps in its' cycling infrastructure, places to enforce preventative safety measures, and techniques for gathering perspectives and insights from city residents. The next section describes both of these methods pulled from bicycle planning initiatives and conversations with bicycle advocates.

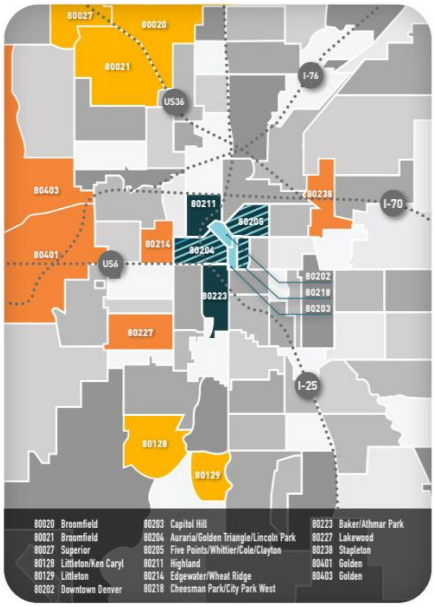
Data Collection

One method for building new bike lanes is to analyze deficiencies in the bicycle network. Denver accomplishes this through collecting information on traffic and bicycle counts, multi-year traffic crash reports, and surface condition data. This information is then used to establish gaps in the bicycle network.

Current cycling infrastructure places a strong emphasis on commuters to the CBD from the Cherry Creek and Stapleton neighborhoods, as is evident from the concentration of bicycle facilities in these neighborhoods. This emphasis on CBD commuters is also reflected in current data collection exercises by the Colorado Department of Transportation (CDOT). Cyclists were counted along 16th Avenue, Montview Boulevard, Cherry Creek Trail, and the Platte River Trail. These facilities are primarily orientated toward residents who commute to the central business district (CBD), which means they exclude a large number of cyclists in the surrounding neighborhoods.

Emphasis on CBD commuters and infrastructure is also reflected in the 2016 downtown commuter survey produced by the Downtown Denver Partnership. A total of 7,547 responses

were collected, with the average commute length by a bicycle being under four miles (Downtown Denver Partnership 2017). Both the survey and count results provide a picture of CBD commuters, but they overlook thousands of people who might bike in the outer neighborhoods *(see Figure 22*).



Average Commute Length (miles)	
Transit	15
Driving Alone	14
Biking	4
Walking	1
Vanpooled	49

Figure 22: Top Commute Options per Zip Code
Source: Downtown Denver Partnership 2017

Emphasis on CBD commuters raises the issue of transportation justice, which is based on the concept that transportation infrastructure should equitably address the needs of all people, regardless of race, sex, economic class, age, or ability. Denver's bicycle network is currently built in the city's most affluent neighborhoods (i.e., Cherry Creek, LODO, and Stapleton) but provides minimal cycling connectivity in the outer, lower-income neighborhoods, such as Globeville. The South Platte River Trail, Globeville's premier green space and trail network, is challenging to access despite its proximity to the neighborhood. This is primarily due to several physical barriers (railway, highway overpasses, and disconnected streets) and navigational challenges that exist between the river and the rest of the neighborhood (City and County of Denver 2014, pg.51).

Public Outreach

The other, and arguably more crucial, method used to build new bike lanes is public outreach. Since the development of Denver's bicycle network, the city has used a variety of techniques aimed at getting more people involved in planning discussions. One public outreach strategy is a citizen's task force, in which a group of elected citizens discusses and deliberate over critical issues. An example of a successful task force comes from the 2015 Bicycle Safety Action Plan (BSAP), where twelve elected district representatives participated in two workshop sessions to discuss bicycle safety solutions (City and County of Denver 2016). Despite having only met twice during the duration of the study, the task force was able to identify several issues and solutions for the current bicycle network (*see Table 9).*

Theme	Issues	Goal/Action
Ordinances & Enforcement	- Out-of-date cycling laws - Irregular enforcement of cycling theft and injuries	- Create regular and balanced enforcement for both cyclists and motorists - Support broader enforcement - Update laws to ensure consistency - Promote programs to deter theft
Traffic Control & Operations	- Lack of automated signals for cyclists	- Promote consistent intersection treatments to clarify expectations for all users - Promote more neighborhood bikeways - Consider alternative cycle routes - Consider lower auto speed limits - Consider re-prioritization of modes and signal timing
Education & Outreach	- Limited knowledge of bicycle rules - A mentality of 'us vs. them' between cyclists, motorists, and pedestrians	- Set a standard for sharing information related to cycling - Get past 'us vs. them' mentality - Support cultural change - Promote multi-pronged education programs - Promote cycle/driver training courses
Physical Conditions & Infrastructure	- Lack of dedicated bike facilities - Disconnected network	- Create a connected network - Build safe, consistent, and intuitive intersections - Install more protected cycle facilities - Create higher standards of infrastructure - Prioritize and separate modes where appropriate - Provide strong signage and wayfinding

Table 9: Taskforce Workshop Goals
Source: City and County of Denver 2016, pg. 6

One of the more successful public outreach strategies Denver uses is community workshops. These workshops help planners and residents engage with one another on critical issues surrounding public safety and infrastructure improvements. Denver used this strategy during each phase of its bicycle network development plan, from the original 2015 Bicycle Safety Action Plan (BSAP) to the most current 2019 Denver Moves: Pedestrian & Trails (DM) Plan. In the BSAP, Denver worked with the task force to generate the four themes, actions, and solutions in *Table 9: Taskforce Workshop Goals* (City and County of Denver 2016). Denver also used the workshop strategy in the 2017 Denver Moves Phasing Plan. This workshop took place over six days between July and August and included several large floor aerial photographs that the public could walk and draw on to discuss their ideas (Hayden and Gannon 2017). Overall, the project had 375 people in attendance (Hayden and Gannon 2017).

Another example of Denver's public outreach strategy is its' communication and marketing outlets (City and County of Denver 2016). For the DM plan, Denver keeps its project website and social media up-to-date with interactive maps, project documents, route and destination changes, and infrastructure challenges the city is currently addressing (City and County of Denver 2019). These platforms also encourage public feedback on all projects undertaken in the DM plan (Hayden and Gannon 2017).

Denver's most recent bicycle safety public outreach strategy is the Vision Zero Community Program. Launched in 2015 by Mayor Michael Hancock, the program allows community members to increase awareness of Vision Zero in their neighborhood by promoting safe streets (The City of Denver 2017). Communities can propose projects to the City, such as street designs, community centers, and transit routes. These projects help build collaboration

between neighbors and instill a sense of empowerment and reciprocity for traditionally vulnerable communities.

DISCUSSION

Data Collection

Overall, the results indicate some disparities in the current bicycle network. First, the majority of cycling facilities are rated as high-stress routes. Over 64% (391.2 miles) of the on-road facilities meet the criteria for Stress Level 4, involve a significant amount of interaction with vehicles, and are considered extremely stressful cycling environments. Of the entire network, less than half (34%) of all cycling routes exist in low-income communities, yet the majority of these communities (78%) are within .5-mile of an off-street corridor. Despite having a moderate amount of access to both on-street and off-street facilities, crashes occur more frequently in low-income communities. Roughly 48%, or 1127, of all crashes, occurred in a low-income community.

Emphasis on CBD commuters raises the issue of transportation justice, which is based on the concept that transportation infrastructure should equitably address the needs of all people, regardless of race, sex, economic class, age, or ability. Denver's bicycle network is currently built in the city's most affluent neighborhoods (i.e., Cherry Creek, LODO, and Stapleton) but provides minimal cycling connectivity in the outer, lower-income neighborhoods, such as Globeville. The South Platte River Trail, Globeville's premier green space and trail network, is challenging to access despite its proximity to the neighborhood. This is primarily due to several physical barriers (railway, highway overpasses, and disconnected streets) and navigational challenges that exist between the river and the rest of the neighborhood (City and County of Denver 2014, pg.51).

Public Outreach

Throughout this exploration of Denver's public outreach process, it became clear that the city is struggling to reach a diverse audience in their search to improve urban cycling. Literature revealed that public outreach events are limited to a small number of residents, as was the case with the 2017 Denver Moves Initiative. Between July 10, 2010, and August 8, 2010, the Denver Moves Taskforce hosted six, four-hour workshops at a variety of locations throughout the city aimed at gathering feedback on the current bicycle network (Hayden and Gannon 2017). In total, just 375 people participated in the event with an average of 50 people in attendance at each workshop. Reasons for this low turnout could be due to some factors.

First, the workshops varied between several locations, including Confluence Park, Civic Center, and City Park, which could have changed the number of participants based on neighborhood demographics. Second, civic participation in Denver has historically been limited to residents who have the time and resources to attend public events. Conversations with public outreach officials revealed that white and affluent residents are typically seen more at these events. These residents are often more vocal at public meetings and are willing to advocate for improved infrastructure and safety in their neighborhood (Bicycle Colorado 2019). Conversations also revealed that funding is typically directed to neighborhoods who advocate for improvements. Simply put, more community interest and feedback equals more infrastructure (Bicycle Colorado 2019). This means that residents who chose not to participate in public outreach events might not have a say in where new infrastructure gets built, further drawing the divide between residential neighborhoods.

CONCLUSION

Despite the growing popularity of commuter cycling in Denver, this research investigated three issues relating to how the development of new infrastructure has proceeded over the last decade. These issues include a lack of cycling infrastructure in low-income communities, the vulnerability (crash statistics) of current infrastructure, and the imbalanced process of implementing cycling infrastructure. Currently, low-stress biking facilities are primarily concentrated near the Lower Downtown, Cherry Creek, Stapleton neighborhoods, which directs most commuter traffic to the central business district. This means that a large number of cyclists in the surrounding neighborhoods are excluded from this network, particularly low-income residents. Denver's approach to expanding its bicycle network is limited to the available data, infrastructure policies and funding, and public outreach. Based on infrastructure and crash data, Denver should focus its attention on improving intersection safety, yet limited funding is being directed to these areas. Furthermore, Denver should embrace inclusive strategies in its public outreach process that incorporate more diverse neighborhood groups.

As prior research has shown, increased cycling paths equate to an increase in physical activity. This inevitably enhances public health, but this outcome only works if it is coupled with an increase in safety. What is missing from the literature and thought the process in city planning is how safety and physical activity are recognized among vulnerable users. Sidewalks, crosswalks, and bike lanes should be designed for every user, but they are too often built in areas with already high levels of accessibility, such as downtown or tourism districts. If the goal of contemporary planning is to create walkable and bikeable cities, planners and designers need to highlight the constraints facing vulnerable communities. By beginning the planning process with vulnerable users in mind, our cities will become more comfortable places to live.

RESEARCH CONTRIBUTIONS

This research adds to the growing literature on active transportation, bicycle urbanism, and transportation justice. Many studies have used the Level of Traffic Stress (LTS) method to measure network connectivity (Mekuria et al. 2017 and Fitch et al. 2016), yet few have compared crash locations and demographic characteristics with the LTS criteria to understand how cycling infrastructure and the prevalence of crashes differ between income classes. This thesis used the LTS method to measure network connectivity and stress tolerance levels at accident-prone locations. It also provides Denver with an equity assessment of its bicycle network, finding that the majority of bicycle facilities do not provide safe routes for low-income communities. Furthermore, an evaluation of crash statistics and transportation funding directly identifies the need to address high crash areas. These results will help Denver, and other cities, build a more just and safer bicycle network.

LIMITATIONS

This thesis involved some limitations. First, the analysis was limited to available data collected on bicycle and vehicle crashes in Denver between 2012-2018. The dataset did not include specific crash information, such as direction or type of crash (broadside, on-coming, rear-end), or rights-of-way information (signaling and traffic lights). This data would have helped identify which type of crashes happen most frequently and who was at fault during the crash.

Second, the attribute table for the Denver bicycle facilities layer contained several blank entries, particularly in the ‘type’ of existing infrastructure column. Roughly a third of this

column contained some known bicycle facility, but the remaining entries were left up to interpretation. Blank entries were assessed visually on the map, and the majority of these entries appeared to be shared use streets. This may have resulted in an overestimation of the total number of shared street data points.

Third, each line segment in GIS signifies a bike path, but it is difficult to discern the width of the path, the type of facility (i.e., separated vs. shared lane), and whether or not the path intersects with vehicular traffic. These factors are crucial in determining the success of a bike facility regarding safety and general route accessibility. However, regardless of this limitation, the results show that most on-road facilities are shared streets and present stressful riding situations.

Finally, there have been a large number of recent changes made in Denver's bicycle network, all of which have not been added to the current dataset. This additional information could provide better insight as to which neighborhoods have access to on-street and off-street facilities.

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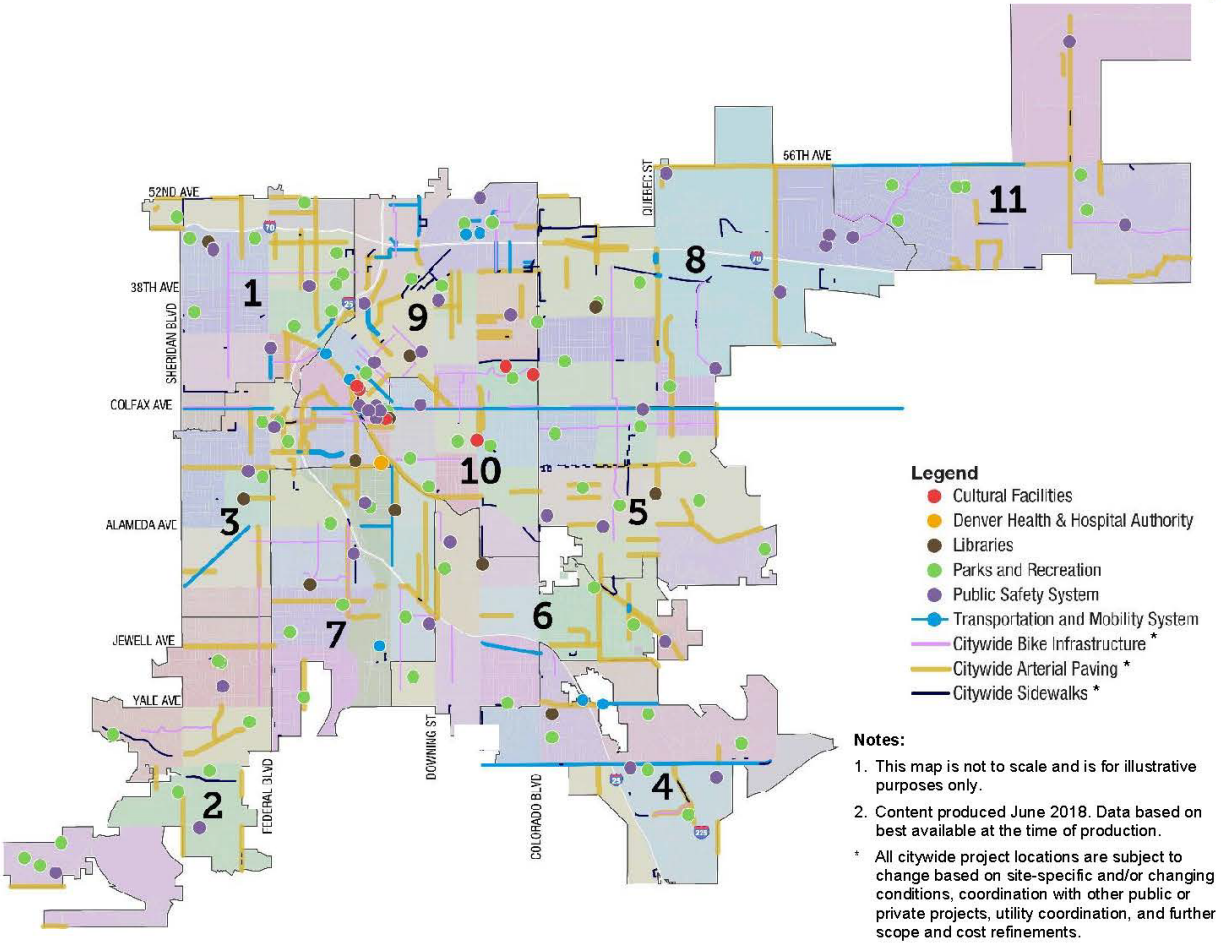
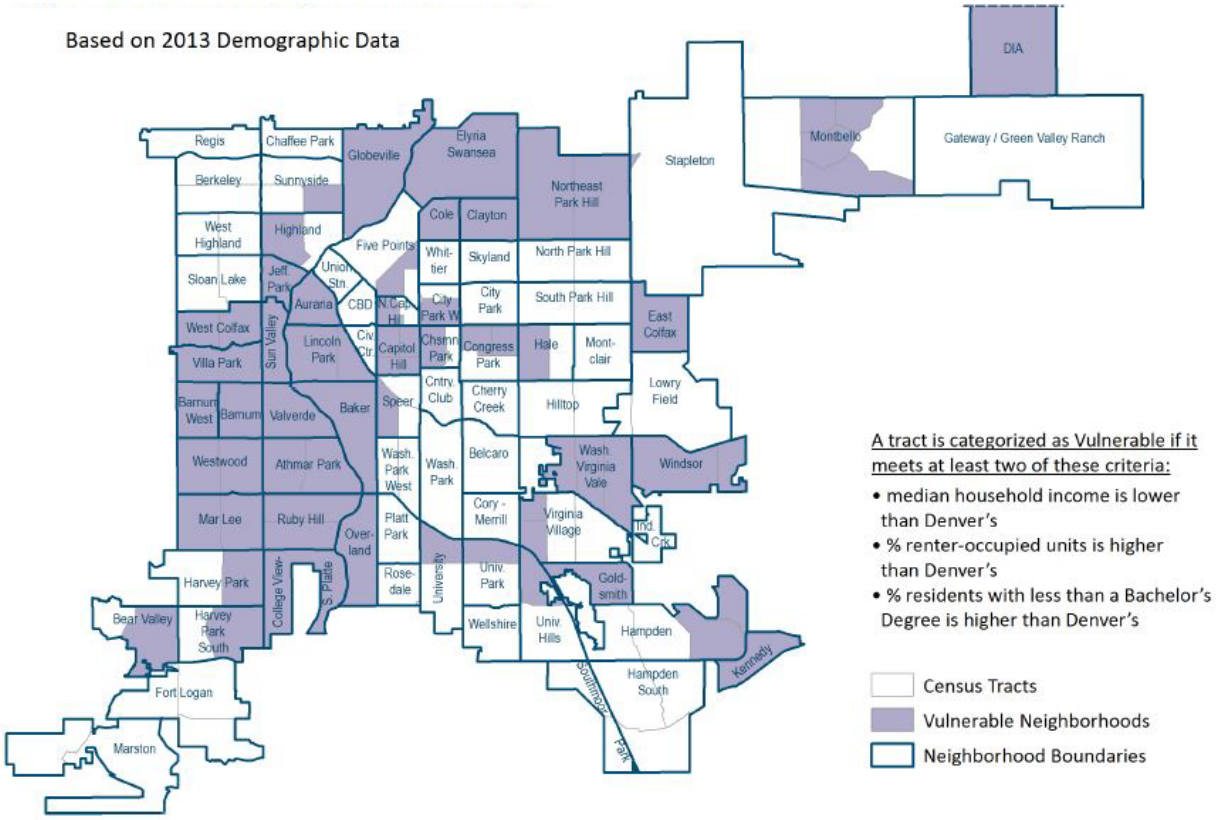
APPENDICES

Appendix A: Map of Elevate Denver Bond Phasing Plan



This map illustrates proposed construction plans for the City of Denver. Using this map, I found projected bicycle facilities improvements and compared these locations to the vulnerable communities.

Appendix B: Map of Vulnerable Communities

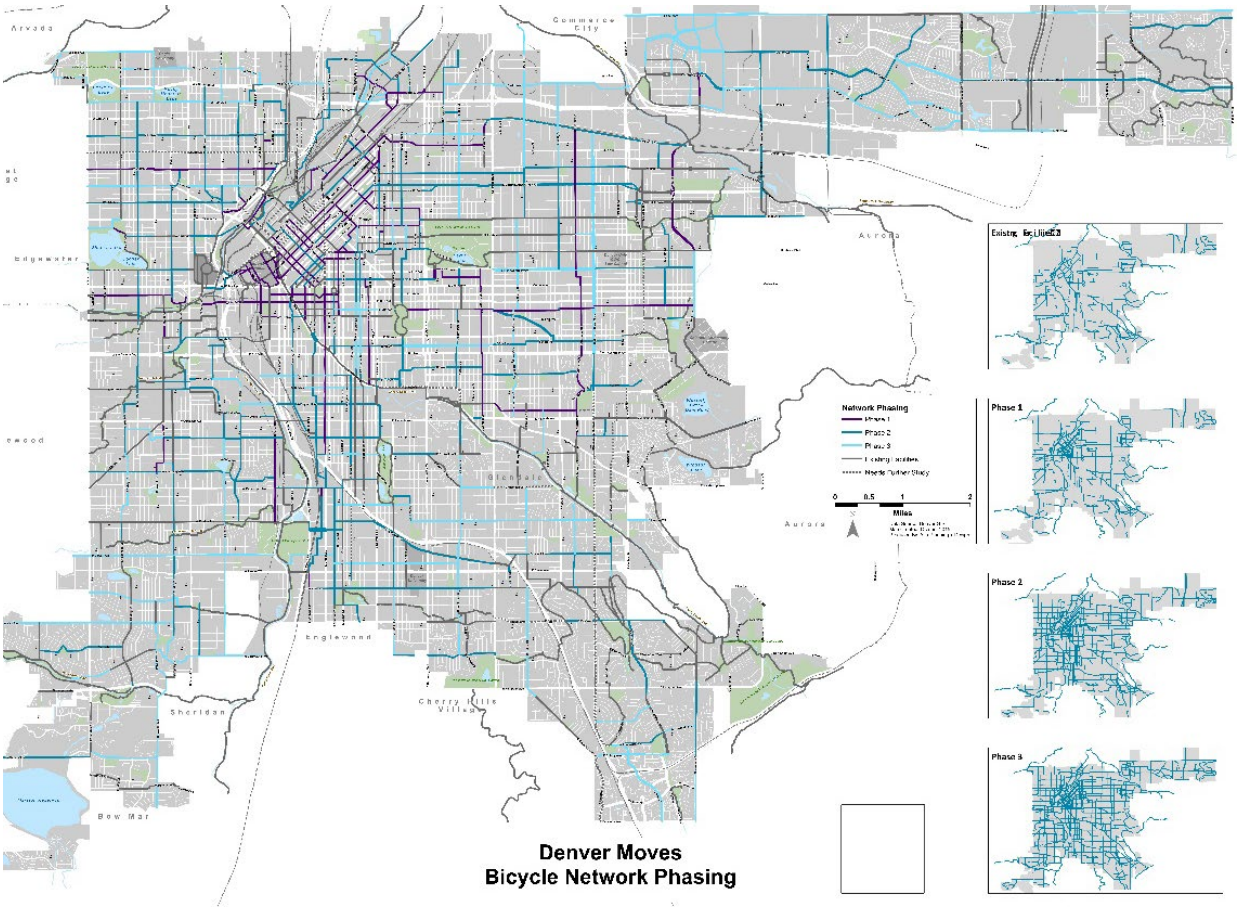


This map illustrates neighborhoods in Denver that are considered "vulnerable". Neighborhoods are categorized as vulnerable if:

- the median household income is lower than $10,000
- the percentage of renter-occupied units is higher than the rest of Denver
- the percentage of residents with less than a bachelor's degree is higher than the rest of the Denver

I used this map to compare existing bicycle facilities and the 2019 proposed bicycle facilities plan to analyze which neighborhoods would be changed by the infrastructure.

Appendix C: Denver Moves Bicycle Network Phasing Plan



This map illustrates a linear progression of the Denver Moves Initiative Plan.

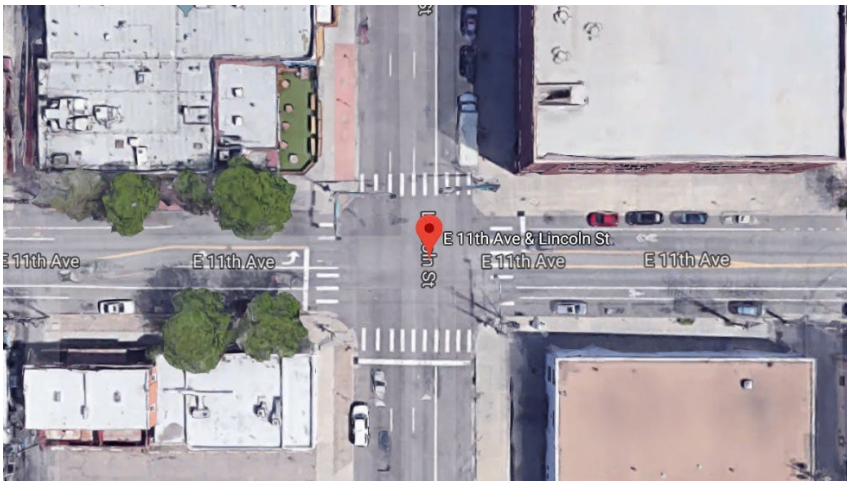
- Purple = bicycle facilities constructed in 2006
- Light Blue = bicycle facilities constructed in 2010
- Dark Blue = bicycle facilities constructed in 2016

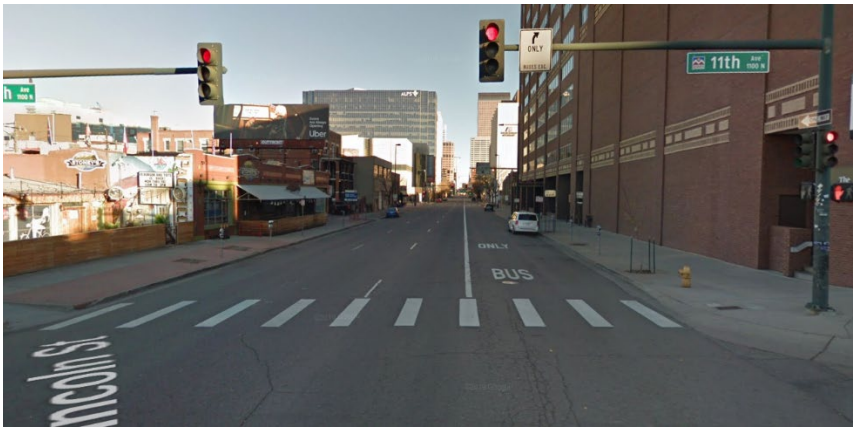
I used this map to compare existing bicycle facilities with the 2019 proposed bicycle facilities.

Appendix D: Bicycle/Vehicle Crash Locations

(all photos courtesy of Google Maps)

CRASH LOCATION	Frequency of Crash	Level of Traffic Stress	Type	Bike Lane Width (ft)
E 11TH AVE / N LINCOLN ST	12	3	striped bike lane	3

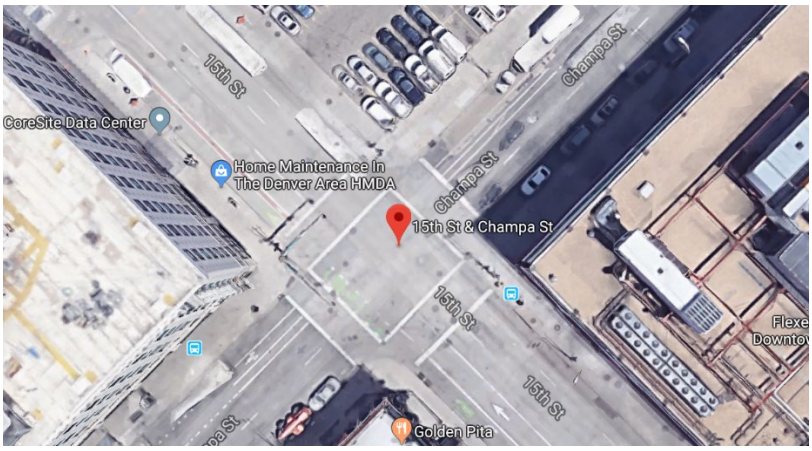




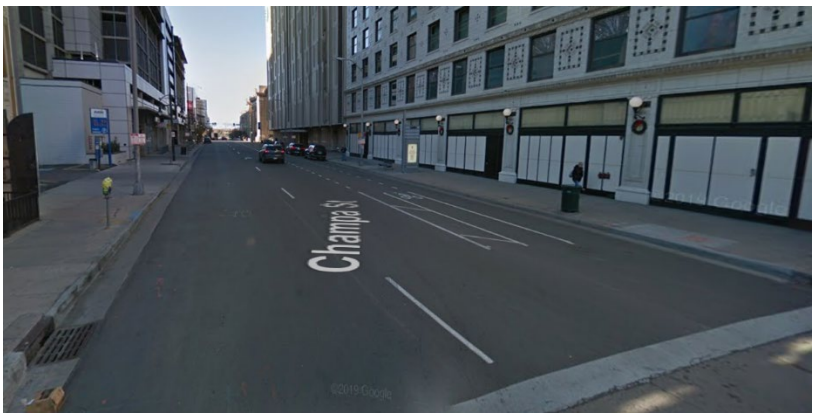
View from Lincoln Street

View from 16th Street

CRASH LOCATION	Frequency of Crash	Level of Traffic Stress	Type	Bike Lane Width (ft)
15TH ST / CHAMPA ST	10	2	buffered bike lane	4

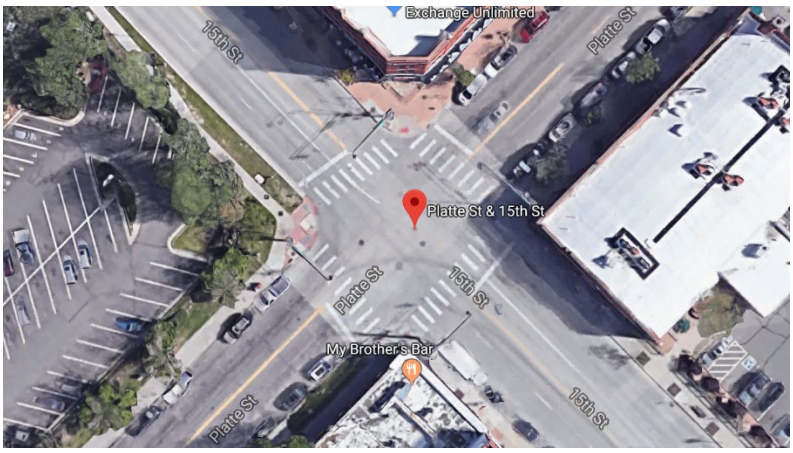


View from 15th Street



View from Champa Street

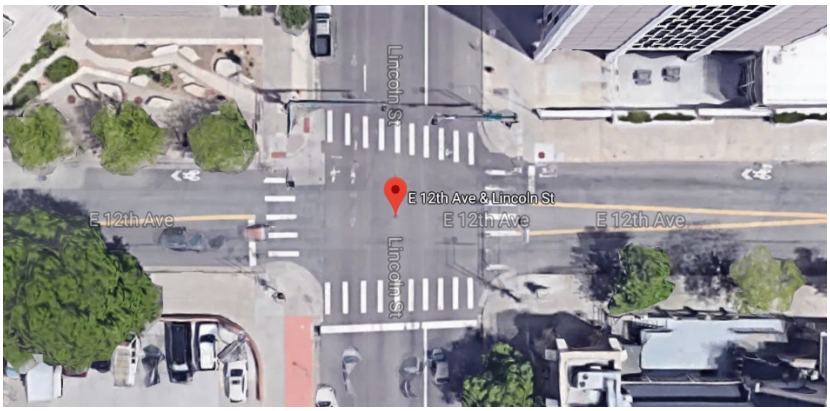
CRASH LOCATION	Frequency of Crash	Level of Traffic Stress	Type	Bike Lane Width (ft)
15TH ST / PLATTE ST	6	4	shared street	0

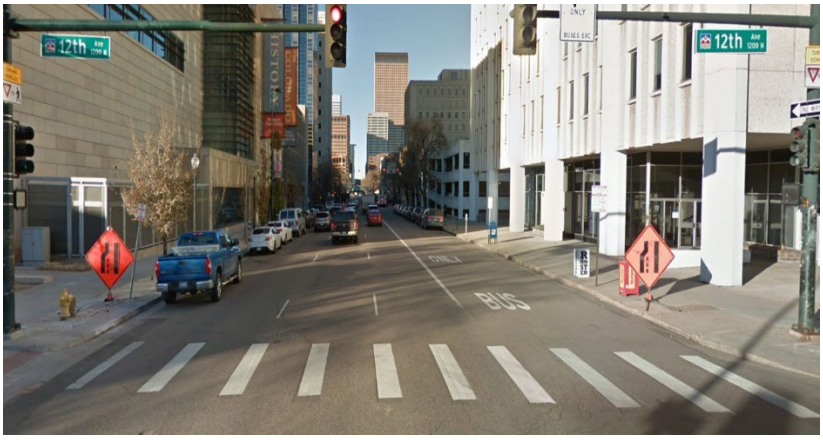


View from Platte Street

View from 15th Street

CRASH LOCATION	Frequency of Crash	Level of Traffic Stress	Type	Bike Lane Width (ft)
E 12TH AVE / N LINCOLN ST	6	4	shared street	0

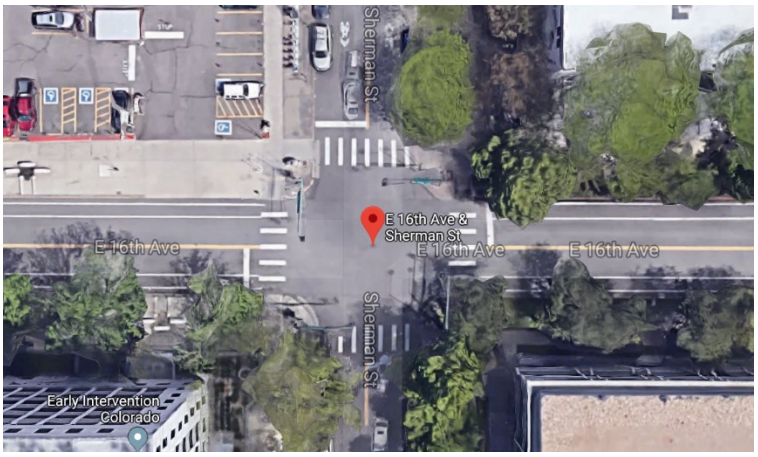




View from Lincoln Street

View from 16th Street

CRASH LOCATION	Frequency of Crash	Level of Traffic Stress	Type	Bike Lane Width (ft)
E 16TH AVE / N SHERMAN ST	6	3	striped bike lane	3



View from 16th Street

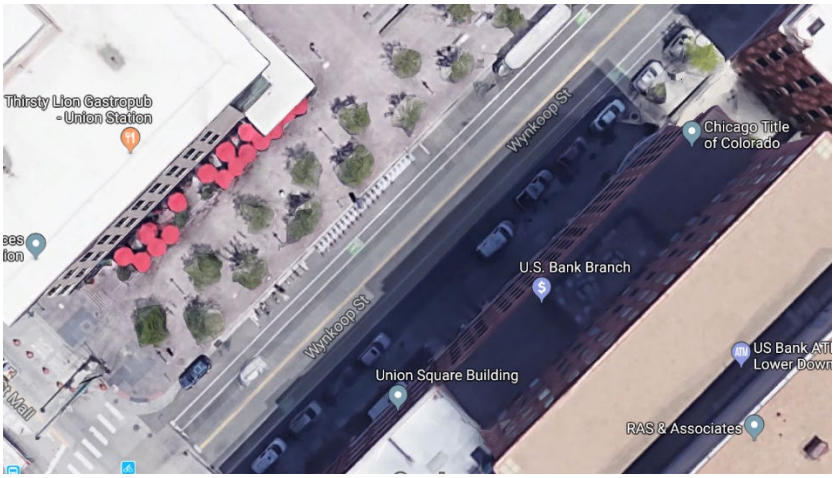
View from Sherman Street

CRASH LOCATION	Frequency of Crash	Level of Traffic Stress	Type	Bike Lane Width (ft)
W 29TH AVE / N ZUNI ST	6	3	striped bike lane	5

View from 29th Ave

View from Zuni Street

CRASH LOCATION	Frequency of Crash	Level of Traffic Stress	Type	Bike Lane Width (ft)
1600 BLOCK WYNKOOP ST	5	2	buffered bike lane	3



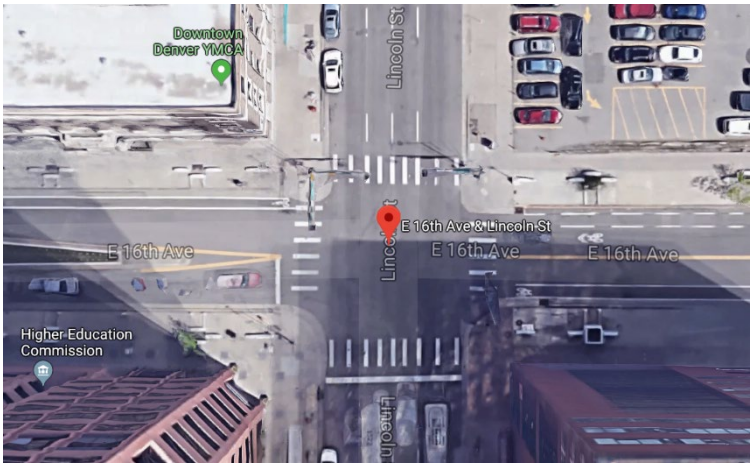
View from Wynkoop Street

CRASH LOCATION	Frequency of Crash	Level of Traffic Stress	Type	Bike Lane Width (ft)
E 16TH AVE / N CLARKSON ST	5	3	striped bike lane	3

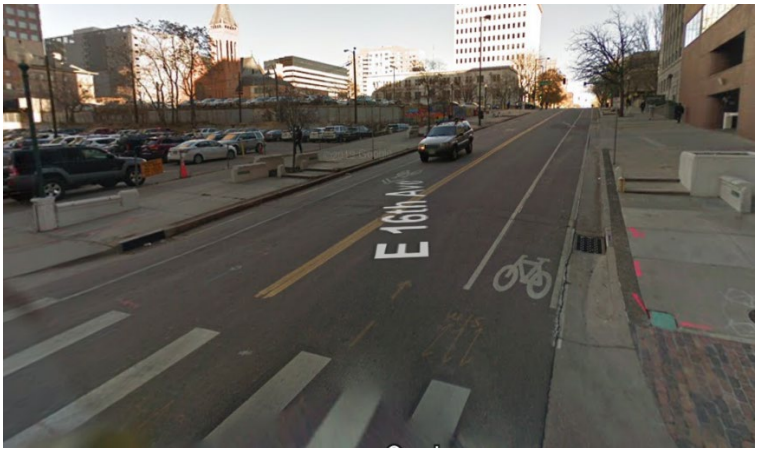
View from Clarkson Street

View from 16th Ave

CRASH LOCATION	Frequency of Crash	Level of Traffic Stress	Type	Bike Lane Width (ft)
E 16TH AVE / N LINCOLN ST	5	3	striped bike lane	3

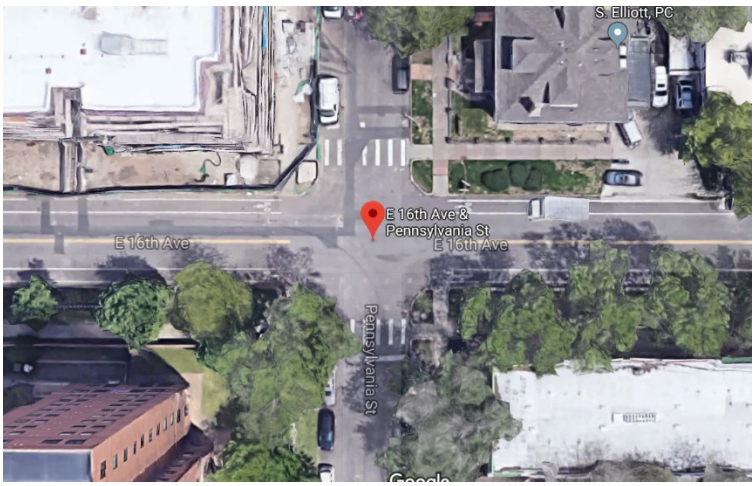


View from Lincoln Street



View from 16th Ave

CRASH LOCATION	Frequency of Crash	Level of Traffic Stress	Type	Bike Lane Width (ft)
E 16TH AVE / N PENNSYLVANIA ST	5	3	striped bike lane	3



View from 16th Ave

View from Pennsylvania Street