Evaluation of Transportation Safety and Security Barriers in Bicyclist Accessibility

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A Research Report from the Pacific Southwest Region University Transportation Center

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16. Abstract
A continuation of automobile dependence over the past half-century within American cities has resulted in significant public health, environmental, and economic challenges. The further motivation of bicycling as a utilitarian and sustainable travel alternative has been identified as a viable solution to address societal concerns regarding physical inactivity, climate change, and transportation inequities. However, to date, a profound increase in bicycle mode shares in most communities remains elusive largely due to an inability to attract new bicyclists via the provision of safer bicycling infrastructure. This report, which is comprised of two studies, introduces a bicyclist routing platform that is sensitive to network barriers and the safety concerns shared by different types of bicyclists and implements the planning tool in eight Arizona metropolitan regions. In the first study, the Cyclist Routing Algorithm for Network Connectivity (CRANC) is designed to identify local and regional discrepancies in bicycling accessibility to jobs, schools, and grocery stores by integrating the concepts of bicyclist types and bicycle level of traffic stress into a new bicycling accessibility metric. In the second study, an analytic framework leveraging the CRANC tool is introduced to provide insights into the interrelationships between cycling accessibility along high-stress bike facilities and observed cyclist conflicts with motorists. In carrying out these studies, this research project intends to offer city officials and transportation researchers both a decision-support tool and the accompanying evidence needed to identify objective and perceived traffic safety barriers that are likely hindering a more widespread and equitable increase in bicycle mode adoption.

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The Pacific Southwest Region University Transportation Center (UTC) is the Region 9 University Transportation Center funded under the US Department of Transportation's University Transportation Centers Program. Established in 2016, the Pacific Southwest Region UTC (PSR) is led by the University of Southern California and includes seven partners: Long Beach State University; University of California, Davis; University of California, Irvine; University of California, Los Angeles; University of Hawaii; Northern Arizona University; Pima Community College.

The Pacific Southwest Region UTC conducts an integrated, multidisciplinary program of research, education and technology transfer aimed at *improving the mobility of people and goods throughout the region.* Our program is organized around four themes: 1) technology to address transportation problems and improve mobility; 2) improving mobility for vulnerable populations; 3) Improving resilience and protecting the environment; and 4) managing mobility in high growth areas.

U.S. Department of Transportation (USDOT) Disclaimer

Disclosure

Steven R. Gehrke (Principal Investigator), Manoj K. Allam, Brendan J. Russo (Co-Principal Investigator), and Edward J. Smaglik (Co-Principal Investigator) conducted this research titled, "Evaluation of Transportation Safety and Security Barriers in Bicyclist Accessibility" at Northern Arizona University. The research took place from August 15, 2022 to December 31, 2023 and was funded by a grant from the Pacific Southwest Region University Transportation Center in the amount of $99,891. The research was conducted as part of the Pacific Southwest Region University Transportation Center research program.

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Abstract

A continuation of automobile dependence over the past half-century within American cities has resulted in significant public health, environmental, and economic challenges. The further motivation of bicycling as a utilitarian and sustainable travel alternative has been identified as a viable solution to address societal concerns regarding physical inactivity, climate change, and transportation inequities. However, to date, a profound increase in bicycle mode shares in most communities remains elusive largely due to an inability to attract new bicyclists via the provision of safer bicycling infrastructure. This report, which is comprised of two studies, introduces a bicyclist routing platform that is sensitive to network barriers and the safety concerns shared by different types of bicyclists and implements the planning tool in eight Arizona metropolitan regions. In the first study, the Cyclist Routing Algorithm for Network Connectivity (CRANC) is designed to identify local and regional discrepancies in bicycling accessibility to jobs, schools, and grocery stores by integrating the concepts of bicyclist types and bicycle level of traffic stress into a new bicycling accessibility metric. In the second study, an analytic framework leveraging the CRANC tool is introduced to provide insights into the interrelationships between cycling accessibility along high-stress bike facilities and observed cyclist conflicts with motorists. In carrying out these studies, this research project intends to offer city officials and transportation researchers both a decision-support tool and the accompanying evidence needed to identify objective and perceived traffic safety barriers that are likely hindering a more widespread and equitable increase in bicycle mode adoption.

Evaluation of Transportation Safety and Security Barriers in Bicyclist Accessibility

Executive Summary

A further motivation of cycling as a sustainable utilitarian travel alternative to motor vehicles has been identified as a viable response to rising societal concerns regarding physical inactivity, climate change, and transportation-related inequities. Yet, even as policymakers, practitioners, and researchers continue to pursue strategies and programs for increasing cycling activity in most American metropolitan regions, significant challenges remain in the provision of safe bike infrastructure with the potential for attracting a more general population to cycling. Importantly, more intentional processes for implementing facility design improvements that can facilitate greater and safer utilitarian cycling activity carries a prospect of alleviating enduring spatial and social inequities faced by under-resourced communities and historically disadvantaged residents who are disproportionately impacted by the escalating costs of motor vehicle access and more likely to live in neighborhoods with higher rates of observed motorist-cyclist crashes.

This research project aims to develop an innovative decision-making tool to transportation planners and practitioners seeking to recognize the perceived barriers in cycling access to subsistence activities across a diverse population of current and prospective cyclists. After introducing this cyclist routing platform, a pair of studies are undertaken to (1) examine the local and regional variations in cycling access to nearby jobs, schools, and grocery stores for individuals with different perceptions of comfort and (2) investigate the relationships between neighborhood context and high-stress cycling accessibility and its subsequent connection to objective cyclist safety. In this project's first of two studies, the Cyclist Routing Algorithm for Network Connectivity (CRANC) is presented as an accessibility-oriented transportation planning tool for modeling routes of three cyclist types (interested but concerned, enthused and confident, and strong and fearless). The CRANC tool is then applied in eight Arizona metropolitan regions to provide insights into intra- and inter-regional differences in safe bike infrastructure provision and its impact on cycling access to potential employment, education, and shopping opportunities. In this project's second study, using routes generated by the CRANC tool, 15-minute isochrones or activity spaces originating from quarter-mile grid cell centroids are produced across the study area for the interested but concerned cyclist type. Guided by a conceptual framework, associations between perceived and objective cyclist safety and their connection to residential context are then modeled using a two-part analytic approach.

Select findings from these two studies, which are intended to provide a planning tool for identifying the perceived and objective barriers to cycling and evidence supporting infrastructure investment, include:

- Interested but concerned cyclists who are considered more risk averse to cycling in mixed traffic and require high-quality facilities to cycle had lower access to jobs, schools, and grocery stores.
- Spatial discrepancies in cycling access to jobs, schools, and grocery stores across metro regions were found as well as local variations among social contexts and a potential urban-rural divide.
- For neighborhoods in which an interested but concerned cyclist could access a school within 15 minutes, a link between higher-stress facilities and increased presence of children was modeled.
- High-stress cycling access to jobs and schools for risk averse cyclists was associated with a higher frequency of nearby motorist-cyclist crashes and those resulting in a more severe cyclist injury.

Introduction

Through the provision of new or improved bike facilities aimed at increasing utilitarian cycling activity, many transportation planners, engineers, and policymakers continue to promote bicycling as a viable alternative to personal automobile travel. Reasons for this support extend beyond the mobility benefits offered by promoting another mode choice to include individual and societal gains related to increased physical activity, decreased air pollutant emissions, and lower travel expenditures. However, even given these recognized advantages of increased cycling mode adoption and the best efforts of cities to further motivate utilitarian cycling activity, cycling in American cities still constitutes a small mode share relative to motor vehicle travel. The crux challenge being how to alleviate the existing perceptive and objective network barriers to cycling that prevent new potential cyclists from adopting this more environmentally sustainable mode of travel for utilitarian trips. Importantly, particular attention should continue to be aimed at increasing the viability of cycling for under-resourced and historically disadvantaged residents, who are disproportionately affected by the financial burden associated with the rising costs of vehicle access to subsistence activities and are more likely to reside within communities that experience higher rates of motorist-cyclist crashes.

This research report, which investigates the perceived and revealed traffic safety concerns of utilitarian cyclists, comprises two studies. In the first study, an accessibility-oriented transportation planning tool sensitive to both bike network conditions and the varying routing preferences of different cyclist types is introduced to support utilitarian bicycling promotion. By implementing this bicycle routing platform in eight Arizona metropolitan regions, spatial differences in cycling access to employment opportunities, schools, and grocery stores are illustrated via the introduction of a new accessibility metric integrating concepts of traffic stress and cyclist preference. The findings from this first study are intended to help identify opportunities for promoting equitable cycling access to subsistence and maintenance activities for individuals who do not presently ride a bike but would if barriers to access were removed, unlocking a latent demand for utilitarian cycling and its greater promotion.

In the second study, the interrelationships between residential context, perceived cycling accessibility, and revealed cyclist safety are investigated using a two-part statistical analysis informed by a proposed conceptual framework. The first analysis examines statistical associations between neighborhood-level sociodemographic and economic characteristics and the perceived safety of existing network conditions for home-based travel to subsistence activities. The second analysis, in turn, examines how this modeled link between context predictors and perceived accessibility relates to observed motorist-cyclist crashes near a potential cyclist's residence. The findings from this second study are aimed at assisting planners and decisionmakers focused on improving cycling conditions and facilitating greater utilitarian cycling activity by identifying and evaluating the connections between safety and security barriers to cycling.

The design, implementation, and results from each of these studies are described in the following two chapters of this report, which concludes with a brief synthesis of this research project's contributions.

Study 1: Cycling Accessibility to Employment, Schools, and Grocery Stores in Arizona Metropolitan Regions

Study background

Bicycling offers myriad societal and individual benefits to cities and those who reside and work within their settings. Beyond mobility improvements, increases in utilitarian bicycling have been linked to public health (1), environmental (2), and economic (3) gains as well as more intrinsic individual benefits (4). This confluence of sustainability advancements has buoyed city efforts to implement strategies and programs targeted at increasing urban bicycling rates (5,6) and extending equitable bike infrastructure access to different population groups (7). However, limited public resources remain available to cities for the creation of dedicated bike infrastructure, which has been identified as a successful approach for cities to elevate bicycling activity among a more general and diverse population (8).

In response, cities and metropolitan regions must continue to pursue the design and adoption of bicycle planning tools capable of identifying opportunities and barriers to expanding utilitarian bicycling, as a flexible and cost-effective travel option for accessing subsistence and maintenance activity locations. By recognizing where gaps exist in the provision of a robust, bike-friendly network to residents with varying experience in bike usage and diverse socioeconomic backgrounds, financial decisions regarding bike facility improvements aimed at increasing its adoption can better consider the different needs of a more diverse population. This study seeks to aid this needed response by cities to further motivate utilitarian bicycling through its focus on the following research aims. First, this study strives to develop a bike network routing engine that is sensitive to individual preferences in route choice, bike infrastructure availability, and travel speed to help inform programmatic decisions related to bike network enhancements. Second, this study aims to assess differences in bicycling accessibility to subsistence and maintenance activity destinations in metropolitan regions across individuals of varying bicycling experience and socioeconomic backgrounds. Through accomplishing these two research aims; this study looks to offer an innovative bicycle planning tool for cities wanting to evaluate the accessibility benefits of bicycling across a general population under given network conditions and identify associated barriers and opportunities to increasing equitable access.

Literature review

Responding to a shift from mobility-related performance metrics, operationalizations of the accessibility concept have become more common in planning studies of utilitarian cycling (9). While notable variations in their implementation exist, an important subset of place-based accessibility metrics that assess the supply of out-of-home activities from a trip origin's location using a gravity model indicator have been adopted to address substantive active transportation planning issues (10, 11). This section provides a review of several recent studies of cycling accessibility to subsistence and maintenance activity destinations, with specific attention given to variation in accessibility measures based on route preferences of different cyclist types and weighting of their out-of-home activity opportunities.

In a study of cycling accessibility to employment opportunities in four metropolitan regions in the United States, Murphy and Owen (12) presented a cumulative opportunities metric that summed the number of jobs available to a cyclist departing a Census block centroid within a 20-minute ride. Although their metric did not discount the value of employment opportunities located farther from the trip origin, their measurement of job accessibility based on different acceptable level of traffic stress (LTS) thresholds reduced the number of reachable destinations for cyclists with varying preferences of traffic safety. Faghih-Imani et al. (13) similarly categorized an OpenStreetMap (OSM) network of streets and bike facilities in Toronto, Canada based on four LTS classes to measure accessibility to employment and population from dissemination areas, finding that job accessibility decidedly improved only when cyclists were allowed to ride on higher stress bike facilities (LTS ≥ 3). In a pair of studies related to this manuscript's analysis, Gehrke et al. (14) and Martinez et al. (15) introduced a bike planning tool that simulates the route preferences of different cyclist types and trade-offs in travel time and LTS to measure potential destination accessibility. Adopting a cyclist typology proposed by Geller (16) and confirmed by Dill and McNeil (17), the former study examined the potential changes in employment and labor force accessibility for the "interested but concerned" and "enthused and confident" cyclists in Cambridge, Massachusetts attributed to introducing different investments in bike-friendly infrastructure (14). The latter study by Martinez et al. (15) adopted a similar cumulative opportunities metric to evaluate differences in cycling accessibility to physical and virtual workplaces for "interested but concerned" cyclists from Census block centroids in Flagstaff, Arizona. Akin to these studies, Hosford et al. (18) also presented a cumulative opportunities measure of destination accessibility that accounted for LTS network designations as well as different cyclist types. Investigating accessibility to grocery and produce stores separately for younger and older cyclists, the authors found that most 15-minute cycling trips in Vancouver, Canada originating from dissemination blocks could access 10 or more grocery stores using lower stress bike facilities regardless of cycling speed. To date, the inclusion of LTS criteria in cycling accessibility studies has represented a reduction in the travel network that is available from different trip origins based on perceptions of cycling comfort rather than a sensitivity in the weight given to different activity destinations based on a cyclist's threshold for comfort.

In their seminal research on measuring accessibility for active travel modes, Iacono et al. (19) supported the logic in adopting cumulative opportunities measures, while also highlighting the conceptual and practical need to dampen the attractiveness of destinations by incorporating an impedance function based on the travel time, distance, or cost specific to cycling behavior. Using revealed travel survey data, the authors estimated separate decay functions of travel distance and time to evaluate cycling accessibility to a set of five activities (e.g., jobs, grocery stores, schools) in Minneapolis, Minnesota (19). Also adopting a gravity-based measure of zonal accessibility normalized by overall study area activity, Li et al. (20) investigated a more extensive list of 42 points of interest including schools and grocery stores to estimate activity-specific cost decay functions for measuring cycling accessibility in Shanghai, China. Introducing a composite bikeability measure consisting of 24 evaluated destination types, McNeil (21) assessed differences in potential cycling accessibility across sampled locations in Portland, Oregon using a gravity-based metric that weighted the contribution of activities based on three service area breaks. Unlike the prior studies that employed Euclidean distance and shortest network path routes, respectively, McNeil (21) incorporated network link characteristics (e.g., bicycle boulevard, bike lane) in addition to distance to assign an effective length to each segment that increased the distance a cyclist would be willing to travel if on bike-friendly infrastructure. Examining the nexus between potential cycling accessibility and revealed cycling trips in Melbourne, Australia, Saghapour et al. (22) introduced a gravity-based metric based on origin-destination travel impedance as well as diversity in land uses and count of activities in a statistical area. In their study, the authors used the median desirable distance across four activity destination types to reflect network impedance (22). While each of these studies adopted gravity-based accessibility metrics with impedance functions, a representation of different tastes in bike infrastructure and cycling conditions across the general population could provide a nuanced assessment of destinations that are reachable by a greater range of existing and latent cyclist types.

A handful of studies have sought to link perceptions of cycling comfort and safety to gravity-based accessibility, including Lowry et al. (23) who introduced a bicycle level of service measure consisting of 10 network-related variables (e.g., vehicle traffic volume, vehicle speeds, number of through lanes) to prioritize bike infrastructure projects in Moscow, Idaho with commercial accessibility as a performance metric. Arranz-Lopez et al. (24) applied distance-decay functions specific to four types of cyclists described by varying socioeconomic attributes of the general population of Zaragoza, Spain to evaluate the willingness to cycle to daily, weekly, and incidental retail activities. Also dividing the study area into 100-meter grid cells, Rosas-Satizabal (25) examined variations in cycling accessibility to employment opportunities and schools in Bogota, Columbia across three cyclist types that were estimated using surveyed data on socioeconomic and trip attributes. Similarly, Ospina et al. (26) investigated cycling accessibility to work and educational activities in Medellin, Columbia for two cyclist types distinguished across 8 socioeconomic attributes using a gravity-based metric with a distance-decay function. These last three studies, which implemented gravity-based accessibility metrics with impedance functions associated with differing cyclist preferences, signify a methodological advancement toward gravity-based accessibility metrics with person-based impedance functions.

This study contributes to the reviewed evidence base by integrating the concepts of cyclist types and varied individual perceptions of traffic safety and comfort into a gravity-based accessibility metric that adjusts the weight of potential activity destinations based on the safety and comfort of modeled routes. A study aim that is accomplished by modeling cycling routes between origin-destination pairings that are specific to the widely referenced cyclist typology by Geller (16) and calculating destination accessibility with a metric comprised of an impedance function that combines these differing route preferences with variations in available bike infrastructure characterized by a popular LTS criteria proposed by Furth et al. (27). In doing so, this study seeks to introduce an informative and intuitive method for evaluating the accessibility-related benefits of utilitarian cycling for a general population under given network conditions.

Methods

Cyclist Routing Algorithm for Network Connectivity (CRANC) 2.0

To represent the cycling route preferences of different individuals, this study introduces a revised version of the Cyclist Routing Algorithm for Network Connectivity (CRANC) planning tool introduced by Gehrke et al. (*14*). GraphHopper, an open-source Java library and web service, serves as the base network routing engine for CRANC 2.0, configured with a bidirectional Dijkstra graph search algorithm applied to OSM and flexible codebase that permits the definition of three cyclist types with varied travel speeds and route preferences informed by network features. In the algorithm, GraphHopper uses the OSM network of streets and paths to generate a graph of directed edges (or links) between nodes (or junctions), where the path between an origin-destination pair that produces the lowest cumulative impedance across edges and nodes becomes the assigned route. Equation 1 is used to calculate the impedance associated with a network edge:

$$W_{ik} = (l_i / v_{ik}) \times a_{ik} \times a_{jk} \quad (1)$$

where W_{ik} is the impedance (or weight) associated with network edge i for cyclist type k, v_{ik} is the speed associated with network edge i for cyclist type k, l_i is the length of network edge i, and a is an aversion factor for cyclist type k associated with both network edge i and its network node j at the head of edge i.

Equation 2 is used to calculate the speed associated with a network edge, which is sensitive to the base speeds of different cyclist types and grade of the network edge:

$$v_{ik} = v_0(i, k) \times (\beta_k G_i)^2 \quad (2)$$

where $v_0(i, k)$ is the base travel speed on network edge i for cyclist type k, G_i is the change in elevation over the length (or grade) of network edge i, and β_k is a constant value applied to uphill or downhill grades dependent on cyclist type k. Excluding the "no way, no how" (NWNH) cyclist type defined by Geller (*16*) as disinterested in cycling, the CRANC 2.0 tool defines routing profiles for the "interested but concerned" (IBC), "enthused and confident" (EAC), and "strong and fearless" (SAF) cyclist types, who currently ride a bike or have some inclination toward utilitarian cycling. In this speed formulation, the β value for the IBC, EAC, and SAF cyclist types is 5.0 for uphill grades and 2.0 for downhill grades. This insensitivity to edge grade, calculated using Shuttle Radar Topography Mission elevation data, across cyclist types resulted in their base travel speeds being only predicated on characteristics of the OSM network edges.

Table 1 provides an overview of the base travel speeds for the three cyclist types, which vary based on the OSM highway tag associated with a network edge and classification of bike facilities in accordance with the National Association of City Transportation Officials (NACTO) Urban Bikeway Design Guide (*28*). Assigned base travel speeds for the IBC and EAC cyclists on network edges without bike facilities align with those previously presented in Gehrke et al. (*14*), while travel speeds on these road classifications for the SAF cyclist type reflect incremental adjustments from the EAC cyclist type. Base travel speeds associated with unprotected bike infrastructure align with the assigned travel speeds for the road class they would typically coincide with, while a constant speed of 18 km/hour was assigned to protected bike infrastructure regardless of cyclist type.

Table 1. Base travel speed assignment by road classification, bike facility, and cyclist type in CRANC 2.0

	Base Travel Speed (km/hour) per Cyclist Type		
Edge Weight Elements	Interested but Concerned (IBC)	Enthused and Confident (EAC)	Strong and Fearless (SAF)
OpenStreetMap 'Highway' Tag			
Motorway/Trunk	15	20	23
Primary/Secondary/Tertiary	14	20	23
Residential	12	16	18
Service	12	12	12
Footway/Pedestrian	10	6	4
NACTO Urban Bikeway Designs			
Bicycle Boulevards	12	16	18
Conventional Bike Lanes	14	20	23
Buffered Bike Lanes	18	18	18

Contra-Flow Bike Lanes	18	18	18
Left-Side Bike Lanes	14	20	23
One-Way Protected Cycle Tracks	18	18	18
Raise Cycle Tracks	18	18	18
Two-Way Cycle Tracks	18	18	18

Apart from traveling at different speeds, each of the three cyclists have varying levels of perceived comfort in cycling with automotive traffic or on dedicated bike infrastructure. In the CRANC 2.0 tool, this perceived comfort is operationalized as an aversion to cycling on or across the different edges and nodes of the street network characterized by a set of attributes, denoted in Equation 3.

$$a_{gk} = 10.5/\left(p_{gk} + 0.5\right) \quad (3)$$

where a_{gk} is the aversion a experienced by cyclist type k when traversing any edge or node of the street network $g = (i, j)$ represented as a reciprocal of the priority index p_{gk} associated with a network edge or node element. A scaling factor of 10.5 was applied so an unchanged (or neutral) priority assignment would result in an aversion factor of 1.0.

Table 2 describes the priority index (and aversion factors) assigned to network edges based on a combination of OSM road classification, surface type, and NACTO urban bikeway design. Attribute levels were defined using OSM tags, with four NACTO-defined bike facility groupings noted below and classified using OSM highway, cycleway, and oneway tags.

- Bicycle Boulevard (highway=<any>, cycleway=shared_lane);
- Bike Lane: Conventional (highway=<any>, cycleway=lane), Left-side (highway=<any>, oneway=yes, cycleway:left=lane), Contra-flow (highway=<any>, cycleway=opposite_lane);
- Buffered Bike Lane (highway=<any>, cycleway:buffer=lane);
- Cycle Track: One-way Protected (highway=cycleway, oneway=yes), Raised (highway=<any>, cycleway=track), Two-way (highway=cycleway).

Table 2. Priority index and aversion factors assigned to network edges in CRANC 2.0

		Network Edge (Link) Characteristics		
Priority Index	Aversion Factor	OpenStreetMap 'Highway' Tag	OpenStreetMap 'Surface' Tag	NACTO Urban Bikeway Designs
0: Exclude	21.00	(none)	(none)	(none)
1: Reach Destination	7.00	Motorway	Any value	(none)
2: (no name)	4.20	Trunk	Any value	(none)
3: Very Bad	3.00	Primary	Any value	(none)
4: (no name)	2.33	Secondary	Any value	(none)
5: Bad	1.91	Service/Tertiary	Any value	(none)
6: Avoid More	1.62	NOT Residential	Any value	Bicycle Boulevards
7: (no name)	1.40	NOT Residential	Any value	Bike Lanes
8: Avoid	1.24	Footway	Any value	(none)
9: Slight Avoid	1.11	Residential	Unpaved	(none)
10: Unchanged	1.00	Residential	Paved	(none)
11: Slight Prefer	0.91	Residential	Any value	Bicycle Boulevards
12: Prefer	0.84	Residential	Any value	Bike Lanes
13: Very Nice	0.78	Any value	Any value	Buffered Bike Lanes
14: (no name)	0.72	Any value	Any value	Cycle Tracks

15: Best	0.68	(none)	(none)	(none)

Note. Priority index value of 10 given to all network edges for the "enthused and confident" and "strong and fearless" cyclist types.

The IBC cyclist type, who prefers dedicated bike facilities, slower vehicle speeds, and lower traffic volumes if cycling alongside vehicles, is assigned a neutral preference for paved, residential streets without bike facilities. Further preference is then given to network edges with dedicated bike facilities, with increasing prioritization for NACTO bikeway designs that physically separate the IBC cyclist from vehicles. In this study, EAC and SAF cyclist types are given neutral preferences for all configurations of network edges and nodes.

Table 3, in turn, details the priority index (and aversion factors) assigned to network nodes based on a combination of encountered traffic control, modeled cyclist turning movement, and annual average daily traffic (AADT) volume associated with the intersection crossing. Here, a neutral presence is given to the IBC cyclist type when crossing an intersection that is uncontrolled or has a yield sign, with no sensitivity regarding the cyclist's turning movement or the AADT of crossing traffic, which is assumed to be controlled and in deference to the approaching cyclist. The IBC cyclist is increasingly risk-averse to intersections with greater traffic controls and higher crossing traffic volumes, and disfavors routes producing left turns more than those which necessitate a right turn or no turning movement. Traffic signal locations for state-operated intersections were provided by Arizona Department of Transportation (ADOT) and merged into the OSM network of nodes. AADT information was provided in street centerline format by ADOT and appended to the OSM network of nodes via a multistep process that assigned AADT values to network links and imputed missing link values with the mean AADT estimate for similarly classified edges in the link midpoint's Census tract, while maintaining a routable cycling network.

Table 3. Priority index and aversion factors assigned to network nodes in CRANC 2.0

		Network Node (Intersection) Characteristics		
Priority Index	Aversion Factor	OpenStreetMap 'Highway'/'Crossing' Tag	Intersection Turning Movement	Annual Average Daily Traffic (AADT) Volume
0: Exclude	21.00	(none)	(none)	(none)
1: Reach Destination	7.00	Traffic Signal	Left	16,000 or above
2: (no name)	4.20	Traffic Signal	Left	8,000 or 15,999
3: Very Bad	3.00	Traffic Signal	Right or None	16,000 or above
4: (no name)	2.33	Traffic Signal	Left	0-7,999
5: Bad	1.91	Traffic Signal	Right or None	8,000-15,999
6: Avoid More	1.62	Traffic Signal	Right or None	0-7,999
7: (no name)	1.40	Stop	Left	8,000 or above
8: Avoid	1.24	Stop	Left	0-7,999
9: Slight Avoid	1.11	Stop	Right or None	Any value
10: Unchanged	1.00	Uncontrolled/Yield	Right or None/Left	Any value
11: Slight Prefer	0.91	(none)	(none)	(none)
12: Prefer	0.84	(none)	(none)	(none)
13: Very Nice	0.78	(none)	(none)	(none)
14: (no name)	0.72	(none)	(none)	(none)
15: Best	0.68	(none)	(none)	(none)

Note. Priority index value of 10 given to all network edges for the "enthused and confident" and "strong and fearless" cyclist types.

Cycling accessibility

This study applies the described CRANC 2.0 planning tool to measure cycling accessibility to employment, school, and grocery market locations for the IBC, EAC, SAF cyclist types across the eight urbanized areas in the State of Arizona governed by a metropolitan planning organization (MPO) policy board. **Table 4** offers a brief population overview of each urbanized area and its largest incorporated city. Each MPO governs an urbanized area consisting of at least 50,000 residents. Phoenix and Tucson are the most-populous Arizona cities and the largest incorporated cities in the state's two transportation management areas, a federal designation given to MPOs with an urbanized population of at least 200,000 residents. Lake Havasu MPO, Sierra Vista MPO, and MetroPlan each have less than 100,000 residents, who predominately reside in the largest incorporated city of their respective planning areas (Lake Havasu City, Sierra Vista, and Flagstaff).

Table 4. Population (2020) of eight urbanized areas in Arizona governed by metropolitan planning organizations

	Designated Planning Area		Largest Incorporated City	
Metropolitan planning organization	Population	Pop. Density	Name	Population
Central Yavapai MPO	139,491	297.54	Prescott Valley	46,785
Lake Havasu MPO	60,424	547.33	Lake Havasu City	57,144
Maricopa Association of Governments	4,055,281	380.46	Phoenix	1,608,139
MetroPlan	83,912	158.32	Flagstaff	76,831
Pima Association of Governments	980,263	106.61	Tucson	542,629
Sierra Vista MPO	70,287	411.04	Sierra Vista	45,308
Sun Corridor MPO	108,061	93.48	Casa Grande	53,658
Yuma MPO	195,807	35.46	Yuma	95,548

Cycling accessibility for this noncontinuous study area of eight urbanized areas was measured by casting a network of quarter-mile grid cells across their jurisdictional boundaries. Grid cell centroids represented the trip origin for each modeled cycling route, while trip destinations were represented as points for school and grocery store locations or as the aggregation of points within a quarter-mile grid cell attributed to its centroid for employment locations. Point-level employment data were provided by the 2017-2021 Arizona Council of Governments and MPO Employer Database; a dataset of all employment locations in Arizona with five or more employees used for MPO transportation modeling and forecasting activities. Public and charter K-12 school locations were geocoded using data provided by the Arizona Department of Education. Grocery store locations were determined using the OSM-provided shop tags of grocery and supermarket.

Leveraging these data sources, cycling trips were modeled for each of the three cyclist types from 451,156 origins to a potential 110,010 employment destinations, 730 grocery stores, and 2,485 schools in the state. Network edges belonging to the modeled routes of all origin-destination pairs were categorized using the LTS 2.0 criteria introduced by Furth et al. (*27*), which designates four levels of perceived traffic safety danger experienced by cyclists to road segments based on the number of travel lanes, AADT volume, and prevailing vehicle speeds. AADT volumes were produced using the aforementioned data sources and imputation processing, while the number of travel lanes and posted speed limits were collected using OSM data, with missing values for the latter data source imputed using a process noted in Martinez et al. (*15*). Across the state's eight MPO designated planning areas, 70% of the network was classified as LTS 1, 6% of the network was classified as LTS 2, 11% of the network was classified as LTS 3, and 14% of the network was classified as LTS 4. Relating these four LTS classifications of street network edges to the cyclist typology adopted in this study, network links with an LTS 1 or LTS 2 designation are suitable for an IBC cyclist, links with an LTS 3 designation are acceptable to an EAC cyclist, and links with an LTS 4 designation are only acceptable for the SAF cyclist type. Important for this study, the factors which determine the routing choice of different cyclist types in CRANC 2.0 are exclusive from those factors that determine an edge's LTS class.

Integrating this application of the LTS concept with a routing of origin-destination pairs using three cyclist profiles, this study introduces a gravity-based accessibility metric to evaluate the impact of present bike infrastructure on modeled cycling accessibility to subsistence and maintenance activity destinations. The expression shown in Equation 4 describes the operationalization of this cycling accessibility metric, which adopts the formulation from Hansen (*29*):

$$A_{ik} = \sum_j O_j f\left(C_{ijk}\right) \quad (4)$$

where A_{ik} is the accessibility to different opportunities (e.g., employment, grocery stores, schools) from the centroid of grid cell i for cyclist type k, O_j is the number of opportunities available at destination j, and $f\left(C_{ijk}\right)$ is an impedance function of the generalized travel cost c from i to j for cyclist type k. In this application, the impedance function takes a value of zero if cycling travel time is greater than threshold t, which is divided into bins ranging from five to 60 minutes by five-minute increments. Yet, if cycling travel time is less than or equal to threshold t then an impedance factor is calculated by adopting Equation 5:

$$f\left(C_{ijk}\right) = d_{ij(LTS)}/d_{ij} \quad (5)$$

where $d_{ij(LTS)}$ is the distance from i to j on edges defined by an LTS class that is suitable to cyclist type k.

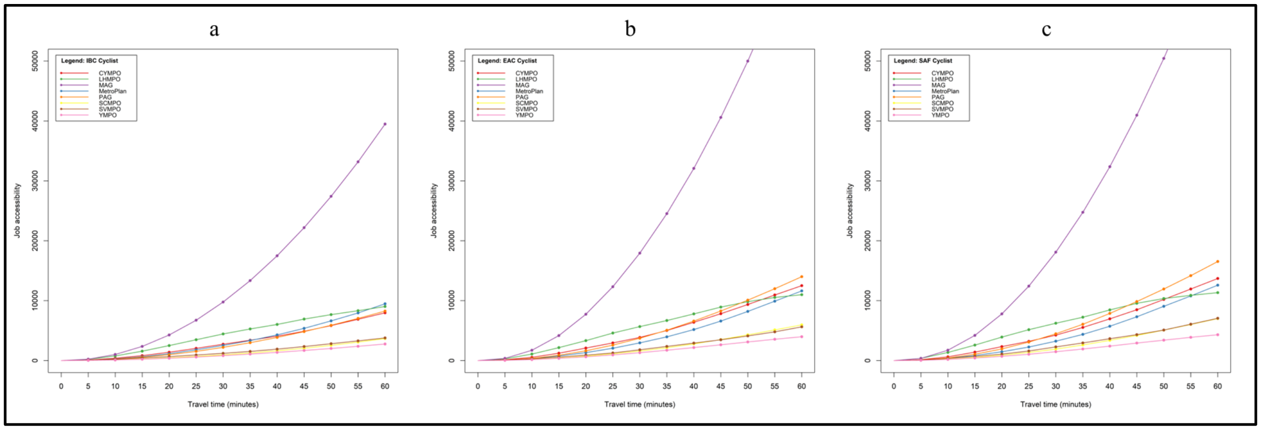
Using results from the application of this metric, variations in cycling accessibility to employment, schools, and grocery stores for the IBC, EAC, and SAF cyclist types are identified across the different MPO urbanized areas. Further differences in subsistence and maintenance accessibility within these eight MPO boundaries are also provided for an IBC cyclist restricted to a 15-minute travel time; a combination chosen to illustrate prospective opportunities and barriers in these planning jurisdictions for unlocking the latent demand of this population segment. For employment accessibility, these described visual overviews are accompanied by an analysis of how 15-minute commutes for IBC cyclists in these study areas differ based on the sociodemographic and economic composition of residents located at the modeled trip origins.

Results

Employment accessibility

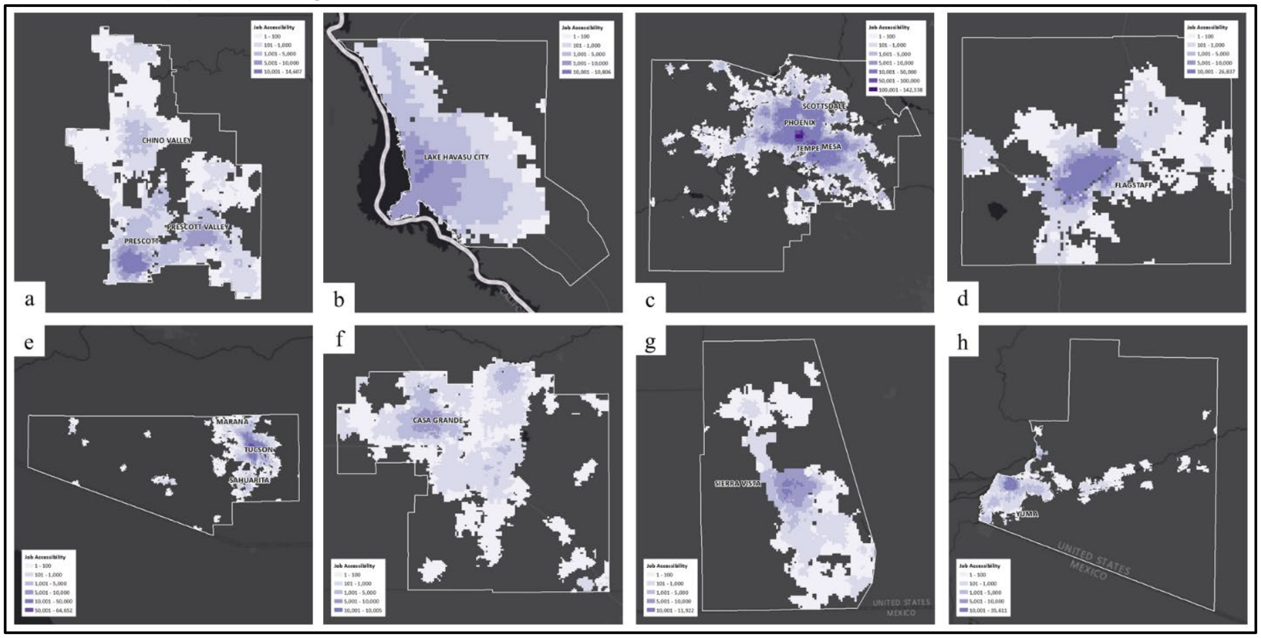
Figure 1 provides an overview of changes in bicycling accessibility to employment opportunities in relation to commute travel times for the three different cyclist types modeled in the eight MPO study areas. Across all cyclist types, MAG consistently has the highest level of job accessibility; an expected outcome given the presence of Phoenix, Mesa, and other populous cities in Arizona, which also serve as economic hubs. PAG, which encompasses Arizona's second largest city, Tucson, however, is steadily found to have an average bicycling access to jobs measure that is more aligned with those of the remaining six MPO boundaries. Analyzing job accessibility at a 15-minute threshold, LHMPO appears to have an average accessibility score across its quarter-mile grid cell centroids below MAG's average value but above all other MPOs. This result is likely attributed to the more compact boundary of LHMPO, which does not extend far beyond the limits of Lake Havasu City. For the IBC cyclist type, a further differentiation occurs at the 30-minute travel time interval in which the average accessibility score for CYMPO, MetroPlan, and PAG is found to be above that of SVMPO, SCMPO, and YMPO. At the furthest extent of this analysis (60-minute travel time), these clusters remain relatively intact, with job accessibility for MAG exponentially snowballing, LHMPO plateauing, and YMPO only gradually increasing.

Figure 1. Average bicycling accessibility to employment opportunities by metropolitan planning organization for the (a) interested but concerned, (b) enthused and confident, and (c) strong and fearless bicyclist types



Exploring intra-MPO differences in bicycling accessibility, **Figure 2** shows the spatial distribution of access to jobs within a 15-minute commute for the IBC cyclist type. Given this large-scale visual overview, clusters of low and high bicycling accessibility can be more clearly identified. Monocentric city models can be seen in the five MPOs of LHMPO, MetroPlan, SCMPO, SVMPO, and YMPO, where employment access is highest in the respective city's downtown areas and dissipates to lower levels in the peripheries. Some exceptions to this spatial trend are seen in SCMPO, which has smaller accessibility centers to the east of Casa Grande; MetroPlan, which has smaller accessibility centers to the northeast and west of Flagstaff; and YMPO, which has an east-to-west higher-accessibility cluster to the south of Yuma. In CYMPO, 15-minute employment accessibility for the IBC cyclist type is greatest in Prescott's downtown, followed by two clusters emanating from the central areas of Prescott Valley and Chino Valley. Expectedly, the highest levels of bicycling access to jobs for this combination of cyclist type and commute time can be seen in the downtowns of Phoenix in the MAG study area and Tucson in the PAG study area, with the former TMA having higher accessibility concentrations also found in Mesa, Tempe, and Scottsdale.

Figure 2. Bicycling accessibility to employment opportunities in 15 minutes by an interested but concerned bicyclist type for the (a) CYMPO, (b) LHMPO, (c) MAG, (d) MetroPlan, (e) PAG, (f) SCMPO, (g) SVMPO, and (h) YMPO regions



To further understand macro differences in bicycling accessibility for prospective IBC cyclists commuting under 15 minutes to potential job opportunities, **Table 5** describes the weighted average of accessibility scores across a set of indicators describing the socioeconomic context of modeled trip origins. As shown in Figure 1a, 15-minute bicycling access to job opportunities for this risk-adverse cyclist type is greatest on average in MAG and LHMPO and lowest in SCMPO and YMPO. For all eight MPOs, 20-34-year-old residents had the highest average accessibility to jobs within 15 minutes for IBC cyclists. In turn, older residents in the MAG, PAG, MetroPlan, and SCMPO regions had the lowest average bike accessibility to jobs within the defined 15-minute commute shed. For all MPOS except MetroPlan and CYMPO, residents possessing an advanced college degree had the highest average accessibility to jobs within a 15-minute commute using lower-stress bike facilities. For the MetroPlan and CYMPO regions, residents with a high school diploma or less had the lowest weighted average of bicycling accessibility to jobs. With regard to the racial and ethnic composition of quarter-mile grid cell residents, American Indian and Alaska Native communities in the two largest MPOs (MAG and PAG) had the lowest weighted average of access to jobs in a 15-minute commute shed using lower-stress bike facilities. In the MAG, PAG, and LHMPO regions, low-income households had the lowest average accessibility to jobs within a 15-minute commute using modeled IBC bicyclist routes.

Table 5. Weighted average of job accessibility in 15 minutes by IBC bicyclist across select socioeconomic variables

	Metropolitan Planning Organization							
Variable	CYMPO	LHMPO	MAG	MP	PAG	SCMPO	SVMPO	YMPO
Job accessibility	825	1563	2362	635	549	253	430	221
Sex								
Female	710*	1339^	2142^	596*	404*	240^	317*	224^
Male	776^	1309*	1720*	605^	426^	230*	332^	174*
Age								

Pacific Southwest Region UTC
University Transportation Center

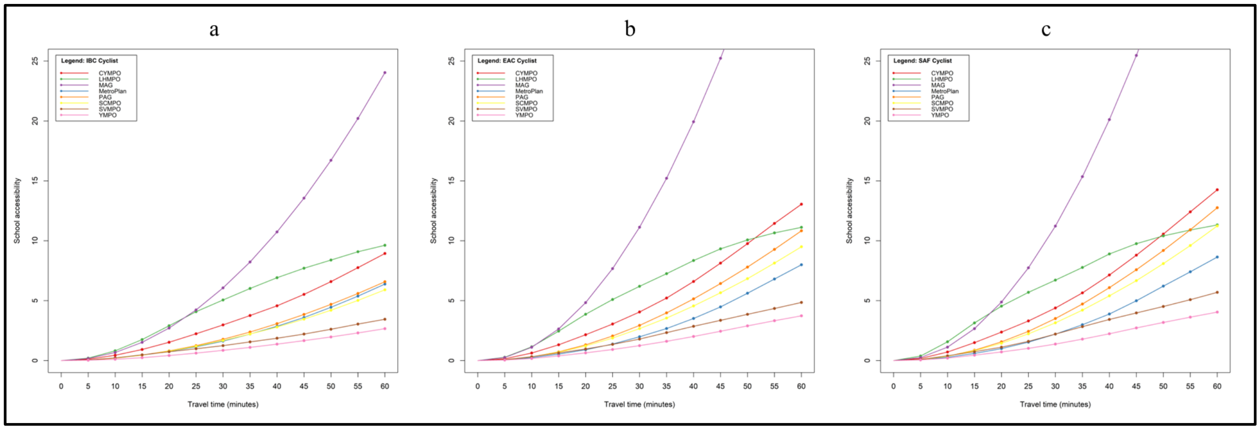
Less than 20 years old	697	1277	2400	794	351	237	333	227
20-34 years old	1065^	1766^	2545^	1037^	595^	287^	428^	229^
35-44 years old	773	1188*	2023	623	413	220	326	228
45-64 years old	636*	1392	1631	415	435	221	254*	138*
65 years old or more	760	1213	1242*	318*	327*	212*	307	188
Education								
High school or less	691*	1271	1520*	568*	263*	276^	331	194
Associates/Some college	781^	1250*	1813	688^	496	228	321*	184*
Bachelors/Graduate degree	747	1647^	2663^	571	698^	162*	323^	222^
Race/ethnicity								
American Indian/AK Native	1342^	1648	512*	861	23*	379	501	776
Asian	786	1168*	4633^	731	2047	259	942^	2205^
Black/African American	966	2750^	4177	260*	2221^	501^	542	1406
Hispanic/Latinx	724*	1693	2296	1154^	745	333	429	221
White, Non-Hispanic	739	1253	1712	522	544	162*	263*	138*
Household income								
Less than $25,000	844^	1199*	1530*	1154^	331*	297^	333	208
$25,000-$49,999	670	1353	1918	931	357	255	373^	210
$50,000-$99,999	835	1214	2272^	558	514^	225	299	249^
$100,000-$149,999	607*	1473	2018	556	447	170*	369	121*
$150,000 or more	672	1652^	1638	365*	460	223	271*	152

Note. ^ = Weighted average of job accessibility is highest among variable subcategories. * = Weighted average of job accessibility is lowest among variable subcategories.

School accessibility

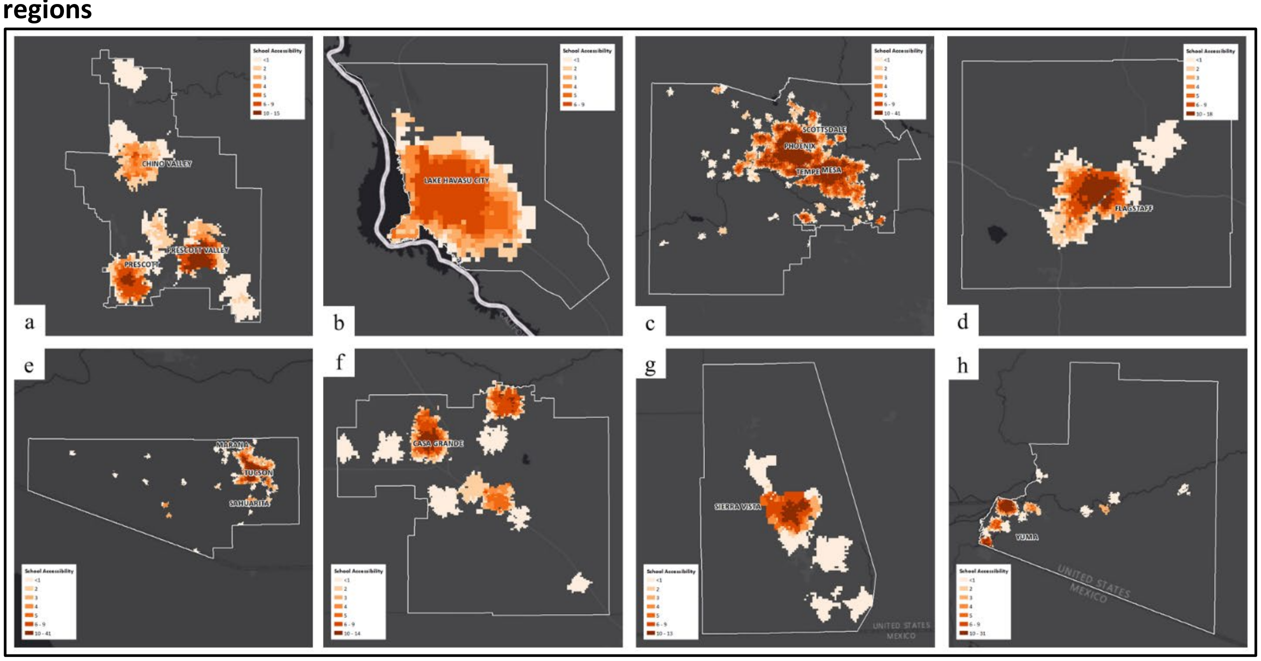
An overview of MPO differences in average bicycling access to school locations for the IBC, EAC, and SAF cyclist types is shown in **Figure 3**. Similar to job accessibility score distributions, modeled MAG trip origins have the highest average bicycling accessibility to schools for all cyclist types when examining trips beyond 25 minutes in duration. Yet, an examination of school accessibility within 15 minutes reveals the LHMPO region as having greater average scores than MAG for the IBC and SAF bicyclist types. Across each bicyclist type, the CYMPO region has the third highest average score of bicycling access to schools in 15 minutes, with all remaining MPOs clustered with lower scores. Of note, only LHMPO (1.75) and MAG (1.52) have accessibility scores greater than one, signifying the average modeled trip origin in all other MPOs does not have a completely bike-friendly route to the nearest school within 15 minutes. The average trip origin for all MPOs except YMPO has a school within a 30-minute ride.

Figure 3. Average bicycling accessibility to schools by metropolitan planning organization for the (a) interested but concerned, (b) enthused and confident, and (c) strong and fearless bicyclist types



Investigating bicycling access to schools for an IBC cyclist riding 15 minutes or less, **Figure 4** shows a slightly more decentralized pattern of accessibility scores than that of job accessibility, which is attributed to the dispersed siting of schools across metropolitan regions. In general, trip origins located within the largest incorporated city of each MPO have the highest bicycling access to school scores. More rural communities in the western portion of the MAG and PAG regions display smaller clusters of bicycling access to schools, but the scores for those grid cells tend to be below the threshold score of one that signifies a completely low-stress route to the nearest school. Similar clusters of trip origins with low school accessibility scores can be found in the northern portion of CYMPO, northeastern portion of MetroPlan, southeastern portion of SVMPO, and central portion of YMPO. In SCMPO, six clusters of low bicycling access to schools can be found in communities outside of Casa Grande.

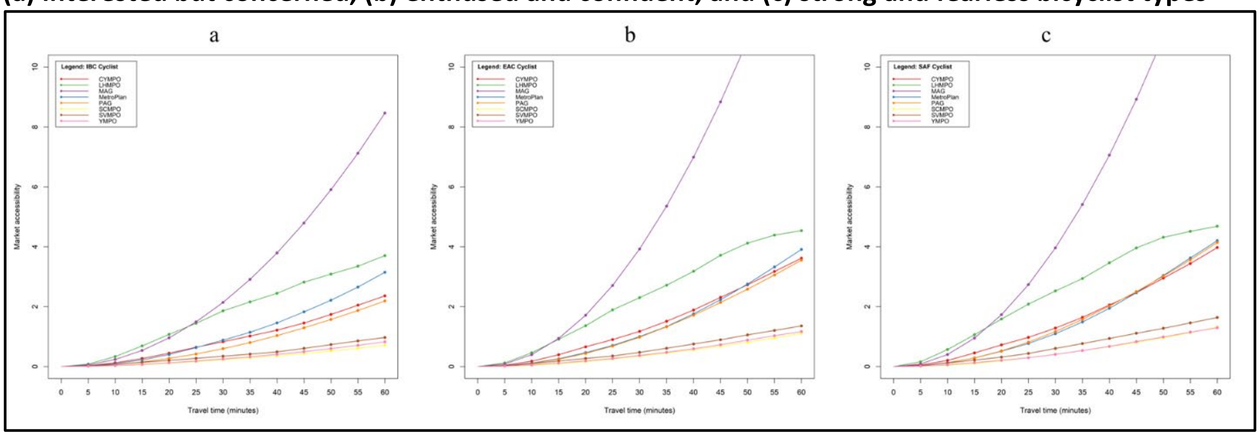
Figure 4. Bicycling accessibility to schools in 15 minutes by an interested but concerned bicyclist type for the (a) CYMPO, (b) LHMPO, (c) MAG, (d) MetroPlan, (e) PAG, (f) SCMPO, (g) SVMPO, and (h) YMPO regions



Grocery store accessibility

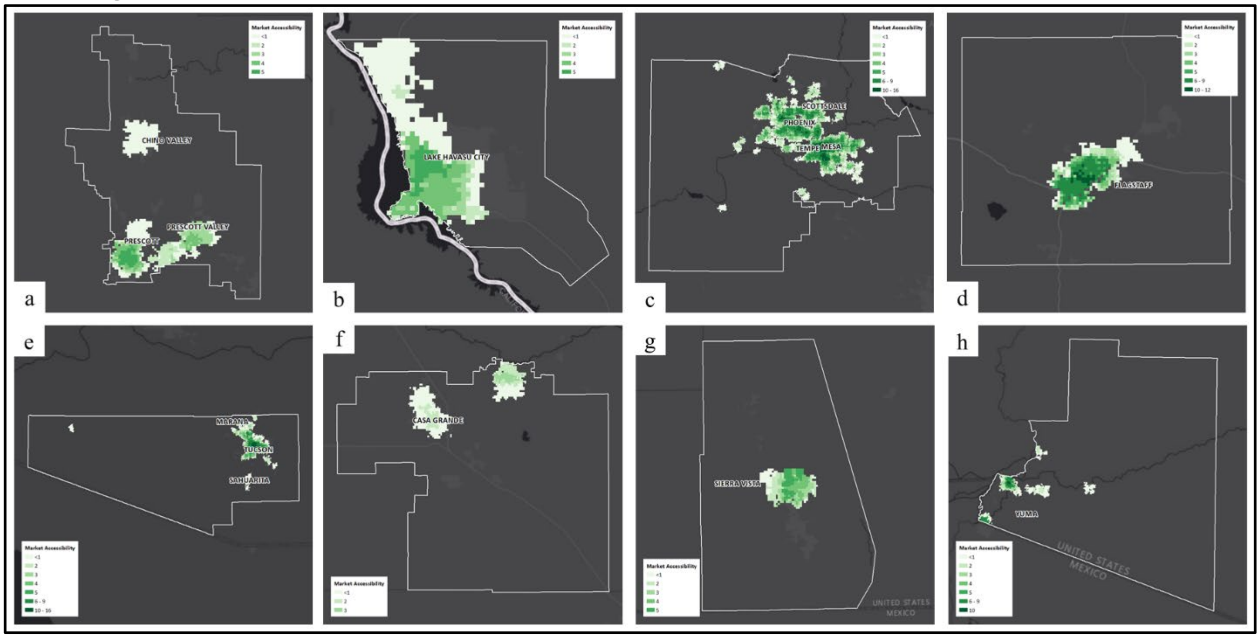
Figure 5 displays bicycling access to grocery stores, measured for each of the three bicyclist types using an accessibility metric sensitive to the availability of facilities suitable for a given bicyclist type, averaged for all trip origins inside the eight Arizona MPO boundaries. The results of this analysis largely align with those of the employment and school accessibility analyses, with MAG and LHMPO origins generally having the highest accessibility scores for modeled routes beyond a 10-minute ride across each bicyclist type. At 15 minutes for the IBC cyclist type, LHMPO (0.69) and MAG (0.54) have the highest access to grocery stores. When the travel time threshold is doubled to 30 minutes, an admittedly long ride for any prospective IBC cyclist, the average bicycling accessibility score for origins in these two MPOs extends beyond the critical value of one. However, the average score associated with origins in the SCMPO, SVMPO, and YMPO regions at this combination of bicyclist type and travel time remains relatively low (SCMPO = 0.23, SVMPO = 0.34, and YMPO = 0.25), indicating that many areas inside these MPOs do not possess low-stress bike routes for their residents to access grocery stores.

Figure 5. Average bicycling accessibility to grocery stores by metropolitan planning organization for the (a) interested but concerned, (b) enthused and confident, and (c) strong and fearless bicyclist types



This seemingly widespread prevalence of food deserts for risk-adverse bicyclists becomes clearer when viewing the spatial distribution of market access scores for IBC cyclists traveling 15-minutes or less, shown in **Figure 6**. In reviewing this set of maps for each MPO, an overall shrinking of quarter-mile grid cells with any level of bicycling access to grocery stores can be viewed. Particularly stark findings are illuminated for the SCMPO region, which has zero trip origins in its largest city (Casa Grande) where a resident recognized as an IBC cyclist can access more than two grocery stores via a low-stress bike route. Similar clusters of low bicycling access to grocery stores are also found in CYMPO's Chino Valley and communities to the east of Yuma in YMPO. While grocery store accessibility bands are largely more restrictive in all eight MPOs when compared to those found for employment opportunities and schools, concentrations of high accessibility scores are found throughout the largest cities in the MAG, MetroPlan, PAG, and YMPO regions. This pair of findings highlights inter- and intra-regional disparities in high-quality bicycling access to grocery stores that exist amongst the eight MPOs in Arizona.

Figure 6. Bicycling accessibility to grocery stores in 15 minutes by an interested but concerned bicyclist type for the (a) CYMPO, (b) LHMPO, (c) MAG, (d) MetroPlan, (e) PAG, (f) SCMPO, (g) SVMPO, and (h) YMPO regions



Study conclusions

As cities and metropolitan regions continue to strive toward providing more sustainable and cost-effective mobility alternatives, the development of extensive networks of bike-friendly facilities has been heralded as a promising policy initiative and programmatic endeavor. Seeking to assist planning practices aimed at achieving this outcome, this study presented a routing platform sensitive to different preferences of current and prospective cyclists regarding roadway characteristics and bike infrastructure availability. Importantly, bike routing decisions were linked to an established cyclist typology to help facilitate a wider understanding of how present network barriers may be impeding city efforts to unlock the latent demand for bicycling among IBC cyclists who require safer bicycling conditions than EAC and SAF cyclists who more commonly traverse citywide streets and paths. This innovative bike planning tool was then implemented in an expansive study area consisting of Arizona MPO areas to evaluate differences in bicycling accessibility to subsistence and maintenance activities across these three cyclist types. In this study's application, an original bicycling accessibility measure that links cyclist type to the LTS classification of streets that would be traversed on their modeled routes was also presented; merging two important bike planning concepts that describe the proclivity for different individuals to bicycle in light of given roadway traffic conditions.

With this application, a number of analytic findings were made that provide further support for planning strategies to expand bicycling access and ultimately its usage. First, on average, modeled routes for IBC cyclists were found to have less access to job opportunities, schools, and grocery stores across all eight of Arizona's MPO jurisdictional boundaries. This identification of existing barriers to safe bike facilities required to encourage ridership among a more general population supports efforts to invest in high-quality infrastructure either through the conversion of LTS 2 facilities to an LTS 1 classification via the provision of off-street bike facilities or reductions in posted speed limits along lower-trafficked streets.

Aside from the increase in the supply of maintenance and subsistence activities in cities which may result from long-term land use changes, the continued adoption of e-bikes may also increase bicycling accessibility as average travel speeds for IBC cyclists using pedal-assist bikes will more approximate travel speeds of EAC and SAF cyclists. Moreover, a fourth segment of cyclists (NWNH) who presently do not cycle may become attracted to an electric version of bicycling thorough its ability to reduce barriers in effort attributed to topography or access attributed to personal physical limitations.

Second, this application of the CRANC 2.0 platform also identified spatial discrepancies in cycling access to jobs, schools, and grocery stores across the different MPOs when examining modeled IBC routes under 15 minutes in duration. As the promotion of the 15-minute city concept garners increased attention amongst planning practitioners, cities should seek to prioritize the provision of bike-friendly infrastructure in under-resourced neighborhoods, as this study found a disproportionate share of low-income households and adults without a college degree had lower access to job opportunities, to help ensure a more equitable distribution of this policy’s intended benefits. Additionally, planning practice should continue its laudable efforts to bridge an urban-rural divide that exists regarding accessibility with alternative mobility options. In this study, decreased bicycling access to grocery stores and schools was found across many MPOs, with notable clusters of low access separated from the higher levels access afforded in larger urban areas found in several outlying communities. To improve continuity in bicycling access to these activities, MPOs should look to help facilitate opportunities for its larger cities to design and develop off-street paths that connect their peripheral amenities to residents of smaller, neighboring towns. A prioritizing of such improvements may be more economically feasible in regard to rights-of-way acquisition and would have an added benefit of providing recreational cycling opportunities to residents of more urban environments.

Ongoing efforts to produce similar bike planning tools or future efforts to improve this introduced routing platform should consider advancements in the following areas. Routing decisions in this study were linked to the safety preferences of different cyclist types; however, the weights given to specific roadway attributes were relative and not necessarily linked to empirical evidence. Future research should identify opportunities to support or revise the sensitivities cyclists have for certain attributes by validating routing decisions with observed data sources such as traces from dockless bikeshare users. Furthermore, weighted averages applied in this study leveraged macro-level sociodemographic and economic data sources, which could be improved upon through the generation of synthetic agents informed by targeted data collection efforts. By doing so, modeled trips could originate from residences (or other activity locations) rather than grid centroids and be attributed to individuals characterized by select attributes and bicycling preferences.

Study 2: High-Stress Cycling Accessibility and Cyclist-Involved Crashes in Arizona Metropolitan Regions

Study background

At present, many Americans are incurring public health-related, environmental, and economic challenges linked to the widespread travel adoption of private vehicles in the past few generations. In 2019, the last calendar year prior to the Covid-19 pandemic onset and its near-term impacts on mobility patterns, there were 36,096 motor vehicle traffic fatalities in the United States and over 1.9 million police-reported vehicle crashes with at least one injured occupant (30). In that same year, the transportation sector accounted for the largest portion of greenhouse gas (GHG) emissions in the nation, with light-duty vehicles (e.g., passenger cars, light-duty trucks) encompassing 58% of GHG emissions in that sector (31). The average American in 2019 spent $9,292 per 15,000 miles traveled, an inflation-adjusted increase of $7,128 attributed to personal vehicle ownership and operation since 1975 (32). Taken together, these negative externalities and others related to increased automobile dependence have contributed to growing societal concerns of physical inactivity (33), climate change (34), and transportation inequities (35, 36). In response, urban policymakers, planners, and practitioners have sought to promote cycling as a sustainable travel substitute for personal cars, with recent evidence highlight the public health, environmental, and economic co-benefits of cycling.

However, calls to increase utilitarian cycling activity often coincide with a realization that many American cities still must alleviate objective and perceptive barriers to cycling that prevent interested residents from any serious consideration toward adopting this alternative mode to the motor vehicle for utilitarian travel. This circumstance reflects a general recognition that the provision of new or improved bike infrastructure may unlock a latent demand for cycling shared by a large segment of the population who perceive current network conditions as unsafe and uncomfortable due to limited bike-friendly infrastructure access. Thus, for urban policymakers and planners, a need exists to better understand how personal security concerns regarding utilitarian cycling, which are subjective and potentially more difficult to quantify, associate with objective traffic safety, which is traditionally operationalized as observed conflicts between roadway users. Further complicating any hypothesized relationship between objective safety and perceived security is the existence of spatial imbalances in bike-friendly infrastructure access and potentially related differences in levels of cycling activity within a general population that taken together may make certain neighborhoods or population segments more likely to be involved in motorist-cyclist crashes simply due to exposure. As such, active transportation researchers should seek to provide greater evidence to urban decisionmakers and planners on the linkages between perceived cycling access to subsistence activities (e.g., work, school) and observed cyclist safety (e.g., crashes) in an effort to inform accessibility-related policies that are more responsive and ultimately promote more sustainable travel opportunities than mobility-centered policies.

Given this assessment, this research seeks to identify a set of macro-level sociodemographic and economic characteristics correlated with utilitarian cycling access to out-of-home activities on routes with safer bike infrastructure and examine how these spatial relationships also connect to personal attributes of cyclists involved in reported motorist-cyclist crashes. Toward accomplishing this research goal, this study proposes two objectives. The first is to empirically examine a conceptualized link between perceived cycling access to subsistence activities for potential cyclists with increased safety risk aversion and observed traffic safety incidents between cyclists and motorists. This study objective is attained via the proposal and subsequent analysis of a proposed framework associating residential context, home-based cycling access to jobs and schools, and crash outcomes observed within defined commute sheds. A second objective is to introduce a new cycling accessibility metric that is sensitive to perceptions of cycling comfort with bike infrastructure conditions. This second study objective is carried out by adopting a cycling routing platform to generate commute sheds and assessing the perceived stress levels of the bike network in the defined activity space. By completing these study objectives, this research seeks to better inform active transportation directives aimed at improving cycling conditions and facilitating greater utilitarian cycling activity by identifying and evaluating the interconnections of transportation safety and security concerns.

The remainder of the chapter is as follows. The next section offers a review of previous academic studies on objective and perceived cyclist access to subsistence activities. The third section describes the data sources and study design, including the conceptual framework linking perceived cycling access to traffic safety. The fourth section describes the analytic results of models examining the macro-level predictors of high-stress cycling access (HSCA) and its subsequent modeled relationship to cyclist-motorist crash frequency. The chapter concludes with a discussion of study contributions and policy implications.

Literature review

A relatively small but expanding body of evidence exists regarding the study of cycling access to jobs and other subsistence activities, with fewer studies also incorporating the concept of perceived traffic safety. Impetus for this increased interest is in part related to the potential for a robust, connected bike network to complement existing high-quality transit services as a strategy for improving transportation inequities. Studying cycling as an access mode to transit stops in Sao Paulo, Brazil, Pritchard et al. (37) employed a gravity-based accessibility metric in finding that bike-and-ride could offer a potential increase to walk-and-ride in terms of job access during peak travel periods but would still pale in comparison to access via personal automobile. Zuo et al. (38) similarly found cycling to be a potential first-and-last-mile solution for transit access to employment opportunities when compared to walk-and-ride job access in Hamilton County, Ohio. In this second study, a cumulative opportunities metric was adopted to identify job access improvements by racial and income groups, with bike-and-ride access limited to low-stress bike network links with fewer than three travel lanes and a posted speed limit of 25 miles per hour. This identification of perceived traffic safety was operationalized by using an early iteration of the level of traffic stress (LTS) metric (39) that introduced a four-level classification scheme to differentiate low-stress (LTS 1 and LTS 2) and high-stress (LTS 3 and LTS 4) bike facilities based on traffic stressors.

Examining cycling as a primary mode for helping alleviate inequitable access, Wang and Lindsey (40) evaluated job accessibility changes from network improvements in Minneapolis, Minnesota. Findings from this study, which used a cumulative opportunity accessibility metric to compare changes related to a complete network and one with only local streets and bike dedicated infrastructure, showed inequities in low-stress cycling access for neighborhoods with higher shares of racial minority residents, households without a vehicle, and families with incomes below the federal poverty level. Kent and Karner (41), in an evaluation of low-stress and equitable utilitarian cycling in Baltimore, Maryland, examined cycling access to jobs, supermarkets, and libraries on routes under two miles comprised of only LTS 1 and LTS 2 and radiating from a sample of 278 population-weighted neighborhood centroids. Employing area-based indicators of race, poverty status, and vehicle ownership, the authors demonstrated a potential for LTS to be used in planning tools for evaluating cycling accessibility and prioritizing bike network improvements.

Several additional studies have incorporated LTS as a perceived reflection of traffic safety in measuring cycling access to employment opportunities. Murphy and Owen (12) sought to identify access gaps in four American metropolitan regions by assigning LTS classes to OpenStreetMap (OSM) network links and nodes and implementing OSM's OpenTripPlanner to generate routes originating from Census blocks with maximum allowable LTS values. Using the generated low-stress (LTS 1 and LTS 2) and high-stress (LTS 1-3) routes and a cumulative accessibility metric with a 20-minute travel time, the authors report differences in worker-weighted job access. Imani et al. (13) similarly adopted the first LTS methodology to identify stress levels on network links in Toronto, Canada and then analyzed home-based cycling mode choice as function of cycling access to jobs using maximum allowable LTS values as well as cycling access to a sample of 188 subway transit station entrances on low-stress (LTS 1 and LTS 2) links. Also studying cycling access in Toronto, Tabascio et al. (42) proposed a trip completion potential metric for work and non-work trips by different modes, finding that cycling was a viable option for short- and medium-length trips given existing network constraints regarding bike-friendly infrastructure and perceived traffic safety.

Investigating cycling access to employment and labor force in Cambridge, Massachusetts, Gehrke et al. (14) introduced a planning tool that integrated perceived safety reflected by the first LTS methodology (39) and variations in routing preferences across different cyclist types (16) to identify accessibility benefits attributed to bike infrastructure investment and implementation. Adopting this planning tool to study differences in access to physical workplaces and those with a virtual presence in Flagstaff, Arizona, Martinez et al. (15) estimated a set of negative binomial models to identify which residential context metrics impacted cycling accessibility for short- and medium-duration trips. Findings from this latter study highlighted spatial differences in job access related to low-stress bike infrastructure availability as well as household income and the racial/ethnic composition of neighborhood residents.

Taken together, this review of cycling accessibility studies has pointed to an existing association between residential environments and access to subsistence activity locations in which historically disadvantaged communities tend to have higher-stress commuting routes. This statistical connection has been revealed using different methodological approaches and study populations but has not been investigated using an analytic framework that associates perceived traffic safety with objective cyclist safety. This study seeks to bolster the evidence base by examining the linkages between residential environment and high-stress cycling access to employment and education opportunities and its subsequent connection to the safety of cyclists in order to better understand the interconnections of cyclist safety and security concerns.

Data and methods

Data sources

Observed cyclist safety data for this study were acquired from the Arizona Department of Transportation (ADOT) as police-reported crash data collected between 2015 and 2019, the last complete and consecutive five-year data panel preceding the March 2020 onset of the Covid-19 pandemic. These data are recorded as incident, unit, and person-level observations, and associated by a common crash identification field. Additionally, the injury severity experienced by each crash-involved person is reported as one of five KABCO categories: K-Injury (fatality), A-Injury (suspected serious injury), B-Injury (suspected minor injury), C-Injury (possible injury), and O-No Injury (property damage only). For this study, only crashes involving a pedalcyclist (cyclist) were analyzed, with incidents located outside of an Arizona Metropolitan Planning Organization (MPO) governing boundary excluded. The final study sample included 6,216 cyclist-involved crashes in which 927 resulted in a severe injury (K- or A-Injury).

Perceived cyclist safety, in turn, was represented as one of four LTS classes (27) designated to all OSM network links located in the eight Arizona MPO study areas. The four-tiered LTS classification system is a second LTS methodology based on the intersection of three criteria for cycling in mixed traffic (number of directional through lanes, prevailing speed limit, and average daily traffic), with facilities measured as LTS 1 or LTS 2 each considered low stress. Adopting Geller's (2006) cyclist typology, these low-stress facilities are suitable for Interested but Concerned (IBC) cyclists, whereas links designated as LTS 3 or LTS 4 are high-stress facilities suitable to Enthused and Confident (EAC) and Strong and Fearless (SAF) cyclists, respectively.

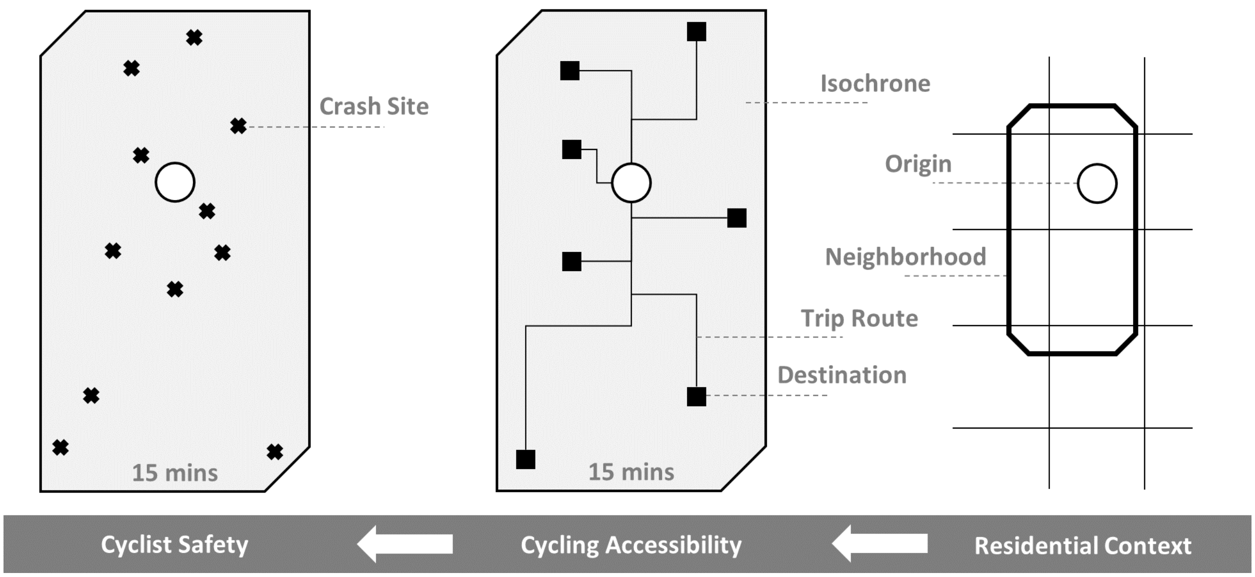
The base OSM network included information for two LTS criteria: number of directional through lanes and prevailing speed limit. Imputed data were generated for OSM links without through lane information by using the "oneway" indicator, where in the case of a false indicator value the number of lanes were halved, and the output was truncated. Missing data for posted speed limits were imputed by combination of OSM "highway" tag and prevailing traffic speed limits in Arizona: residential (25 miles per hour), service (35 miles per hour), secondary (55 miles per hour), and primary (65 miles per hour). For the third LTS criterion, average annual daily traffic (AADT) data were appended to the OSM network with data obtained by ADOT, who provides annual motor traffic volume reports based on a statewide network of permanent automatic traffic recorders supplemented by temporary counts at short-term data collection sites. ADOT AADT data were provided in centerline format and only collected for a sample of network links, which necessitated aligning incongruent network data sets via geoprocessing tools and then imputing AADT values for OSM's divided roadway links. Missing link-level traffic volumes were then imputed by calculating the mean AADT value for links in a Census tract by each "highway" tag (residential, service, secondary, and primary) and attributing that AADT value to those OSM links without an ADOT-collected AADT value.

Additional data were collected using American Community Survey (ACS) five-year data from 2015-2019. These sociodemographic and economic data were collected at a Census tract geography across the study areas as a representation of residential context. Collected attributes, which were operationalized as shares in the study sample, included sex, age, educational attainment, race and ethnicity, household income, and household vehicle ownership.

Analytic design

Figure 7 illustrates the analytic framework adopted for this study. In the framework, the context around a cyclists' residence is viewed as a predictor of cycling accessibility. Individuals and associated households are reflective of different sociodemographic and economic attributes, impacted by residential sorting, self-selection, and a host of other micro- and macro-level mechanisms and conditions. The resulting residential patterns are likely to produce different levels of cycling access to subsistence activities such as employment or school due to spatial variations in the location of activity sites and presence of bike infrastructure, with this combination leading cyclists in some contexts to have fewer nearby activities and commutes on more stressful facilities. In turn, residential contexts where high-stress cycling accessibility (HSCA) exists are then hypothesized to result in more observed cyclist-involved crashes.

Figure 7. Analytic framework linking cycling accessibility to residential context and observed cyclist safety



Operationalizing this framework, a cyclists' residence is represented as the centroid of a quarter-mile grid from a system of grid cells cast across the State of Arizona. The sociodemographic and economic context for a synthesized cyclists' residence is characterized by the information of the Census tract that the gird centroid overlaps. Each centroid within Arizona's eight MPO boundaries represents a cycling trip origin. To permit an analysis of residential context impacts on cycling accessibility, this study used the Cyclist Routing Algorithm for Network Connectivity (CRANC) 2.0 (see Study 1) to create 15-minute isochrones that extend from each grid cell centroid (or trip origin).

CRANC 2.0 is an extension of an accessibility-oriented decision-support tool designed and implemented by Gehrke et al. (14). The network routing tool was developed to account for topography and variations in travel speeds and routing preferences of the IBC and EAC cyclist type, permitting the IBC cyclist type to have a user-defined tolerance for cycling on high-stress facilities. The second iteration of the tool advances the initial deployment by (i) adding a routing profile for the SAF cyclist type; (ii) accounting for differences in the preferences and aversions of the three cyclist types regarding traffic controls, turning movements, and crossing mixed-traffic vehicle volumes found at intersections; and (iii) modifying segment preferences to also be sensitive to surface types and the presence of different urban bikeway designs including bicycle boulevards, bike lanes, buffered bike lanes, and cycle tracks. Importantly, the routing preferences of the three different cyclist types are insensitive to the three LTS criteria, which permits an unbiased inspection of how modeled routing decisions relate to the potential traffic stress exhibited by the current network.

For this study, cycling accessibility reflected the perceived safety encountered by an IBC cyclist attempting to commute to nearby employment and educational opportunities and was operationalized as HSCA. HSCA was calculated as the sum of LTS 3 and LTS 4 facility lengths within a 15-minute isochrone originating from a quarter-mile grid centroid divided by the total distance of all bike network facilities contained by the 15-minute isochrone. Of note, HSCA-related isochrones were only calculated for those centroids in which at least one employment or education opportunity could be accessed within a 15-minute travel time, which resulted in separate study samples for employment (n=104,831) and school (n=49,723) accessibility. Point-level employment data were collected by the 2017-2021 Arizona Council of Governments and MPO Employer Database; a dataset of all employment locations in Arizona with five or more employees that is used for MPO transportation modeling and forecasting activities. Public and charter K-12 school locations were geocoded using data provided by the Arizona Department of Education. For each 15-minute isochrone created by the CRANC 2.0 tool, an enumeration of these out-of-home subsistence activities extending from the quarter-mile grid cell centroids in the study area as well as cyclist-involved crashes was also completed and attributed to the sample of grid centroids.

With reference to the analytic framework, the hypothesized interrelationship between residential context, cycling accessibility, and cyclist safety was investigated using a two-step modeling approach. For the initial step, two ordinary least squares (OLS) regression models were estimated with the HSCA attributed to grid centroids for employment and school accessibility modeled as a function of either the number of jobs or schools in the 15-minute isochrone as well as the surrounding residential context of the trip origin (grid centroid). Separate OLS equations of HSCA for employment and school opportunities were estimated to isolate the different factors that may be significantly associated with high-stress cycling access and because of the separate study samples. In a second step, the frequency of cyclist-involved crashes within 15-minute isochrones was estimated using a negative binomial (NB) modeling approach as a function of the predicted HSCA of the associated grid cell from the previous modeling step and a set of sociodemographic attributes of the cyclist observed in the reported crash. Herein, separate NB analyses were performed for all crashes and a segment of those total cyclist-involved crashes in which the cyclist incurred a more severe (K- or A-Injury) injury. The result of this second analysis is the estimation of four separate NB models: one model of total cyclist-involved crashes related to HSCA to school locations, a second model of severe-injury cyclist-involved crashes related to HSCA to school locations, a third model of total cyclist-involved crashes related to HSCA to employment locations, and a fourth model of severe-injury cyclist-involved crashes related to HSCA to employment locations.

Results

Descriptive statistics

Table 7 provides a summary of the predictors tested in the separate analyses of HSCA to employment and school locations. The set of social context variables measured at a quarter-mile grid cell extent were used in the specification of OLS models of HSCA, while variables described at a 15-minute isochrone geographic extent were used in the specification of NB models of total and severe injury cyclist involved crashes. All variable measurements are calculated for the pooled study area of eight MPO boundaries.

Table 7. Descriptive statistics of study samples

	Employment Accessibility		School Accessibility	
Variable	Mean	Median	Mean	Median
Scale: 15-minute isochrone				
Level of traffic stress 1 distance (meters)	308,515	65,622	15,746	9,993
Level of traffic stress 2 distance (meters)	27,659	4,274	1,499	842
Level of traffic stress 3 distance (meters)	20,657	2,051	1,108	439
Level of traffic stress 4 distance (meters)	7,611	391	395	90
Street network distance (meters)	374,467	78,554	19,126	12,285
High-stress cycling accessibility	0.076	0.047	0.089	0.064
Number of jobs	4,399	238		
Number of schools			6.504	4.000
Total (KABCO) crash frequency	11.460	0.000	23.830	4.000
Severy injury (KA) crash frequency	4.232	0.000	8.813	1.000
Cyclist: Sex: Female	0.087	0.000	0.156	0.125
Cyclist: Sex: Male	0.335	0.000	0.576	0.747
Cyclist: Age: Less than 20 years old	0.111	0.000	0.209	0.128
Cyclist: Age: 20-64 years old	0.249	0.000	0.432	0.167
Cyclist: Age: 65 years old or more	0.053	0.000	0.080	0.000
Scale: Quarter-mile grid cell				
Sex: Female	0.491	0.499	0.499	0.502
Sex: Male	0.509	0.501	0.501	0.498
Age: Less than 20 years old	0.232	0.230	0.252	0.256
Age: 20-34 years old	0.172	0.171	0.188	0.182
Age: 35-44 years old	0.114	0.112	0.120	0.120
Age: 45-64 years	0.264	0.258	0.252	0.245
Age: 65 years old or more	0.219	0.180	0.187	0.154
Education: High school or less	0.357	0.375	0.365	0.345
Education: Associates/Some college	0.330	0.341	0.330	0.336
Education: Bachelors/Graduate degree	0.254	0.259	0.305	0.278
Race/Eth.: American Indian/AK Native	0.067	0.004	0.058	0.004
Race/Eth.: Asian	0.022	0.008	0.029	0.013
Race/Eth.: Black/African American	0.025	0.008	0.034	0.017
Race/Eth.: Hispanic/Latinx	0.283	0.228	0.298	0.224
Race/Eth.: White, non-Hispanic	0.573	0.616	0.548	0.613
HH Inc.: Less than $25,000	0.165	0.143	0.156	0.124
HH Inc.: $25,000-$49,999	0.206	0.198	0.196	0.190
HH Inc.: $50,000-$99,999	0.306	0.313	0.310	0.308
HH Inc.: $100,000 or more	0.322	0.289	0.338	0.320
HH Vehicles: 0	0.044	0.019	0.049	0.026
HH Vehicles: 1	0.295	0.281	0.303	0.289
HH Vehicles: 2 or more	0.661	0.696	0.648	0.679

Regarding those variables adopted to reflect the residential context of modeled subsistence cycling trips, the typical neighborhood composition was approximately split among male and female residents, with the largest age cohort in the employment accessibility sample being between 45 and 64 years and the school accessibility sample also having a large share of residents under 20 years old. The school accessibility study sample has a larger percentage of residents with a four-year college or graduate degree. The distribution of identified racial and ethnic minority groups, household income brackets, and household vehicle counts are consistent across the two study samples.

In examining variables related to cycling accessibility and safety, the distribution of network lengths across LTS categories is fairly balanced between the two study samples, with the average distance of LTS facilities inside 15-minute isochrones decreasing as perceived stress levels increase. In all, there is a greater average distance of bike network segments inside isochrones constituting the employment accessibility sample in comparison to the school accessibility sample. Combining these individual components of HSCA in the two samples, a slightly higher average HSCA value is found within isochrones in the school accessibility sample. The average number of employment opportunities that are accessible in a 15-minute isochrone is 4,399, while the average number of isochrone-contained school sites in the school accessibility sample is 6.50. Further comparing the study samples, a higher frequency of total cyclist-involved crashes and crashes that resulted in a more severe injury (K- or A-Injury) to the cyclist was found in the school accessibility sample than the employment accessibility sample. Accordingly, on average, a higher number of male and female cyclists were involved in crashes found within a 15-minute isochrone in the school accessibility sample in addition to each of the three defined age cohorts.

High-stress cycling accessibility

Specifying HSCA values as a function of control variables for the frequency of activities and total network distance in the 15-minute isochrone as well as numerous residential context variables associated with the modeled trip origin, **Table 8** shows results from the separate employment and school accessibility models. Reviewing OLS model results of school accessibility, modeled trip origins (quarter-mile grid cell centroids) with a greater number of jobs and network availability inside a 15-minute cycling travel shed were more likely to have higher associated levels of HSCA. Hence, those neighborhoods with a higher supply of nearby jobs and available bike infrastructure, which may facilitate greater cycling commute activity, are more likely to also have a greater share of higher-stress bike routes. With respect to residential context, trip origins in areas with a higher percentage of female residents and people under the age of 20 years (i.e., dependents) are more likely to experience higher HSCA to nearby jobs. Similarly, neighborhoods with a higher share of adults with a high school degree or lower educational attainment and African American or Asian residents are more likely to experience greater HSCA to jobs within a 15-minute commute. In contrast, modeled trip origins with increased average household incomes and greater vehicle access were more likely to have a positive association with HSCA to nearby jobs. This model finding may be linked to traditional residential growth patterns that often find more affluent households living in suburban environments conducive to auto travel.

Table 8. Residential context predictors of high-stress cycling accessibility to employment and schools

	Employment Accessibility			School Accessibility		
Variable	Beta	SE	p-value	Beta	SE	p-value
Intercept	-0.027	0.009	0.003	0.142	0.012	<0.001
Scale: 15-minute isochrone						
Street network distance (meters)	0.001	0.000	<0.001	0.001	0.000	<0.001
Number of jobs	0.001	0.000	<0.001			
Number of schools				-0.001	0.000	<0.001
Scale: Quarter-mile grid cell						
Sex: Female	0.039	0.006	<0.001			
Age: Less than 20 years old	0.031	0.006	<0.001	0.014	0.008	0.094
Age: 65 years old or more	-0.022	0.004	<0.001	-0.022	0.006	<0.001
Education: High school or less	0.014	0.004	<0.001			
Race/Eth.: American Indian/AK Native	-0.021	0.003	<0.001	-0.028	0.005	<0.001
Race/Eth.: Asian	0.074	0.005	<0.001			

Race/Eth.: Black/African American	0.101	0.009	<0.001	0.060	0.012	<0.001
Race/Eth.: Hispanic/Latinx	-0.045	0.003	<0.001	-0.036	0.004	<0.001
HH Inc.: $50,000-$99,999	0.001	0.000	<0.001	0.001	0.000	0.001
HH Inc.: $100,000 or more	0.046	0.003	<0.001	0.032	0.005	<0.001
HH Vehicles: 1	0.113	0.009	<0.001			
HH Vehicles: 2 or more	0.052	0.008	<0.001	-0.053	0.011	<0.001
Model Summary						
Adjusted R-squared			0.041			0.030
Number of observations			104,831			49,723

Turning to the results of the school accessibility model, cycling trip origins with higher network availability and a lower count of public and charter schools within 15-minute isochrones were associated with higher values of HSCA to schools. While the former finding mirrors the previously described relationship between infrastructure availability and HSCA to nearby jobs, the negative association between the count of school sites and HSCA to schools may highlight a discrepancy in high-quality cycling access to schools in less urban environments where their siting is less common. Similar to the employment accessibility model's results, a trip origin surrounded by an increased percentage of individuals under 20 years of age was associated with higher HSCA values. Therefore, in general, quarter-mile grid cells with at least one school within a 15-minute bike trip were more likely to witness a positive connection between the number of children living in the area and high-stress cycling access to nearby schools. School accessibility model results produced comparable findings regarding the connection of race/ethnicity and average household income with HSCA to what was estimated in the employment accessibility model. However, a negative modeled association was observed between HSCA to schools and neighborhood share of households with two or more vehicles, highlighting a further importance on increasing the amount of low-stress bike infrastructure near schools.

Figure 8 and **Figure 9** illustrate the spatial distribution of predicted HSCA in quarter-mile grid cells casted across the eight MPO study boundaries for employment opportunities and school sites, respectively. While variation exists in different MPO boundaries, in general, clusters of predicted HSCA with higher values exist in the outer part of those MPOs characterized by a more monocentric development pattern (e.g., LHMPO, MetroPlan, SVMPO). Although attributable to a higher share of LTS 3 and LTS 4 bike facilities, these higher HSCA values are also likely related to a relatively lower availability of potential cycling routes to nearby jobs and schools. This latter condition of limited available infrastructure also likely explains the increased presence of cells with a zero value for HSCA found in the outermost reaches of these study areas, which potentially contain a greater share of recreational, non-roadway facilities that are attractive to the IBC cyclist type. Overall, a general assessment of the two sets of maps reveals a much more expansive coverage area for employment accessibility, with lower non-zero values of HSCA to jobs tending to be found in central city neighborhoods. A similar trend holds true for HSCA to schools, but with notable concentrations of grids with predominately higher-stress bike facilities in their 15-minute isochrones that are centrally located in the CYMPO, SCMPO, and SVMPO regions.

Figure 8. Predicted high-stress cycling accessibility (HSCA) to employment locations in Arizona metropolitan planning organization governing boundaries

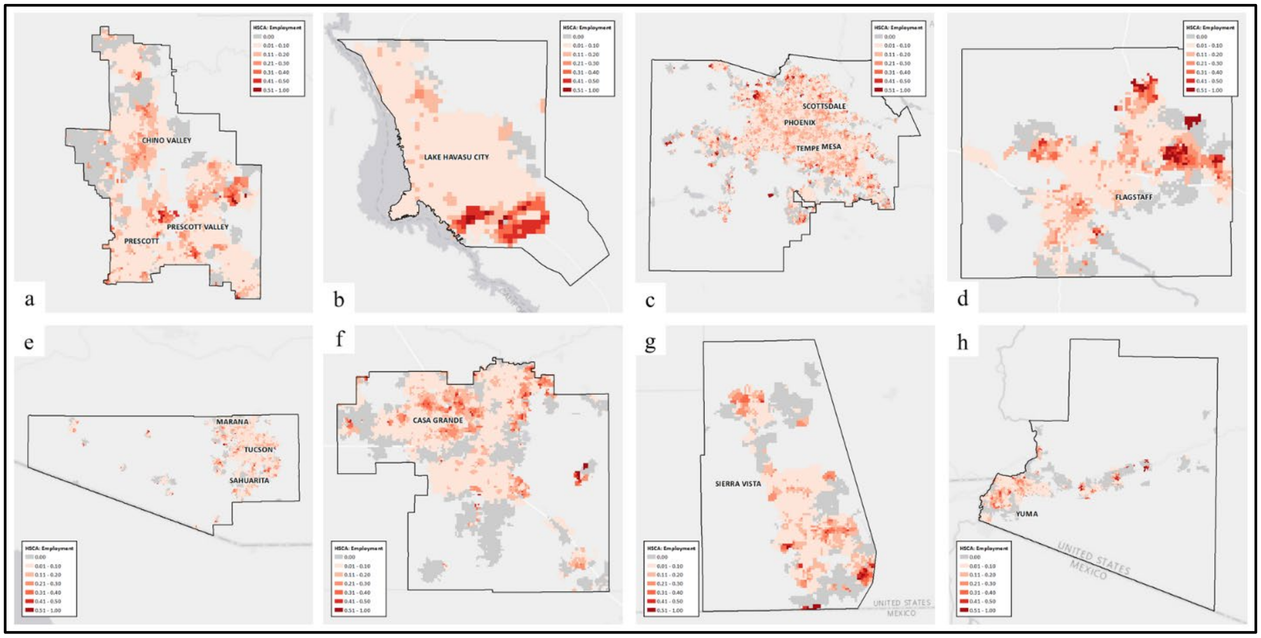
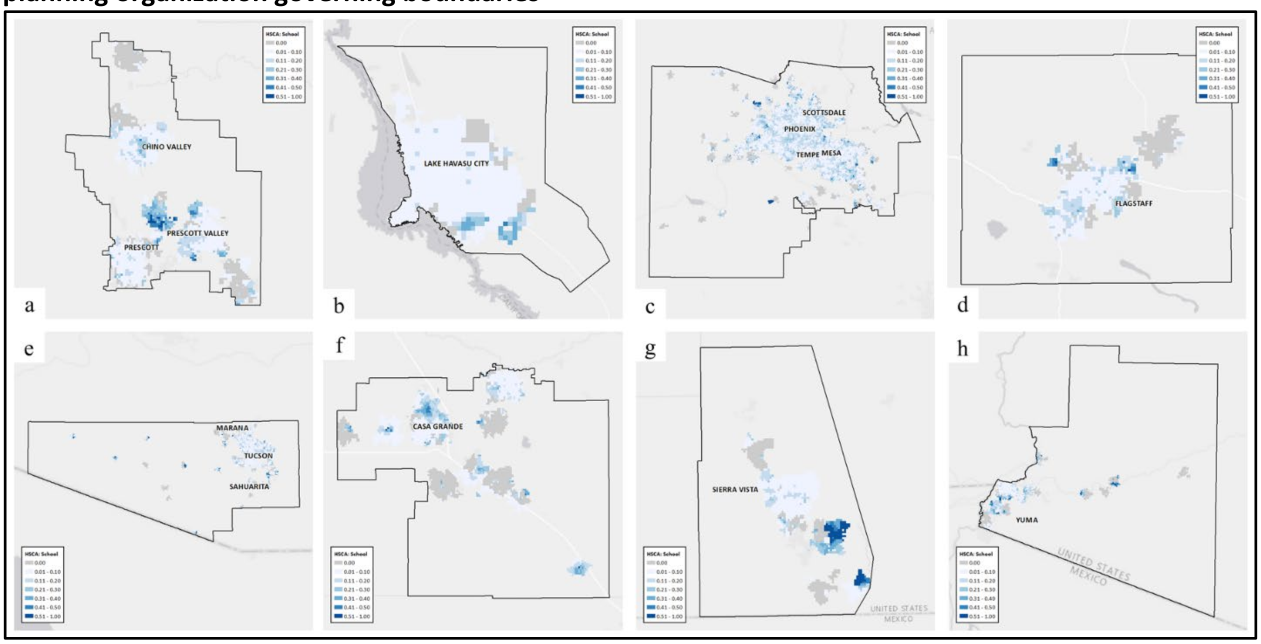


Figure 9. Predicted high-stress cycling accessibility (HSCA) to school locations in Arizona metropolitan planning organization governing boundaries



Cyclist safety and high-stress cycling accessibility

Provided the results of the HSCA models of cycling trips to nearby employment and school locations, the second part of this study's analysis was to identify how predicted HSCA values and cyclist attributes relate to observed traffic safety conflicts (i.e., cyclist-involved crashes with motorists). **Table 9** shows the results of separate NB models identifying significant predictors of total and severe-only cyclist-involved crashes in the employment accessibility sample. Overall, the models demonstrate comparable associations regarding variable significance, coefficient magnitude, and directional relationship. Confirming a study hypothesis, those quarter-mile grid cells with higher predicted HSCA values were significantly related to an increased frequency of total and more severe (K- or A-Injury) cyclist-involved crashes. Accordingly, in terms of cycling access to nearby jobs, an IBC cyclist type who perceives a higher-level of stress in the network immediately surrounding their residence is more likely to have had more total and severe cyclist-involved crashes occur within their nearby residential context. Additionally, female cyclists and those cyclists on each end of the age spectrum were found to have a greater proclivity of being involved in reported cyclist-motorist crashes.

Table 9. HSCA to employment and safety-related predictors of total and severe cyclist-involved crash frequency

	Total (KABCO) Crashes			Severe Injury (KA) Crashes		
Variable	Beta	SE	p-value	Beta	SE	p-value
Intercept	-2.534	0.033	<0.001	-3.374	0.040	<0.001
Scale: 15-minute isochrone						
Predicted high-stress cycling accessibility	21.398	0.428	<0.001	21.865	0.505	<0.001
Cyclist: Sex: Female	14.770	0.039	<0.001	14.337	0.044	<0.001
Cyclist: Age: Less than 20 years old	3.162	0.030	<0.001	2.672	0.035	<0.001
Cyclist: Age: 65 years old or more	2.995	0.041	<0.001	2.035	0.048	<0.001
Model Summary						
Theta (SE)			0.247 (0.001)			0.198 (0.001)
Akaike Information Criterion (AIC)			430,658			302,134
Number of observations			104,831			104,831

Table 10, in turn, summarizes the estimation results of NB models of total and severe crash frequency in 15-minute isochrones as a function of isochrone-level predictions of HSCA to schools and characteristics of cyclists involved in observed crashes with motorists. Akin to the prior set of NB model results, a greater predicted value of HSCA to schools was associated with an increased count of both total and severe injury crashes. This pair of findings similarly supports a hypothesized relationship that areas with perceived stress for IBC cyclist types also have a higher propensity for realized cyclist-involved crashes with motorists. With concern of cyclist characteristics, female cyclists were more likely to be involved in total and more severe crashes after statistically controlling for predicted HSCA. However, adults aged 65 years and older, who are reasonably less likely to cycle to local school sites, were discovered less likely to be involved in severe injury crashes. Yet, crashes with cyclists under the age of 20 years old, who are potentially more likely to bike to school, were found to be more prevalent within 15-minute isochrones in the school accessibility sample.

Table 10. HSCA to schools and safety-related predictors of total and severe cyclist-involved crash frequency

	Total (KABCO) Crashes			Severe Injury (KA) Crashes		
Variable	Beta	SE	p-value	Beta	SE	p-value
Intercept	-1.449	0.058	<0.001	-2.387	0.066	<0.001
Scale: 15-minute isochrone						
Predicted high-stress cycling accessibility	29.892	0.646	<0.001	30.270	0.738	<0.001
Cyclist: Sex: Female	9.204	0.040	<0.001	9.081	0.045	<0.001
Cyclist: Age: Less than 20 years old	0.200	0.030	<0.001			

Cyclist: Age: 65 years old or more				-0.375	0.057	<0.001
Model Summary						
Theta (SE)			0.372 (0.002)			0.302 (0.002)
Akaike Information Criterion (AIC)			349,103			257,080
Number of observations			49,723			49,723

Study conclusions

This study has sought to offer greater evidence to transportation planners and policymakers regarding the connection between perceived cycling access to subsistence activities and observed cyclist safety. In doing so, this study introduced and assessed a conceptual framework for investigating relationships between the perceived access for risk-averse cyclists to nearby out-of-home activity sites and observed cyclist-motorist crashes. A contribution to the existing evidence base aimed at generating evidence on how perceptions of cyclist security with existing conditions are informed by residential contexts and in turn relate to revealed cyclist safety as well as identifying where spatial differences in bike network comfort exist. Relatedly, this study also implemented a recently-introduced cycling accessibility-oriented tool to provide a new method for spatially identifying areas where cycling access to nearby subsistence activity sites is likely marred by a greater prevalence of perceived traffic stress. Statistical associations between the resulting HSCA metric and the social context near modeled trip origins offered insights into neighborhood differences that exist regarding low-stress cycling access to jobs and schools.

Highlighting HSCA-related model results, IBC cyclists with greater job opportunity in a 15-minute commute were more likely to have a greater share of high-stress bike facilities, which may subsequently leave this untapped market of potential future cyclists less likely to choose this more sustainable travel mode given existing network conditions. Therefore, opportunities exist for transportation planners and city officials to continue support for high-quality bike infrastructure in employment-rich districts to help foster alternative means for employees to reach their workplaces. Additionally, in neighborhoods where IBC cyclists have at least one public school located within a 15-minute ride, an increased share of individuals under 20 years of age was associated with a higher proportion of network links with an LTS 3 and LTS 4 rating. This finding reveals that in Arizona metropolitan regions, many students may face physical barriers to riding their bike to school related to vehicle traffic volumes, speeds, and a general lack of high-quality bike infrastructure. Thus, MPO and city planning staffs should seek new partnerships or funding programs (i.e., administration of Safe Routes to School studies) to identify and implement facility improvements to provide students a safer network for cycling to school. In general, model results found that predicted HSCA to employment and education sites was highest for IBC cyclists residing in neighborhoods beyond central city districts and inner-suburbs. This general finding across the two OLS models highlights a greater condition in many cities related to the robustness of high-quality bike networks and supports continued efforts by MPOs and cities to alleviate gaps and increase connectivity to further facilitate cycling between predominately residential suburban developments and subsistence activity locations in more urban areas.

In terms of modeled connections between perceived HSCA and objective cyclist safety, predicted HSCA to both jobs and schools was related to a greater frequency of nearby cyclist-motorist crashes and a subset of crashes that resulted in a more severe injury to the cyclist. This model outcome helps substantiate an empirical link between perceived cyclist comfort and revealed cyclist safety in the context of subsistence activity spaces or accessibility isochrones. As transportation planners seek ways to offer more diversity in mobility options, the growing recognition of this connection should offer impetus for the provision of safer bike facilities as a means of attracting a latent demand among IBC cyclists for utilitarian cycling activities. In neighborhoods where a school could be reached within a 15-minute bike ride by an IBC cyclist, a positive and significant modeled relationship was found between cyclist-motorist crash frequency and the crash-involved cyclist being under 20 years old. This association between observed cyclist-motorist crashes and younger cyclists helps emphasize the potential safety benefits of low-stress active transportation facilities in areas with nearby schools and a related uptick in young travelers who may bike for utilitarian purposes.

Although this study offers evidence on the connections between perceived cycling accessibility and cyclist safety that can help support active transportation initiatives, limitations exist that should be addressed buy future research. First, this study only accounts for neighborhood-level predictors of HSCA related to the sociodemographic and economic composition of residents, with opportunities for future research to explore the additional impact of observed and perceived built environment metrics on cyclist accessibility and safety. Second, future research in this area should consider alternative modeling specifications that both expand or alter the proposed framework and explicitly account for spatial relationships and errors as well as consider access to other out-of-home activities by different cyclist types and varying travel sheds. Finally, while this study examined the relationships between cycling access and safety across a relatively large and heterogeneous study area, future research should assess the transferability of these findings to other contexts and perhaps give more concentrated concern on urban settings where utilitarian cycling is most likely to thrive due to activity and infrastructure supply.

Conclusion

The two studies comprising this research project offer needed insights into the perceived and objective barriers to utilitarian cycling through the introduction and application of an accessibility-oriented active transportation planning tool. The first study described the design of the CRANC tool and its subsequent application to aid in the detection of intra- and inter-regional disparities in cycling access to employment opportunities, schools, and grocery stores for cyclists who vary in their routing preferences and aversion to traffic safety risk. A general outcome from this application across Arizona metropolitan regions is that cyclists who prefer low-stress facilities with fewer potential motorist interactions had the lowest level of access to each of these out-of-home activities. This study finding helps to illustrate that although efforts continue to remove perceived network barriers to utilitarian cycling, further work is needed to motivate cycling among a more general population through future investments in bike-friendly infrastructure that reduce cyclist-motorist interactions. A second general outcome of this first study was an identification of spatial discrepancies in cycling access to jobs, schools, and grocery stores across the different regions for shorter trips by IBC cyclists. Neighborhoods with a higher share of low-income households and residents without a college degree were found to have lower access to job opportunities, underscoring a need for future high-quality bike infrastructure investments to help close existing cycling access gaps.

The second study offered a second application of the CRANC planning tool in an effort to understand the associations between neighborhood-level social characteristics and perceptions of cyclist security and its subsequent relationship with observations of cyclist safety. Model results from an investigation into the first connection found that IBC cyclists residing in neighborhoods beyond downtowns and immediately surrounding inner-suburban locales are more likely to experience a greater share of high-stress facilities when accessing employment and education sites. This study finding demonstrates that an urban-rural divide also likely exists in terms of bike-friendly infrastructure provision and that efforts to alleviate gaps in connectivity between predominately residential developments and employment-rich districts should be given greater attention in metropolitan regions. Model results related to the latter connection found that neighborhoods with greater high-stress cycling access to jobs and schools were associated with an increased frequency of nearby cyclist-motorist crashes and incidents resulting in a more severe injury to the crash-involved cyclist. Offered this modeled relationship between perceptions of cyclist security and observations of cyclist safety in the context of short-distance utilitarian travel, transportation planners should continue to identify and implement safety-related strategies and countermeasures for attracting a latent demand for utilitarian cycling activity that exists among a more risk-averse general population.

Taken together, the studies described in the research report offer transportation researchers, planners, and decisionmakers a new planning tool capable of providing insights into how bike network conditions relate to the ability for a more diverse population of cyclists to safely reach important daily life activities.

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Data Management Plan

Products of Research

Primary data described and analyzed in this report were collected for its first and second studies. For the first study, which examined differences in cycling access to jobs, schools, and grocery stores across three cyclist types, expansive data sets of summarized reachable destinations across the State of Arizona were amassed and distilled to manageable region-specific data sets, grouped by destination type. These raw data sets and subsequent versions of cleaned tabular data were analyzed to produce tables and figures provided in this report's second chapter. For the second study, which analyzed residential determinants of perceived high-stress cycling accessibility and the latter introduced concept's connection to revealed cyclist safety, a set of statistical models were specified and estimated using primary data collected from the implementation of the planning tool introduced in the first study and motorist-bicyclist crash data provided by the Arizona Department of Transportation. These separate data sets were related, cleaned, summarized, and analyzed, with results and other tabular data presented in the report's third chapter.

Data Format and Content

The tabular data sets collected and analyzed for this research report are formatted as comma separated values (.csv) or database files (.dbf), with analyses conducted within the open-source R programming language for statistical computing. These data files and analytic scripts have been uploaded to a Harvard Dataverse ("Replication Data for PSR-22-05") the contains the following content for the two studies:

- Study 1: Cycling Accessibility to Employment, Schools, and Grocery Stores in Arizona Metropolitan Regions
    - "cranc_utc_01a_access-metric-schools-markets.R" is a script that merges raw outputs of accessible school and grocery market sites from grid centroids, varied by cyclist type and travel time into regional data sets (e.g., access_saf_markets_ympo.dbf) to generate introduced cycling accessibility metric.
    - "cranc_utc_01b_access-metric-employment.R" is a script that merges raw outputs of accessible employment opportunities from grid centroids, varied by cyclist type and travel time into regional data sets (e.g., access_saf_employment_ympo.dbf) to generate introduced cycling accessibility metric.
    - "cranc_utc_02_access-data.R" is a script that compiles regional data sets into uniformed data sets (dat_access_ibc_e.csv), joined with grid data (e.g., grid_1_4mi_az_mpo.dbf), and used in analysis.
    - "cranc_utc_04_access-data-analysis.R" is a script used to perform the study's modeling analysis on employment accessibility, with census data (e.g., context_acs_grids.csv).
    - "cranc_utc_05_access-plots" is a script used to create study-related graphics in report.
- Study 2: High-Stress Cycling Accessibility and Cyclist-Involved Crashes in Arizona Metropolitan Regions
    - "cranc_utc_03_crashes-data.R" is a script that merges raw outputs of crash data sets (e.g., ibc_cympo_crash_analysis.csv) and census data (e.g., context_acs_grids.csv) to produce study sample data sets (dat_crashes_ibc_15_e.csv; dat_crashes_ibc_15_s.csv).
    - "cranc_utc_06a_crashes-models-employment.R" is a script used to perform the study's modeling analysis of high-stress cycling accessibility (employment) and crash frequency.
    - "cranc_utc_06b_crashes-models-schools.R" is a script used to perform the study's modeling analysis of high-stress cycling accessibility (schools) and crash frequency.

Data Access and Sharing

The data sets and analytic scripts used in this research report can be found in "Replication Data for PSR-22-05" on Harvard Dataverse (https://doi.org/10.7910/DVN/WZCHS0). Large disaggregate data sets associated with each study will be retained on a password-protected external drive accessible by the Principal Investigator, which can be shared with the general public for research purposes upon request.

Reuse and Redistribution

Tabular data and associated scripts that are published on Dataverse or large locally-stored data sets may be reused and redistributed for research purposes with permission from report's Principal Investigator.