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Disparities in public transit accessibility and usage by people with mobility disabilities: An evaluation using high-resolution transit data

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ABSTRACT

Many people with mobility disabilities (PwMD) rely on public transit to access crucial resources and maintain social interactions. However, they face higher barriers to accessing and using public transit, leading to disparities between people with and without mobility disabilities. In this paper, we use high-resolution public transit real-time vehicle data, passenger count data, and paratransit usage data from 2018 to 2021 to estimate and compare transit accessibility and usage of people with and without mobility disabilities. We find large disparities in powered and manual wheelchair users' accessibility relative to people without disabilities. The city center has the highest accessibility and ridership, as well as the highest disparities in accessibility. Our scenario analysis illustrates the impacts of sidewalks on accessibility disparities among the different groups. We also find that PwMD using fixed-route service are more sensitive to weather conditions and tend to ride transit in the middle of the day rather than during peak hours. Further, the spatial pattern of bus stop usage by PwMD is different than people without disabilities, suggesting their destination choices can be driven by access concerns. During the COVID-19 pandemic, accessibility disparities increased in 2020, and PwMD disproportionately avoided public transit during 2020 but used it disproportionately more during 2021 compared to riders without disabilities. This paper is the first to examine PwMD's transit experience with large high-resolution datasets and holistic analysis incorporating both accessibility and usage. The results fill in these imperative scientific gaps and provide valuable insights for future transit planning.

1. Introduction

Public transit is essential infrastructure for people with mobility disabilities (PwMD). Lower incomes and lower private vehicle ownership rates create greater needs for reliable public transit (Jolly et al., 2006; Kwon and Akar, 2022). In the United States, adults with disabilities have a higher share of transit usage than their non-disabled counterparts (U.S. Department of Transportation, 2018). Because fixed-route transit systems in many cases cannot provide inclusive and reliable services, alternative mobility solutions such as door-to-door paratransit and ride-hailing can be advantageous. However, these on-demand services can be expensive, and paratransit services can take a long time to schedule and have strict conditions for uses (Miah et al., 2020). These factors can contribute to higher dependency on fixed-route transit services to meet the daily mobility needs of PwMD (Jolly et al., 2006).

PwMD can face disadvantages with respect to using public transit. Although the Americans with Disabilities Act of 1990 (ADA) guarantees equal access for people with disabilities to fixed-route transit and complementary paratransit services (Thatcher et al., 2013; United States, 1990), transit services can still be inaccessible due to non-inclusive stop and station designs. Further, when accessing and egressing public transit, PwMD generally travel at lower speeds, have shorter travel distances, and have higher sensitivity to the existence and quality of sidewalks than non-disabled riders. These factors can create disparities in accessibility and usage of public transit by PwMD (Kwon and Akar, 2022).

Previous research focuses on the accessibility of transit facilities rather than accessibility within the broader built environment and infrastructure. Many past studies discuss the disadvantages of PwMD as compounding other transportation disadvantages faced by people of color and low-income households (Borowski et al., 2018; Ermagun and Tilahun, 2020). However, there is also a lack of evidence focusing on the disparities of PwMD's transit experience from the aspects of both the usability (i.e., transit system and built environment) and usage (i.e.,

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passengers and population). A holistic and high-resolution equity analysis is necessary for further scientific understanding, policy, and system planning.

This paper uses high-resolution public transit and infrastructure data to quantify the accessibility and usage of fixed-route transit services by PwMD and their equity issues. Using General Transit Feed Specification real-time (GTFS-RT) data and Automatic Passenger Count (APC) data, we calculate accessibility and transit use for three groups: persons without disabilities, powered wheelchair users, and manual wheelchair users. These high-resolution data provide new insights into understanding the transit experiences of PwMD. We find large disparities in powered and manual wheelchair users' accessibility relative to people without disabilities. We show the impacts of sidewalks on accessibility disparities among the different groups. We also find that PwMD using fixed-route systems are more sensitive to weather conditions. Further, we find differences in the usage of public transit by time of day and the spatial pattern of bus stop usage by PwMD. We further find that these disparities increased during the COVID-19 pandemic.

The paper is structured as follows. In the literature review section, we summarize the literature about transit accessibility and usage of PwMD. We then introduce the data and method of the paper, followed by the analysis results. We finally conclude the findings and lessons for future transit planning and administration with the discussion of limitations in the paper.

2. Background

In this section, we discuss the experience of people with mobility disabilities (PwMD) with public transit from two perspectives: transit accessibility and transit usage. We identify the research gaps with respect to these two topics that motivate our research.

2.1. Transit accessibility of people with mobility disabilities

Transit accessibility for economically and physically challenged populations is a key evaluator of urban social equity (Grisé et al., 2019). Adults with disabilities in the US have a higher share of fixed-route transit trips compared to non-disabled adults (Bureau of Transportation Statistics, 2022). However, several factors also contribute to the disparities in accessibility. PwMD have slower movement speed and shorter movement distances when accessing and egressing public transit. They are also sensitive to poor sidewalk infrastructure and the lack of inclusive transit facilities.

2.1.1. Speed

PwMD generally have lower average speeds when moving through an environment. While non-disabled people move at an average speed of 1.4 m/s (Browning et al., 2006; Fitzpatrick et al., 2006), manual wheelchair users may travel more slowly depending on the person's physical condition and the condition of their wheelchair. Some papers report speeds ranging from 0.19 to 0.79 m/s based on wheelchair athletes or over short durations of time (Sonenblum et al., 2012; Tolerico et al., 2007). Power wheelchairs can remedy some of these mobility difficulties. Cooper et al. (2002) surveyed the average speed of electric wheelchair users; the average speed in the middle of a day is around 0.4 to 0.6 m/s.

2.1.2. Reachable distance

The maximum walking distance to bus stops is highly heterogeneous among transit riders. Widely accepted values of maximum walking distance to public transit ranges from 400 to 800 m (Calthorpe, 1993; Guerra et al., 2012; Zhao et al., 2003). At the same time, PwMD travel significantly shorter distances than their non-disabled counterparts due to lower travel speeds combined with reasonable limits on public transit access time during travel (Farber and Páez, 2010). Shorter maximum walking distance negatively impacts PwMD's transit accessibility in three ways: 1) some stops cannot be accessed, limiting potential route choices; 2) some transfers are not possible due to shorter walking/rolling distance; and 3) the accessible area quadratically decreases with shorter maximum distance.

2.1.3. Sidewalks

PwMD are more sensitive to the quality of infrastructure, such as sidewalks, than people without mobility disabilities. Difficulties that PwMD face include missing sidewalks (low connectivity), uneven surfaces, and missing curb cuts at crossings (J. Park and Chowdhury, 2018; Saha et al., 2019). The last two factors are important but easily overlooked, as non-disabled people can usually pass through broken sidewalks, while PwMD may face physical difficulties or even injuries (Wolf et al., 2007). Improvement in the walking environment is more likely to enhance transit access for people with mobility disabilities, as well as encourage them to use transit for their day-to-day travel (Kwon and Akar, 2022).

2.1.4. Transit amenities

Inaccessible stop and vehicle design often pose unfavorable conditions for PwMD. Only 3% of the bus stations in the US are ADA-compliant as of 2017 (Sprung and Chambers, 2017). PwMD often identify the unavailability of shelters at bus stations and insufficient spaces for their mobile devices as barriers toward their transit use (J. Park and Chowdhury, 2018; Unsworth et al., 2021). Although 98.2% of transit agencies in the USA have designed their vehicles in an ADA-friendly manner (Sprung and Chambers, 2017), PwMD often experience difficulties and even injuries while boarding and alighting through the bus-deployed wheelchair ramps due to steepness and unsupportive design thresholds (Frost et al., 2020).

Some studies examine the disparities in PwMD's physical accessibility in a broader environment. For example, Casas (2007) is among the first to assess disabled people's disparity in accessibility for any transportation modes. Pyer and Tucker (2017) show the ramifications of barriers to transportation, including public transport, for British teenage wheelchair users by interviews. Grisé et al. (2019) compare PwMD's and non-disabled people's transit accessibility to jobs in Montreal and Toronto, Canada, and find large disparities. Alldredge (2019) use online survey to investigate barriers and perceived accessibility of transit riders with disabilities in Utah. Fernandes-Ferreira et al. (2020) find PwMD still face significant accessibility barriers to tourist attractions in Bangkok, Thailand. Lope and Dolgun (2020) use Gini coefficient to calculate the inequality in disabled population's access to trams services in Melbourne and find significant inequality. However, research on the disparity in PwMD's physical accessibility of public transit systems is still lacking. Although it is well-known that PwMD experienced unequal levels of accessibility in transit systems, very few papers quantify the extent of the disparity, especially in car-dependent cities in the US.

2.2. Public transit usage of people with mobility disabilities

The challenges of using fixed-route public transit often create preferences by PwMD for personal vehicles. However, due to physical and economic challenges, they are less likely to own or otherwise have access to a car than non-disabled people (Jolly et al., 2006). The ratio of PwMD workers travelling as passengers in personal vehicles is almost twice as that for non-disabled persons (U.S. Department of Transportation, 2018). K. Park et al. (2022) conducted a systematic review of mode choice among people with disabilities. The prevalence of driving ranges between 2.6% to 82.7%, making it one of the main transportation modes (Brucker and Rollins, 2019; Crudden et al., 2015).

Although on-demand ride hailing and paratransit services can fill the mobility needs of some PwMD (Schmöcker et al., 2008), fixed route transit services remain crucial for many. The poverty rate among PwMD is twice as high as their counterparts without mobility disabilities (LaPlante and Kaye, 2010), meaning that on-demand ride-hailing is not affordable. Paratransit services can have strict requirements for usage, and may not be convenient due to requirements for advance scheduling (Miah et al., 2020). This leaves fixed-route public transit as a crucial service for many PwMD. In fact, adults with disabilities in the US have a higher rate of fixed-route transit usage than their non-disabled counterparts (U.S. Department of Transportation, 2018). About 4.6% to 51% of people with disabilities used public transportation (Bezyak et al., 2017; Douglas et al., 2012); buses are the most widely used, with up to 74% of individuals using them for their trips (Bezyak et al., 2017).

The travel patterns of PwMD are also significantly different from people without disabilities. For example, a U.K. study found that PwMD are more likely to travel shorter distances, turn down a job because of travel difficulties, and become dissatisfied with the reliability of public transit (Jolly et al., 2006). It is necessary to discuss the experience of people with mobility disabilities when analyzed with other types of disabilities due to the complexity and nuance (Levine and Karner, 2023).

3. Methods

In this section, we first present our transit data sources; we then introduce our accessibility measures based on space-time prism concepts from time geography (Miller, 2017). We then discuss a scenario-driven approach to assess the differential accessibility impacts of sidewalk infrastructure. Finally, we discuss our methods for analyzing public transit usage.

3.1. Data

Our study area is the Columbus metropolitan area, Franklin County, Ohio, USA; Franklin County is home to 1.3 million people with about 64,000 people with ambulatory difficulty per 2019 American Community Survey (US Census Bureau, 2020). Our analyses also focus on the Central Ohio Transit Authority (COTA) bus system, which serves about 50,000 people daily and increasing until 2019 with >3000 bus stops. Our study time period ranges from May 2018 to November 2021. We use two large high-resolution datasets in this paper.

3.1.1. GTFS schedule and real-time data

General Transit Feed Specification (GTFS) data are the de facto data standard to exchange transit-related information (Antrim and Barbeau, 2017; Liu and Miller, 2020). GTFS encompasses two data standards: GTFS static and GTFS real-time, which respectively represent the scheduled timetable and real-time status of the public transit system (Google, 2021; Google Developers, 2020). We collected these data from the COTA GTFS application programming interface (API) feed in a MongoDB database.

3.1.2. APC data

We obtained Automatic Passenger Counter (APC) data from COTA, which are generated by sensors installed on buses that track passenger movement (Chu, 2010). Transit agencies use these data to estimate ridership in their systems. The APC data includes counts of passengers boarding and alighting at each stop, as well as the number of times that bike racks in front of each bus were activated. APC data can be used to understand general ridership patterns as well as the realized bike-transit multimodal demand.

3.1.3. Paratransit usage data

For comparative purposes, we also use paratransit usage data from 2018 to 2022 from COTA. Due to its private nature, these data were stripped of identifiers, and the origin and destination of each trip were aggregated to the nearest census block group centroid to avoid revealing the home addresses of paratransit users.

The novelty of these datasets is threefold: first, the datasets have few sampling biases (the unbiasedness of APC data is discussed in the appendix). As prior research mostly uses survey, interview, or questionnaire (K. Park et al., 2022), sampling bias is a major concern. On the other hand, all three data used in the paper either record every bus or user's behavior (GTFS and paratransit) or justified to eliminate the bias (APC). Second, the resolutions and ranges of the data are much higher, meaning that analysis can be conducted on both disaggregated and aggregated levels, spatially and temporally. This is very hard to achieve with traditional data. Finally, with the data pipeline and analytics introduced in this paper, all the analysis can be performed as a system performance measure. In other words, high-resolution data enable us to measure the experience of PwMD and performance of the system in an on-demand and economic manner, providing guidance to actual planning and operation. However, we acknowledge that survey data are still crucial and necessary, and they can provide more and better insights that cannot be covered by automated high-resolution data, such as travel demand and preference.

3.2. Physical accessibility

Physical accessibility measures the geographic limits of a transit passenger's reachable area given a time budget for travel (e.g., 30 min). All else being equal, higher accessibility means more opportunities are available to the person. We use a well-established time geography concept – the space-time prism (STP) – to measure transit users' physical accessibility (Hägerstrand, 1970). The STP measures the envelope of all possible paths in space with respect to time for a given travel and activity participation episode. There are three possible STP scenarios: 1) between two locations with corresponding departure and arrival times; 2) from all possible origins to a single destination with an arrival time; and 3) from a single origin with a departure time to all possible destinations (Miller, 2017). In this paper, we treat bus stops as single origins (case 3). While the STP consists of space and time dimensions, its spatial footprint – the potential path area (PPA) – shows the geographic extent of the STP.

When applying the STP to bus stops, it is possible that the corresponding STPs will overlap spatially due to close bus stop spacing. Ideally, the STP measures would fuse these accessible potential path areas, so the intersection areas are only counted once. However, it is time-consuming to precisely calculate the dissolved area of such a STP, especially when we have millions of STPs in our study. Therefore, we do not fuse the STPs in our analysis, meaning there is potential double-counting of accessible areas, especially as these areas become larger (see the appendix for more information).

We use two STP measures to quantify an upper and lower bound on physical accessibility. First is an *implicit PPA*, which is defined as the number of accessible stops from a stop given a time budget (Liu et al., 2022). We first introduce a decision variable:

$$\delta_{ij\tau\phi} = \begin{cases} 1, if\ t_{ij\phi} \leq \tau \\ 0, if\ t_{ij\phi} > \tau \end{cases} \tag{1}$$

where $\delta_{ij\tau\phi}$ represents if a user can arrive at another stop j from stop i at time point ϕ within the time budget τ, and $t_{ij\phi}$ is the shortest travel time between stops i and j starting from a time point ϕ. To calculate the shortest travel time, we develop a time-dependent Dijkstra routing engine in Python, which utilizes actual arrival time at each stop from the GTFS real-time data (Liu et al., 2022; Liu and Miller, 2022; Wessel and Farber, 2019). Time-dependent means that the travel time in each link depends on a user's arrival time at the starting node (Gendreau et al., 2015). This means that the travel time cost for each link is dynamic with larger computational load, but the results are more accurate and closer to users' actual transit experience. Based on the decision variable, we define implicit PPA as:

$$I_{i\phi} = \left\{ \sum_{j \in S} \delta_{ij\tau\phi} | \forall \tau \in \mathrm{T} \right\} \tag{2}$$

where I_i^{ϕ} represents the implicit PPAs from stop i at time point ϕ with different time budgets, while T is the set of all time budgets and S is the set of stops. The implicit PPA only measures the accessibility to network nodes and does not consider accessible areas outside the transit system network. Therefore, we introduce (non-fused) *planar PPA* to overcome its limitation. We first define the accessible area by walking/rolling for each destination stop after alighting the bus as follows:

$$s_{ij\tau\phi} = \pi\cdot\left(max\left(min\left(\left(\tau - t_{ij\phi}\right)\cdot v , d\right) , 0\right)\right)^2 \tag{3}$$

where d is the maximum walking/rolling distance. The area represents the additional area that a passenger can reach outside the system. The planar PPA is defined as:

$$S_{i\phi} = \left\{\sum_{j\in S} s_{ij\tau\phi} | \forall\tau \in \mathrm{T}\right\} \tag{4}$$

The planar PPA considers the impact of area and favors higher density of stops and more route choices.

As we discuss in the background section, a wheelchair user can face multiple extra difficulties, including slower travel speed, lower reachable distance, fewer passable sidewalks, and lack of accessible transit facilities – compared to a person without disabilities. In our analysis, we choose three representative groups, i.e., non-disabled users, powered wheelchair users, and manual wheelchair users, and assign travel speed and walking distance based on the literature (see the Background section). Specifically, we assign 1.4 m/s, 0.5 m/s, and 0.2 m/s as their average speed, respectively. We also select 700 m as the maximum walking distance for non-disabled people. We translated this into a maximum travel time (500 s) for non-disabled people based on their travel speed, and then translated that into a maximum distance for powered and manual wheelchair users based on their average speeds, which are 250 m and 100 m, respectively. We choose 30 min as the time

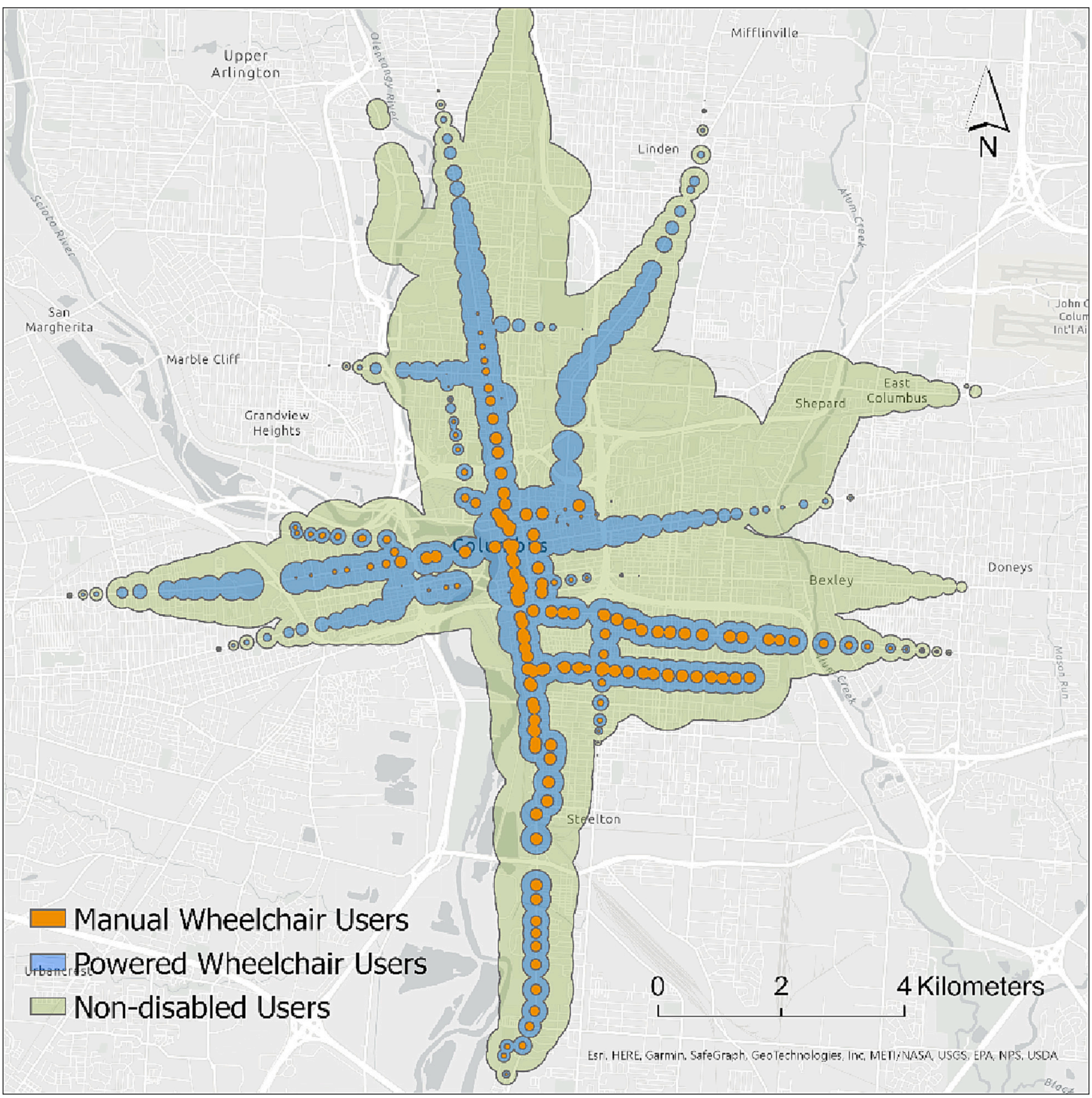

Fig. 1. An example of fused PPAs for the three types of users from a stop in downtown Columbus with a time budget of 30 min (PPA fused for the visualization purpose).

budget in most analyses in the paper, because 30 min, called Marchetti's constant, is a good benchmark for one-way travel (Marchetti, 1994).

Fig. 1 shows an example of three PPAs in the accessible areas of the three groups. Note that we use fused PPAs here for visualization purposes, the analyses below are based on implicit PPA and unfused planar PPA. This example illustrates the stark differences in public transit accessibility faced by PwMD.

We measure the disparity in PwMD's accessibility with its deviation from non-disabled people's accessibility of people without mobility disabilities:

$$d_i^{\phi} = \frac{S_{i\phi}^N - S_{i\phi}^W}{S_{i\phi}^N} = \left\{ \frac{\sum_{j\in S} s_{ij\tau\phi}^N - \sum_{j\in S} s_{ij\tau\phi}^W}{\sum_{j\in S} s_{ij\tau\phi}^N} \cdot 100\% \middle| \forall\tau \in \mathrm{T} \right\} \tag{5}$$

Where $S_{i\phi}^N$ and $S_{i\phi}^W$ are non-disabled users' and PwMD's STP, respectively. d_i^{ϕ} is the deviation of PwMD's accessibility from their non-disabled counterparts. The measure range is [0%, 100%], assuming that PwMD do not have greater accessibility than people without mobility disabilities, with 0% indicating no disparity in physical accessibility and 100% indicating complete disparity.

3.3. Impacts of sidewalk on accessibility

Sidewalk availability and quality can influence transit accessibility in a direct and fundamental way despite not being an explicit part of public transit systems (Kwon and Akar, 2022). Sidewalk determines if a wheelchair user can pass between stops and therefore influences the route choice of the user. To measure the impacts of sidewalk on accessibility, we use sidewalk inventory data acquired from the Mid-Ohio Regional Planning Commission (MORPC, 2021). The data contain all the recorded sidewalks in the Franklin County area and the status of each sidewalk segment. The status fields categorize sidewalk segments into six classes: 1) sidewalks; 2) worn paths; 3) multi-use paths (e.g., green trail); 4) marked crossings; 5) unmarked crossings; and 6) sidewalks with unknown status.

Based on the data and the time-dependent Dijkstra routing engine, we determine the passable sidewalks for PwMD during all possible transfers in the process of path finding based on several assumptions. First, PwMD cannot pass worn paths due to the uneven surface. Second, PwMD cannot pass unmarked crossings on major roads but can pass short unmarked crossings on minor roads such as residential streets and alleys. Third, PwMD will not use sidewalks with unknown conditions due to their lower confidence in mobility (Rushton et al., 2011). Fourth, PwMD can pass sidewalks and multiuse trails (the latter are designed to be ADA-compliant). In contrast, non-disabled people can pass through all sidewalks of different conditions and types in the inventory. To assess these assumptions, we conduct a sensitivity analysis to measure different sidewalk conditions' impact on accessibility. Network connectivity is also a primary factor that impacts transit accessibility. van Eggermond and Erath (2016) point out that Euclidean-based accessibility analysis (i.e., relying on a circular buffer as accessible area) overlooks the infrastructure and overestimates PwMD's accessibility. We therefore test three different road scenarios and their impacts on accessibility: Euclidean-based connections, open street map roads, and sidewalks.

In addition to the above three scenarios, we test the sensitivity to sidewalk surface conditions as they affect user confidence, as discussed in the Background sections. Moreover, confidence also determines whether a wheelchair user will use the sidewalk. A wheelchair user may avoid the sidewalk if they do not know the sidewalk condition. Mobility confidence is impacted by several factors, such as wheelchair type (e.g., powered or manual wheelchairs) and physical conditions (Atoyebi et al., 2019; Sakakibara and Miller, 2015).

Table 1 summarizes the five sidewalk scenarios in our analysis. We use the classification field in original sidewalk inventory to simulate the impact of physical surface condition and confidence. From top to bottom, mobility confidence and tolerance toward poor infrastructure become lower.

Table 1
Five sidewalk scenarios in the analysis.

Scenario	Infrastructure representation	Empirical scenario
1	Euclidean distance	PwMD can freely move in any direction (not accounting for the road network; simplistic base case)
2	All open Street Map (OSM) roads as of early 2022	PwMD can navigate through all roads.
3	All sidewalks and crossings regardless of status	PwMD can navigate through all sidewalks and street crossings.
4	All sidewalks except worn paths and long unmarked crossings	PwMD can navigate through all paved sidewalks and short street crossings.
5	Same as above, but sidewalks with unknown status are removed	PwMD can navigate through all known paved sidewalks and short street crossings.

3.4. Usage analysis

We measured ridership using the APC and paratransit usage data. Actual ridership of the APC data contains ridership of people with mobility disabilities and non-disabled people at each stop. We filter out the outlier ramp activations and remove the ramp activation counts that exceed the total ridership.

We conducted two analyses of fixed-route PwMD ridership, fixed-route general ridership, and paratransit ridership to understand the travel patterns and disparity in usage between PwMD and non-disabled riders. First, we examined the temporal patterns of the ridership by group, focusing on the impacts of the pandemic in the first wave of the pandemic and the persistent impacts during 2021. We also examine the relationship between the fixed-route ridership and weather variables (temperature and precipitation) for each day. Second, we analyze the spatial patterns of ridership by group and their distinctions, focusing on the variations of the ratio of PwMD's trips in the general ridership. We also investigate the differences between the top 5% stops with the highest ridership of both PwMD's and general ridership. We study the difference between the usage pattern of fixed-route general ridership, fixed-route PwMD ridership, and paratransit ridership. We finally compare the ratio of ridership groups to local population at the census block group level.

4. Results

4.1. Accessibility

There are striking disparities in accessibility among people with mobility disabilities (PwMD) and non-disabled users. Using implicit PPAs and a 30-min time budget, we find that powered and manual wheelchair users' accessible stops are 59% and 75% less than their non-disabled counterparts in average from 2018 to 2021. With planar PPAs and a 30-min time budget, powered and manual wheelchair users' accessible areas are 95% and 99% less than their non-disabled counterparts. The disparity is larger when measuring with planar PPA due to the quadratic relationship between area and radius (maximum walking/rolling distance).

4.1.1. Temporal patterns

Table 2 shows annual estimates of disparities among powered and manual wheelchair users compared to non-disabled persons using the implicit and planar STP measures. Recall from eq. (5) that 0% means no disparity, 50% means non-disabled users' accessibility is twice as PwMD, and 100% means complete disparity. Table 2 illustrates the striking levels of disparities facing both PwMD groups: with a 30-min time budget, people using powered wheelchairs can access less than twice as

Table 2
Annual pattern of disparity in implicit and planar PPA for wheelchair users for time budgets of 30 and 60 min.

	30 Minutes Time Budget							
	Implicit				Planar			
	Powered Wheelchair		Manual Wheelchair		Powered Wheelchair		Manual Wheelchair	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD
2018	58.06%	0.44%	74.05%	0.33%	94.80%	0.04%	99.48%	0.01%
2019	58.06%	0.40%	73.94%	0.32%	94.81%	0.03%	99.48%	0.01%
2020	60.63%	0.14%	76.02%	0.15%	95.10%	0.02%	99.51%	0.01%
2021	59.99%	0.05%	75.15%	0.10%	95.03%	0.02%	99.50%	0.00%
	60 Minutes Time Budget							
	Implicit				Planar			
	Powered Wheelchair		Manual Wheelchair		Powered Wheelchair		Manual Wheelchair	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD
2018	39.04%	0.41%	58.34%	0.38%	92.68%	0.06%	99.23%	0.01%
2019	39.51%	0.42%	58.61%	0.37%	92.74%	0.07%	99.23%	0.01%
2020	45.15%	3.40%	64.53%	2.70%	93.44%	0.38%	99.34%	0.05%
2021	44.58%	0.81%	63.99%	0.59%	93.44%	0.12%	99.33%	0.01%

many bus stops, whereas manual wheelchair users can reach less than a quarter of the bus stops in the COTA system. The disparity in reachable geographic area is even more striking: almost complete disparity, confirming that the example in Fig. 1 is a common condition across the system. Increasing the time budget to 60 min decreases disparities, but they remain high, particularly for manual wheelchair users. This suggests that PwMD must spend considerably more time to achieve accessibility levels enjoyed by the non-disabled population. This also implies that PwMD who use public transit may face conditions of time poverty due to the high time pressures required to achieve accessibility (Williams et al., 2016).

Pre-pandemic (2018–2019) accessibility disparities were relatively stable, while accessibility during the COVID-19 pandemic (2020–2021) significantly decreased for all users due to service cuts (i.e., reduced frequency and number of routes). Table 2 also indicates that disparities faced by both powered and manual wheelchair users' accessibility increased during 2020 and stayed high in 2021, despite recovery in accessibility overall. In July 2020, non-disabled people's accessible stops decreased by 22% compared to July 2019, while the number is 31% and 32% for powered and manual wheelchair users, respectively; non-disabled people's accessible area decreased by 15%, while the number is 29% and 30% for powered and manual wheelchair users. Meanwhile, the pandemic-related disparity increase is larger for longer time budgets, suggesting that the pandemic has larger impact on longer travels' equity.

4.1.2. *Spatial patterns*

Fig. 2 visualizes the spatial disparities in powered wheelchair users' (blue) and manual wheelchair users' (orange) accessibility compared to users without mobility disabilities using the implicit PPA measure. Both maps vividly illustrate the substantial disadvantages faced by PwMD who use public transit: in much of the city, PwMD have accessibility levels that are 60–100% below public transit users without mobility disabilities. Strikingly, Fig. 2 also shows that the core of the city – the

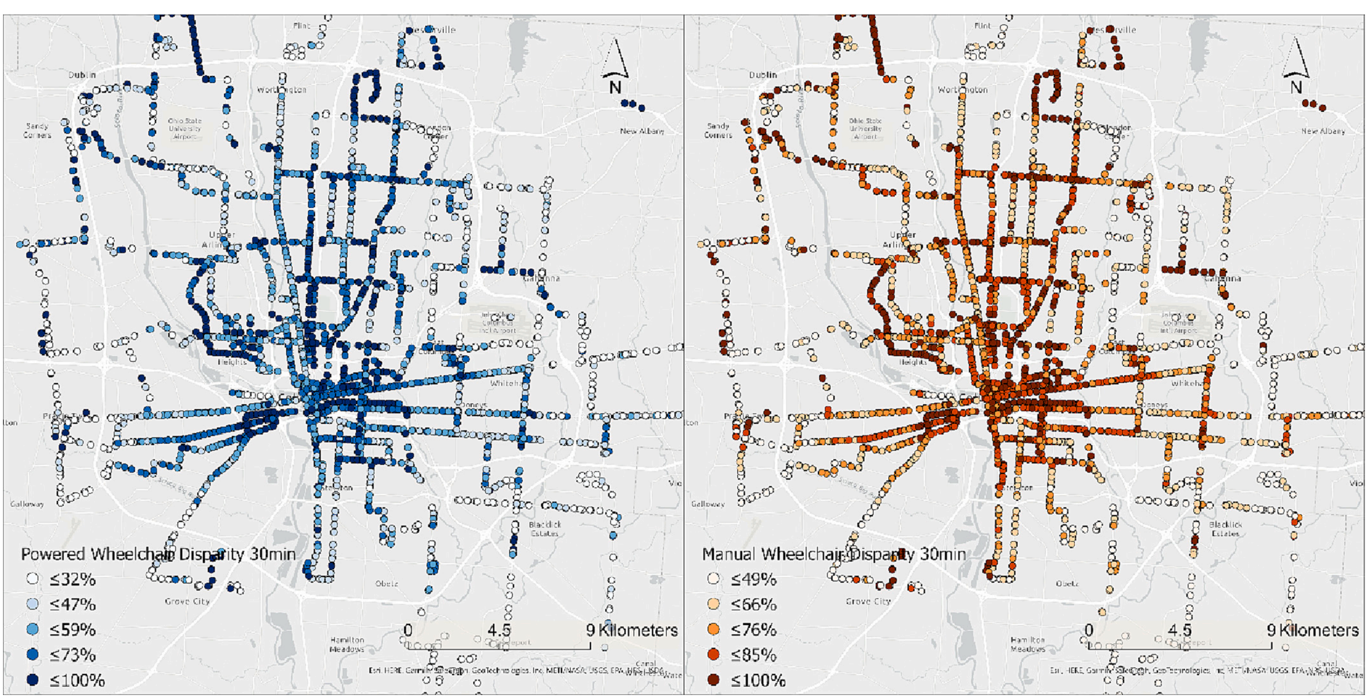

Fig. 2. spatial pattern of STP disparity with time budget of 30 min with quantile classification (left: powered wheelchair users; right: manual wheelchair users).

place with the highest overall ridership and accessibility – is also the place with the highest disparities among these user groups.

Fig. 3 illustrates the spatial patterns of disparity with different travel time budgets. Disparities for both wheelchair user groups and both STP measures decrease with higher time budgets. With longer time budget, the non-disabled people's PPA will reach a maximum limit due to the limited number of stops to access in the transit system. Therefore, the disparity level in the city center will decrease after that point as PwMD's PPA increases. We define this phenomenon as *saturation* (Liu et al., 2022). Table 2 and Fig. 3 both show the disparity is higher with shorter (and more realistic) time budget. Meanwhile, there is a trend that higher disparities clusters move outward from the city center to suburbs with bigger time budgets. However, this does not necessarily mean longer time budgets are more favorable for PwMD, because the lower disparity values are because non-disabled people's accessibility stops growing due to physical limitation, rather than higher accessibility for PwMD.

4.1.3. *Impacts of sidewalks on accessibility*

Fig. 4 shows results for the sidewalk accessibility analysis (see Table 1). This figure compares the average number of accessible stops with a time budget of 30 min for the three user groups; each scenario is applied to every group equally to simulate the impact of infrastructure on both groups. Recall that the scenarios range from generous to most restrictive: Scenario 1 is an unrealistic overestimation (Euclidean distance), Scenario 2 assumes all roads are passable, and Scenario 3, 4, and 5 increasingly conservative assumptions regarding what is passable.

Fig. 3. Disparity in manual wheelchair users' implicit PPA with time budget of 15 min (upper left), 30 min (upper right), 60 min (lower left), and 90 min (lower right).

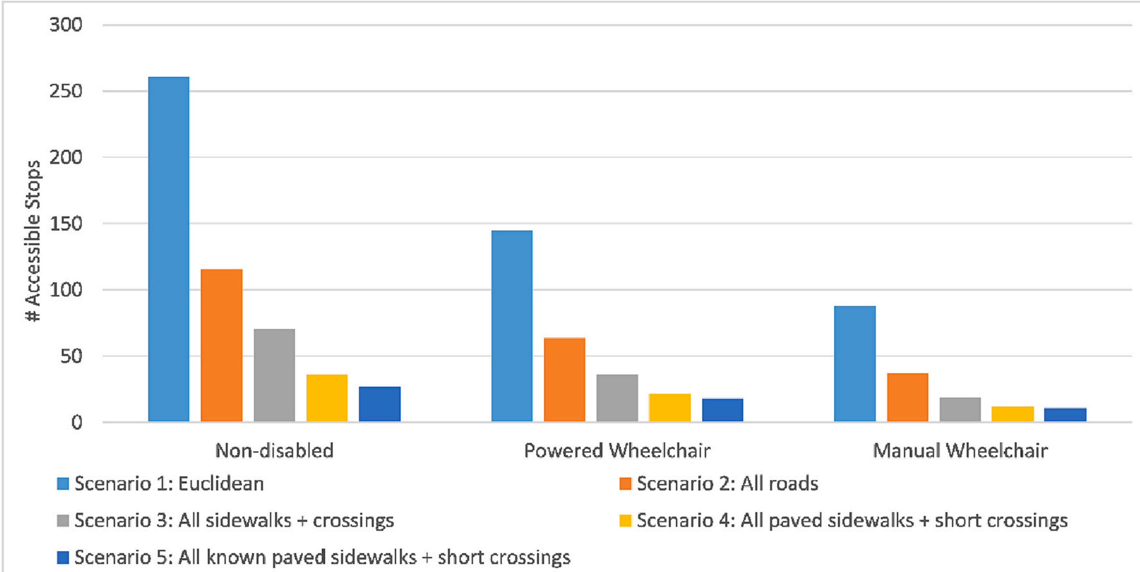

Fig. 4. Average number of accessible stops in 30 min for the three groups.

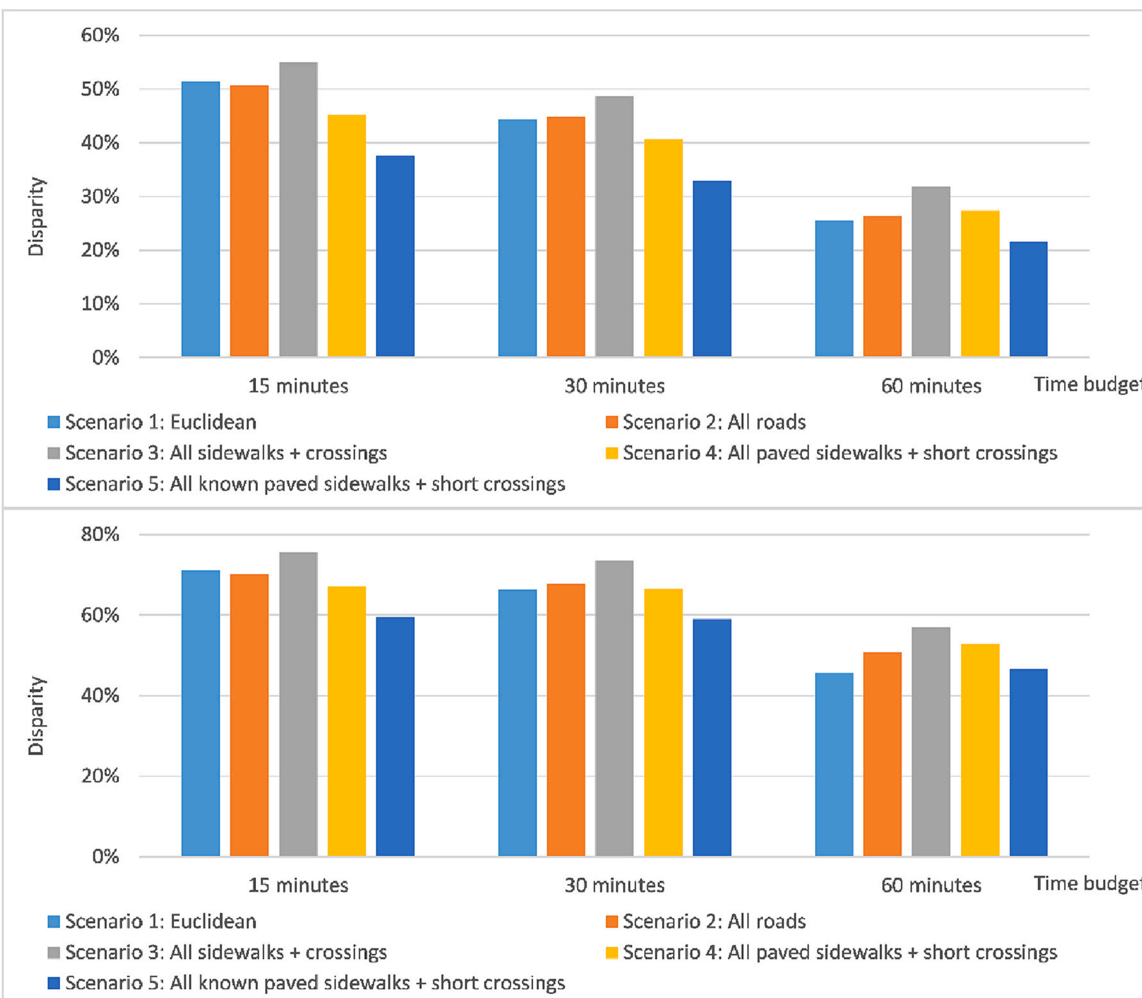

Fig. 5. powered (top) and manual (bottom) wheelchair users' disparity in accessibility with five sidewalk scenarios. Both non-disabled and PwMDs are applied to the same corresponding sidewalk scenario.

With more conservative sidewalk infrastructure, transit users' accessibility rapidly decreases. This proves that using a simple Euclidean-based accessibility calculation (scenario 1 in Table 1) can overestimate a non-disabled person's accessibility by 73% compared to scenario 3 and PwMD' accessibility by 87% compared to scenario 5. This, again, shows the importance of sidewalk infrastructure and its representation in the analysis of accessibility.

Fig. 5 shows the relative disparities in accessibility of the two wheelchair user groups compared to users without mobility disabilities; again, the same network is applied to both groups in each scenario. Although the pattern can be rather nuanced, there are two general trends. First, for scenarios 3–5, more sidewalks are associated with higher disparity. In other words, although more complete sidewalks benefit both non-disabled people and PwMD, non-disabled people benefit more. This is because PwMD have lower speed and reachable distance and cannot fully use a more complete sidewalk network, while non-disabled people can fully use the complete sidewalk, especially during transfers, which results in higher disparity. Another trend is that Euclidean space and OSM networks, which have much more complete network connectivity, are more favorable for PwMD compared to the full sidewalk scenario, especially for larger time budgets. This shows a non-linear relationship between accessibility disparity and sidewalk networks. This could also guide future sidewalk planning; although everyone can significantly benefit from a better sidewalk network as shown in Fig. 4, PwMD only receive more benefit than non-disabled people when the sidewalk connectivity reaches a very high level.

4.2. Transit usage

Despite the barriers, about 100–900 PwMD used fixed-route transit every day during the four years of our study time period in Columbus, which accounted for about 1% of all fixed-route ridership during that time. About 5% residents of the Columbus metropolitan area have ambulatory difficulties, according to ACS 2019 5-year estimates, with some census tracts having up to 30% people with ambulatory difficulties. This suggests that a smaller proportion of people with mobility difficulties choose fixed-route public transit in Columbus, possibly due to the barriers faced. Meanwhile, 100–900 people also used paratransit services daily: the total paratransit trips are about 1.5 times higher than the fixed-route wheelchair ridership despite the difficulties in booking this service. Note that paratransit service also serves people with other types of disabilities besides people with mobility disabilities.

4.2.1. Daily patterns

Fig. 6 shows daily ridership patterns for the general population, wheelchair users on fixed-route transit, and paratransit service users. We show both the daily patterns and the 7-day rolling average (thick line). The ridership shows very different temporal patterns from 2018 to 2022 as shown. We divide the study time period into pre-pandemic era (2018–2019) and pandemic era (2020–2021). The fixed-route general and paratransit ridership was stable from 2018 to 2019 with some seasonal variations, such as holiday seasons in both years. In contrast, PwMD fixed-route ridership was more volatile with more obvious and

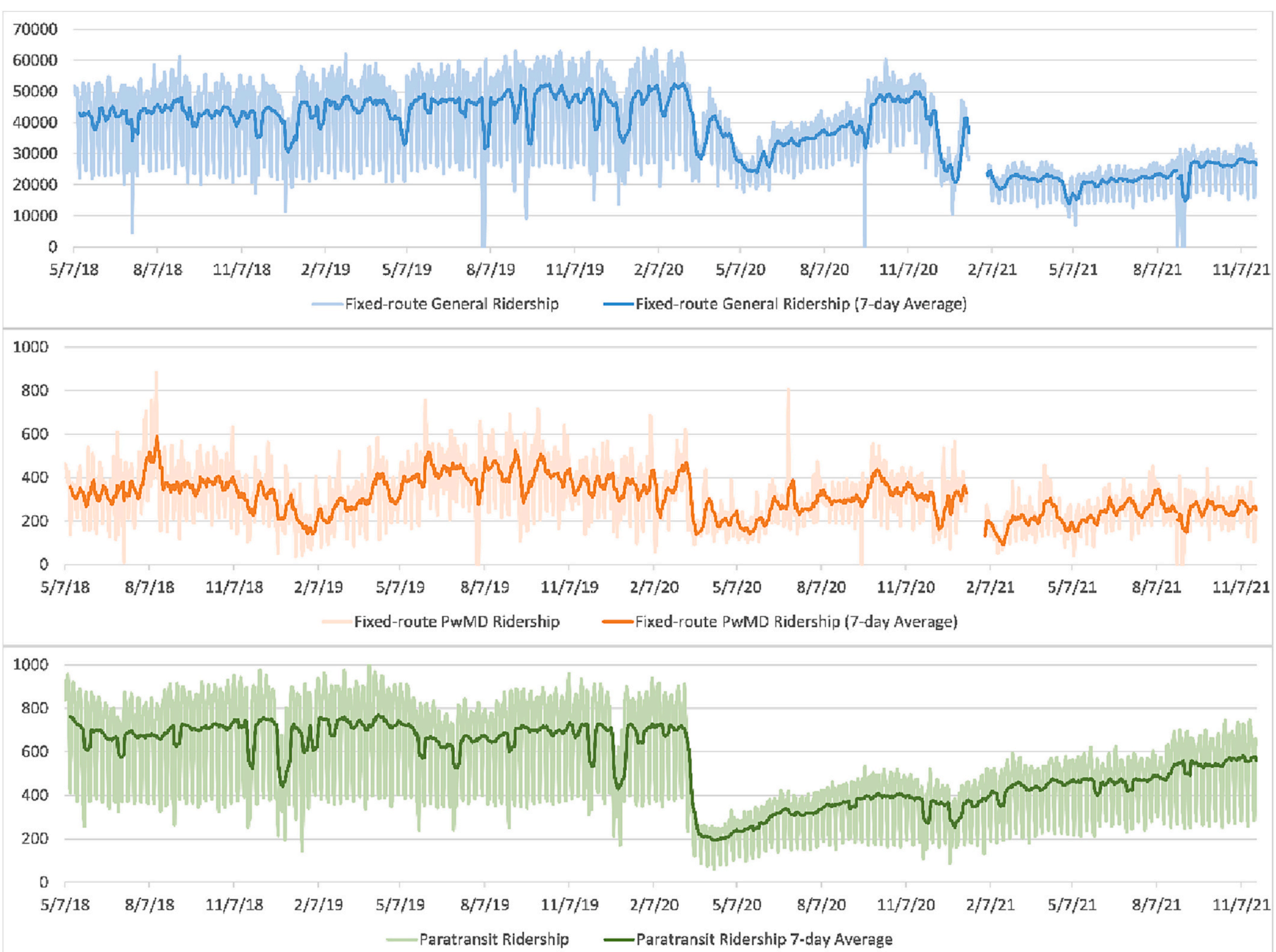

Fig. 6. Daily ridership and 7-day average for fixed-route general ridership, fixed-route PwMD ridership, paratransit ridership.

persistent seasonal change, including low ridership rates during the winters. To confirm this, we analyzed ridership patterns based on weather data, and found that PwMD fixed-route ridership is positively correlated with temperature (Pearson's correlation test $p < 0.001$) and negatively correlated with precipitation ($p = 0.007$), while fixed-route general ridership and paratransit ridership are not correlated with temperature and precipitation. This suggests that PwMD are more weather sensitive and less likely to use fixed-route service during cold and raining/snowing days compared to non-disabled people.

Fig. 6 also shows the impacts of the COVID-19 pandemic. Since March 2020, the COVID-19 pandemic has negatively impacted the ridership of the public transit systems across the United States (He et al., 2021; Liu et al., 2020). We calculate and compare the change rate compared to 2019 average for general ridership and wheelchair user ridership during the first wave of the pandemic. Both experienced a sudden decrease since mid-March, but wheelchair user ridership decreases more compared to general ridership. This shows that PwMD were more cautious with fixed-route public transit compared to non-disabled people during the early stage of the pandemic. However, the paratransit declined more compared to fixed-route transit, suggesting that PwMD are more reliant on the fixed-route service.

In addition to the initial disturbance, the pandemic's disruption is persistent and temporally heterogeneous. After reaching the lowest point in May 2020, the ridership experienced steady recovery and almost reached the pre-pandemic level in November 2020 possibly due to free fare policy (Ferenchik, 2020). However, the general ridership soon plunged to the lowest point in the beginning of 2021. Due to the coincident timing and tenacity of the decline, we hypothesize that the resumed fare collection starting from Jan 11th may be the cause (Warren, 2020); however, future research should test the theory directly. After the availability of COVID vaccines and boosters in 2021, the fixed-route general ridership experienced a steady increase, but this was still generally lower than the lowest point of the first wave of the pandemic as of Nov 2021. On the other hand, the decline of PwMD fixed-route ridership during the same time is disproportionately small, and the ratio of PwMD significantly increases. This may be because most of the PwMD can always ride fixed-route service free of charge due to COTA's ADA policy (COTA, 2022), which shows the importance of economic factors in people's mobility decision-making. This also suggests the greater transit dependence among PwMD. Meanwhile, paratransit's price never changed during the pandemic, so the steady increasing trend is very similar to the recovery pattern in other transit systems.

4.2.2. Hourly patterns

Fig. 7 shows the hourly ridership profile aggregated from 2018 to 2022. All three curves are significantly different. PwMD in fixed-route system only have one peak in the middle of a day, while general ridership shows the typical pattern of two peaks in the morning and afternoon commuting hours. Paratransit ridership also has two peaks, but both peaks are significantly earlier than the fixed-route general curve. The difference suggests the importance of paratransit service for PwMD's commuting. It is possible that PwMD may use transit for many purposes in addition to commuting.

4.2.3. Spatial patterns

Fig. 8 shows the spatial patterns of PwMD ridership ratio relative to the general ridership, and Fig. 9 shows the top 5% stops for the general population and PwMD. The maps show that the highest ridership is in the downtown, routes leading outward from downtown, and some separate clusters around points of interest such as shopping and commercial centers. Meanwhile, some parts of the suburbs also have a very high share of PwMD, which is consistent with the distribution of people with ambulatory difficulties in the city of Columbus.

Fixed-route service usage is highly unequal for both general passengers and PwMD. Compared with general passengers, the top 5% stops with highest PwMD ridership account for more ridership share, but these stops are more dispersed geographically. The top 5% stops with highest ridership account for 48.6% of total general ridership, while top 5% stops with highest PwMD ridership account for 61.3% of that ridership. Compared with the ridership patterns of the general population, PwMD's ridership has two major differences: 1) stops with high PwMD's ridership (shown as red dots in Fig. 9) are more spatially dispersed, and those stops are mostly located around commercial centers, hospitals, utilities, and public parks; 2) stops with high wheelchair user ridership tend to concentrate in the downtown area rather than the three major corridors. The differences suggest that PwMD's trips can be more destination driven as compared to non-disabled passengers, targeting major points of interest such as hospitals.

Fig. 10 compares the ratio of ridership groups to local population at the census block group level and to each other. Maps (a), (b), and (c) in Fig. 10 visualize the ratio of the three ridership to general population (fixed-route general ridership) or PwMD population (fixed-route PwMD and paratransit ridership), respectively. Compared to fixed-route services, paratransit ridership has a significantly more compact and smaller core and a high arc-shaped cluster in the northern part of the city. To show the relationship between paratransit and fixed-route service, map

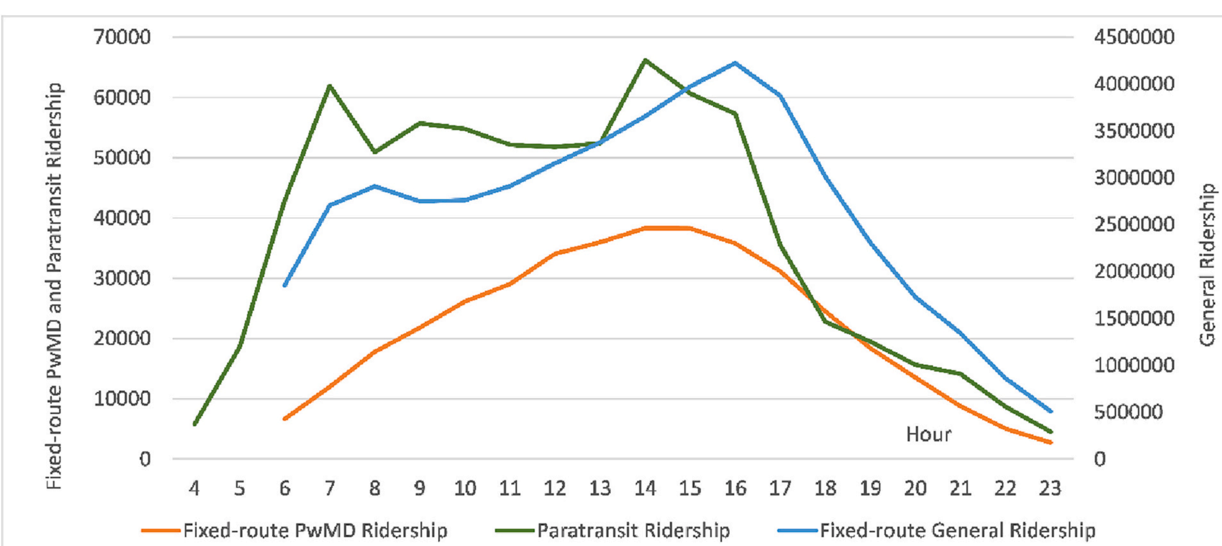

Fig. 7. Hourly ridership profile aggregated from 2018 to 2022.

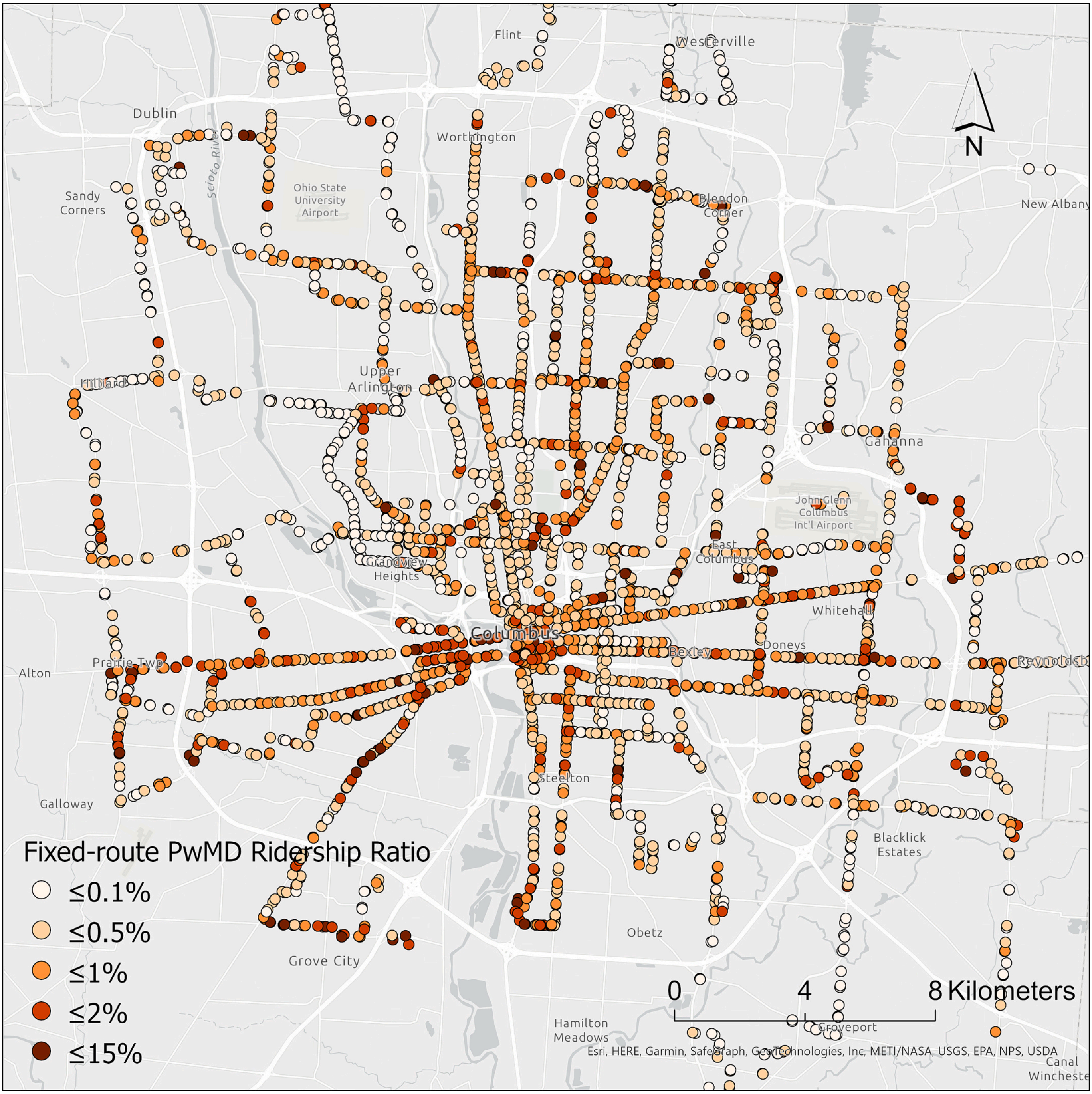

Fig. 8. PwMD ridership's ratio in the general ridership at each stop.

(d) in Fig. 10 visualizes the ratio of paratransit and fixed-route usage with bivariate color map in 2 × 2 quantile classification. The blue color shows the quarter with high fixed-route usage rates but low paratransit usage rates; most of the census block groups locate in the outskirts of the urban area due to the availability of fixed-route transit services. The red color shows the quarter with low fixed-route usage rate but high paratransit usage rate; most locate in the northern part of the suburbs. This pattern shows a complementary relationship between the two services.

4.3. Interplay between the accessibility and usage

Public transit accessibility and usage are interconnected for both non-disabled people and PwMD; the Pearson correlation tests show that general ridership and non-disabled people's accessibility are positively correlated ($p < 0.001$), while the PwMD ridership and powered wheelchair users' accessibility are also positively correlated ($p < 0.001$). This shows that stops with higher accessibility also tend to have higher ridership and vice versa. However, the correlation is stronger for non-disabled people (adjusted R-squared = 0.16) than PwMD (adjusted R-squared = 0.14). Meanwhile, Fig. 11 also shows the bivariate map of ridership and accessibility for non-disabled people and PwMD. It shows that non-disabled people's ridership and accessibility are geographically more clustered together than PwMD. However, both ridership measures are not significantly correlated with the disparity measures.

5. Conclusions

People with mobility disabilities (PwMD) face barriers that create

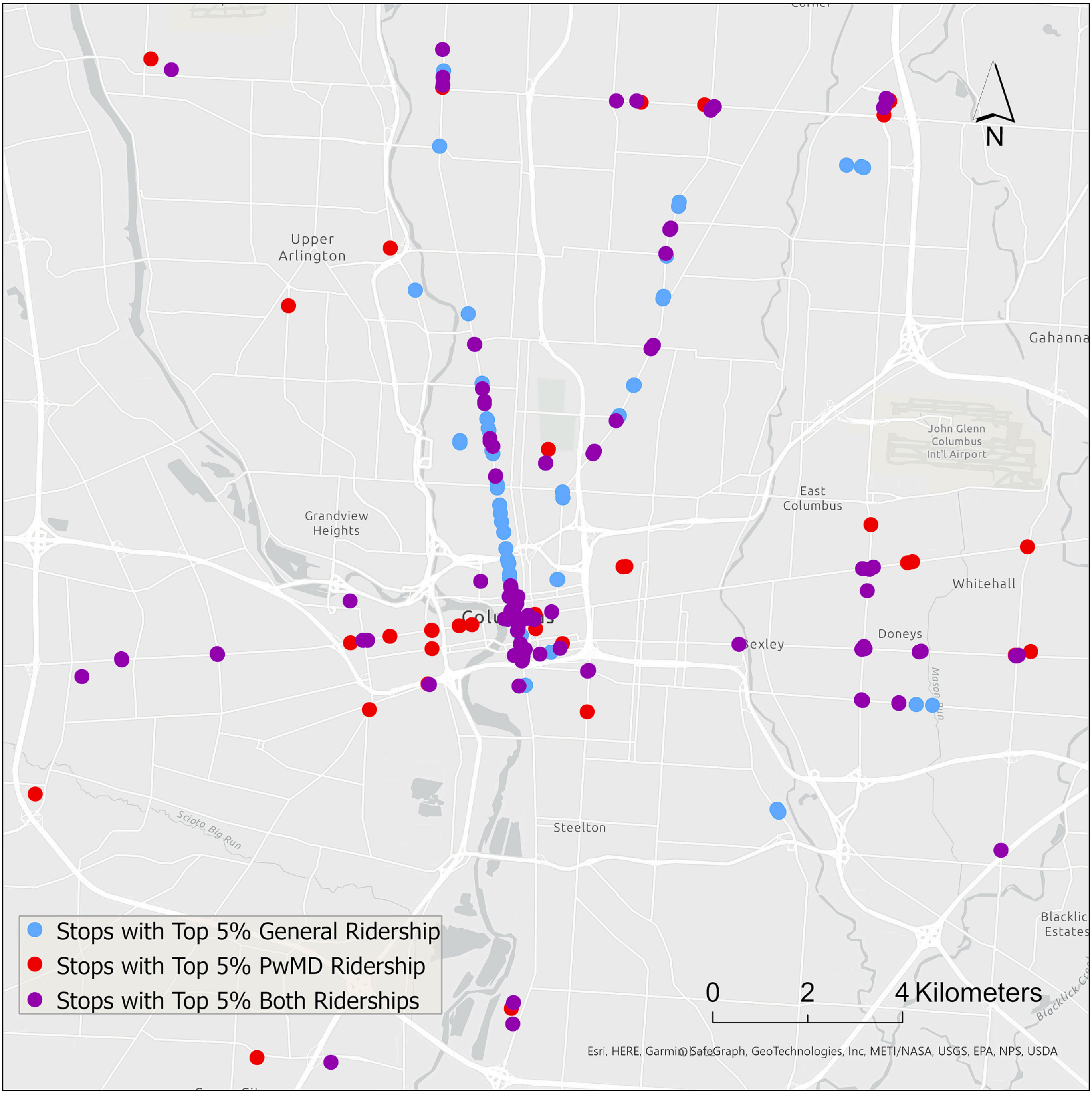

Fig. 9. Stops with top 5% general ridership (blue), wheelchair user ridership (red), and both (purple). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

disparities in accessibility to crucial resources via fixed-route transits systems (U.S. Department of Transportation, 2018). Despite progress such as the American with Disabilities Act, large disparities in both transit accessibility and usage persist among PwMD and people with disabilities (Kwon and Akar, 2022). Research on these disparities is lacking, particularly at high levels of spatial and temporal resolution due to lack of available data. In this paper, we calculate and compare the accessibility and transit usage of persons with mobility disabilities (PwMD) with general ridership in Columbus, Ohio, USA from 2018 to 2021 using high-resolution data for transit ridership, real-time transit feed, and sidewalks. We quantify accessibility with two measures: number of accessible stops using implicit space-time prisms and total accessible area using planar space-time prisms. We also use APC and paratransit usage data to compare temporal and spatial patterns of transit users by PwMD relative to the general population.

The disparities in PwMD's accessibility are striking. Powered wheelchair users' accessible stops and accessible areas are significantly less than non-disabled people, while the disparities for manual wheelchair users are even larger. For example, powered wheelchair users' accessible geographic areas are 25% of that for general ridership, and manual wheelchair users' accessible areas are only 1% of that for general ridership. These large disparities reconfirm the substantial disadvantages that PwMD face when using fixed-route transit systems. The COVID-19 pandemic moreover widened the existing disparities in PwMD's accessibility.

Accessibility disparities between PwMD and non-disabled people

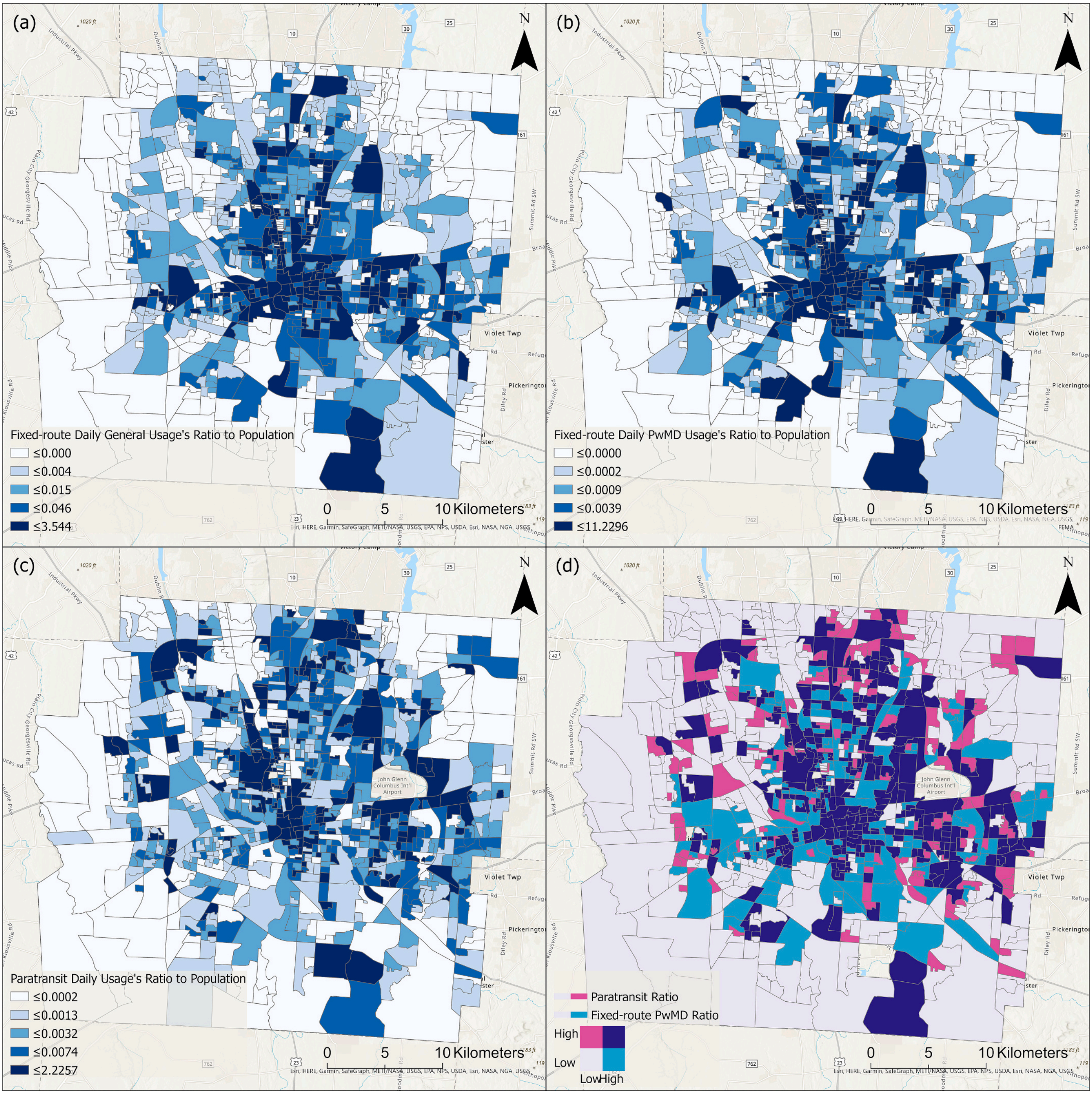

Fig. 10. Spatial patterns of three ridership's ratio to local population and bivariate choropleth map of paratransit and fixed-route service's ratio to population.

vary greatly in space. The urban center, the place with most ridership and highest accessibility in the region, also has the biggest disparity in accessibility for PwMD. Disparities across space gradually decentralize but decrease with larger time budgets for travel. The sidewalk infrastructure also has a substantial impact on accessibility. For example, Euclidean-based simulations may overestimate a non-disabled person's accessibility by 268% and PwMD's accessibility by 690%, which shows the importance of sidewalk infrastructure for transit systems, and the need to represent this infrastructure when estimating transit accessibility.

Despite all the disadvantages, a good share of fixed-route ridership is by PwMD, and their pattern is very different from the general ridership and paratransit ridership. They are more sensitive to weather conditions, more likely to take transit in the middle of a day rather than peak hours, and their trips appear more selective, targeting destinations like shopping centers and hospitals. The pandemic also had negative impacts on all three riderships. PwMD's fixed-route ridership decreased more during the first wave. All riderships experienced steady increase since May 2020 throughout the year 2020. In 2021, the general ridership plunged to the lowest point, while PwMD's ridership remains relatively stable, and paratransit keeps rising. This suggests economic factors' impacts on mobility choices, and some wheelchair passengers' trips may not be substituted easily due to the lack of alternative mobility choices.

Another important injustice is the imbalance between usability and usage for PwMD. In the spatial sense, although the downtown core area has the highest accessibility and usage, it also has the highest disparity in accessibility. In the temporal sense, the service cut since July 2020 reduces accessibility and increases the disparities for PwMD.

Fig. 11. bivariate map of ridership and accessibility for the case of non-disabled people (left) and PwMD (right).

Nevertheless, their usage of the public transit system remained relatively high, illustrating the essential nature of fixed route public transit services.

This paper uses new sources of high-resolution transit data to gain important insights into the not well-understood PwMD public transit accessibility and usage. First, accessible facilities (e.g., ADA-friendly stop and vehicle designs) are a necessary, but not a sufficient condition, for PwMD's public transit equity. Fixed-route public transit services are not favorable for PwMD, and all the disparities suggest the importance of paratransit services as a complement, which is also reflected in the usage patterns. Second, despite not being an explicit part of transit systems, sidewalk infrastructure is an important yet often overlooked factor that has substantial impacts on transit accessibility by PwMD. Finally, economic factors can outweigh accessibility factors when it comes to mobility choice for many PwMD, such as the different behaviors of fixed-route and paratransit users during 2021. In conclusion, all the different behaviors of transit users in wheelchair, such as high sensitivity to bad weather, disproportionately higher usage in 2021, different hourly profile, and utilitarian trip patterns, suggest that they are among the most vulnerable and dependent users in the system.

The paper has limitations, and there are multiple directions that future research can follow up. First, we use average speed and average travel distance in our calculations, while people can have different travel speeds depending on their physical conditions. In that sense, the disparities can only represent an average trend but not individual experience. Second, APC data are aggregated to stops; the data do not record trip-level information and track the movement of users. The ramp activation information also does not record whether the movement is for boarding or alighting. Paratransit usage data are not exclusive for PwMD or people with mobility disabilities either. Data with more detailed information should reveal more insights about the usage patterns. Third, the paper does not address the disparities within the PwMD in fixed-route transit systems due to the lack of socioeconomic information in the APC data. Columbus, like many US cities, is highly segregated, and minorities could face extra difficulties that are not apparent in our analysis. Fourth, our study uses retrospective real-time accessibility measures (Wessel and Farber, 2019), which has been shown to overestimate accessibility (Liu et al., 2022). Fifth, we use non-fused measure when calculating accessible area, which will overestimate the area due to double counting (see appendix for more analysis). Finally, our study does not consider stop and bus design during the calculation of accessibility; in reality, stop design can make a large impact on whether a wheelchair user can board and alight a bus. With all these limitations in consideration, the disparities in PwMD's accessibility are likely to be even larger.

CRediT authorship contribution statement

Luyu Liu: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft. **Armita Kar:** Conceptualization, Methodology, Writing – review & editing. **Ahmad Ilderim Tokey:** Methodology, Writing – review & editing. **Huyen T.K. Le:** Conceptualization, Methodology, Writing – review & editing. **Harvey J. Miller:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing.

Data availability

The authors do not have permission to share data.

Appendix A. Appendix

A.1. APC data's unbiasedness

Not every bus has APC sensors installed; about 50% of all buses have APC sensors. We calculate the sampling rate of trips in the APC data to the total trips derived from GTFS data for each route as shown in Fig. 12. The sampling rates range from 35% to 91%. Despite variations on different routes, APC data cover all routes and do not only target certain routes.

To remedy the bias in the sampling process, we calculate the sampling rates of each route in each day and justify the ridership accordingly. By doing this, we assume that the sampling rate in different hours of a day is relatively even, and sampled buses do not cluster around certain hours in a day. To validate this assumption, we calculate the sampling rate in each hour in each day. Fig. 13 shows that the sampling

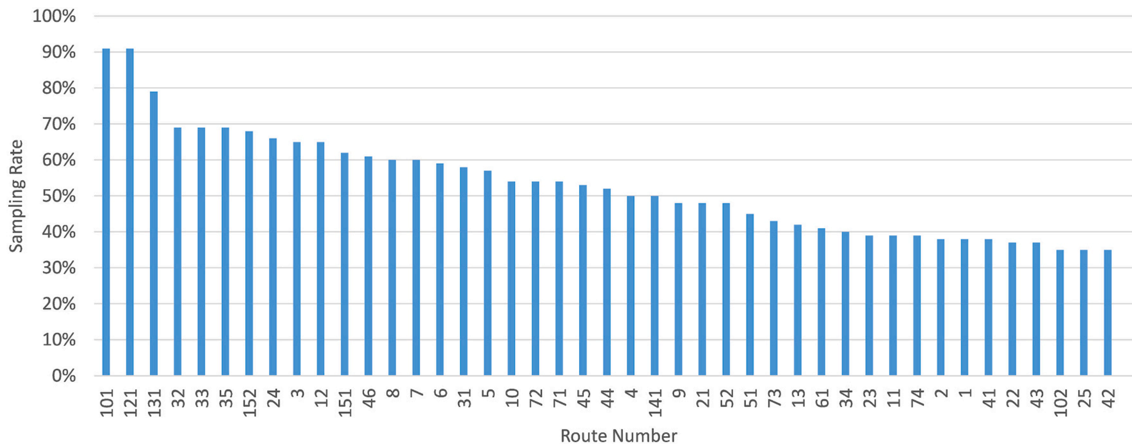

Fig. 12. Sampling rate of each route in COTA bus system.

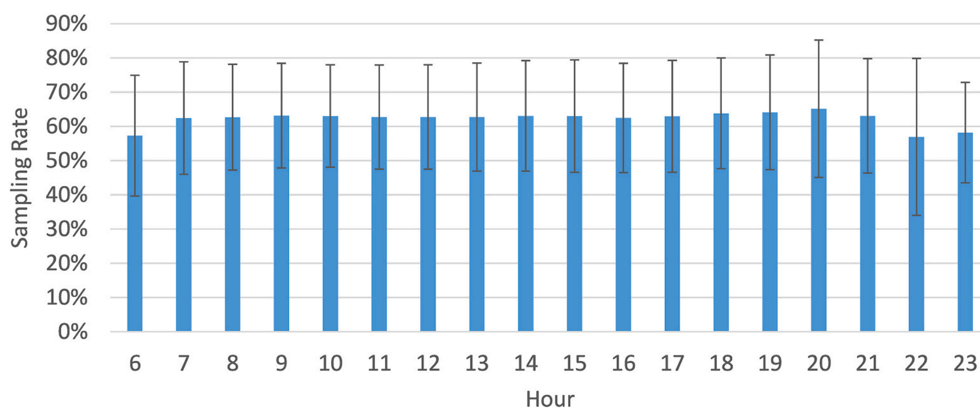

Fig. 13. hourly average sampling rate and deviation standard deviation.

rates in different hours are around 65% and stay almost the same, which confirms that the sampling process of APC data does not skew toward certain hours.

A.2. Comparison of non-fused and fused area-based disparity measures

Due to the large number of STPs, it is almost impossible to accurately calculate the dissolved accessible area. Therefore, we use non-fused area as a compromise. We already know that non-fused measure will

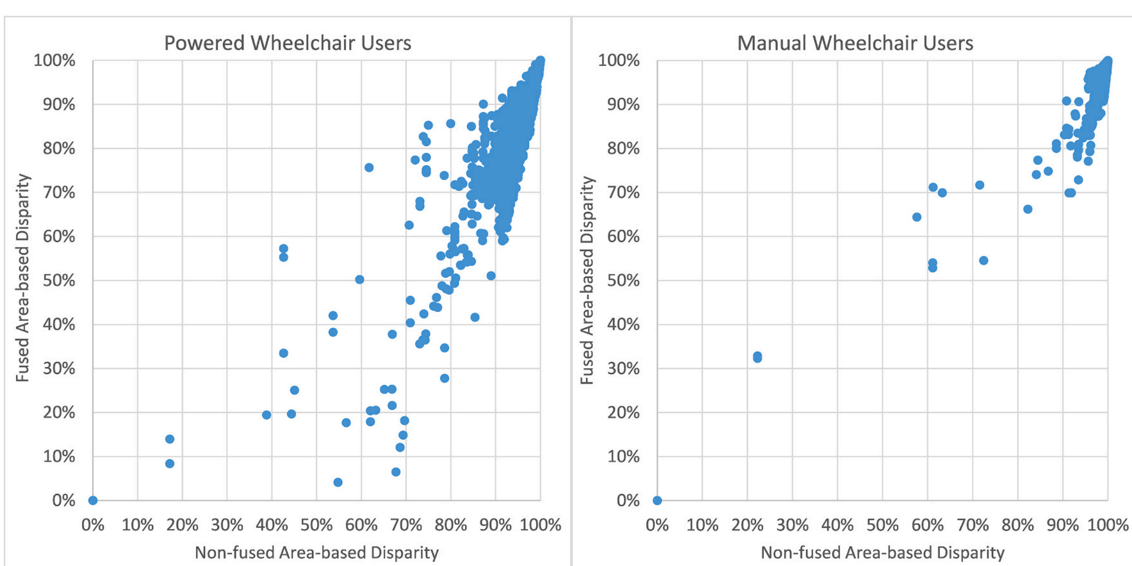

Fig. 14. comparison between two version of area-based disparity measures for powered and manual wheelchair users.

overestimate the area due to double counting. Therefore, we select a sample of the STPs at 8 am on a typical day in 2018 and compare the two versions of area-based disparity measures. Fig. 14 shows that the two measures are positively correlated, but non-fused area-based disparity can overestimate the disparity. However, on the other hand, most cases are clustered around a small region above 60% for fused measure and 80% for non-fused measure, where the correlation is much stronger. Meanwhile, we use implicit STP as another measure of disparity, which will underestimate the actual disparity. In that sense, the two measures serve as strict upper and lower bounds of the actual disparity level.

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