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# Exploring Neighborhood Differences in Bicycling Accessibility to Physical and Virtual Workplaces

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**Abstract**
Health concerns brought about by the Covid-19 pandemic, coupled with technological advancements over the past two decades have altered the traditional workplace setting. Some professionals in the tertiary and quaternary economic sectors have grown accustomed to virtual working environments, whereas others, including essential workers, have experienced less flexibility in this regard and continue to commute to physical work settings. During the pandemic, residents of underresourced communities, who were more likely to adopt lower-cost shared-use travel modes and would have benefited from good access to high-quality bicycling infrastructure, embodied a greater share of the nonhealthcare workforce who was required to commute to a physical work setting. This circumstance highlighted a need for research that examines bicycling accessibility to workplaces distinguished by telework potential, with a hypothesis that underresourced communities with more limited mobility options have poorer bicycling access to traditional workplace settings. In response, this study, which describes the application of a novel bicyclist routing algorithm, investigated how these differences in job accessibility relate to variations in the social context of neighborhoods where bicyclist commute trips originate, and the level of traffic stress incurred by a current or prospective bicyclist along modeled routes in Flagstaff, AZ. Study findings, which in part confirmed its hypothesis while also noting a latent demand for bicycling to physical workplaces along low-stress facilities, offer unique insights into how the changing nature of work should be accounted for as active transportation planners and policy makers seek to provide safer and more robust bicycle networks to their diverse communities.

**Keywords**
bicycles, equity (justice), level of service, planning and analysis, access/accessibility

Continued advancements in information and communication technologies and the immediate impacts of Covid-19 pandemic travel restrictions starting in March 2020 resulted in the sudden and dramatic increase of teleworking. Telework, or the ability for an employee to forego their commute to perform work-related duties remotely (*1*), has risen in prominence over the last two decades (*2*) to become a commonly employed practice by many professionals in the tertiary (service-based) and quaternary (knowledge-based) sectors of the economy. Accordingly, employees in professions related to communication, financial services, and information technology were well-situated and perhaps better capable of transitioning to a home-based work environment at the pandemic's onset than employees in other sectors (e.g., manufacturing) or those deemed to be essential occupations. Essential workers, who continued to commute to physical establishments during the height of the pandemic, represent a range of employees from different industries, with

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individuals from underresourced communities representing a significant share of nonhealthcare workers required to commute to a physical setting during the pandemic (*3*). Having to commute to a physical establishment for work demands reliable mobility options, with personal vehicle ownership more likely to place a financial burden on low-income households and residents of underresourced communities (*4*). Furthermore, during the onset of the pandemic, the adoption of non-automobility options such as public transit, which remained available as a lower-cost travel option, were positively associated with disease transmission (*5*).

In more common times, as well as the extraordinary circumstances brought about by the Covid-19 pandemic, bicycling has the potential to offer an inexpensive and more sustainable commute mode than the automobile. However, many American cities have incomplete bike networks that require bicyclists to traverse commute routes with long stretches of high-stress facilities. Furthermore, many individuals who would be interested in bicycling because of its economic, health, and environmental benefits if a safe and connected network existed are likely to continue to forego bicycling for personal safety reasons. As such, alleviating network barriers faced by current bicyclists and individuals, who for safety reasons have not considered bicycling as a feasible option when commuting to their physical workplace, is a growing area of pursuit for local planning agencies. Merging a need for innovative planning tools capable of identifying the latent demand for bicyclists if given safer bicycling facilities and understanding the changing nature of work, this research sought to implement a modern bicyclist network routing platform to investigate the role of neighborhood context and bicycling route comfort in accessibility to physical (and virtual) workplaces by bicyclists with varying levels of traffic risk aversion. A study hypothesis was that neighborhoods with a higher representation of low-income and racial or ethnic minority residents, who reflect a large share of nonhealthcare essential workers, required to commute during the pandemic, are more likely to have poorer access to physical work environments when commuting via bicycle.

In addressing this research aim, the structure of this study of bicycling accessibility in Flagstaff, AZ is as follows. First, a review of prior bicycling accessibility studies is offered, with a later focus on those with a social equity–based lens. This review is followed by a description of data and methods used to classify bike network stress and bicyclist route choices as well as a delineation of physical and virtual jobs and analysis of job destination accessibility. A third section discusses the descriptive and modeling results of this study's application of a bicyclist network routing platform to understand neighborhood differences in bicycling accessibility, which is followed by a concluding section that describes this study's contributions.

## Literature Review

Although the study of bicycling access to destinations has been relatively limited in planning practice (*6*), recent contributions have established a knowledge base underscoring its value to active transportation study, progress in measurement, and development as a new planning tool to help address transport inequities. Only in the past decade have accessibility studies of bicycling risen to greater prominence (*7*), with initial studies in this research area centered on the idea of bikeability or suitability for bicycling within a given geographic boundary. In an early suitability study of commuting by bicycle in Arizona, Sisson et al. created quarter-mile buffers around 14 elementary school locations and scored the bikeability of their enclosed street links based on traffic conditions and roadway design characteristics; they found that most school locations were adequate for school-aged children to bicycle (*8*). In a study of bikeability in Vancouver, Canada, Winters et al. developed a bicycling planning tool that generated an index based on bike facility availability, topography, connectivity, and local destinations to visualize areas of low and high suitability for bicycling across the city (*9*). McNeil similarly sought to operationalize the bikeability of particular neighborhoods in Portland, OR via an objective assessment of weighted destination types (e.g., schools, stores, parks) found within various sizes of catchment areas extending from 26 locations across the city (*10*). The results of this study found that centrally located neighborhoods characterized by higher household incomes had better bikeability than neighborhoods with lower-income households and more suburban street networks.

Further progressing this field of research, several bicycling accessibility studies have demonstrated the added benefit of classifying the underlying bike network and potential bicycling route alternatives based on traffic safety and security. Incorporating perceived bicycling comfort, Lowry et al. introduced a method for calculating bikeability that used an existing accessibility measure and approach for classifying any facility that permits bicycling with an objectively defined bicycle level of stress (*11*). The application of this planning assessment tool in Moscow, ID, was done to evaluate a set of capital investment scenarios for improving bikeability within the city. Imani et al. (*12*) applied a four-tiered level of traffic stress (LTS) measure (*13*) to a street network in Toronto, Canada, while adopting a cumulative opportunities accessibility metric to estimate bicycling access within a 30-min commute based on LTS thresholds. Neighborhood cycling access to jobs was bifurcated at

5,000 jobs to distinguish between low and high access levels, which informed the specification of a binary logit model to identify associated predictors. In a northern Delaware study, Furth et al. advanced their four-tiered LTS measure to account for annual average daily traffic and other road design configurations to similarly examine job accessibility by bicycling only on low-stress facilities (*14*). Owen and Murphy estimated accessibility to jobs by bicycling for the 50 largest metropolitan regions in the United States with a similar four-tiered LTS measure applied to street networks and travel time calculations using OpenTripPlanner software (*15*).

Other notable studies have also evaluated bicycling accessibility by assessing network connectivity with isochrones generated by employing routing processes. In an early nonmotorized accessibility study, Iacono et al. put forth a set of practical strategies for addressing issues with measuring walking and bicycling accessibility related to zonal structure and travel networks in calculating access to shopping destinations via the shortest network path between two census geographies (*16*). Cabral et al. evaluated low-stress bicycling connectivity improvements in Edmonton, Canada spurred by the addition of 20 km of protected bicycle lanes via the application of a shortest path algorithm with a detour factor used to remain exclusively on a low-stress network (*17*). Gehrke et al., in turn, measured improvements in bicycling access to employment opportunities related to the proposed introduction of a shared-use pathway in Cambridge, MA, that applied the Cyclist Routing Algorithm for Network Connectivity (CRANC), which simulates the routing preferences of different bicyclist types associated with road types, bicycle facility availability, and elevation (*18*).

Conceptual advancements in bicycling accessibility measurement have also been accompanied by social-equity-focused studies, conducted to help identify communities who are likeliest to benefit from bike facility improvements and disparately affected by existing bike network conditions. In the context of this study, understanding how past bicycling accessibility research has analyzed impacts to underresourced communities could offer some insights into the associations between non-healthcare essential workers and bicycling access to physical workplaces. Houde et al. (*19*) used six nonconsecutive years of bicycling infrastructure snapshots in Montreal, Canada to determine whether citywide expansions in bike network connectivity improved bicycling accessibility for low-income populations, immigrants, older residents, and children. Study results revealed that although low-income individuals generally had good bicycling access throughout the 25-year period, a strong decrease in access was observed for immigrants and seniors, with little improvement for districts with higher shares of children (*19*). In a study of bicyclist access to employment or educational opportunities in Bogota, Columbia, Rosas-Satizábal created a potential accessibility metric with a distance decay factor and inequality indicators to identify social inequities between bicyclist groups, finding that one-half of Bogota's bicyclists have access to less than 10% of all employment and educational opportunities owing to the city's urban structure and longer travel distances for lower-income residents to downtown job sites (*20*). In another South American study of bicyclist accessibility, Mora et al. examined whether the expansion of a bicycling network in Santiago, Chile over 15 years had disparate impacts for communities characterized by residents of different income cohorts, concluding that most high-quality bicycling facilities are located in central communities characterized by residents earning higher incomes (*21*). Incorporating LTS classifications of road networks into a study of bicycling access in Rio de Janeiro and Curitiba, Brazil, Tucker and Manaugh similarly found that each city had substantially more bicycle infrastructure in wealthier areas and, subsequently, these residents have higher job accessibility along safer routes (*22*). In a Minneapolis, MN, study of socioeconomic discrepancies in job accessibility via low-stress bicycling facilities and links in the overall street network, Wang and Lindsey compared Gini coefficients to assess the potential social inequities faced by disadvantaged populations, finding that low-stress, multiuse urban trails were less likely to be distributed in census block groups with higher racial or ethnic minority populations and more families living in poverty (*23*). Kent and Karner, in a Baltimore, MD, bicycling accessibility study, introduced a set of performance measures to compare the potential accessibility benefits and socioeconomic impacts of infrastructure projects, highlighting options from their analysis with the potential to better serve disadvantaged neighborhoods experiencing racial segregation, higher levels of poverty, and lower vehicle ownership rates (*24*).

Taken together, this review has highlighted some of the conceptual and empirical advancements of recent research investigating location-based bicycling accessibility. Specifically, greater focus has been placed on implementing accessibility metrics that account for the perceived quality of the network for bicycling and quantifying the impact of current or proposed bicycle facilities on destination accessibility of underresourced communities. This research aims to meet this practice standard for examining bicycling accessibility while also contributing to a growing evidence base assessing the social equity implications of bicycling access to destinations by (i) measuring destination access with a network routing engine that is behaviorally reflective of actual bicyclists who are likely to consider alternative routes to the

**Table 1.** Level of Traffic Stress (LTS) Classification based on Travel Lanes and Speed Limits

| Number of travel lanes per direction | Presence of on-street bike lane | Posted travel speed (mph) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 20 | 25 | 30 | 35 | 40 | 45 | 50 + |
| 1 | No | LTS 1 | LTS 1 | LTS 2 | LTS 2 | LTS 3 | LTS 3 | LTS 4* |
| | Yes | LTS 1* | LTS 1* | LTS 2 | LTS 2 | LTS 3 | LTS 3 | LTS 4 |
| 2 | No | LTS 3 | LTS 3 | LTS 3 | LTS 3 | LTS 4 | LTS 4 | LTS 4 |
| | Yes | LTS 2 | LTS 2 | LTS 2 | LTS 3 | LTS 3 | LTS 3 | LTS 4 |
| 3 | No | LTS 3 | LTS 3 | LTS 4 | LTS 4 | LTS 4 | LTS 4 | LTS 4 |
| | Yes | LTS 3 | LTS 3 | LTS 3 | LTS 4 | LTS 4 | LTS 4 | LTS 4 |

*Classification differs from Furth et al.'s LTS designation (*14*).
*Source*: Adapted from Furth et al. (*14*)

shortest path, (ii) offering nuance in the types of employment destinations that are most likely to generate a latent demand for utilitarian trips, and (iii) investigating whether underresourced communities have poorer bicycling access to traditional workplace settings. To this end, this study's application of an original bicyclist network routing platform to identify differences in bicycling accessibility to physical and virtual worksites attributed to varying neighborhood-level socioeconomic attributes seeks to offer a technical advancement that can be adopted by transportation planners to prioritize facility investments that address existing transport inequities.

## Data and Methods

The first subsection provides a description of the bike network data source and methods used to classify its links based on perceived traffic safety. This enhanced street network is a requisite input for the bicycling routing-algorithm described in the second subsection, which generates geographic boundaries (isochrones) for enumerating destinations. The third subsection details the data sources and methods for delineating physical and virtual employment destinations as well as contextual measures of the socioeconomic and demographic attributes of residents at modeled trip origins. The last subsection describes the statistical modeling strategy adopted to identify the contextual factors associated with bicycling accessibility to physical and virtual jobs.

### *Bike Network Classification*

To understand the perceived comfort of the street network for bicycling, an updated version of the four-tiered LTS classification scheme (*14*) initially described by Mekuria et al. (*25*) was adopted for this study. The updated version of the LTS scheme classifies segments based on traffic characteristics (e.g., travel lanes, posted travel speeds) and the presence of dedicated bike infrastructure. For this study, a modified version of this updated LTS scheme was applied to Flagstaff, AZ using the OpenStreetMap (OSM) transportation network (Table 1). The use of this open-source and editable transportation network for LTS classification enhances the transferability of the network output but requires some aggregation of categories because of data availability limitations with regard to bike lane widths and daily traffic volumes. Where posted travel speed ("maxspeed" tag) gaps existed in the crowd-sourced OSM data set, an imputed value based on the OSM "highway" tag designation and prevailing traffic speed limits in Arizona was inserted: residential = 25 mph, service = 35 mph, secondary = 55 mph, and primary = 65 mph.

The application of this study's modification to the second LTS classification scheme is shown in Figure 1. The transportation network in Flagstaff, which includes both on- and off-street (e.g., shared-use trails) facilities, spans 839 mi. Nearly three-quarters (72%) of the city's network is defined as LTS 1 (very low stress), with 18% of all facilities classified as LTS 2 (low stress), 2% of the city's facilities classified as LTS 3 (moderate stress), and the remaining 8% classified as LTS 4 (high stress). Using the classification of bicyclist types first proposed by Geller (*26*) and substantiated by Dill and McNeil (*27*, *28*), transportation facilities with a classification in the final LTS category are only suitable for the "strong and fearless" bicyclist type, whereas the first two LTS categories describe a facility that would be comfortable for an "interested but concerned" bicyclist, and those facilities classified as moderate stress (LTS 3) are suitable for "enthused and confident" or "strong and fearless" bicyclist types (*25*).

### *Bicyclist Routing Engine and Bicycling Accessibility*

This study adopted the CRANC, previously introduced by Gehrke et al., to calculate bicycling accessibility with a common cumulative opportunities metric (*18*). The CRANC transportation planning tool uses GraphHopper, an open-source Java library and web

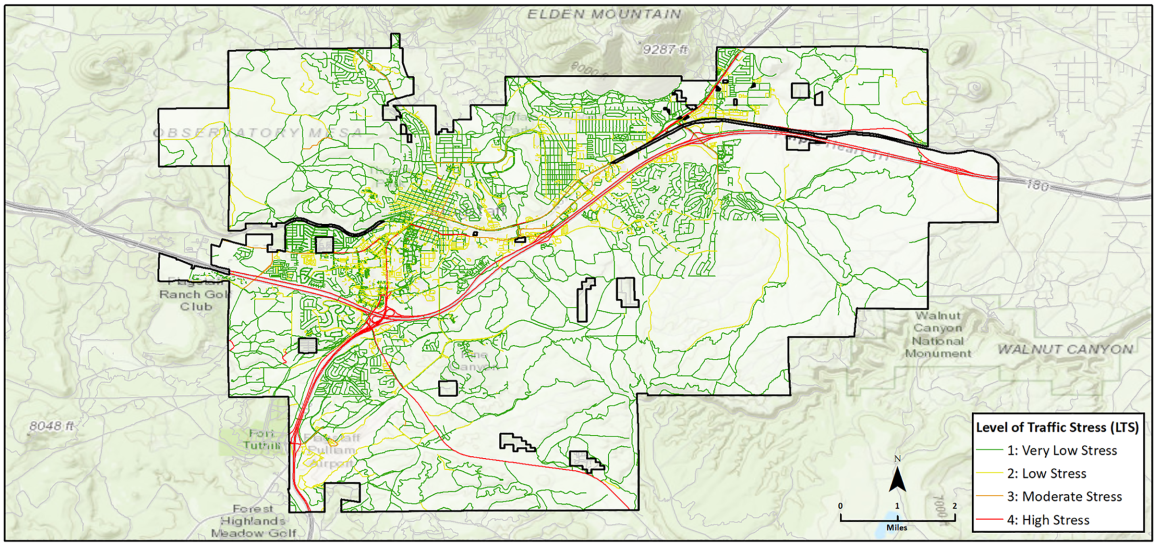


**Figure 1.** Street network in Flagstaff, AZ classified into four categories by bicyclist level of traffic stress (LTS).

service, as its base network routing engine, with modifications that permit the creation of distinct bicyclist profiles with route and travel speed differences that are sensitive to link-level changes in network facilities and topography. GraphHopper's base network routing-algorithm generates an internal representation of the street network as a graph of directed links (or edges) between two nodes. In this study, OSM network data for Flagstaff were extracted using Geofabrik tools to identify links, while nodes were represented as U.S. census block centroids in the study area. For all origin–destination pairs, after assigning impedance values to the graph's edges based on road segment length as well as the speed of a bicyclist type and their aversion to the road segment, the GraphHopper routing-algorithm determines the route between the two trip ends with the lowest summation of impendence values. In this study, only routes generated for an "interested but concerned" bicyclist who travels at a slower speed than the "enthused and confident" bicyclist profile, and has greater sensitivity to changes in elevation over a road segment's length, were analyzed. Greater detail on the assignment of travel speeds based on road class and bicyclist type and aversion factors based on road class and available bicycle facilities is provided in the research by Gehrke et al. (*18*).

Having refined and transferred the CRANC tool to this study's setting, the next step was to measure the bicycling accessibility of the "interested but concerned" to a set of destinations. Using the GraphHopper isochrone module, the travel time for the interested but concerned bicyclist was computed from every U.S. census block centroid contained in the city's boundary (trip origin) to all centroids in Coconino County, including the city of Flagstaff (trip destinations). Figure 2 offers an illustration of the result of this process for an exemplar trip origin. The attributes associated with any destination centroid within the 30-min isochrone for a particular trip origin were then related to the U.S. block where the trip origin was located. For this study, 2,076 U.S. census block centroids were found in Flagstaff and 20,267 centroids inside Coconino County. Additionally, the percentage of network facilities classified by different LTS categories within an isochrone was attributed to the centroid of the originating census block.

### Employment and Social Context Measurement

Identifying the U.S. census block geography as the unit of analysis for measuring bicycling accessibility, the 2019 Longitudinal Employer-Household Dynamics (LEHD) data set's workplace area characteristics file was used to represent employment locations. Although the 2019 workplace information has the benefit of signifying employment characteristics before the onset of the Covid-19 pandemic, its representation at a 2010 decennial census geography required augmentation for these data to complement Flagstaff's current boundary and the most recent available information on neighborhood socioeconomic context. As such, the 2010 U.S. census blocks that intersected the city's current boundary were selected, with the centroids of the blocks overlapping the city's boundary placed in the portion of the block congruent with the current city boundary.

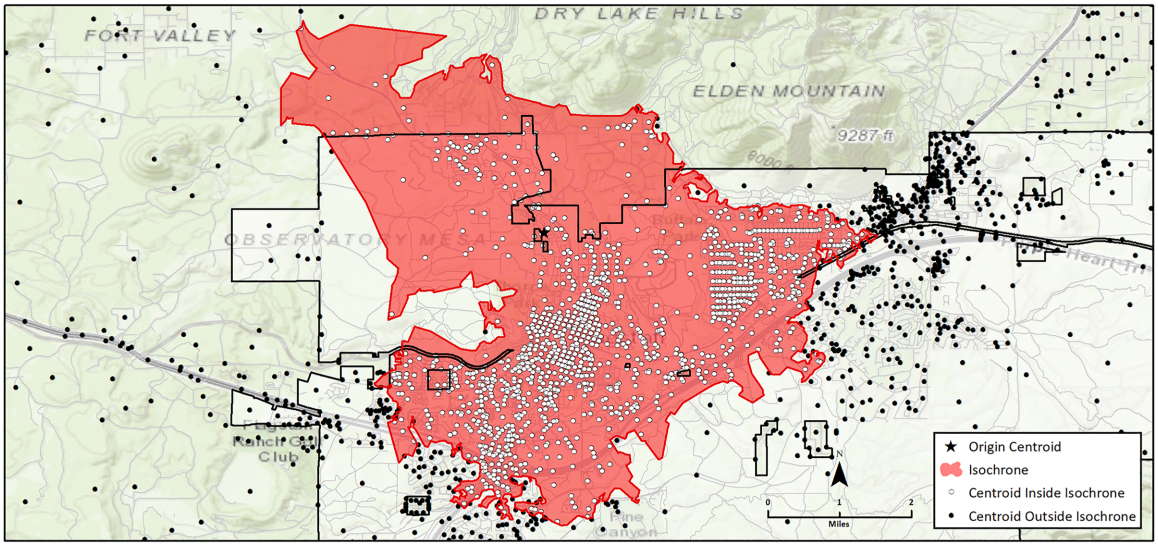


**Figure 2.** Illustration of centroids located in 30-min isochrone for the "interested but concerned" bicyclist type.

Using the revised distribution of census block centroids in Flagstaff and blocks outside of the city but within Coconino County, the next step was to determine which types of jobs located in a block required the physical presence of a worker (physical jobs) and those jobs that could be performed remotely (virtual jobs). In this study, the distribution of jobs that could be performed at home, according to their two-digit North American Industry Classification System (NAICS) code determined by Dingel and Neiman, was applied to each census block geography (*29*). Whereas the share of potential telework jobs by NAICS code reflects a national employment distribution and fails to capture more regional or industry-related nuances, the adoption of Dingel and Neiman's research for this study permitted a representation of physical and virtual jobs at a relatively disaggregate geography and across the same industry code breakdown offered by the LEHD data set. Table 2 shows the virtual share factor for each two-digit NAICS industry code and the subsequent classification of estimated physical and virtual jobs in Flagstaff. An investigation of Table 2 reveals that Flagstaff had a high representation of employment opportunities in the Educational Services industry, most of which (71%) could be conducted remotely. However, four of the five highest industry-level job estimates found in the study area were most likely to be physical jobs requiring a commute, with Health Care and Social Services (24%), Accommodation and Food Services (7%), Retail Trade (22%), and Manufacturing (36%) all popular industries in the city with lower virtual shares.

The collection of block-level physical and virtual job totals, determined by applying the virtual job shares noted in Table 2, was used to estimate the number of jobs that could be accessed by an "interested but concerned" bicyclist in 30 min. To help characterize the social context of the block-level trip origins, a set of individual- and household-level measures were constructed from 5-year estimates of the 2016 to 2020 American Community Survey. Table 3 summarizes these selected measures, which include the gender, age, and race or ethnicity distribution of study area residents as well as the distribution of annual incomes, housing tenure, and vehicle ownership rates of study area households.

## *Statistical Modeling*

Using block-level information on the number of jobs that could be reached via a 30-min bicycle commute by an "interested but concerned" bicyclist and the social context of their trip origin, a pair of negative binomial (NB) models were estimated to explore bicycling accessibility to physical and virtual jobs. The specification of an NB model was selected because the cumulative job total outcome was a nonnegative integer. Although Poisson count models could have been estimated to identify the social context predictors of bicycling access to physical or virtual jobs, the use of an NB model specification permitted a relaxation of the equidispersion assumption in a Poisson count model that indicates equality in the conditional mean and variance functions. The structure for the NB models in this study is,

$$\lambda_i = exp(\beta x_i + \varepsilon_i) \quad (1)$$

**Table 2.** Physical and Virtual Jobs by North American Industry Classification System (NAICS) in Flagstaff, AZ

| NAICS | NAICS description | Virtual Share* | Estimated Number of Jobs | | |
|---|---|---|---|---|---|
| | | | Physical | Virtual | Total |
| 11 | Agriculture, Forestry, Fishing and Hunting | 0.13 | 67 | 10 | 77 |
| 21 | Mining, Quarrying, and Oil and Gas Extraction | 0.37 | 3 | 2 | 5 |
| 22 | Utilities | 0.41 | 101 | 71 | 172 |
| 23 | Construction | 0.22 | 1,519 | 428 | 1,947 |
| 31–33 | Manufacturing | 0.36 | 2,294 | 1,291 | 3,585 |
| 42 | Wholesale Trade | 0.67 | 326 | 663 | 989 |
| 44–45 | Retail Trade | 0.22 | 3,053 | 861 | 3,914 |
| 48–49 | Transportation and Warehousing | 0.25 | 402 | 134 | 536 |
| 51 | Information | 0.80 | 86 | 343 | 429 |
| 52 | Finance and Insurance | 0.85 | 73 | 413 | 486 |
| 53 | Real Estate and Rental and Leasing | 0.54 | 222 | 261 | 483 |
| 54 | Professional, Scientific, and Technical Services | 0.86 | 149 | 917 | 1,066 |
| 55 | Management of Companies and Enterprises | 0.86 | 24 | 144 | 168 |
| 56 | Administrative and Support and Waste Management… | 0.43 | 719 | 543 | 1,262 |
| 61 | Educational Services | 0.71 | 1,901 | 4,653 | 6,554 |
| 62 | Health Care and Social Assistance | 0.24 | 5,544 | 1,751 | 7,295 |
| 71 | Arts, Entertainment, and Recreation | 0.36 | 751 | 423 | 1,174 |
| 72 | Accommodation and Food Services | 0.07 | 6,316 | 476 | 6,792 |
| 81 | Other Services (except Public Administration) | 0.43 | 551 | 416 | 967 |
| 92 | Public Administration | 0.43 | 677 | 510 | 1,187 |
| Total | | | 24,778 | 14,310 | 39,088 |

*Share of potential virtual jobs weighted by wage is adopted from Dingel and Neiman (29).

**Table 3.** Descriptive statistics for City of Flagstaff, AZ

| Variable | Unit* | Mean | SD | Min. | Max. |
|---|---|---|---|---|---|
| Jobs with physical workplaces | B | 35.29 | 114.78 | 0.14 | 2,572.36 |
| Jobs with virtual workplaces | B | 18.10 | 123.21 | 0.13 | 3,954.75 |
| Population, male | BG | 0.50 | 0.10 | 0.00 | 0.87 |
| Population, female | BG | 0.49 | 0.10 | 0.00 | 0.80 |
| Population, 17 years old or less | BG | 0.20 | 0.12 | 0.00 | 0.66 |
| Population, 18–24 years old | BG | 0.15 | 0.19 | 0.00 | 0.99 |
| Population, 25–34 years old | BG | 0.14 | 0.09 | 0.00 | 0.42 |
| Population, 35–49 years old | BG | 0.16 | 0.02 | 0.00 | 0.34 |
| Population, 50–64 years old | BG | 0.18 | 0.10 | 0.00 | 0.58 |
| Population, 65 years old or more | BG | 0.16 | 0.14 | 0.00 | 0.83 |
| Population, White | BG | 0.54 | 0.30 | 0.00 | 1.00 |
| Population, Black/African American | BG | 0.01 | 0.03 | 0.00 | 0.27 |
| Population, American Indian/Alaskan Native | BG | 0.25 | 0.35 | 0.00 | 1.00 |
| Population, Asian | BG | 0.02 | 0.03 | 0.00 | 0.23 |
| Population, Native Hawaiian/Pacific Islander | BG | <0.01 | <0.01 | 0.00 | 0.02 |
| Population, Hispanic/Latino | BG | 0.14 | 0.14 | 0.00 | 0.70 |
| Household, annual income: $10,000 or less | BG | 0.08 | 0.10 | 0.00 | 0.46 |
| Household, annual income: $10,000–$24,999 | BG | 0.15 | 0.14 | 0.00 | 0.74 |
| Household, annual income: $25,000–$49,999 | BG | 0.20 | 0.12 | 0.00 | 0.62 |
| Household, annual income: $50,000–$99,999 | BG | 0.32 | 0.16 | 0.00 | 0.78 |
| Household, annual income: $100,000–$149,999 | BG | 0.13 | 0.11 | 0.00 | 0.51 |
| Household, annual income: $150,000 or more | BG | 0.10 | 0.10 | 0.00 | 0.44 |
| Housing unit, tenure: Own | BG | 0.60 | 0.30 | 0.00 | 1.00 |
| Housing unit, tenure: Rent | BG | 0.37 | 0.29 | 0.00 | 1.00 |
| Household, vehicle ownership: 0 | T | 0.06 | 0.06 | 0.00 | 0.20 |
| Household, vehicle ownership: 1 | T | 0.31 | 0.11 | 0.00 | 0.48 |
| Household, vehicle ownership: 2 | T | 0.35 | 0.10 | 0.00 | 0.57 |
| Household, vehicle ownership: 3 | T | 0.18 | 0.09 | 0.00 | 0.42 |
| Household, vehicle ownership: 4 or more | T | 0.08 | 0.05 | 0.00 | 0.22 |

*Note*: B = block; BG = block group; T = tract; Min. = minimum; Max. = maximum; SD = standard deviation.
*United States Census geographies.

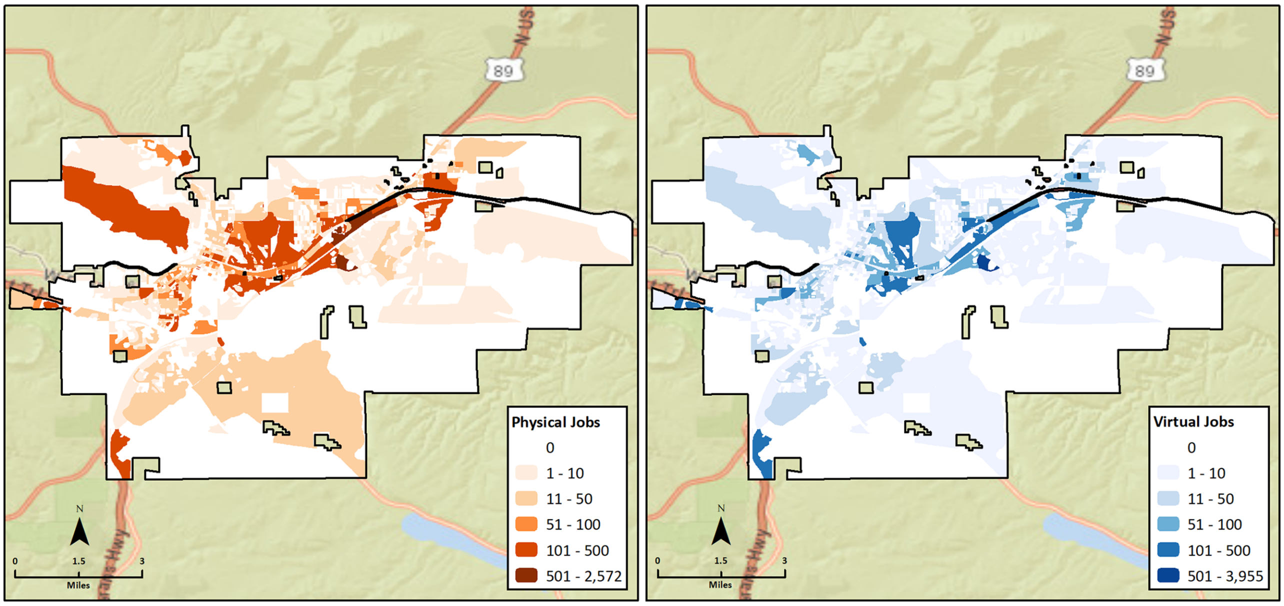


**Figure 3.** Distribution of (*a*) physical and (*b*) virtual job locations by census block in Flagstaff, AZ.

where $x_i$ is a set of contextual variables associated with census block $i$, and $\varepsilon_i$ is a gamma-distributed error term with a mean of 1 and a variance of $\alpha^2$. The addition of this error term permitted the variance to differ from the conditional mean,

$$var[y_i] = E[y_i] + \alpha E[y_i]^2 \quad (2)$$

Each NB model of job access (physical and virtual) was estimated by starting with a base specification that included control variables related to the percentage of the transportation network within the isochrone produced for a given census block that was classified as an LTS 1, 2, or 3 facility, and a measure of the population density in the trip origin's census block. An addition of significant social context predictors to this initial model specification was then tested by performing a backward elimination process in which nonsignificant ($p > 0.10$) predictors were iteratively eliminated from a full model specification, keeping the aforesaid control variables. Once a model specification with these control variables and social context predictors that were marginally significant was found, a specification that reintroduced any missing levels of the categorical predictor variables was estimated. Building on this specification, a final model that tested the interactions between statistically significant predictors describing the main effects of block group-level race/ethnicity and annual income distributions was then estimated. The findings from this final model estimating bicycling accessibility to physical and virtual workplaces were intended to inform whether underresourced communities have poorer bicycling access to traditional workplace settings in the study area.

## Results

This section is divided into two subsections. The first subsection describes the spatial distribution of virtual and physical workplaces in the study area, followed by a description of the variation in bicycling access to these two destination types across trip origins. The second subsection describes the modeling results of estimating bicycling access to physical and virtual jobs as a function of origin-related contextual factors.

### *Physical and Virtual Job Distribution and Bicycling Accessibility*

Figure 3 is a side-by-side visualization of the distribution of physical and virtual jobs in the city of Flagstaff. A review of census blocks grouped in the highest physical job category and clusters of blocks with higher concentrations of physical jobs revealed land use patterns that were specific to the study area, and common locations for prospective bike commutes. Physical job locations were predominately scattered east-to-west, adjacent to U.S. Route 66 and the railroad tracks that bisect the northern and southern halves of the city (Figure 3*a*). The proximity of these two facilities and Interstate-40, which also runs east-to-west on the eastern half of the city, has a likely association with the stretch of manufacturing and

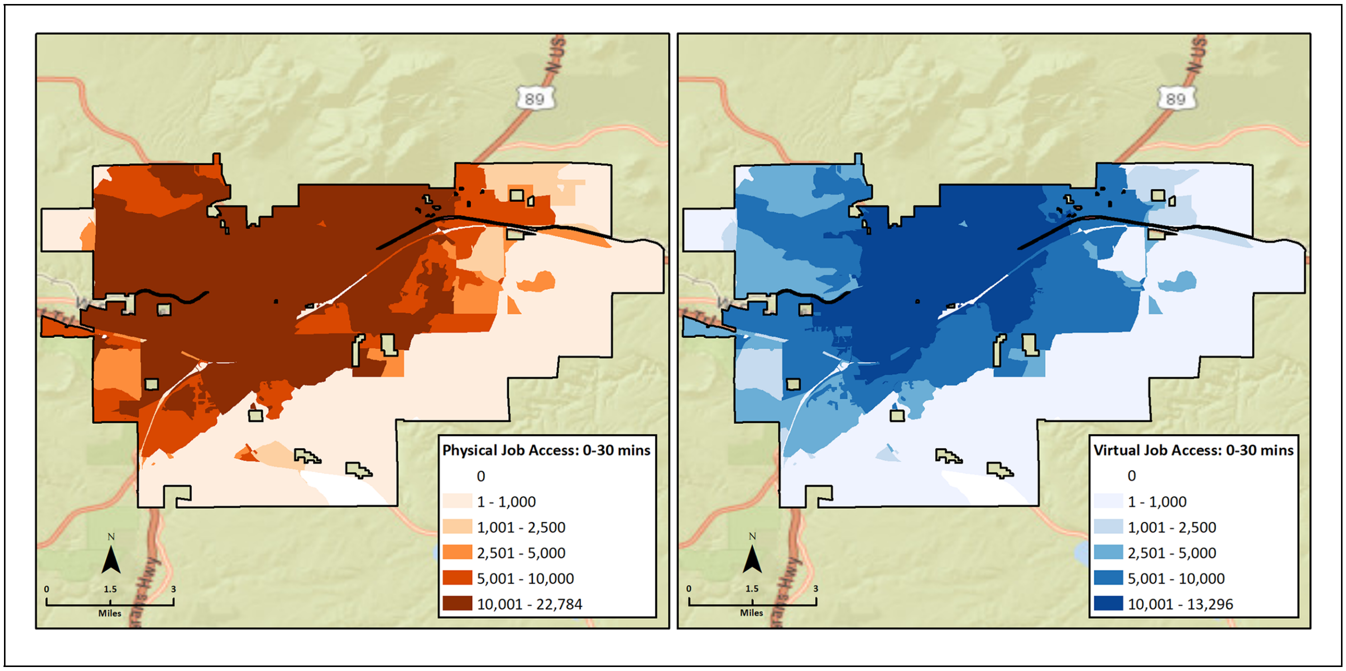


**Figure 4.** Bicycling accessibility to (*a*) physical and (*b*) virtual job locations by census block in Flagstaff, AZ.

warehousing job locations within the central-eastern portion of the city. The Flagstaff Mall and its high share of retail job positions can be seen in the northeast, whereas other large physical job concentrations pertaining to commercial highway stores are noticeable to the east of the city's centrally located downtown. The central-western portion of the city, which includes a cluster of smaller retail shops and larger big box stores, has a cluster of blocks with 50 to 500 physical jobs, whereas smaller census blocks with more than 500 physical jobs, which include Northern Arizona University (NAU) and Coconino Community College, are located south of the city's downtown.

In contrast, census blocks with higher counts of virtual jobs were fewer in number and generally located in more confined clusters along the aforementioned transportation facilities in the city's eastern half (Figure 3*b*). Although many of the same census blocks with high virtual job totals mirrored those areas with more physical jobs, a handful of smaller blocks in the city's downtown and western half had blocks with virtual job totals that were classified in a higher category (i.e., 500 and above versus 101 to 500). These identified blocks tended to be the location of administrative offices for local or state governments or smaller financial firms. In all, although there were notable discrepancies in the distribution of census blocks based on the location of physical and virtual jobs, most areas with a higher intensity of physical jobs were also the location of virtual jobs, albeit with a slightly lower total of the latter job type. This descriptive finding is probably related to a lack of diversity in the job sectors found in Flagstaff and the circumstance that the city is home to some larger companies that have a strong manufacturing, retail, or warehousing presence and a smaller percentage of jobs associated with information, finance and insurance, or management.

With an understanding of the distribution of physical employment locations and the share of positions at current workplaces that could be performed virtually, Figure 4 provides a visualization of the number of physical and virtual jobs that could be reached within a 30-min commute by an "interested but concerned" bicyclist. Given the higher number of physical jobs located in Flagstaff, it is unsurprising to see from this second side-by-side comparison that bicyclists from the majority of residences could reach over 10,000 potential jobs within the designated travel time. Potential "interested but concerned" bicyclists who reside in the western half of the city had stronger bicycling access to physical jobs, whereas improvements could also be found in neighborhoods to the south and southeast of the city's downtown. In all, physical and virtual job access appeared to be greatest for residents in centrally located neighborhoods north of Interstate-40, with no clear distinction of census block clusters where residents would have less accessibility to physical jobs.

To better identify any measurable differences between physical and virtual job accessibility for "interested but concerned" bicyclists, Figure 5 visualizes block-level differences in job access, in which darker shades of orange

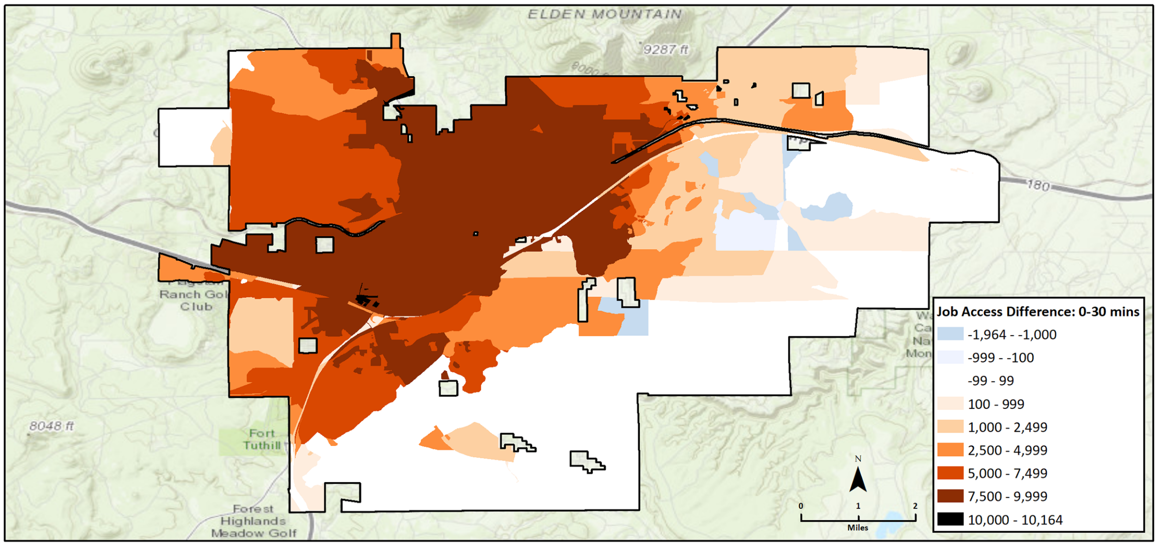


**Figure 5.** Differences in bicycling accessibility to physical and virtual jobs by census block in Flagstaff, AZ.

reflect larger physical job access disparities and darker shades of blue reflect greater discrepancies in virtual job accessibility by bicycle. From this map, several census blocks where residences were found to have greater bicycling accessibility to virtual jobs can be found in the city's eastern half. Although the number of blocks meeting this condition was limited, their location in the sparsely populated neighborhoods away from the city's larger economic hubs is unsurprising. In turn, the cluster of census blocks with the highest number of physical jobs that can be accessed in a 30-min bicycling commute in comparison to virtual jobs was located at the northwest corner of where Interstate-40 intersects Interstate-17. This area has few residences, is the site of a Walmart as well as a several restaurants and hotels, and benefits from low-stress access through Northern Arizona University to manufacturing and warehousing sites located in the central-eastern part of the city. Whereas those areas with the largest discrepancy between physical and virtual job access were found in the northern half of Flagstaff, blocks immediately to the southeast and southwest of the aforementioned interstate junction were also found to have disproportionate bicycling access to physical job locations. These two areas are largely residential areas with single-family houses and an underlying suburban street network.

### *Determinants of Bicycling Accessibility to Physical and Virtual Jobs*

To complement the above description of bicycling access to physical and virtual jobs, Table 4 shows the estimation results of three NB models identifying the neighborhood-level predictors of bicycling access for an "interested but concerned" bicyclist to physical and virtual jobs. Models 1 and 3 display estimation results for physical and virtual job access, respectively, without interaction terms, whereas Model 2 includes any statistically significant interaction terms between household income categories and racial or ethnic population distributions that were found to be significant main effects in the Model 1 specification. Although model results are presented for both physical and virtual job accessibility, focus is given to the results of the physical job access models, as these job sites are most likely to necessitate a physical commute. Models were specified with three control variables: the share of network facilities classified as LTS 1 (very low stress) in a census block's 30-min isochrone, the share of network facilities classified as LTS 2 (low stress) or LTS 3 (moderate stress) in a census block's 30-min isochrone, and the number of residents per acre in the census block where a prospective bike commute would originate.

In Model 1, an increase in the percentage of low-stress bike facilities in a 30-min isochrone was negatively associated with bicycling access to physical jobs, whereas a positive relationship was found between this outcome variable and the percentage of low or moderate stress bike facilities. A potential justification of this result is that for an "interested but concerned" bicyclist in Flagstaff to reach more physical job locations, they would need to ride on facilities classified by a higher LTS category. Looked at differently, although many physical job locations in the city are centrally located, some workplaces can be found in the peripheries of the

**Table 4.** Negative Binomial Model Estimates of Physical and Virtual Job Access within 30-min Bicycle Trip

| Variable | Model 1: physical job access | | Model 2: physical job access | | Model 3: virtual job access | |
|---|---|---|---|---|---|---|
| | Beta | SE | Beta | SE | Beta | SE |
| Intercept | 1.76** | 0.65 | 1.36* | 0.67 | −0.15 | 0.60 |
| 30-min isochrone: share of LTS 1 facilities | −1.81* | 0.81 | −1.36^ | 0.81 | −2.91** | 0.76 |
| 30-min isochrone: share of LTS 2 and 3 facilities | 10.06** | 2.32 | 9.01** | 2.31 | 13.01** | 2.17 |
| Persons per acre | −0.02 | 0.02 | −0.01 | 0.02 | −0.06** | 0.76 |
| Population: 50–64 years old | 2.78* | 1.14 | 3.24** | 1.17 | 3.08** | 1.05 |
| Population: Black/African American | 1.01 | 3.94 | −0.98 | 3.94 | 19.07** | 3.63 |
| Population: Hispanic/Latino | 1.31* | 0.56 | 2.34** | 0.70 | 2.16** | 0.52 |
| Household annual income: $10,000 or less | −3.73** | 1.27 | −0.68 | 1.80 | −4.91** | 1.18 |
| Household annual income: $10,000–24,999 | 2.36* | 1.02 | 2.90** | 1.02 | 4.06** | 0.94 |
| Household annual income: $50,000–99,999 | −1.52^ | 0.84 | −1.71* | 0.84 | 0.20 | 0.78 |
| Household annual income: $100,000 or more | −2.69** | 0.75 | −2.51** | 0.75 | −1.21^ | 0.69 |
| Household annual income: $10,000 or less × Population: Hispanic/Latino | na | na | −15.14** | 6.10 | na | na |
| Model summary | | | | | | |
| Number of observations | 2,076 | | 2,076 | | 2,076 | |
| Theta (SE) | 0.07 (0.01) | | 0.07 (0.01) | | 0.08 (0.01) | |
| Log-likelihood | −3,715.89 | | −3,713.55 | | −3,277.71 | |

*Note*: SE = standard error. ^$p$-value < 0.10; *$p$-value < 0.05; **$p$-value < 0.01. na = not applicable.

city or along major corridors where low-stress facilities do not exist. Although not significantly predictive of bicycling access to physical jobs, a negative link between population density and virtual job access appears to help confirm the previous visual description that less populated (or more suburban) settings are more likely to have better bicycling access to worksites where employees do not necessarily have to leave their residence for work. This finding may be attributed to an abundance of low-stress facilities found in low density, residential areas, and a potential higher relative prevalence of virtual job-sites outside of the city's main employment districts.

Looking at the significant neighborhood-level predictors in Model 1, an origin with a higher share of individuals between 50 and 64 years was associated with improved physical job access. This positive association suggests that older individuals still within the workforce are likely to have high-quality bicycling access to workplaces demanding in-person employment, but that this segment of the population who is generally less likely to bicycle (*30*) may be hesitant to adopt this mode for commuting. Similarly, origins with a higher share of residents who identify as Hispanic or Latino tended to have stronger physical job access via lower-stress bike routes than their counterparts. This revealed a possible latent demand for sustainable travel from a community noted elsewhere (*31*) to reflect a population segment with growing bicycling adoption rates. In turn, origins with a higher share of Black/African American residents were nonsignificant in the prediction of physical job access but positively and significantly predictive of increased virtual job access by bicycling. Together, these model findings suggest that communities with a higher share of racial or ethnic minority residents in the Flagstaff study area may have higher access to traditional workplace settings, although the quality of those facilities appears to vary in relation to LTS.

With regard to household income, origins with a higher concentration of residents on either side of the income continuum were found to have a negative association with physical job access by bicycling. Although there is an expectation that higher income individuals are less likely to bicycle for commuting (*32*), individuals in the lowest income cohort may be more likely to rely on a more affordable commuting option to reach physical workplaces. Accordingly, the results from Model 1 suggested that individuals in the lowest income category had lower bicycling access to employment opportunities than residents in the same area who earn an annual household income between $25,000 and $49,999. However, it is important to recognize that residents in the lowest household income cohort may also include individuals who are retired from the workforce; receive a small, fixed income; and no longer commute to a physical workplace. In turn, residents with an annual household income between $10,000 and $24,999 were more likely to have greater bicycling access to physical job locations than residents in areas with a higher share of households earning between $25,000 and $49,999. U.S. federal poverty guidelines note that households with one, two, or three members in the lower of these two low-income cohorts live below the federal poverty level. Consequently, more focused planning efforts should be made to promote bicycling within these communities as a lower-cost and potentially safe mode of commuting to physical workplaces.

Turning to the estimation results of Model 2, which expands the specification of Model 1 to include an interaction term between the census block distributions of households reporting an annual income below $10,000 and individuals who identify as non-White, Hispanic/Latino, a significant decrease in physical job access by bicycle was found in neighborhoods with a higher share of residents at this intersectionality. This finding supports a study hypothesis that neighborhoods with a greater representation of lower-income and racial or ethnic minority residents were more likely to have poorer access when commuting via bicycle to physical work environments.

## Conclusions

This study of bicycling accessibility to physical and virtual job locations sought to contribute to an expanding field of bicycling research. First, this study described the refinement of a previously developed bicyclist routing platform (*18*) and its application in a new study area. This adaptation of the CRANC tool to use OSM as an underlying network and to quantify the potential stress encountered by a bicyclist based on a four-tier LTS classification scheme has improved the potential transferability of this open-source planning tool and offered greater nuance in routing an "interested but concerned" bicyclist who may not view a network as a simple dichotomy of low- and high-stress links. This application of the CRANC tool to Flagstaff, AZ, which is characterized by an extensive off-street trail network and topographic variation, also required routing algorithm improvements related to sensitivity in link-level elevation changes and surface conditions.

Second, this study sought to offer insights in relation to bicycling accessibility to physical and virtual job locations, with a clearer identification of the former job type needed to further parse out where additions or improvements to bicycling facilities can be made to help promote utilitarian travel by this more sustainable and healthy mode. Recent global circumstances coupled with ongoing technological advancements have brought to light the ability for some jobs to be performed remotely or at home and the necessity for others to have a worker's physical presence. During the Covid-19 pandemic, these physical jobs were generally held by essential workers, who were more likely to travel during the height of the pandemic and be more susceptible to disease transmission when using public transit (*3*). Given that many essential workers are also more likely to earn a low wage (*33*), prioritization for the provision of high-quality bicycling facilities near employment districts with a higher concentration of physical jobs should be considered as a further means of providing a safe, healthy, and low-cost travel option to urban residents.

Third, the findings from this study's analysis of cumulative accessibility to physical job locations hinted at the potential latent demand for bicycle commuting for residents who may traditionally be less likely to adopt this travel mode. Census block origins with a higher percentage of older working-age adults, individuals who identify as Hispanic or Latino, and households with lower annual incomes were all more likely to have better bicycling access to physical job locations when considering lower-stress routes and slower travel speeds. However, many of these communities have been previously found to constitute a relatively low share of bicyclists who currently commute in the United States. Accordingly, these findings support a growing need for continued analyses that could help to better inform transportation planners and policy makers about how to market bicycling as a potentially feasible, safe, and cost-effective travel alternative to commuting by car, and to ensure that facility improvements for small, critical gaps to a safe network are prioritized to offer continuity in low-stress bicycling conditions.

Also of importance, the application of this introduced bicycle routing engine to investigate whether underresourced communities have poorer bicycling access to traditional workplace settings revealed interesting insights. Whereas neighborhoods with a higher share of individuals who identified as Hispanic or Latino were found to have greater bicycling access to physical jobs, neighborhoods with a higher share of individuals who reported an annual household income below $10,000 were found to have lower levels of accessibility. Moreover, neighborhoods with a greater share of both Hispanic or Latino residents and lower-income households were found to have poorer bicycling access to physical job opportunities. This study finding points to the continued importance of examining the intersection of socioeconomic identities in transportation planning and the potential benefit that CRANC and other similar decision-making tools may have in helping to recognize communities where bike facility improvements should be prioritized to improve access.

Although this study has offered the aforementioned contributions, future research should address some of its more prominent limitations. Although notable advancements to the CRANC tool were made for its application in a small urban setting, greater variation in travel times and employment opportunities are likely to be found in more populous cities. As such, future studies adopting this bicycling planning tool should look to assess larger metropolitan regions with greater land use diversity and more polycentric development patterns. In addition to physical context variation, the transferability of this planning tool across various decision makers could be improved through its application in other social and cultural contexts. Future attention should also be given to job accessibility afforded to other bicyclist types (e.g., "enthused and confident") to offer further indication of origins where considerable gaps in a safe bike network exist and hinder use of potential commute routes for more risk-averse bicyclists. Relatedly, alternative travel times or accessibility metrics with a distance decay function could be adopted to better emphasize employment locations that can be more quickly accessed by an "interested but concerned" bicyclist, as a half-hour may be a lofty expectation for enticing a future bicyclist with limited experience to use this commute mode. While also pursued in other accessibility studies (*15*), future applications of the CRANC tool or other bicycling routing platforms should explore the use of actual trip origins (e.g., residences) or destinations (e.g., worksites) rather than block centroids to better account for potential high-stress barriers near either trip end. Furthermore, in modeling predictors of physical job access, greater importance should be given to the potential impact of other contextual variables such as the built environment or traffic safety conditions as well as alternative statistical approaches that account for spatial biases in modeled predictors and outcomes to provide a more comprehensive assessment of bicyclist accessibility to physical or virtual job locations.

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## Author Contributions

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