Designing Interactive Data-driven Tools for Understanding Urban Accessibility at Scale

Manaswi Saha

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Reading Committee:

Jon E. Froehlich, Chair

Jeffrey Heer

William Howe

Program Authorized to Offer Degree:

Paul G. Allen School of Computer Science & Engineering

University of Washington

Abstract

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Manaswi Saha

Chair of the Supervisory Committee:

Jon E. Froehlich

Paul G. Allen School of Computer Science & Engineering, University of Washington

Accessibility of urban infrastructure affects the mobility and safety of people, but *disproportionately* affects people with mobility disabilities. For example, missing curb ramps and uprooted sidewalks can significantly impact the day-to-day travel and safety of wheelchair users. However, there is an immense lack of comprehensive tools to understand and assess urban accessibility and aid decision-making.

In this dissertation, I explore the issue of understanding urban accessibility and designing tools for it, with a specific focus on sidewalk accessibility for people with mobility disabilities. I aim to transform how we collect, quantify, visualize, and communicate urban accessibility data through interactive tools. Towards this goal, I have a two-fold vision: (1) mapping the physical accessibility of the world for people with mobility disabilities and (2) empowering people with interactive data-driven tools for urban-accessibility related decision-making (*e.g.,* daily living, policymaking).

I take a multi-stakeholder approach and characterize urban accessibility as a three-pronged problem: *People*, *Data*, and *Tools*. To address these problems, this dissertation follows three research threads: (1) *Socio-Political Environment Analysis* [*People* problem]: Understanding multi-stakeholder interactions and decision-making in a civic ecosystem that leads to inaccessible infrastructure, (2) *Scalable Data Collection* [*Data* problem]: Building scalable approaches to address the lack of comprehensive city-wide accessibility datasets, and (3) *Interactive Data-driven Decision-Making Tools* [*Tools* problem]: Designing interactive tools for aiding in-situ and remote accessibility decision-making.

Across the threads, I bring multiple perspectives from varied stakeholders and diverse decision-making contexts to inform the design of future tools in this space. Specifically, I study five stakeholder groups, namely, policymakers, department officials, accessibility advocates, people with mobility disabilities, and caregivers. Using qualitative studies, online street view imagery, and techniques from crowdsourcing, visualization, and computer vision, I develop sets of design guidelines and a suite of interactive tools that enable stakeholders to surface underlying causes of inaccessibility, build and raise awareness, and present relevant information for making decisions across daily living, city planning, political advocacy, and policymaking.

Full Committee

Jon E. Froehlich, Chair

Associate Professor, Paul G. Allen School of Computer Science & Engineering (UW)

Jeffrey Heer

Professor, Paul G. Allen School of Computer Science & Engineering (UW)

William Howe

Associate Professor, UW School of Information

Anat Caspi

Affiliate Assistant Professor, UW Department of Electrical and Computer Engineering

Bo Zhao, GSR

Associate Professor, UW Department of Geography

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Acknowledgments

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1 Introduction

Urban accessibility, particularly physical infrastructure such as streets and sidewalks, support us in our ability to reach destinations. While urban inaccessibility affects everyone, it significantly impacts people with mobility disabilities (or, MI individuals[1]) such as people using wheelchairs, walkers, and canes [254]. Inaccessible physical infrastructure disproportionately affects them by making day-to-day tasks prohibitive such as going to work, traveling to unfamiliar cities, and getting to medical facilities. While urban infrastructure includes buildings, transit, and pedestrian infrastructure, I primarily focus on sidewalks.

Sidewalks form the backbone of pedestrian infrastructure. Accessibility barriers such as missing curb ramps, uplifted surfaces (*e.g.,* due to tree roots), and blocked sidewalks (*e.g.,* due to utility poles or parked cars) inhibit mobility for MI individuals (Figure 1.1). In the US, amongst 30 million people with mobility disabilities, half report using mobility aids including wheelchairs (3.6 million), canes or crutches, and walkers (11.6 million) [58]. Despite 30+ years since the Americans with Disabilities Act (ADA) was passed in 1990 [361], sidewalk accessibility still remains an issue.

[1] We used medical-centric terms such as "people with Mobility Impairments (MI) and "people with Visual Impairments (VI)" in the early on projects. However, we switched it to a broader and a more inclusive term "people with mobility disabilities", to include *anyone* who uses a mobility aid such as a wheelchair, cane, walker, or a stroller. This term allows including *all* people who experience mobility challenges beyond those having upper and/or lower body physical impairments, such as older adults, people with other medical conditions that cause mobility challenges (*e.g.,* someone with POTS), and people with visual impairments. For consistency, we did not change the acronym for this group across projects. Therefore, throughout this dissertation, I use the acronym *MI* to refer to people with mobility disabilities.

Figure 1.1: Illustration showing a range of sidewalk issues. In this dissertation, I have focused primarily on four of sidewalk features: curb ramps, missing curb ramps, obstacles, and surface problems.

One of the fundamental impediments to addressing sidewalk accessibility and larger urban accessibility issues is the lack of comprehensive tools to understand, assess, and make decisions (*e.g.,* sidewalk repairs) [***Tools*** problem]. As a result, lawsuits remain the most common method of drawing attention to the problem, holding cities accountable, and making change happen (*e.g.,* forcing mandatory sidewalk repairs). For example, several cities have been sued with multi-million dollar lawsuits for ADA violations [65, 118, 199, 206, 207, 225, 272, 344], including major cities like New York, Seattle, San Francisco, and Los Angeles. However, lawsuits often happen after a catastrophic incident–*e.g.,* someone becoming a paraplegic after an accident due to a cracked sidewalk [207]. Beyond government accountability, making daily living decisions (*e.g.,"where should I live that is accessible?"*) and answering planning or policymaking questions (*e.g.,"where do we allocate resources for sidewalk repairs?"*) is also challenging without relevant data and tools. This presents a need for comprehensive tools that (a) provide a sense of the state of (in)accessibility of the physical urban infrastructure, (b) visualize and quantify (in)accessibility, and (c) surface the root causes such as any demographic inequity and disparity in resource allocations for underserved areas within cities. Developing these accessibility-aware tools is identified as one of the grand challenges [124].

The lack of such comprehensive tools that cater to wide range of decision-making questions has three primary reasons: (1) Insufficient understanding of the impact of the socio-political complexities on accessible infrastructure development decision-making and the role of data/tech therein, (2) Inadequate urban-scale data collection methods to acquire relevant data, and (3) Insufficient understanding on how to effectively utilize this data to design tools for diverse stakeholders and decision contexts.

Past work has suggested that the broader social, cultural, economic, and political environment barriers contribute to urban inaccessibility [150, 371]. For example, cities' civic ecosystem has multiple stakeholders (*e.g.,* policymakers, transit department officials, people with disabilities), each with individual priorities that might conflict with each other and diverse accessibility needs, leading to ineffective decisions taken around accessibility (***People*** problem). Note, ‘people’ inherently includes the context within which these stakeholders operate and thus, suggests understanding the problem domain context as well.

The second reason for the lack of tools is the absence of comprehensive and relevant accessibility datasets for these diverse contexts (***Data*** problem). Prior work has extensively studied the physical barriers in the environment through traditional approaches of manually auditing city streets and sidewalks [254, 366]. However, no scalable approaches exist for digitally collecting such accessibility data at scale.

Finally, designing for such diverse decision contexts while considering the varied stakeholder perspectives and data needs is challenging. While past work has studied individual contexts separately [158], further investigation is needed to understand how stakeholders want to interact with this data and what data representations would best cater to the diverse contexts.

In this dissertation, I characterize urban accessibility along these three prongs to develop a deeper understanding of the influence of the socio-political context on urban scale decision-making and design of tools in this multi-stakeholder space. Further, I investigate the design of interactive data-driven tools that provide actionable insights about infrastructure (in)accessibility.

1.1 Thesis Statement

The dissertation claim is summarized in the following thesis statement:

> Interactive data-driven tools for urban accessibility that incorporate the social, political, and individual contexts of varied stakeholders lead to multi-faceted decision-making tools providing actionable insights.

1.2 Dissertation: Overview and Contributions

To support my thesis claim, this dissertation contributes an analysis of the urban accessibility domain, its stakeholders and users, and studies the role and design of data-driven technology within the socio-political complexities of the civic decision-making ecosystem.

I take a multi-stakeholder approach to study the needs of diverse stakeholder groups, referred as 'stakeholders' for the rest of the dissertation. Specifically, there are two primary stakeholder groups: (1) *People who are directly affected by inaccessible infrastructure*. They include MI individuals (*e.g.,* wheelchair users, cane users, guide dog users) and caregivers. (2) *People who are responsible for making change i.e., improving infrastructure accessibility*. They include policymakers such as elected officials; department officials such as from Department of Transportation (DOTs); accessibility advocates such as NGOs, non-profits, or individuals. Finally, a third group are the volunteers who are crucial towards large-scale data collection efforts and may not directly benefit from accessibility improvements.

I pose the overarching research question of *"how can data-driven technology support stakeholders in understanding, advocating, and making decisions about urban accessibility?"* I aim to transform how we collect, quantify, visualize, and communicate urban accessibility data. This dissertation research involves designing, building, evaluating, and deploying a suite of interactive data-driven tools for mapping and assessing urban accessibility.

I break down the overarching research question along the previously identified three-pronged problem space of urban accessibility:

- **RQ1:** How do stakeholders assess urban accessibility and what are the factors in their decision-making processes? (*People* problem)
- **RQ2:** How do we gather sidewalk accessibility data at scale? (*Data* problem)
- **RQ3:** How might we design accessibility-aware tools to facilitate understanding, decision-making, and communication of urban accessibility data? (*Tools* problem)

1.2.1 Dissertation Overview

For addressing each of these problems, my research follows three threads: (i) Socio-Political Environment Analysis (RQ1), (ii) Scalable Data Collection (RQ2), (iii) Interactive Data-driven Decision-Making Tools (RQ3).

To address the people problem (RQ1), Chapter 3 captures the first thread where I uncover urban accessibility assessment decision-making processes for infrastructure development of multiple stakeholders, the socio-political challenges therein, and the role of data and technology supporting stakeholder needs [306].

Chapter 4 covers the Scalable Data Collection thread (RQ2), where I present Project Sidewalk, a Google Street-View based tool for crowdsourcing sidewalk accessibility data remotely and at scale [238, 308, 310]. I further show how we designed, deployed, and evaluated Project Sidewalk through three studies: public city-wide deployment, data validation, and an interview study.

Finally, towards designing urban accessibility tools (RQ3), I present two design-probe studies that generate design implications for two applications: interactive visualizations (Chapter 5) [309] and AI-driven in-situ navigation (Chapter 6) [307]. The tools aim to allow stakeholders to enquire and assess the state of urban (in)accessibility in-situ during travel for people with visual disabilities and remotely by multiple stakeholders. The tools answer questions such as *"What is around me?"*, *"Why does my neighborhood have poor accessibility?"*, *"What are the major areas that need significant repairs?"*, *"Is accessibility poor in historically underserved areas with low socioeconomic status?"*.

1.2.2 Thesis Contributions

Contributions from my dissertation research are two-fold: academic and real-world impact. The key academic contributions (Figure 1.2) include,

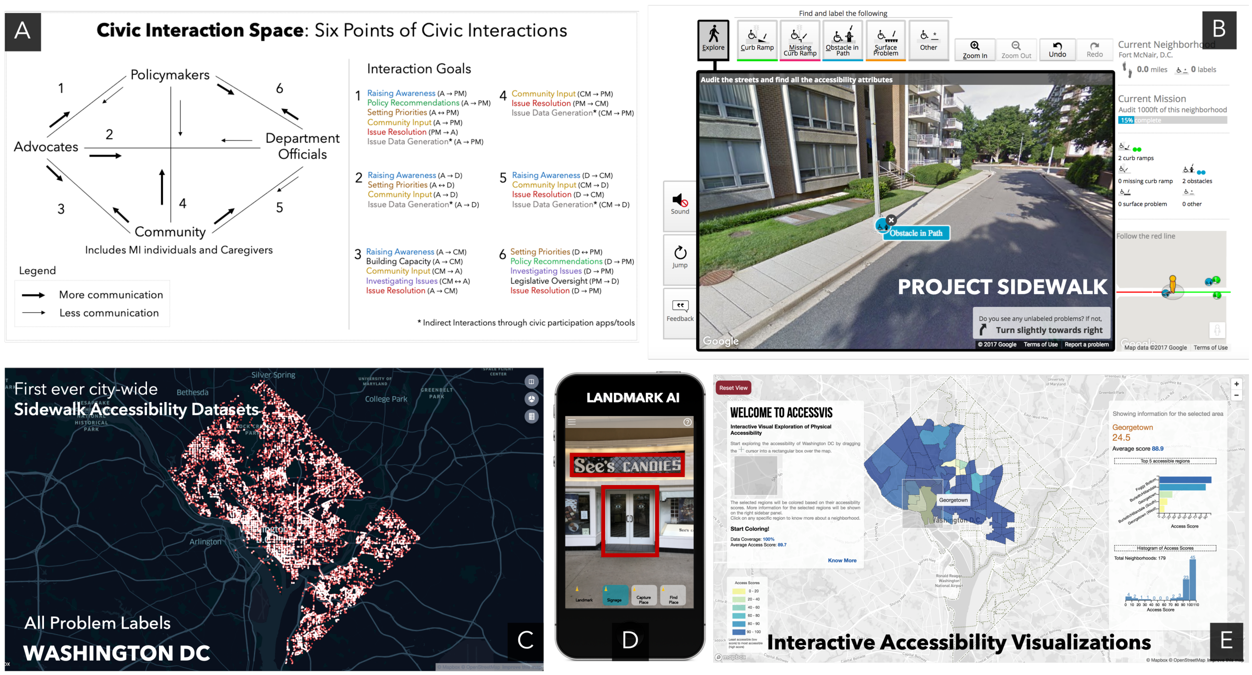

Figure 1.2: Overview of the dissertation contributions (clockwise from the top): Civic Interaction Space (Subfig A), Project Sidewalk (Subfig B), City-scale Sidewalk Datasets (Subfig C), and Interactive Data-driven Tools (Subfig D-E).

(i) demonstrating multi-stakeholder analysis as a method to understand complex socio-political realities of a civic and urban ecosystem as well as understand human-data interactions with urban accessibility datasets [306, 309]

(ii) a *Civic Interaction Space* that lays out the roles of and interactions between stakeholders in a civic decision-making structure and identifies points of technological interventions for urban accessibility tasks [306]

(iii) *Project Sidewalk* demonstrating a scalable approach for remote data collection of sidewalk accessibility at scale [239, 310]

(iv) the first-ever tech-enabled and publicly available city-wide sidewalk accessibility datasets with over 260,000+ labels from the pilot deployment in Washington DC [239, 240, 308]

(v) AccessVis, a set of design guidelines for building interactive geo-visualization tools for urban accessibility through the analysis of stakeholders' sensemaking practices interacting with urban accessibility data [309]

(vi) *Landmark AI*, a prototype demonstrating an AI-driven navigation approach using computer vision with audio-based AR to overcome the wayfinding challenge of the last few meters of destinations where GPS fails [307]

Beyond academic contributions, this research has led to real-world impact by inspiring (i) 10+ cities around the world to deploy Project Sidewalk [232–238] for informing policymaking (*e.g.,* San Pedro (Mexico)'s Pedestrian Master Plan), (ii) research efforts in universities to develop automated data collection approaches using our datasets [376, 378], and (iii) data enthusiasts visualizing these datasets for their personal context and needs [263, 264].

2 Background and Related Work

In this chapter, I review relevant work framing the dissertation. Specifically, I present a background on mobility disabilities and the corresponding physical access needs, followed by a review of urban accessibility definitions, what constitutes an accessible environment, and the laws and regulations that govern infrastructure development. Finally, I review what interactive data-driven tools exist in this space. Related work specific to a particular chapter is introduced before that chapter.

2.1 Target Community: People with Mobility Disabilities

People with mobility disabilities have some form of mobility impairment, which can be caused by sensory impairments (*e.g.,* loss of vision or hearing), motor impairments (*e.g.,* loss of function in the lower- and/or upper-body), and cognitive impairments. Depending on the type and severity of disability, MI individuals may choose to use different forms of mobility aids such as wheelchairs, canes, and/or walkers. Both the type of MI and form of mobility aid impacts how an individual may move about and navigate a city. For example, people with vision impairments may use canes or guide dogs and use physical features of the environment as landmarks for navigation [29, 113, 307]. People in wheelchairs require wide sidewalks without path obstacles such as poles, surface degradations, or missing curb ramps. In this dissertation, we focus on individuals having an impairment affecting their lower and/or upper body extremities as well as people with visual impairments (blind or low-vision); both groups' mobility is directly impacted by inaccessible physical infrastructure. Collectively, I refer to them as MI individuals throughout this dissertation. The implications from our findings on data/tool needs to support daily living decisions would likely apply to other groups as well.

2.2 Defining Urban Accessibility: Confluence of Accessibility, Mobility, and Disability

Urban accessibility is a wicked problem[1] spanning multiple disciplines such as transportation and urban planning, disability studies, human geography, and urban sociology. To understand what makes a '*built environment*' inaccessible, we need to understand the confluence of *accessibility*, *disability*, and *mobility*.

Since the 1950s, urban accessibility has been primarily studied within transportation and urban planning. Here, researchers broadly characterize accessibility as *"interactions between human and lands"* [156], and more specifically, *"the ease or difficulty for people to reach opportunities and services"* [92, 371]. These definitions strongly tie accessibility to mobility within cities [219], however, they do not account for mobility and physical differences across individuals [73, 333]. In contrast, the socio-political model of disability defines disability as *"a product of a dynamic interaction of human and the environment"*, an expansion of the earlier definition [156], and shifts the emphasis from *"the individual"* to *"the broader social, cultural, economic, and political environment"* [149, 150, 188]. In this dissertation, I adopt this socio-political model to advance understanding of the barriers to urban infrastructure accessibility [157, 253].

Prior work has shown that built infrastructure [111, 254, 366] and socio-economic status [5, 49, 128, 146, 371] can lead to inequities in access to opportunities and services of an MI

[1] Wicked problems are *"ill-defined and they rely upon elusive political judgment for resolution"* [81, 300]. Rittel and Webber cast public policy and planning problems such as urban accessibility as wicked where there is no definitive formulation or clear solution

individual. Beyond availability of built infrastructure, quality of access across the entire spectrum of physical access needs is crucial: from accessible pedestrian infrastructure (*e.g.,* sidewalks) to public transportation (*e.g.,* buses, trains) and transit infrastructure (*e.g.,* elevators, subway platforms) to the accessibility of destinations (*e.g.,* buildings and facilities). In this dissertation, I focus on pedestrian infrastructure accessibility, specifically sidewalks; however, the participants often referred to accessibility issues along the entire spectrum, allowing us to draw broader implications on factors influencing accessible infrastructure development.

My focus is on sidewalks which are a part of the 'public right-of-way', defined as the land or property reserved for transportation purposes [48]. According to the *US Access Board* and *Federal Highway Administration* (FHWA) guidelines [47, 48, 114], accessible sidewalks include wide pathways and clearly defined zones such as pedestrian clear zone, sidewalk furniture zone (*e.g.,* utility poles), and the frontage zone (*e.g.,* storefront entrances)—Figure 2.1. The guidelines also require that sidewalks have minimal obstacles and protruding objects, moderate grades and cross slopes. For example, sidewalks must have as a minimum width of 1.525m (5ft) for pedestrian zones (Figure 2.1a) and a four-by-four foot length for perpendicular curb ramp at intersections (Figure 2.1b). Non-compliance constitutes a disabling built environment for an MI individual [150, 177].

2.3 Laws and Regulations

This dissertation focuses on the geographical context of the United States. In the US, the first public policy measure by Congress was the *Architecture Barriers Act of 1968* (ABA) [45, 248]. However, a growing movement of disability rights activists began reframing disability not as a problem of mind or body but as a socially constructed form of societal oppression [110]. Bolstered by these efforts, the Rehabilitation Act of 1973 was passed stating that no qualified individual with a disability should be excluded from or denied benefits of any

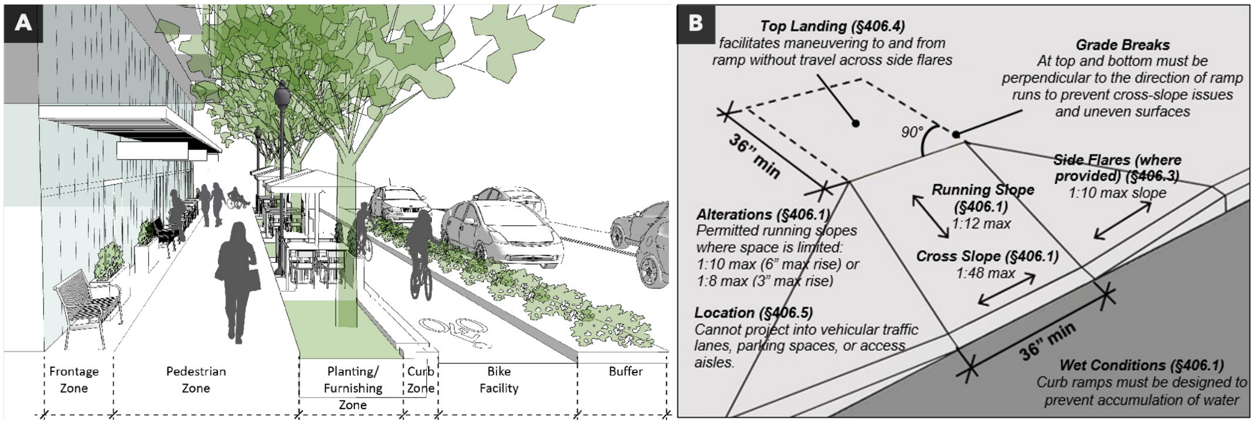

Figure 2.1: Illustrations of sidewalk and curb ramp design. Figure A shows City of Montgomery's Urban Design Guidelines on designing sidewalks [285]. US Access Board requires a minimum of 5ft width for Pedestrian Zones. Figure B shows the design of an accessible curb ramp [46].

program receiving federal assistance (29 U.S.C. 794d. Section 504). It was not until the landmark Americans with Disabilities Act (ADA) in 1990 [248], however, that protections were extended beyond the government sector. Critically, the ADA recognized the minority status of Americans with disabilities—modelled after the Civil Rights Act of 1964–and required places of *"public accommodation"* to provide people with disabilities appropriate aids or services [361].

Together, the Rehabilitation Act and the ADA regulate the accessibility of public rights-of-way and facilities in the US [48]; however, they do not define the specific accessibility standards themselves. For this, the US employs the US Access Board—an independent federal agency responsible for developing official accessible design requirements [48, 360] (Figure 2.1). Compliance is mandatory and enforced by the Department of Justice.

The impact of these policies on pedestrian infrastructure can be seen in cities, where, for example, curb ramps are increasingly common at street intersections [1, 82, 108, 293, 345]. However, despite 30 years since the passage of the ADA, most cities still remain inaccessible

[348]. In the US, lawsuits typically led by advocacy groups are the most common way of holding cities accountable [42, 70, 206, 345]. However, lawsuits only draw attention to the problem after the fact—*e.g.,* an accident due to a cracked sidewalk [207]. Alternatively, proactive measures to assess and track urban accessibility can promote accountability; however, with few exceptions [350, 352], these measures are not yet part of a city audit process due to time-consuming and expensive traditional physical audit methods. Crowdsourced data collecting tools (*e.g.,* [286, 310]) offer promising opportunities to quickly assess accessibility at scale. Additionally, new efforts demonstrate the power of involving citizens early in the infrastructure planning process and the use of technology to formulate and implement better policies [283]. Next, I review how data-driven technology and tools are currently being employed for urban accessibility needs across daily living, urban planning, policymaking, and advocacy.

2.4 Interactive Data-driven Urban Accessibility Tools

The aim of this dissertation is to transform the way we collect, quantify, visualize, and communicate urban accessibility data to support various stakeholder needs across diverse decision-making contexts. Across stakeholders [306], the data and task needs can be categorized into macro and micro level [309]. Macro level needs include urban planning (*e.g.,* prioritizing resources), policymaking (*e.g.,* conducting holistic analysis), and advocacy (*e.g.,* raising awareness). Micro-level needs include daily living decisions (*e.g.,* navigation). In this section, I frame my work by reviewing existing data-driven tools that serve these contexts, categorized across *data collection and generation*, *assessment and analytics*, and *communication and decision-support* for urban accessibility.

Data Collection and Generation Tools

Understanding urban accessibility at scale requires high-quality city-scale data on accessibility of the physical infrastructure. Efforts from universities, technology companies, and non-profit organizations have resulted in web-and mobile-based tools for gathering building and transit accessibility data such as Google Maps [10, 41], *WheelMap* [260, 380], UnlockedMaps [362], and others [125]. In this dissertation, I present *Project Sidewalk* [239, 310], a web-based crowdsourcing tool for collecting sidewalk accessibility data at scale.

Beyond raw accessibility data, there is also the need for capturing and generating the city streets and sidewalk network structure for serving tasks such as accessible navigation between destinations. While current mapping and navigation apps have comprehensive street network data, sidewalk networks are largely missing in these tools. Initial work by Bolten *et al.* [54] investigated algorithmically generating a well-connected sidewalk and crossing pedestrian graph. Very recently, Hosseini *et al.* [168] have started exploring crowd+ML pipelines with streetscape and satellite imagery for semi-automatically building a sidewalk network topology.

Finally, in addition to data collection and generation tools and techniques, established data standards are needed to ensure interoperability of the collected datasets from diverse settings [54, 124]. For example, cities and non-profits collecting their own accessibility datasets vary in the formats, granularity, and data types. As a result, the diversity of dataset formats significantly impacts design and development of interactive tools for urban planning due to data integration issues [125]. Recent standards such as *OpenSidewalks* [341] and *Accessibility Cloud* [6] are pushing towards addressing the lack of data standards and formats for urban accessibility. However, much work is needed to push these standards towards wider adoption across cities and independent organizations [125].

Assessment and Analytic Tools

Once we have well-formatted standardized datasets, next is the need for data-driven tools that consume these datasets to help discover and analyze patterns of (in)accessibility in cities. These assessment and analytic tools are envisioned to find socio-economic correlates to accessibility such as demographics, income, and geographic contexts and support cross-city comparisons. To enable these analytic tasks, we need city-scale accessibility metrics and models that are parameterizable to account for different factors of analyses such as sidewalk accessibility features, mobility profiles, and socio-economic factors. In this dissertation, we developed a preliminary accessibility model called *AccessScore* [220] that parameterizes sidewalk features and mobility level (*e.g.,* manual wheelchair *vs.* powered wheelchair). We used this model to create urban accessibility visualizations for later design probe studies [309]. However, the model is very simple and does not adequately capture the complexity in diverse mobility and accessibility needs as well as support socio-economic analysis. Recent work by Bolten *et al.* [53] propose more comprehensive metrics, namely, *normalized sidewalk reach (NSR)* and *sidewalk reach quotient (SRQ)*, a walkshed-based metric and an inequity estimate respectively, that are based on individual pedestrian mobility profiles to evaluate their pedestrian access to the sidewalk network. More on accessibility metrics and models are covered in Section 5.2.2.

With these metrics and models, novel accessibility-infused tools can be developed ranging from accessible transit [334] to urban accessibility maps [51, 158, 220, 309]. Urban accessibility visualizations can enable identifying macro-level patterns such as inaccessible hotspots to micro-level patterns such as causes for inaccessibility in specific neighborhoods to complex analyses such as equity of access. With increasing number of urban-scale accessibility datasets, more accessibility-infused tools are now being developed. In this dissertation, I specifically study urban accessibility visualizations within the context of multi-stakeholder needs: how these diverse decision-contexts impact the design of geovisual analytic tools for urban accessibility.

Communication and Decision-Support Tools

Finally, the third category of tools are for communication and decision-support. These tools help convert analysis results into actionable insights for individual decision-making, by providing relevant context associated with the quantitative analysis. As a result, communication and decision-support tools operate in the realm of sensemaking and persuasion towards driving actions and decisions.

In this dissertation, I studied two categories of communication and decision-support tools: (1) visualization and storytelling tools (2) trip planning and navigation tools. Visualization and storytelling tools allow end users to create immersive stories by combining text, interactive maps, and other multimedia content. They can be designed to serve as a persuasive medium to support goals such as raising awareness. They also allow stakeholders, especially, non-technical users, to make sense of the raw data and associated analyses. As a result, they are commonly used for macro-level urban-scale decision-making needs (*e.g.,* civic text visualizations [31]). Other examples include using commercial tools such as Tableau Public [338] and ArcGIS [21] to create custom visualizations and story maps by data enthusiasts and non-profits (*e.g.,* Disability Rights WA's story map showing testimonials from MI individuals [374]). I studied the stakeholders' sensemaking practices to understand the information needs for aiding and driving decisions for their personal contexts (*e.g.,* daily living, advocacy).

Within the second tool category, I investigated the design of daily living (micro level) decision-making tools for people with mobility disabilities. These tools allow MI individuals to utilize urban accessibility datasets for accomplishing tasks such as finding an accessible path to travel or neighborhood to live or visit. Tools such as *AccessMap* [51, 54] provides customizable navigation support by visualizing pedestrian accessibility tailored to their personal mobility level (*e.g.,* manual wheelchair *vs.* cane user). *WheelMap* [260, 380] helps users find accessible destinations to visit. I specifically investigated tools for providing in-situ navigational guidance for people with visual disabilities (*Landmark AI* [307]) and determining neighborhood accessibility to determine where to live (*AccessVis* [220, 309]).

3 Urban Accessibility as a Socio-Political Problem: A Multi-Stakeholder Analysis

This chapter explores the socio-political context of urban accessibility, where I interviewed five primary stakeholder groups (N=25): (1) people with mobility disabilities, (2) caregivers, (3) accessibility advocates, (4) department officials, and (5) policymakers. Using a multi-stakeholder approach, I identify the different stakeholder perspectives, their accessibility assessment and decision-making practices, their data needs, their interactions with each other, and the existing challenges for making accessible infrastructure development decisions. Using the insights from these interviews, I explore how may technology enhance the stakeholders' decision-making processes and facilitate accessible infrastructure development.

3.1 Introduction

The United Nations' *New Urban Agenda* positions equity and inclusion as core principles of modern urban development [176]. However, understanding, planning, maintaining, and even defining *urban accessibility*—from sidewalks to public transportation to buildings—is complex and has long-challenged urban planners and governments [73]. While early work focused on understanding the impact of *physical barriers* on access and quality of life [111, 159, 254, 310, 366], more recent work investigates the underlying and often less visible *social* and *political* barriers [131, 209, 254, 265, 366]. Though valuable in broadening the foci of urban accessibility research, this work has focused on only one or two stakeholder groups such as occupational therapists, architects [209] or people with disabilities [366].

In this work, we present a complementary, multi-stakeholder analysis of the priorities, perspectives, and local decision-making around urban accessibility—specifically, pedestrian infrastructure (Figure 3.1)—in three US cities: Seattle, Washington DC, and New York. We performed semi-structured interviews with 25 participants drawn from five stakeholder groups: (1) *policymakers* who develop city-wide accessibility policies and regulations, (2) *department officials* who implement and maintain these regulations (e.g., Department of Transportation, Office of Aging), (3) *accessibility advocates* who work towards changing ineffective policies, (4) *people with mobility impairments* (MI individuals) who have some form of mobility disability and directly experience (in)accessible environments; and (5) *caregivers* who are friends, family members, or professionals that care for MI individuals.

The semi-structured interview had two-parts: a formative component, which asked about perspectives of, approaches for, and decision-making processes around urban accessibility, and a design probe component, which examined reactions to envisioned urban accessibility analysis and visualization tools. In this work, we focus solely on the former to examine urban accessibility as a socio-political problem and how civic technologies may support change in this context. Here, change refers to improving accessibility development efforts. We seek to address the following research questions:

- **RQ1:** Across stakeholder groups, what are the information needs and challenges for assessing and making decisions around urban accessibility and the role of data and technology in these practices?
- **RQ2:** How do stakeholder groups communicate and interact together to assess priorities and make decisions?
- **RQ3:** What are the future design opportunities to improve existing assessment and decision-making practices?

Figure 3.1: Examples of sidewalk accessibility barriers. The last sub-figure shows multiple barriers present together: missing ramp, no sidewalk, and uneven surface.

Using iterative qualitative coding, we identify and present three high-level themes related to: data and technology practices, decision-making, and challenges impeding accessible infrastructure development. Our findings highlight the technological barriers in assessing urban accessibility as well as the socio-political barriers to infrastructure development. For the former, we identified disparities amongst groups in data and tool access. For example, policymakers had the least data/tool access while advocates had insufficient tools to fit their needs. For the latter, we found the presence of many actors, organizations, and their conflicting interests complicated decision-making and made accountability towards accessibility improvements hard. Combined with limited funding and public disinterest, political will to bring change was also affected.

Our work contributes to the growing CSCW/HCI literature on urban governance and civic systems using multi-stakeholder analysis as a method [24, 83, 193]. Using this approach, we extend prior work [209] by presenting the first US-focused study that brings multiple perspectives to understand accessible infrastructure development processes. Our contributions include: (1) understanding current practices and challenges of working within the socio-political realities of a civic ecosystem, (2) the role of technology in supporting and potentially undermining existing practices, (3) a *civic interaction space* that lays out the roles of and interactions between stakeholders in the civic decision-making structure, and (4) identifying points of future technological interventions in the form of data-driven assessment and civic engagement tools for improving accessibility through planning, advocacy, and policymaking.

3.2 Related Work: Civic Technology for Accessible Infrastructure Development

CSCW and HCI literature [23, 99, 106, 214, 281] suggests that civic engagement practices and the supporting civic tech have the potential to: (1) enable transparent interaction between the government and the public, promoting accountability [23, 84]; (2) help public officials make decisions around project planning [215]; (3) guide advocates [12, 22, 23, 132] and engage the public to participate in city decision-making [87, 202, 271, 312]. While civic tech has been studied broadly for infrastructure planning [83, 212, 213, 215, 216, 256], we explore the largely underexplored needs of urban accessibility planning and infrastructure development.

In the last decade, there has been a rise in data-driven civic participation tools for crowdsourcing data around urban accessibility. Few examples include 311 service requests [379] and citizen-reporting apps such as *SeeClickFix* [320], *StreetBump* [335], and others [116, 216, 252, 328]) to log broken sidewalk and other physical infrastructure issues. Beyond citizen-reporting apps that require physical presence at locations, remote inspection tools crowdsource accessibility issues (*e.g.,* via online streetview imagery [310]). In this chapter, we further investigate the role of data and civic technology in urban accessibility beyond data collection. We specifically expand our focus from daily living needs for MI individuals (*e.g.,* [54, 158]) to urban-scale decision-making: identify differences in needs and availability of data-driven decision support tools for advocacy, city maintenance, and policymaking.

More recently, Olivier and Wright argued going *"beyond volunteerism toward a model of citizen-led service commissioning"* that encourages long-term engagements with *multiple* stakeholders through relational models of public service instead of transactional models where citizens act as consumers of government-led services [281]. Rooted in participatory design methods [267], the relational model encourages shared governance via collaborative decision-making practices [14, 283] that ensures citizens' voices are heard and reflected in government policies [72]. While participatory methods have been used to design accessibility-aware assistive tools [158], no efforts have yet been made to study the needs for developing tools that support citizen participation in infrastructure planning decisions to address accessibility issues. In this chapter, I introduce a civic interaction space based on our findings and insights from prior CSCW case studies [83, 87, 271] on understanding the challenges in operating within complex socio-political urban contexts with participatory tools and processes.

3.3 Interview Study

3.3.1 Methodology

To better understand contrasting perspectives, decision-making practices, and socio-political factors surrounding urban accessibility in US cities, we conducted semi-structured interviews with five stakeholder groups (N=25): (1) *policymakers* (*e.g.,* elected officials from city councils or their legislative staff members), (2) *department officials* (*e.g.,* employees from city transportation departments (DOTs) and related organizations), (3) *accessibility advocates* (*e.g.,* those working or volunteering in disability advocacy groups or organizations), (4) *MI individuals*, and (5) *caregivers*. The interview session had two parts: a formative inquiry asking about experiences with urban accessibility and a *design probe* inquiry soliciting reactions to interactive visualizations of sidewalk accessibility data. Below, we focus our analyses on Part 1 that investigated the decision-making practices and uncovered socio-political factors affecting accessibility development efforts.

Our Part 1 interview script included questions shared across all five stakeholder groups as well as a group-dependent set. For the shared questions, we asked about urban accessibility perspectives, how they assess “accessibility”, and the role of data and technology therein. For the group-specific questions, we asked department officials, policymakers, and advocates groups about their role in their organization and the citizen engagement practices used. We

P#	Group	Affiliation	Role(s)	Additional Notes
P1	M			Powered Wheelchair User
P2	M			Powered Wheelchair User
P3	D & C	Department of Transportation	Sidewalk Repair Program Manager	Father under care
P4	C			Husband under care
P5	M			Powered Wheelchair User
P6	C			Daughter under care
P7	A & C	Tech-based Disability Adv. Org.	Director	Daughter under care
P8	D	Department of Transportation	Asset Management Strategic Advisor	
P9	M			Manual wheelchair User
P10	M			Cane User
P11	A	Walkability Adv. Org.	Vice Pres., Policy Committee Chair	
P12	D	Department of Transportation	ADA Coordinator	
P13	A & M	Disability Adv. Org.	Senior official	Manual Wheelchair User
P14	A	Neighborhood Adv. Group	Co-lead	Former Mayoral Candidate
P15	A & M	City Commission for Disabilities	Member	Cane User
P16	A	Law Firm	Partner, Lawyer	
P17	PM	City Council	Policy Analyst	Assists all city council members; Liaison between DOT and the council
P18	PM	State Legislation	Ex-State Representative	Former Mayoral Candidate
P19	D	Office of Disability Rights	ADA Architect	
P20	A & C	City Commission for Disabilities	Volunteer	Husband under care
P21	D	Department of Transportation	Chief Performance Officer	
P22	D	Department of Transportation	ADA Coordinator	
P23	PM	City Council	Analyst	
P24	A	Disability Adv. Org.	Executive Director	
P25	PM	City Council	Elected Official	

Table 3.1: Participant demographics. For groups, M=MI individuals, C=caregivers A=advocates, D=department officials, and PM=policymakers. Five participants self-identified into multiple group categories.

also enquired about accessibility considerations during decision-making such as when moving to a new neighborhood (for MI/caregivers) or when determining where to allocate time and resources (for department officials, policymakers, and advocates). The full study session lasted approximately two hours (Part 1 was approximately 30 minutes). Sessions were audio and video recorded and conducted in person by the first author in the participants' respective city. At the beginning of the interview, participants completed a pre-study questionnaire gathering demographic data, where participants self-identified with a group(s). Participants were compensated US$25/hour and up to US$30 for transportation costs.

3.3.2 Participants

We recruited 25 participants (11 female) aged between 25–72 (*Mean*=48.3, *Median*=45, *SD*=14.5) across three major US cities: Washington DC (*N*=5), Seattle (*N*=19), and New York (*N*=1). All three cities have a mayor-council form of government, where the city council members are elected members responsible for developing policies (legislative branch) and the mayor directs the city departments (*e.g.,* DOT) for implementing those policies (executive branch) [266]. Across these cities, we had six department officials (D), eight accessibility advocates (A), four policymakers (PM), seven MI individuals (M), and five caregivers (C). Five participants identified with two stakeholder groups and were interviewed from both perspectives (Table 3.1). Participants were recruited through mailing lists, word-of-mouth, social media, and directed emails. Below, we refer to participants by 'P' suffixed by their participant number and stakeholder group [$D \mid A \mid PM \mid M \mid C$].

3.3.3 Analysis Method

The audio recordings were transcribed and we thematically analyzed the interviews using a mixture of deductive and inductive coding [56]. The primary researcher prepared an initial codebook based on the interview questions. Four researchers coded a randomly selected transcript. We used Cohen's Kappa [367] for establishing inter-rater reliability (IRR); three pairs of IRR values were calculated with respect to the primary researcher. For the first iteration, the average IRR was 0.41 (pairwise IRRs: $R1_\kappa$=0.63, $R2_\kappa$=0.35, $R3_\kappa$=0.24) suggesting more iterations [367]. The codebook went through three such iterations of removing and/or collapsing conflicting codes and resolving disagreements, before establishing substantial agreement (*range*=0.61–0.80) at an average IRR of 0.68 (pairwise IRRs: $R1_\kappa$=0.81, $R2_\kappa$=0.62, $R3_\kappa$=0.61). The final codebook contained 62 codes grouped into seven high-level themes, including assessment methods, data sources and tools used, and prioritization practices and factors (Table 3.2). The remaining transcripts were divided amongst the four researchers and coded independently using the final codebook (Appendix A).

Major Themes	Description
T1: Participant Roles	What roles did stakeholders have as an official in their organization towards accessibility development? Applicable only to advocates, policymakers, and department officials.
T2: Barriers to Travel	What do stakeholders look for when assessing state of accessibility and needs? Describes the barriers that people with mobility disabilities face. Code examples include personal barriers, physical barriers, building accessibility.
T3: Assessment Methods	What were the assessment methods used for accessibility? Code examples include visual inspection, taking pictures, physical audits, surveys, ask people.
T4: Accessibility Metrics	How did stakeholders quantify accessibility? Code examples include sidewalk feature measurements, priority index, building feature measurements, travel time.
T5: Data Sources	What data do they rely on for making these assessments? Code examples include citizen provided data, internal data sources, external/agency data, open data.
T6: Digital Tools Used	What digital tools do participants use (if any) for making accessibility assessments? Code examples include online streetview imagery, imaging equipment, satellite imagery, GIS and mapping tools.
T7: Prioritization Practices and Factors	What parameters/factors are considered when making assessments and decisions? How do they or would want to prioritize when making decisions (*e.g.*, for resource investments, policy making, advocacy efforts, daily living)? Code examples include infrastructure utilization, population density, area demographics, decision-making questions, limitations

Table 3.2: Codebook summary of our seven high-level themes. Detailed list of codes available in Appendix A. T2 and T4 are not covered due to their prominence in prior work (see [254, 366]).

3.4 Findings

We categorize our findings into four groups: (1) data and technology practices for accessibility assessments, (2) interactions between stakeholders influencing accessible infrastructure development, (3) decision-making practices related to urban accessibility, and (4) complexities and challenges for city-scale decisions. Across these categories, we highlight similarities and differences in perspectives among our stakeholder groups. Participant quotes have been lightly edited for concision, grammar, and anonymity.

3.4.1 Overview of Stakeholders and Perspectives

To contextualize our findings and establish each stakeholder group's position, we first synthesize their key needs, goals, and responsibilities related to urban accessibility. Upon analysis, we recognized that both MI and caregivers voiced similar perspectives, leading us to subsequently combine them. MI individuals make up 58.3% (7/12) of the combined group.

MI/Caregivers (N=12). MI individuals and caregivers emphasized safety and quality of physical access—to transportation and destinations—as well as the freedom and support to move around a city. For example, *"Is it going to be a smooth [curb ramp], is it going to end in a safe place, not out in the middle of the traffic?"* (P6C), *"How accessible is the entrance to the building? Are there stairs?"* (P10M), *"Is there transit and where is it?"* (P15AM). These decision-making factors are dictated by personal needs and are granular in nature.

Policymakers (N=4). Policymakers care about the prioritization and distribution of resources amongst several urban issues, one of which is accessibility. A key concern and tension is funding: *"Making the funding pie for walking facilities as big as possible when we would have budget negotiations, really putting a strong stake in the ground"* (P18PM). Policymakers must carefully balance new proposed capital projects, which are typically easier to fund, with maintenance projects: *"Do we only invest in new sidewalks or do we invest in repairing our existing sidewalks?"* (P25PM). Given that policy decisions affect the entire city, equitable distribution of resources is an important consideration especially for serving historically underserved neighborhoods. This involves *"...working with my constituents, particularly my constituents who may be disabled. [...] We would literally just talk about parts of the district that were in need of additional investment. I would then go and specifically advocate for those investments."* (P18PM).

Department Officials (N=6). Department officials are the implementers. They are responsible for executing policy and making accessibility improvements to create ADA-compliant infrastructure. Their primary concern is understanding how best to utilize allocated funds: *"what are potentially the highest priority sidewalks?"* (P12D). To do so, they first understand current infrastructure conditions to identify unsafe or inaccessible locations (*e.g.,"Are there minimum clearance issues? [...] Cross slope issues?"* —P8D, *"If it's lifted, is it sunk* *in?"*—P21D). To inform their decision making, department officials conduct precise, onsite measurements of infrastructure and potential accessibility issues.

Advocates (N=8). Advocates represent people in need. They closely engage with the disability community to understand and change the status quo, gather support around issues, and act as an intermediator with the city leadership: *"We [an advocate] ask a representative from either the council, [...] or [city] department to come to a commission meeting so that we can ask them about any upcoming ideas or projects that might be happening to address that concern"* (P15AM). Their primary concern is to maximize the impact of their advocacy efforts and affect change, which requires raising awareness around issues: *"We do a tremendous amount of what's called systems advocacy, and we do a great deal of education of community leaders in [city-name] and [state-name] concerning the status of people with disabilities"* (P24A). In addition to understanding the city infrastructure, advocates are interested in understanding city politics for efficient and impactful communication with the government. They identify and investigate ongoing problems and hold administrators accountable, as P14A explained: *"There's a new curb bulb or new curb ramp, but they didn't install it correctly. Like when did that happen and how? Was it a part of this administration [...]?"*.

3.4.2 Data and Technology Practices for Accessibility Assessments

To understand how our stakeholders perceived, experienced, and assessed pedestrian accessibility—in their daily and/or professional lives—we asked participants about their assessment practices and the role of data and technology therein. Across stakeholder groups, two primary methods emerged: in-person and technology-mediated approaches.

In-person Methods

The two primary in-person methods were (1) physical inspections, where participants went out to assess the built environment and (2) engaging with people, where participants interacted with others to gain knowledge.

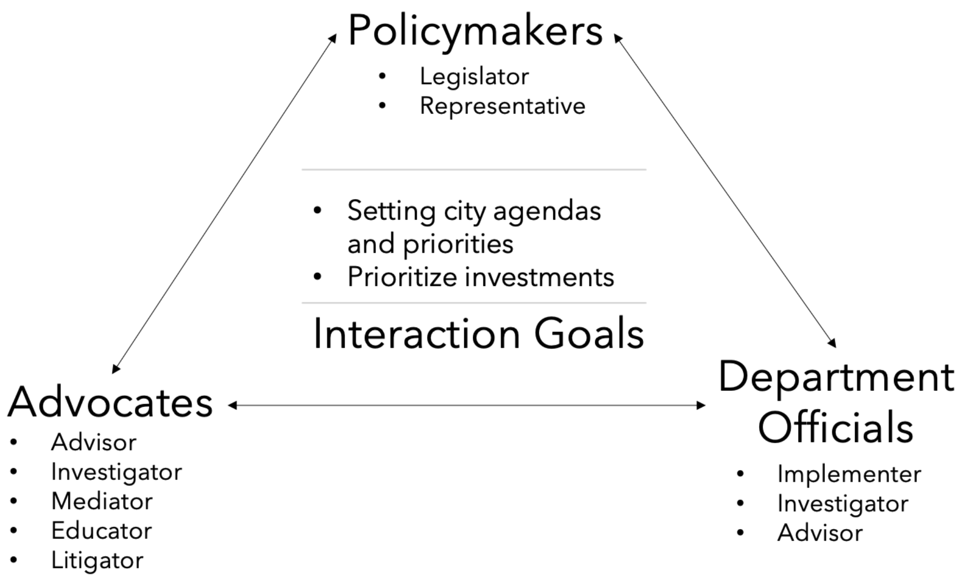

Figure 3.2: Roles and Interactions between groups involved in city-scale decision-making.

Physical inspections. All stakeholder groups used some form of physical on-site inspection—which were perceived as the most accurate and up-to-date technique—but they differed in terms of purpose, measurement approach, and outcome. MI individuals and caregivers constantly "inspect" as part of their everyday lived experience, taking note of safe, accessible routes in situ. As P5M describes: *"If [a sidewalk is] too steep of an angle, I have to tip my chair back. Or if there's a big bump, I'd have to go extra slow."* In contrast, department officials took precise measurements using specialized civil engineering tools to ensure ADA compliance and inform maintenance and construction efforts. Though this quantitative data lacked the qualitative nuance of the MI experience, it could be easily input into planning tools. As P8D, a DOT official, explains:

> *"We use non-subjective data measurements to collect that [sidewalk] information...apply a condition algorithm, in addition to what we found along the sidewalk to say is it very poor, poor, fair, good, or excellent condition sidewalk? An excellent condition sidewalk has at least 48" of width, it has a cross slope of no more than 2%. It has no observable issues along the sidewalk for barriers."* (P8D)

Similarly, but with varied measurement technique and purpose, advocates used both physical measurements as well as taking pictures of sites to gather evidence for accessibility litigations and advocacy campaigns. As P24A described,

> *"In our survey, [...] people used actual measurements of each curb ramp. We documented that at least 77% of the curb ramps in [city] were missing, not constructed according to Americans with Disabilities Act standards, or were not maintained and were broken in a way that is dangerous not only for people using wheelchairs but also canes and walkers."* (P24A)

Advocates also resorted to creative methods such as using their shoes as an instrument to gauge surface issues: *"I use my shoes. If the heave is bigger than that, then that's really bad."* (P11A).

In contrast, policymakers did not conduct precise physical audits themselves but instead relied on formal reports from city departments. They did, however, participate in neighborhood walk-throughs [231] with their constituents to better understand issues in their localities either proactively or reactively to citizen complaints. A department official described a walkthrough involving all stakeholder groups, which blends physical inspections with citizen engagement:

> *"We'll do mayor's walk through [...] that'll be a walk with the mayor and the community and all the agencies. We walk for two miles and look at everything from signs to sidewalks to ramps to abandoned cars, vacant buildings. So, it's usually 30 or 40 government employees and anywhere from 30 to 100 citizens."* (P21D)

Engaging with People. While physical inspections provided visual validation, direct measurements, and experiential evidence, engaging with people enabled understanding on-the-ground "lived" experiences of MI individuals as exemplified by an advocate (P24A): *"people being stuck at the base of an improperly constructed curb ramp, or being jettisoned from their chair into the street as a result of a wrongly-designed curb ramp."* Similarly, for MI individuals and caregivers, these personal experiences became the next most trusted information source after their own when making life decisions (*e.g.,* traveling to unfamiliar locations): *"I've found that able bodied people, they're not reliable because they don't look with the eyes of a disabled person."* (P1M).

Each group differed in their approach and purpose to gather these personal accounts. Similar to prior work [83], we found department officials performed both transactional service engagements and relational engagements. Transactional engagements involved acquiring subjective experiences reactively through 311 service requests or proactively through large-scale field surveys to inform project priorities and investments. Relational engagements [83, 281, 368] involved engaging with advocates and the public through community meetings to gain deeper understanding of issues: *"We go to seven to 12 ANC [advisory neighborhood commissions] meetings every two weeks, roughly. Those are representatives of the community. [...] We go to those meetings [...] where the public is supposed to work through those [ANC] people"* (P21D). In contrast, policymakers primarily performed relational engagements through townhalls, the aforementioned neighborhood walk-throughs, and digital media to develop trust and build public support from potential voters. Unlike government officials, advocates collected lived experiences primarily through personal interactions with people with disabilities and the community to run campaigns for raising awareness, educating community leaders, drawing public attention to an issue, and gathering evidence for issue-based litigations. Depending on the goal, often a combination of the in-person methods was utilized to complement the gathered qualitative evidence. An advocate explained,

> *"We created this class action based on, at first, anecdotal evidence obtained through focus groups, interviews, review of data, public notification, and [then] direct on-the-ground, monitored surveys using an approved instrument, so that we could be confident that we [were able to] generalize beyond anecdotal evidence, which is often disdained, despite its validity."* (P24A)

Despite the benefits, policymakers found it challenging to engage with a wide range of people due to the need for additional effort, time, continued motivation to participate, especially for unpaid volunteers and resource-constrained engaged citizens:

> *"Usually, we'll only have the ANC commissioner, the hyper-local representative for that area and ANCs tend to be somewhat representative but it's also not paid so people have to either have the time or the resources to do it. And then usually on top of that, we'll maybe get like one or two other residents that generally are already pretty well plugged in to that process. So yeah, I will say it's difficult to hear from a wider range of people but that's a problem everywhere."* (P23PM)

Technology-based Assessment Methods

All groups utilized some form of a digital tool to help locate and assess inaccessible areas. Unlike other groups, department officials had access to specialized mapping and analytic tools such as ArcGIS's Field Maps (formerly, Collector app) [20] and Cyclomedia [91], which enabled complex geo-spatial analyses such as connecting demographics with accessibility conditions to help inform planning. In contrast, policymakers desired summary reports and visualizations to help gain broad overviews and make resource appropriation decisions. For example, P18PM mentioned using geo-located dot maps: *"Nothing super sophisticated but city maps with dots saying, 'There is a broken sidewalk here. There is a curb cut here.'"* (P18PM). Advocates created maps for their own analytical understanding and to aid advocacy efforts: *"We have created maps of the city and we have used them to overlay obstacles to transportation, so that we can identify on a map showing where people in the greatest need live, the transportation deserts for people with disabilities"* (P24A). Finally, MI and caregivers used publicly available mapping tools, such as Google Street View (GSV) or AccessMap [51], to assess both the accessibility of routes and destinations (reaffirming work by Hara *et al.* [158]).

Our stakeholders relied on a variety of data sources for achieving their group-specific goals and tasks such as using online streetview imagery to perform initial remote assessments. However, for some stakeholders such as policymakers, the availability, quality, and accessibility of datasets limited data-driven analyses and decision making; many city data sources were only available-on-request. As a result, advocates and policymakers relied on external sources (*e.g.,* from transit agencies) and open data sources (*e.g.,* collision and incident reports, planning documents, academic research). Advocates desired up-to-date data that were often not readily available (*e.g.,* pedestrian and bicycle incidents). Consequently, they often resorted to unconventional data sources such as news articles about accessibility issues in an area, subpoenas, and depositions. In contrast, MI individuals and caregivers did not explore these avenues, likely due to high costs of access and low returns.

Limitations. Despite their advantages, the value of technology-based methods was limited by the appropriateness of tools and underlying data sources. Most commercially available tools did not provide up-to-date information, a key need of advocates and people with disabilities—for example, locations of construction blockages. The most common tool used by all groups, especially MI/caregivers, was GSV, yet participants found it insufficient due to a lack of precise information (*e.g.,* curb ramp slope), obstructed views, and outdated imagery: *"Often they are so delayed in reaching the Internet that they're not relevant to current conditions, or they may have been remedied or they may have been assessed by us as being fine, but then become damaged because they are so delayed"* (P24A). These limitations can be attributed to the fact that GSV was not designed with accessibility concerns at the forefront.

Similar concerns of lack of reliable, up-to-date, and granular data sources also hold true for open city data sources. Department officials mentioned maintaining an accurate reliable dataset of sidewalk issues is challenging due to high maintenance costs. Beyond mapping tools, existing visualization tools were insufficient to inform and aid people in making goal-oriented decisions around urban accessibility. Policymakers and department officials both described a lack of visual tools in legislator and city meetings: *"As a legislator, we very rarely got briefed with visual tools. It was very sad."* (P18PM). The policymaker P18PM, who previously worked as an advocate, further noted: *"Honestly as an advocate, we would have* *been much more likely to use finely grained visual tools so that we could, from the ground up, help develop policy".*

3.4.3 Interactions between Stakeholders for Accessible Infrastructure Development

In this section, we explore interactions between stakeholder groups and their decision-making practices around accessible infrastructure development. We focus on policymakers and department officials who govern, plan, and implement infrastructure development and advocates who attempt to influence policy decisions and voice MI/caregiver concerns.

Figure 3.2 summarizes the role of the three stakeholders in accessible urban development, which we expand on below. All stakeholder interactions were to achieve two key goals: (1) setting city priorities and agendas and (2) prioritizing investments. We first elaborate how policymakers and department officials interacted and worked together and then explain the various roles advocates adopted to participate in the decision-making process.

Role of Policymakers and Department Officials

To achieve the two decision-making goals, both stakeholders worked together to investigate accessibility issues, evaluate the issues' impact, set funding priorities, develop policies and courses of action, and monitor progress. As legislators and elected representatives, policymakers are responsible for developing laws and regulatory measures. As advisors, investigators, and implementers, department officials assist policymakers to meet the set agendas by developing and implementing infrastructure maintenance plans.

As the first step of developing action plans, policymakers identified the most vulnerable populations affected by inaccessible infrastructure. To do so, further analyses into the specific accessibility issues and their impact were determined with the help of department officials, who conduct analyses using field data such as sidewalk condition assessments. Further, both stakeholders interacted with the affected communities to ensure citizen needs were represented in the decision-making process. While department officials engaged with people with disabilities to inform their maintenance plans, policymakers focused on communicating process and potential outcomes to their constituents. Policymakers also oversaw departmental progress on identified priorities: *"[one role of] the legislative department is oversight. Bring in the [city DOT] to explain themselves [...] - what is their approach for addressing scooter use on sidewalks?"* (P17PM).

Beyond determining citizen needs, budgeting was the next crucial element for developing action plans. Policymakers controlled the budgetary allocations. When formulating plans, they asked questions such as: *"how efficient is this [an action plan]; how much money are we spending; can we move things around? [...]"* (P17PM) and relied on department officials to bring policy recommendations forward. Based on allocated funds, department officials determined the specifics of the action plan: *"I will work on identifying, given the budget we have, usually around $3 to $5 million a year, which sidewalks are in greatest need of repair. And then we work on drawing up plans and scheduling those projects with our internal crew staff."* (P8D).

Role of Advocates

While policymakers and department officials had significant control from within the government, advocates externally influenced policies and investment plans by taking on several roles: investigator for locating issues, advisor for providing policy recommendations, educator for raising awareness around issues, mediator for bridging the gap between government and the public through communication, and litigator for fighting on behalf of the people in need.

As investigators, advocates identified communities in need of assistance and the barriers they faced. Based on their investigations, they sought support from the political leadership to make them aware of accessibility issues in their constituencies by educating them: *"We look at disparities between people with and without disabilities on each of the issues and across* *each of the populations and publish reports that we make available to policymakers [and] community leaders"* (P24A).

Communicating with policymakers involved understanding the political atmosphere, dynamics of city politics, and building relationship. For instance, advocates identified who had the most power and who they had to convince or negotiate with for affecting change

> *"In [our city] for example, the mayor runs the DOT and really has a lot of power. And in theory, the city council controls the purse strings, controls how funding is doled out. [...]. And so, I'd look at that and see, is this something where I'd be butting heads with the mayor all the time... or is it something where the council members could actually make something happen?"* (P14A)

To effectively communicate, advocates identified policymakers' priorities and concerns and accordingly framed their requests: *"Trying to get to know legislators and sort of understand them so that you can [...] frame the issue in a way that makes sense to them."* (P11A). Additionally, serving on advisory boards to the mayor, city council, and/or city departments allowed for closer interactions and influence over policy decisions. As advisors, they had *"a voice at the table"* (P18PM) representing community needs, helping set agendas, and crafting ADA transition plans for barrier removal:

> *"The city council or the mayor or a department [DOT] would reach out to myself, my co-chair or liaisons and say 'Hey, we are thinking about putting curb cuts in this neighborhood. We want to make sure we do it right. Either can I send a legislative aid to come to your meeting or can you give us some recommendations on how to do that?'"* (P15AM)

Finally, for raising public awareness, advocates conducted campaigns through various media to draw attention to the identified accessibility issues. For example:

> *"...[We] went to the public media—the large newspapers, television stations, radio stations—and talked about these problems and we had them film people with disabilities attempting to navigate, to cross streets, and demonstrating by physically showing what happens when a curb ramp is*

> *improper. These were aired publicly, drawing attention to the issue so that the general public might know, including people with disabilities who might then come forward with their issues."* (P24A)

3.4.4 Decision-Making Practices for Accessible Infrastructure Development

Continuing with the three stakeholder groups—policymakers, department officials, and advocates—we describe decision-making practices related to accessible infrastructure development. In short, all stakeholder groups attempted to maximize impact of the limited funding and ensure equitable distribution; however, groups differed in their goal, data access, and analysis approaches. We elaborate on this decision-making workflow by first discussing impact assessment considerations followed by a set of prioritization factors and strategies.

Impact Assessment Considerations

Participants described two considerations for assessing potential investment impact: equity and gentrification. For equity, stakeholders analyzed how investments reached across socio-economic strata of the city. Similar to past studies [16, 142, 273, 385, 386], policymakers and advocates noted that some neighborhoods remained historically underserved and mobility issues disproportionately affected people of color and people with disabilities, who commonly relied on public transit and pedestrian infrastructure: *"People who are Hispanic and Latino, and people who are Black or African-American would be disproportionately affected, because they live in greater concentrations in low-income housing, according to our statistical portraits. And they have less access to transportation due to transportation deserts in their neighborhoods, the lack of access to subway, elevators, ramps, escalators."* (P24A). An elected official described the need for conscious and aggressive efforts towards making cities equitable:

> *"The city has a commitment, and I have a commitment personally, [...] to try to make our city more equitable. To the extent that inequities exist, and they exist massively in [city-name], we need to be making disproportionate investments to undo the disproportionate investments made by prior generations."* (P25PM)

Policymakers and advocates also assessed the impact of urban development on gentrification and displacement: *"A complicated reality is that gentrified neighborhoods tend to be more accessible neighborhoods, which is complicated for a whole host of reasons"* (P13AM). As urban neighborhoods gentrify, their street-level infrastructure is upgraded, improving accessibility; however, those who could benefit the most are often forced out due to unaffordability. This complex relationship between urban investment and impact on livability and affordability has long-been a concern amongst the urban planning community since the 1960s [121, 133, 135, 140, 398]. However, the specific role of accessibility is still an open question, as P25PM explains:

> *"Another factor that is complicated [...] is will this [...] investment accelerate displacement? If I'm in a low-income neighborhood in a community that doesn't have any sidewalks, I think it would be appropriate to make significant investments in sidewalks to improve accessibility. But if everyone that lived in that neighborhood rents and as soon as they put in sidewalks, their landlords are going to raise the rents because it's now a more desirable neighborhood. And the people [...] that I was trying to help now no longer live in that neighborhood because they had to move to another neighborhood without sidewalks because that's all they can afford, then ... we just think we've fixed the problem, but we haven't. Frankly, it's not often with sidewalks, but it's with bigger transportation investments like light rail or transit investments [...] or road improvements. But sidewalks certainly can fit in there, too."* (P25PM)

Prioritization Factors and Strategies

Building on these considerations, the three stakeholder groups prioritized geographic areas largely based on infrastructure utilization, population density, proximity to important destinations, citizen complaints, demographics, and comparing (in)accessibility levels between regions. As one policymaker summarized, *"[We consider] how many people are using the sidewalk; how high a priority is it? Maybe not just how many people but how many people with special needs are using the sidewalk? What are the destinations around it so that you can assess again from [a] prioritization standpoint?"* (P18PM).

Each approach had its own advantages and limitations and thus required using complementary methods together. For example, infrastructure utilization and population density, both aimed at maximizing impact by serving as many people as possible, can create inequities in serving communities in need if demographics are not considered:

> *"Someone may live in a residential area that typically would not fall high on the list if we were going to prioritize denser locations first. But if we know that there's someone living on that street who uses a wheelchair or has a mobility impairment, we have that separate list where they [citizens] can help generate and prioritize curb ramps to be repaired at those more residential locations that maybe we wouldn't get to as quickly."* (P3DC)

Similarly, citizen complaints (*e.g.,* 311 requests), commonly used as a low-cost decision support tool [64, 372], alone would be insufficient as voices of certain communities may never be heard. Low participation may be caused by time constraints, commonly seen in low income communities where people work multiple jobs, or limited technology access [83]. P21D noted that these external circumstances need to be carefully weighed in while making data-driven decisions. P23PM suggested taking proactive measures such as actively seeking out historically underserved communities:

> *"We'll frequently hear from people, constituents actively coming to us more from those western half neighborhoods, and so whenever I hear from someone there, I try to intentionally say, 'Is there somewhere else in the ward where this issue might be happening where we may not necessarily hear from someone and actually seek that out?'"* (P23PM)

Finally, comparing accessibility between regions was also useful in addressing inequities across areas. For example, policymakers compared conditions between neighborhoods, *"Trying to understand, relative to neighbors, 'Is this a well-served neighborhood by sidewalks or not?' Looking at that, a percentage or some sort of measurement that shows where these [neighborhoods] rank."* (P25PM). Further, comparing with other cities also aided advocates in pushing for more accessibility efforts by demonstrating success stories to government officials: *"'Look what [City-name]'s doing. You should do more of that, because [...] when you give people a dedicated revenue stream, they can get stuff done.'"* (P11A).

3.4.5 Challenges in Accessible Infrastructure Development

Across the different stakeholders and their decision-making practices, we highlight socio-political and economic factors that impeded accessible infrastructure development.

Socio-Political Challenges

Social and political attitudes of city decision makers and the general public towards accessibility caused several tensions, including lack of support from city leadership, public disinterest, government inaction, conflicting priorities and responsibilities within and across organizations, and inconsistent regulations.

Lack of Support from City Leadership and Public. Though critical for urban accessibility, a common issue for maintenance projects was their inability to attract elected official or public attention vs. new development:

> *"You have to really make it a priority and keep making it a priority for a long time. And that's hard for our political system. We're not built for that. We're built for crisis. We're built for 'go do this one big thing.' [...] But that's not how it works. [...] I think as a country, specifically as a state, [we] have this obsession with not wanting to talk about the basics. We don't want to talk about maintenance. [...] We don't want to focus on those because they're not sexy. They're not interesting but they're crucial."* (P11A)

Similar to prior work [209], obtaining support from city leadership becomes challenging without their vested interests:

> *"Only if a legislator had a particular interest would you then request to have a [transportation] committee hearing on the state. We often didn't, in part because when I was there, the chair was not particularly interested in pedestrian issues so that was not a real focus of the committee."* (P18PM)

Similarly, public disinterest weakens advocacy efforts due to a lack of strong, persistent citizen voices: *"The challenge is that it's competing priorities and that pedestrian voices usually are low in number when people go to advocate for things because everybody wants to talk about the new bright, shiny thing."* (P11A). Public disinterest can directly influence the interest of decision makers in accessibility issues. P17PM elaborated that anticipating the lack of public interest in an issue—*"will the public pay taxes for this issue?"* –could lead policymakers to reduce the issue's priority on their political agenda:

> *"At the end of the day, it becomes a political discussion of how much money do we think the citizens are willing to vote for... it's going to be nine council members and the mayor deciding, 'here's what we think the population will bear', and it becomes more of a political discussion and less of a policy one."* (P17PM)

Lack of Government Action. In addition to disinterest, lack of proactive action hampered accessible infrastructure development. An advocate (P24A) explained that despite their efforts in presenting a case supported by evidence such as existing citizen complaints and making formal inquiries for an implementation plan, the city DOT only responded when the advocacy organization filed a lawsuit: *"We went to the [City-name] Department of Transportation, which has jurisdiction, and we identified all of these issues and sought a negotiation to create a plan that would be very specific and concrete, identifying the work to be done at every curb ramp and at every intersection that's missing curb ramps across the city. We provided our evidence. [...] The city having refused to come to an agreement, we were forced to go to court. We won."* (P24A). Even with sufficient evidence of inaccessible infrastructure, the communication with the DOT failed, further highlighting the need for change in social and political attitudes.

Conflicting Priorities and Responsibilities. Accountability towards resolving issues becomes challenging when conflicting priorities and responsibilities, and discoordination between agencies results in inaction. Often, for policymakers, making funding available becomes a negotiation between agencies. For example, getting transit agencies to invest in updating sidewalk infrastructure: *"In some areas, it meant asking them to invest in some pedestrian infrastructure that might be a block or so away from their [transit] stations. They would push back and say, 'that's your responsibility'. So, it becomes a negotiation."* (P17PM). As a result, policymakers spend significant time in encouraging better coordination:

> *"We did spend a lot of time thinking about how best to inspire better coordination between transit agencies. For example, what happens if you were going between jurisdictional boundaries? [Anonymized-org-name] Transit to [Anonymized-org-name] Transit, somebody's trying to get to [City-name]. We spent a lot of time thinking about how to use some of these funds as a carrot to get transit agencies to do a better job of coordinating [...] particularly on the jurisdictional issues."* (P18PM)

In addition to within-city conflicts, state and city governments deflect fault and blame one another. For example, an advocate described a legal case of a sidewalk accident on a public bridge, wherein the state DOT was responsible for bridges and city DOT was for sidewalks:

> *"So underneath the sidewalk was the state's problem, and the sidewalk itself was the city's [problem]. Both of them had a problem inspecting. The state did find this problem, find that there was an unsafe drop off, about two years before Mr. [Anon-name] was injured, but they took no action. They should have contacted the city and they didn't. The city ultimately was responsible for fixing it."* (P16A, a lawyer working on a lawsuit against the city for a sidewalk-related accident)

Inconsistent Regulations. Due to the decentralized nature of accessibility infrastructure updates, variance in accessibility guidelines across agencies slowed down or led to ineffective accessibility improvements. P11A described a project where *"[Anon-org-name] Transit decided they were going to put a light rail station fairly proximate to Lighthouse for the Blind"*. Since the light rail location fell under the Federal Highway Administration (FHWA)'s jurisdiction, cross organizational differences in accessibility guidelines complicated the development process:

> *"All of the other [Anon-org-name] Transit stations fall under the Federal Railway Administration (FRA) guidelines. So, they have guidelines for the touch sensors for people who are both deaf and blind. But FHWA, which controls the rules for that particular station because of where it's located, they do not have that standard. So [Anon-org-name] Transit was going to design this station, which is four blocks away from the single biggest concentration of deaf blind people in the state with no tactile sensors whatsoever."* (P11A)

To resolve this situation, the advocates *"got them to agree to put in electrical conduit and a station marker where the sensors will be"* (P11A). Once the federal rule changes, taking about two years, accessibility features would be added. The result of these regulation differences led to an inaccessible environment for an extended period of time.

Economic Challenges

While the socio-political challenges were often a result of human interactions or lack thereof, there were severe economic constraints to accessible infrastructure projects. Funding for infrastructure improvements is a complex issue that involves public support, competing priorities from capital projects, and political constraints. Cities rely on various funding sources such as levies, property taxes, project specific funding, and grants from local transit agencies and government. However, due to lack of public support as seen earlier, it can be challenging to levy taxes: *"They [public] understand the importance of doing it, but they also don't necessarily want to pay more taxes to pay for it."* (P11A).

In general, sidewalks are severely underfunded, particularly for maintenance and repair. P3DC explained, for a total sidewalk replacement value of approximately $5.4 billion, and a 100-year replacement cycle, the ideal yearly required funding would be $54 million. However, current available funding is between $3 to $5 million—a deficit of $50 million/year. Most funding goes to capital projects or *"mega projects like the waterfront tunnel downtown"* (P11A). Due to state and federal mandates, capital projects funded with federal dollars lead to the development of peripheral accessible infrastructure. Sidewalk maintenance projects do not get enough funding unless the conditions are severe and need immediate repair. Additionally, P3DC commented on the transient nature of available funding and the challenges to sustain over time without public interest: *"[after] a levy that lasts for nine years, if the voters don't vote to renew that levy then that money potentially goes away as well"*. Even though funding is a valid concern, advocates argued that "cost" as a defense for inaccessibility is harmful: *"Very often, people focus on the costs of remedying barriers, but failing to remedy barriers also has costs. [...] It affects social isolation, employment, access to health care, and many other factors"* (P24A).

3.5 Discussion

Our findings highlight how urban accessibility is not just about inaccessible physical infrastructure but also the underlying socio-political factors that influence its development. Building on prior work [130, 131, 209], we identified how specific socio-political tensions impede infrastructure development, including conflicting priorities, unclear burden of responsibility, lack of public interest and participation, and conflicting regulations. In this section, we discuss two underlying socio-political challenges: lack of accountability and lack of civic participation. We observe that both issues are a result of communication gaps between stakeholders, which requires us to understand the civic interactions more closely when multiple stakeholders are involved in a decision-making process. Thus, we introduce a civic interaction space that looks at interactions between stakeholders and explores opportunities for improving communication.

3.5.1 Exploring the Role of Civic Technologies in Urban Accessibility

Within CSCW and HCI literature [19, 50], civic tech has been positioned as a platform for open collaborative government and community action, facilitating civic conversations and collaborative decision-making practices [87, 120, 208, 368]. Establishing trust between stakeholders is at the core of a successful civic engagement model [141, 163]. In our findings, *lack of accountability* and *civic participation* were two significant issues in accessible infrastructure development. Trust strongly interconnects both issues: increasing accountability leads to increased trust in the government, which further reinforces and encourages civic participation. Below, we elaborate on these two issues within urban accessibility and present open questions for the CSCW community working on civic tech.

Lack of accountability. Due to the decentralized nature of accessibility improvements, the seamless blend between private and public spaces in urban centers, and current governmental policies, individuals and agencies lack a clear understanding of *who* is responsible for accessible infrastructure. In US cities, DOTs manage street and sidewalk infrastructure on public land; however, commercial building entrances and indoor spaces are the purview of private businesses and sidewalks adjacent to residences are the property owner's responsibility [103, 104, 351]. These interdependencies, though core to urban life, create conflict and obscure accountability [369]. As P22D stated when describing tensions between a privately-owned transit agency and their governmental organization: *"[it's] city vs. private vs. federal". How can civic technology better surface these tensions and allow private citizens and governmental agencies to track and assess accessibility progress and, ultimately, increase accountability?*

Lack of Civic participation. Relatedly, the issue of perceived public disinterest by policymakers and department officials can impact infrastructure development. For example, without voter interest on transportation levies, policymakers have difficulty funding large transportation projects through taxes. Public disinterest is often the result of being unaware of inaccessible environments or lack of perceived personal impact. This suggests a need for wider awareness amongst communities about accessibility and the importance of civic participation. Current engagement practices of 311 service requests are largely volunteer based and often have inadequate representation of citizen voices. A successful approach to bring wide-scale policy change has been disability activism [59, 150, 200] such as the 1990

ADA civil rights legislation [361] and the 2019 block-the-box legislation in Washington[1] [210, 355]. The success of such initiatives leads us to ask, *how can civic technology support new practices that strengthen the collective voice of the people to drive change?*

3.5.2 Civic Interaction Space: Enabling Civic Interactions in Urban Accessibility

Drawing on our findings and prior work on civic engagement practices (*e.g.,* voting, advocacy, and grassroots-level activism) [12, 23, 83, 364], we introduce a *Civic Interaction Space* (Figure 3.3) that (a) highlights the points of interaction between stakeholders in urban accessibility and (b) visualizes the similarities and differences in communication (or, interaction) goals between them. The space includes interactions occurring directly through personal communication [22] and indirectly through civic participation apps/tools [98, 215]. To simplify the space, we include MI/Caregivers within the larger 'Community' stakeholder group while acknowledging that some interactions do occur between communities, where policymakers or advocates act as mediators. Mapping the similar interaction goals across stakeholders reveal the varying contexts within which they are accomplished—crucial for facilitating better support through civic tech. For example, 'raising awareness' by an advocate for a community (Figure 3.3: point 3) *vs.* a department official to a policymaker (Figure 3.3: point 6) would pose differences in message framing as well as environmental constraints wherein the interaction occurs (*e.g.,* rigid and risk-averse political structures *vs.* widely varying interests of the general public). Although applicable to any urban socio-political agenda with multiple stakeholders, we demonstrate the utility of this interaction space by taking urban accessibility as an example.

For urban infrastructure planning decisions, most interactions are between department officials and policymakers, with advocates providing community-specific solutions and policy

[1] 'Don't block-the-box' legislation was passed via House Bill 1793, which permits Seattle to use camera enforcement to fine motorists from blocking crosswalks and bus lanes [355]

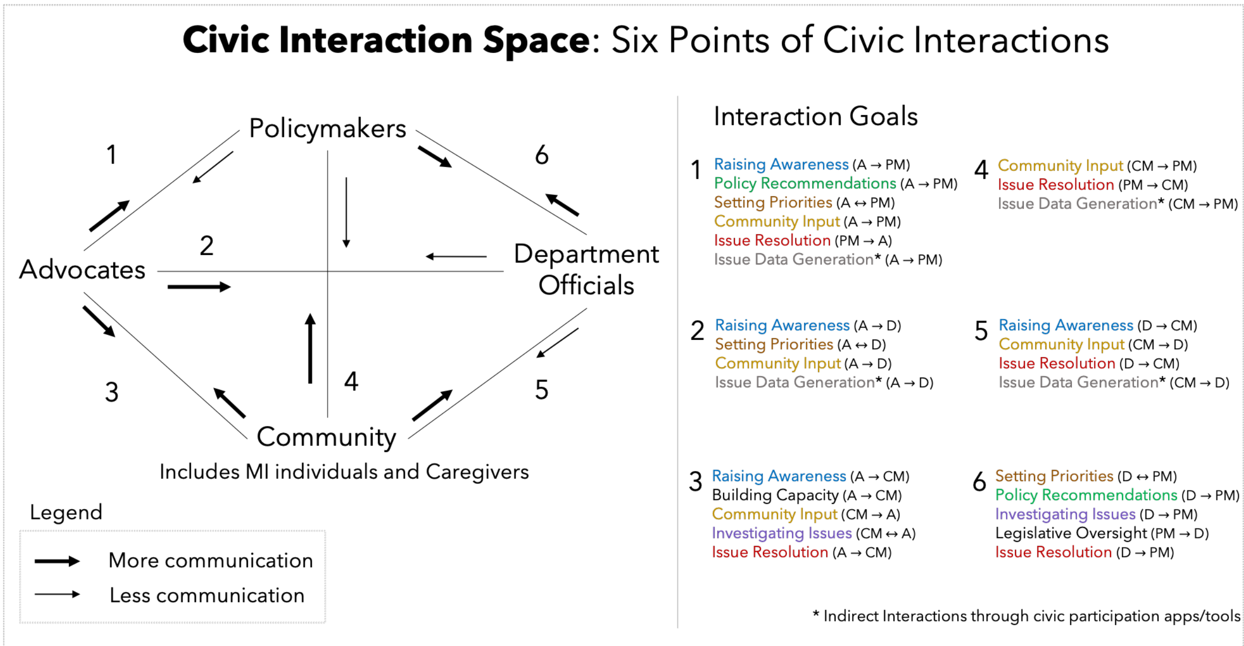

Figure 3.3: Civic Interaction Space. Illustrates the different civic interactions between the primary stakeholder groups and identifies six points of interactions. Groups are denoted by: CM=community includes, MI/caregivers and general public, A=advocates (and activists), D=department officials, and PM=policymakers. The perceived number of interactions between stakeholders is represented by the weight of the arrows. For example, high interactions between policymakers and department officials due to interdependent roles vs relatively less interactions between government officials and citizens

recommendations to the local government and serving as intermediaries for communities-in-need. To reimagine participatory processes for a *collaborative* decision-making environment, we walk through two areas that need strengthening in urban accessibility–improving community input and supporting advocacy efforts.

Improving Community Input and Government Feedback. From Figure 3.3 (points 4 and 5), there is an asymmetry between the amount of communication from the community to government officials *vs.* the limited reciprocal government feedback. *How do we increase government response to close the feedback loop, to ensure sustained civic participation over time,* *and to establish a collaborative decision-making environment?* Currently, the interaction is heavily one-sided with community input such as sidewalk service requests being the primary communication medium for making citizens' voices heard [229] (Figure 3.3: points 1-5). This is primarily due to the prevalence of transactional service models in most cities, whereby local governments are the service providers [281, 368]. However, *how* a government responds to the community input in terms of planning policies, decisions, and actions is not always communicated back–the key for developing a transparent democracy [112]. For example, knowing how a citizen request on fixing broken sidewalks in their neighborhood is being processed and turned into a decision such as whether their neighborhood receives a work order or not and why. Additionally, the transactional nature of service models do not allow iterative decision-making with the public, wherein they can contribute during intermediary decision-making [87]. With the emergence of digital civics [87, 281, 368], there are a growing number of participatory models that cities could use. For urban accessibility, feedback tools are needed to establish a stronger two-way interaction with the government, bring citizens "in the know" about their inputs' impact on planning decisions, and establish trust leading to sustained participation. Furthermore, new mechanisms for tracking progress based on citizen input and channels to communicate with the appropriate party are needed to improve accountability [55].

Supporting Advocacy Efforts. In contrast, lack of communication is not seen as the major concern with advocates. They are typically in a position of having a dialogue with the local government branches for setting city priorities and agenda through advisory boards (Figure 3.3: points 1 and 2). However, advocates are resource constrained with insufficient tool support. *How do we better facilitate advocates in their interactions with both the government and the community?* Similar to prior work [13, 22], our findings showed that advocates often used ad-hoc approaches such as repurposing available data sources to investigate sidewalk issues. While these dynamic practices provide flexibility and agility to advocates, lack of appropriate tools lead to time-consuming laborious efforts to acquire relevant data. Prior

CSCW work emphasized designing for such dynamic practices rather than "system designs that rely on stability and persistency" of work processes [22]. New easy-to-use tools are needed to support agile work practices while providing a framework to support organizing efforts. For example, building capacity and raising awareness often require advocates to build alliances amongst groups that have common interests such as pedestrian and bicyclists interest groups, both having a shared goal of making sidewalks better. Tools that support these needs by, for example, facilitating assemblage of relevant information pertaining to their shared interests would better support advocacy efforts.

3.5.3 Critical Reflection on the Role of Data and Technology for Change

We return to our overarching goal of examining the role of technologies to support change in the socio-political context of urban accessibility. Systemic change requires solutions within social, political, and economic contexts. The use of technology for change, although promising, comes with caveats—technology is not a panacea to socio-political problems; the sheer complexity requires multi-faceted solutions [4, 164, 346, 347]. Despite its limitations, technology can play an important role in social change. Toyama [346] states that technology acts as an amplifier of underlying human practices. In our discussions above, we carefully proposed technical solutions that consider the underlying socio-political challenges and attempted to not overemphasize the impact of these interventions. Similarly, data also comes with its own biases and limitations. By supplementing quantitative with qualitative data, tools can aid stakeholders to make holistic assessments and decisions. However, would technology-mediated solutions impact the quality of civic interactions?

Prior work has shown that the use of technology for facilitating civic interactions is both useful and detrimental. While technology supports advocacy work in creating better infrastructure policies [23] and increases engagement with policymakers [250], the use of technology can also reduce the relational aspect of engagements valued by policymakers [83]. Along the same thread, HCI systems built for mediating civic interactions fail when underlying human relationships are strained [163]. This was seen in the failure of Harding *et al.* 's prototype engagement technology due to fears, vulnerabilities, and mistrust between stakeholders with the *"civic authority fearing litigation and the public anticipating disinterest and inaction from the authorities"* [163]. Although a department official spoke in support of litigations as an accountability measure, lawsuits put the onus on the disability community, prevent proactive measures, and give compliance with accessibility standards a negative overtone. New accountability measures such as feedback mechanisms discussed earlier to track impact of citizen input have the potential to affect change. However, system designers need to first establish trust relationships between stakeholders for such technological interventions to be successful [163]. Finally, consistent with prior work [132], we found equity and inclusion issues may arise with tech-based civic participation (*e.g.,* apps/tools) and can promote systemic exclusion: *"those who have access to tech and identify as technologically adept end up having more power in a movement over those who have less or limited access"* [132]. This brings us to ask, how do we handle power disbalance inherent with these technologies? How do we avoid such inequalities in access while developing tech-mediated solutions? We leave these open questions for future research.

3.5.4 Limitations

First, the studies were conducted in few large metropolitan US cities with established civic engagement and infrastructure assessment practices. Our findings may only be specific to those local governments and may not generalize to rural areas or international contexts. Future work should study urban accessibility issues across regions, cultures, and political structures, as we have begun to do in our recent preliminary work [123]. Second, we had a limited number of participants and diversity within each stakeholder group (*e.g.,* out of four policymakers, two were elected officials). Though interviewing more elected officials would have been useful, we found similar challenges in civic engagement practices as prior work [83]. Further, the proposed civic interaction space should include other tertiary stakeholders such as transit agencies who address accessibility needs. Finally, our study interviews were primarily with people with lower body impairments. Future work should include more perspectives from people across a broader set of sensory, physical, and cognitive abilities.

3.6 Chapter Conclusion

In this chapter, we investigated urban accessibility as a socio-political problem by studying the various assessment, decision-making, and citizen engagement practices. Using multi-stakeholder analysis, this work presents an expansive view of methods and challenges in making accessibility improvements. We tease apart each stakeholder's roles and interactions within the urban decision-making structure for accessible infrastructure development. Our study found several socio-political tensions impeding infrastructure development, including conflicting interests, unclear burden of responsibility, public disinterest, and limited funding. To facilitate accessibility efforts in this socio-political context, we identified six points of civic interactions and proposed directions for future technologies to utilize complementary data- and citizen-driven approaches, while acknowledging that technology is a facilitator rather a solution to socio-political problems.

4 Project Sidewalk: Collecting Sidewalk Accessibility Data at Scale

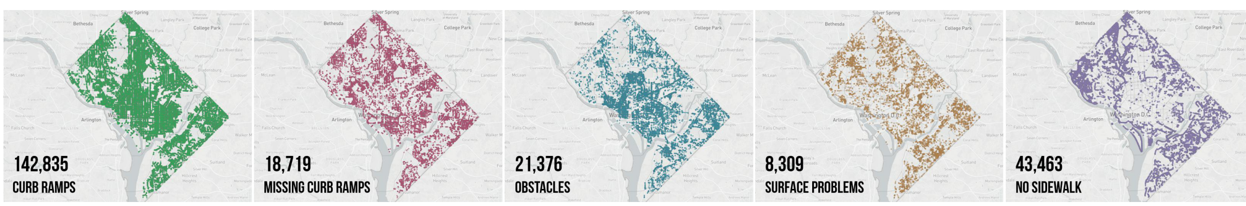

Figure 4.1: In an 18-month deployment study of Project Sidewalk, we collected 205,385 sidewalk accessibility labels, including curb ramps, missing curb ramps, sidewalk obstacles, and surface problems. Each dot above represents a geo-located label rendered at 50% translucency. Try out the tool at http://projectsidewalk.io.

This chapter explores the problem of urban-scale data collection of sidewalk accessibility. We specifically investigate sidewalk accessibility from a wheelchair user's perspective.

We introduce *Project Sidewalk*, a new web-based tool that enables online crowdworkers to remotely label pedestrian-related accessibility problems by virtually walking through city streets in Google Street View. To train, engage, and sustain users, we apply basic game design principles such as interactive onboarding, mission-based tasks, and progress dashboards. In an 18-month deployment study, 797 online users contributed 205,385 labels and audited 2,941 miles of Washington DC streets. We compare behavioral and labeling quality differences between paid crowdworkers and volunteers, investigate the effects of label type, label severity, and majority vote on accuracy, and analyze common labeling errors. To complement these findings, we report on an interview study with three key stakeholder groups (*N*=14) soliciting reactions to our tool and methods. Our findings demonstrate the potential of virtually auditing urban accessibility and highlight tradeoffs between scalability and quality compared to traditional approaches.

4.1 Introduction

Geographic Information Systems (GIS) such as *Google Maps*, *Waze*, and *Yelp* have transformed the way people travel and access information about the physical world. While these systems contain terabytes of data about road networks and points of interest (POIs), their information about physical accessibility is commensurately poor. GIS websites like *Axsmap.com*, *Wheelmap.org*, and *AccessTogether.org* aim to address this problem by collecting location-based accessibility information provided by volunteers (*i.e.,* crowdsourcing). While these efforts are important and commendable, their value propositions are intrinsically tied to the amount and quality of data they collect. In a recent review of accessibility-oriented GIS sites, Ding *et al.* [101] found that most suffered from serious data sparseness issues. For example, only 1.6% of the Wheelmap POIs had data entered on accessibility. One key limiting factor is the reliance on local populations with physical experience of a place for data collection. While local users who report data are likely to be reliable, the dependence on *in situ* reporting dramatically limits scalability—both *who* can supply data and *how* much data they can easily supply.

In contrast, we are exploring a different approach embodied in a new interactive tool called *Project Sidewalk* (Figure 4.2), which enables online crowdworkers to contribute physical-world accessibility information by *virtually* walking through city streets in Google Street

View (GSV)—similar to a first-person video game. Rather than pulling solely from local populations, our potential pool of users scales to anyone with an Internet connection and a web browser. Project Sidewalk extends previous work in streetscape imagery auditing tools like *Canvas* [27], *Spotlight* [36], *BusStop CSI* [157], and *Tohme* [161], all which demonstrate the feasibility of virtual auditing and, crucially, that virtual audit data has high concordance with traditional physical audits. However, this past work has focused on small spatial regions, relied on specialized user populations such as public health researchers [27, 36] and paid crowdworkers [157, 161], and has not been publicly deployed.

In this chapter, we present an 18-month deployment study of Project Sidewalk in Washington DC. In total, 797 users contributed 205,385 geo-located accessibility labels and virtually audited the entirety of Washington DC (1,075 miles of city streets; see Figure 4.2). As the first public deployment of a virtual auditing tool, our research questions are exploratory: How can we engage, train, and sustain crowd workers in virtual accessibility audits? Are there behavioral and/or labeling quality differences between paid crowd workers and volunteers? What are some common labeling mistakes and how may we correct them in future tools? Finally, how do key stakeholder groups react to crowdsourcing accessibility and what are their concerns?

To address these questions, we analyzed interaction logs from our DC deployment, performed a semi-controlled data validation study, and conducted semi-structured interviews with three stakeholder groups (N=14): government officials, people with mobility impairments (MI), and caretakers. In our deployment study, we found that *registered* volunteers completed significantly more missions, on average, than our *anonymous* volunteers (M=5.8 *vs.* 1.5) and that our *paid* workers—who were compensated per mission—completed more than both (M=35.4 missions). In the data validation study, paid workers also significantly outperformed registered and anonymous volunteers in finding accessibility problems (*recall*=68% *vs.* 61% and 49%, respectively) but precision was roughly equivalent for all groups (~70%). Our findings also show that the number of found issues significantly increases with the number of labelers per street—with five labelers, recall rose from 68% to 92%.

To complement these findings, our interview study asked about perceptions of and experiences with urban accessibility and solicited reactions to Project Sidewalk and the idea of crowdsourcing accessibility in general. All three stakeholder groups were positive: while government officials emphasized cost-savings and civic engagement, the MI and caregiver groups focused more on personal utility and enhanced independence. Key concerns also arose, including data reliability, maintenance, and, for the MI participants, whether labels properly reflected their accessibility challenges (the latter echoes findings from [158]).

In summary, the contributions of this work include: (i) Project Sidewalk, a novel web-based virtual auditing tool for collecting urban accessibility data at scale; (ii) results from an 18-month deployment and complementary data validation study exploring key behavioral and labeling quality differences between volunteer and paid crowdworkers; (iii) findings from semi-structured interviews with three stakeholder groups soliciting reactions to Project Sidewalk and identifying key concerns and design suggestions; (iv) and our large, open-source sidewalk accessibility dataset[1], which we believe is the largest of its kind. By scaling up data collection methods for sidewalk accessibility, our overarching aim is to enable the development of new accessibility-aware mapping tools (*e.g.,* [158, 221]), provide increased transparency and accountability about city accessibility, and work with and complement government efforts in monitoring pedestrian infrastructure.

4.2 Related Work

We present background on sidewalk accessibility, survey existing methods for collecting street-level accessibility data, and review volunteer geographic information (VGI) systems.

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[1] http://projectsidewalk.io/api

4.2.1 Street-Level Accessibility

Accessible infrastructure has a significant impact on the independence and mobility of citizens [2, 280]. In the U.S., the *Americans with Disability Act* (ADA) [361] and its revision, the *2010 ADA Standards for Accessible Design* [360], mandate that new constructions and renovations meet modern accessibility guidelines. Despite these regulations, pedestrian infrastructure remains inaccessible [147, 174]. The problem is not just inaccessible public rights-of-way but a lack of reliable, comprehensive, and open information. Unlike road networks, there are no widely accepted standards governing sidewalk data (though some recent initiatives are emerging, such as OpenSidewalks [341]). While accessible infrastructure is intended to benefit broad user populations from those with unique sensory or physical needs to people with situational impairments [388], our current focus is supporting those with ambulatory disabilities. In Project Sidewalk, we focus on five high-priority areas that impact MI pedestrians drawn from ADA standards [358–360] and prior work [246, 254]: *curb ramps*, *missing curb ramps*, *sidewalk obstacles*, *surface problems*, and the *lack of a sidewalk* on a pedestrian pathway.

4.2.2 Collecting Street-Level Accessibility Data

Traditionally, collecting data on street-level accessibility has been the purview of local and state governments; however, with widespread access to the Internet and smartphones, three alternatives have emerged: *in situ* crowdsourcing where a user explicitly captures and reports data [88, 101, 247, 260], automatic or hybrid reporting using sensors [60, 183, 198, 294, 330], and remote crowdsourcing using streetscape imagery [148, 157, 160, 161]. Each approach has benefits and drawbacks—*e.g.,* in terms of data type, maintenance, and coverage—and should be considered complementary. While *in situ* crowdsourcing relies on local knowledge and is likely to produce high-quality data, both academic and commercial tools have struggled with data sparsity [101], perhaps because of high user burden and low adoption. Automatic reporting tools lower user burden by implicitly capturing accessibility

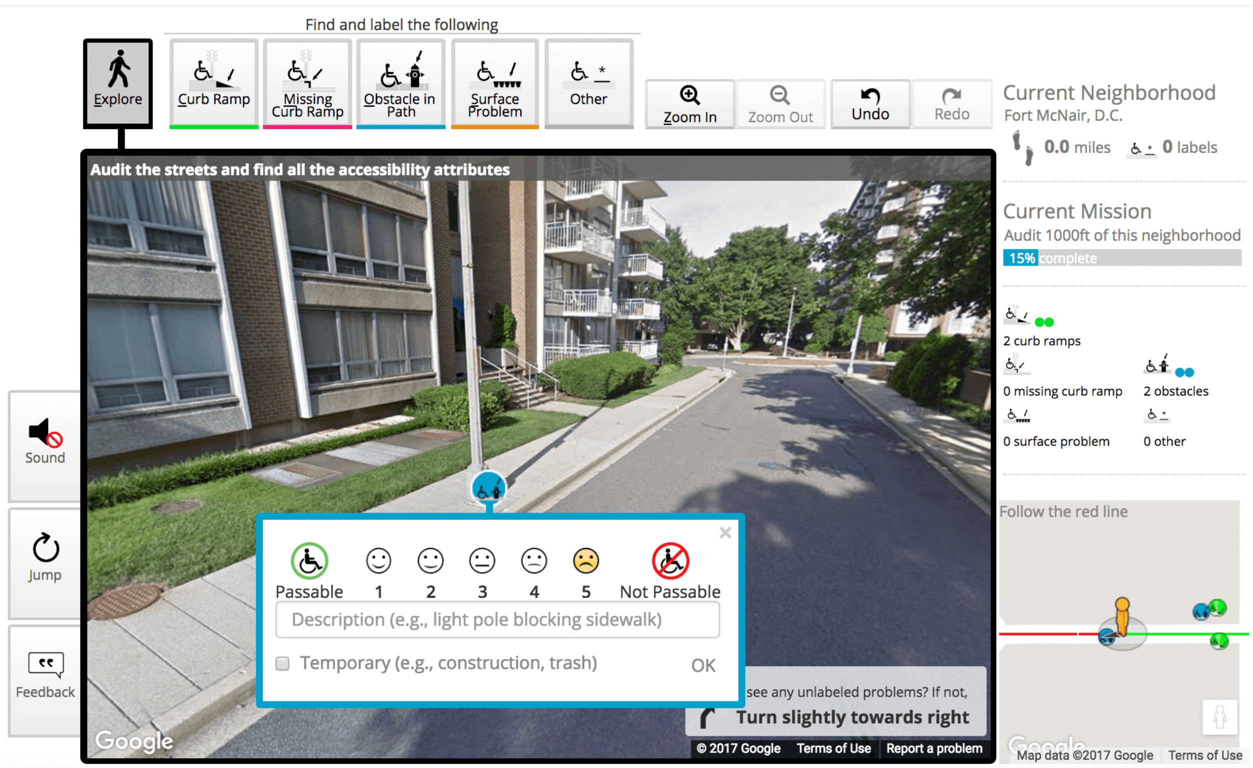

Figure 4.2: In Project Sidewalk, users are given missions to explore city neighborhoods and find accessibility problems. The UI is comprised of four parts: (center) GSV-based exploration and labeling pane; (top) button menu bar; (right) mission pane with progress tracking and navigation; (left) and settings menu. See the Supplementary Video for a demonstration.

data using smartphone- or wheelchair-based sensors; however, accurately converting these quantitative measurements (*e.g.,* accelerometer data) to useful sidewalk assessments is still an open research area. Moreover, these tools are limited to capturing where wheelchair users already go, not where they are *unable* to go (though [189] is attempting to address this limitation, in part, by combining sensor data with continuous video recording).

Most related to our work are virtual auditing tools of street-level accessibility using streetscape imagery. While initial research focused on establishing the reliability of GSV-based audits compared with traditional, physical-based methods [28, 76, 304, 384], more recent work has introduced and evaluated web-based tools in controlled studies [148, 157, 160, 161]. Project Sidewalk builds on these systems by gamifying the user experience and supporting open-world exploring via missions—similar to first-person video games. Additionally, we present the first public deployment study, which enables us to uniquely compare user behavior and labeling performance across user groups and contributes the largest open dataset on sidewalk quality in existence.

4.2.3 Volunteered Geographic Information (VGI)

Project Sidewalk is a new type of *volunteered geographic information* (VGI) system [153]. In VGI, non-experts contribute GIS-related data through open mapping tools—*e.g., Wikimapia*, *Mapillary*, *CycloPath* [284], and most notably, *OpenStreetMap* (OSM). In comparison to more authoritative sources, VGI data quality and spatial coverage are key concerns [17]. While some studies have shown comparable quality between VGI and government maps [151, 152, 245], recent work has identified strong biases in contributions correlated with population density [244, 296]. We address this limitation by combining both volunteer and paid crowd workers and by eliminating the need to have physical access to a place to contribute data. Our work contributes to VGI by analyzing contribution patterns and labeling quality differences between these two user groups.

4.3 Project Sidewalk

To use Project Sidewalk, users visit http://projectsidewalk.io on a laptop or desktop (touch-screens are not currently supported). The landing page provides a brief description of the tool—both its purpose and how to use it—along with basic statistics and visualizations to encourage participation. Upon clicking the '*Start Mapping*' button, new users are greeted by a multi-stage interactive tutorial to learn both about the user interface and basic accessibility concepts. Once the tutorial is completed, users are auto-assigned a neighborhood in DC and given their first mission. Missions guide users through specific neighborhood streets: as the user walks virtually along their route, they are asked to find, label and rate street-level accessibility issues. After completing a mission, a "mission complete" screen is displayed and a new mission is assigned. Users can choose to contribute anonymously or to register and login. We prompt anonymous users to register after finishing their first street segment. Registered users can resume missions and check their contribution activity on an interactive dashboard. Currently, however, there is no way to view or compare performance to others (*e.g.,* a leaderboard).

Training users. Training crowdworkers is difficult, especially for subjective judgment tasks like classifying entities [11]. While a wide range of training approaches are possible—from ground truth seeding with real-time performance feedback to qualification tasks that ensure proficiency [299]—our current training strategy is three-pronged. First, new users are presented with an interactive tutorial, a technique common to modern video games called *onboarding* [290]. We onboard users through an initial *guided* mission that explains the UI and key game mechanics, provides information about street-level accessibility concepts, and monitors and helps the user correct mistakes. As users step through the onboarding experience, their mission status pane is updated just like a normal mission. In total, there are 37 onboarding parts, which are designed to take less than four minutes.

Figure 4.3: Project Sidewalk has five primary color-coded label types: curb ramps, missing curb ramps, obstacles, surface problems, and no sidewalk. The images above are example accessibility issues found by users in our public deployment.

Second, after completing onboarding, initial missions include pre-scripted help dialogs that are triggered based on user behavior. For example, after panning 360° around their first street intersection, Project Sidewalk helps the user use the top-down mission map to take a step in the right direction. These help dialogs are complementary to onboarding: there is an inherent tradeoff between building skills and knowledge through initial training time, and actually having the user begin using the tool in earnest.

Finally, throughout every mission, our tool continuously observes user behavior and provides brief, transient usage tips to encourage proper labeling behavior and increase user efficiency. For example, if we observe that a user is not providing severity ratings, we provide a friendly reminder. If we observe only mouse clicks, we encourage keyboard shortcuts. These one-line tips auto-disappear and can also be explicitly dismissed. Importantly, we cannot provide *corrective* labeling feedback because we do not know about a label's correctness *a priori*.

Exploring and labeling. Similar to [157, 161], Project Sidewalk has two modes of interaction: *explorer mode* and *labeling mode*. In explorer mode, users follow turn-by-turn directions to explore their assigned mission routes using GSV's native navigation controls. If users get lost exploring, they receive reminders to return to their mission routes, which can be clicked to auto-jump back. At any location, the user can pan (360° horizontally and 35° vertically) and zoom to assess sidewalks more closely. The user's FOV is 89.75°.

Users enter the labeling mode by clicking on a labeling button. There are five primary label types: *curb ramp*, *no curb ramp*, *obstacle*, *surface problem*, and *no sidewalk* (Figure 4.3). In this mode, all interactions for controlling movement and the first-person camera view (*e.g.,* pan, pitch) are disabled and the mouse cursor changes to a circular icon representing the selected label. To place a label, the user clicks directly on the accessibility target in the GSV image. A context menu then appears, which asks the user to rate problem severity on a 5-point scale where '5' represents an impassable barrier for someone in a manual wheelchair. The user can also enter additional notes in a description text field or mark a problem as temporary (*e.g.,* due to construction). After closing the context menu, Project Sidewalk automatically reverts to explorer mode.

Project Sidewalk seamlessly repositions applied labels in their correct location as the user pans or zooms—thus, labels appear to "stick" to their associated target. However, once a user takes a step, their labels are no longer visible in the GSV interface (unless they return to their original labeling location). This is due to GSV API limitations. Instead, previously placed labels can be viewed on the top-down mission map.

Missions. Missions serve a two-fold purpose: first, as a game mechanic, they provide an easy-to-understand and engaging narrative for directing data collection tasks. Second, from a system design perspective, missions provide a flexible approach to discretize, assign, and distribute work. Though we envision a variety of future mission types—*e.g.,* data validation missions, labeling user supplied imagery—our current system focuses on encouraging exploration and labeling in the GSV interface. Users are assigned a high-level goal of auditing a neighborhood and then routed on missions of increasing length and complexity within that neighborhood. Mission lengths increase from 500ft to a maximum of 0.5mi (2,640ft). Mission feedback is provided via a mission status pane, completion screens, and, for registered users, an interactive dashboard. If a user gets stuck during a mission, they can choose to "jump" to a different part of their assigned neighborhood or manually choose a new neighborhood. For finishing a mission or completing a neighborhood, users are rewarded with mission completion screens and sound effects.

4.4 Implementation, Data, and API

Creating a robust, usable, and publicly deployable system required a significant human-centered design and engineering effort. Our open-source *GitHub* repository[2] has 2,747 commits from 20 team members and 43,898 lines of developed code (excluding comments). Project Sidewalk's backend is built in *Scala* and *PostgreSQL* with the *PostGIS* spatial extension, and the frontend is in *JavaScript* and *HTML/CSS*. Below, we describe four key implementation areas: preparing a city for deployment, work allocation algorithms, triangulating and clustering labels, and our API.

4.4.1 Preparing a City

Project Sidewalk has two data prerequisites for deployment: GSV and OSM availability. To construct a street network topology, we extract OSM `<way>` elements marked with street-related tags within a city's geographic boundary. We also extract `<node>` and `<nd>` elements for metadata (e.g., lat-long coordinates) and links between nodes and edges. Because `<way>` polylines can extend multiple city blocks, we create smaller units, called *street segments*, by partitioning streets at each intersection. For DC, this resulted in 15,014 street segments with a total length of 1,164 miles. We filtered 892 segments that contained highways and/or where GSV imagery was unavailable due to government security precautions. In total, we were left with 14,037 segments over 1,075 miles (Figure 4.4).

[2] https://github.com/ProjectSidewalk/SidewalkWebpage

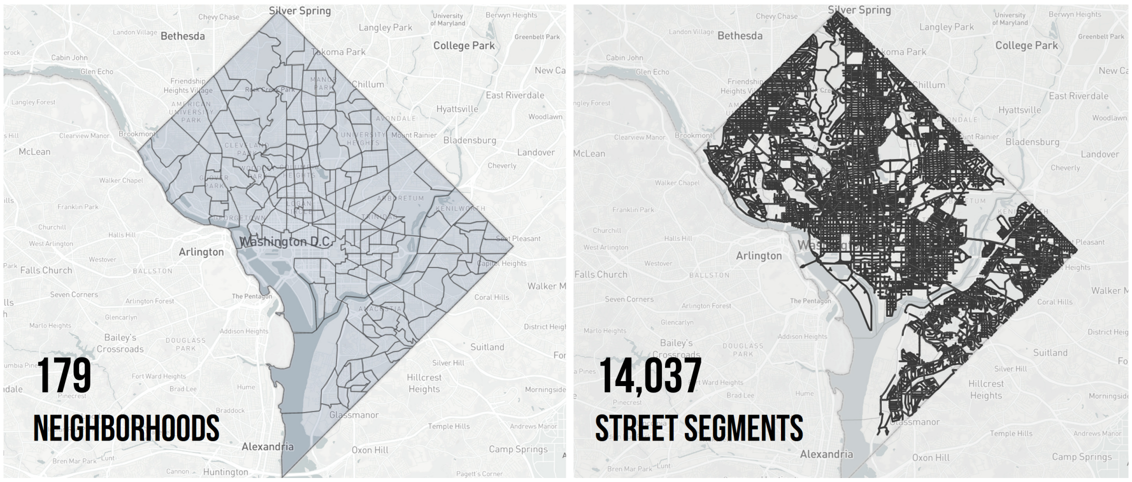

Figure 4.4: DC's 179 neighborhoods and 14,037 street segments (1,075mi), which we used in the Deployment Study.

4.4.2 Allocating and Distributing Work via Missions

Allocating and distributing work is a two-step process consisting of assigning neighborhoods then street segments. We use the *mission* construct to do both. We iterated on these task allocation algorithms throughout our deployment as we discovered inefficiencies or mistakes. Below, we present our current approach, which was used for the last three months of our deployment, and briefly mention old approaches.

Our current version is based on a "work quality" threshold determined by analyzing labeling behavior from our research group and informal manual reviews of end-user contributions. We define a "good" user as someone who contributes a minimum of 3.75 labels per 100 meters on average. While labeling frequency is an imperfect proxy for worker quality, it is easy to implement and fast to compute. We integrate this quality metric to prioritize street segments:

$$priority_{street} = \begin{cases} 1, & \textit{if cnt('good' users)=0} \\ 1/(1+x), & \textit{otherwise} \end{cases}$$

where, x = *cnt("good" users) + 0.25 * cnt("bad" users)*. This algorithm prioritizes street segments inversely proportional to the number of previous audits with a weight penalty assigned for "bad" users.

Allocating neighborhoods. Users are given missions to explore and label assigned neighborhoods. Neighborhoods are allocated at two points: after a user completes onboarding and after they complete a previously assigned neighborhood. In earlier versions of Project Sidewalk, we randomly assigned users to neighborhoods within the top ten lowest completion rates. This approach, however, treated all previous work equivalently. In the current version, we incorporate street segment priority by first calculating the mean priority of all street segments for each neighborhood and then randomly assigning neighborhoods from a list with the top five highest means. Users can also choose their own neighborhoods; however, this feature was somewhat hidden and not prominently used in our deployment.

Calculating mission routes. Mission routes are composed of street segments, which are dynamically selected when a user reaches an intersection (*i.e.,* the end of a segment). To enhance immersion and limit user confusion, the routing algorithm attempts to select contiguous segments whenever possible. In older versions of Project Sidewalk, the segment selection algorithm simply chose a randomly connected segment that the current user had not already audited. However, this failed to incorporate work completed by other users, which was inefficient. In our current implementation, for each neighborhood, we maintain a discretized list of unaudited street segment priorities (*bin size*=0.25). When a user reaches an intersection, we randomly select any unaudited connected street segment with the same discretized priority as the highest one in the neighborhood list. If none exist, we inform the user that they have completed this part of the neighborhood and automatically transport them to the highest priority remaining neighborhood street. We use a similar process for positioning users when they first begin a new neighborhood—we place them at the beginning of the highest priority street segment.

4.4.3 Project Sidewalk Data

In Project Sidewalk, users label streetscape panoramas projected into 3D space [138]. We need to convert these 3D-point labels to 2D lat-lng coordinates and then aggregate multiple labels for the same target into a single cluster.

3D to 2D. To obtain geo-located labels from the 3D projection, we use: (i) the panorama's 3D-point cloud data, which is obtained by LiDAR on the GSV cars; (ii) the *lng,lat* coordinate of the GSV car; and (iii) the x_{img},y_{img} position of the label on the panorama. More specifically:

$$\begin{pmatrix} lng_{target} \\ lat_{target} \end{pmatrix} = \begin{pmatrix} lng_{GSV\_car} \\ lat_{GSV\_car} \end{pmatrix} + \begin{pmatrix} \Delta lng \\ \Delta lat \end{pmatrix}$$

where, we compute Δlng, Δlat by using the x_{img},y_{img} label position on the panorama and the 3D-point cloud data to obtain the offset *dx,dy,dz* at x_{img},y_{img}. The offset is in meters, which we convert to Δlng, Δlat and plug into the equation. See the function `imageCoordinateToLatLng(imageX, imageY, lat, lng)` in MapService.js (Line 1275) in the GitHub repo.

Raw label data. For each label, we record three sets of information: who provided the label and when, how the data was collected in GSV (the user's *POV*, *heading*, *source panorama id*), and information about the label itself, such as *label type*, *lat-long position*, *x,y position* on panorama, *severity rating*, *textual description*, and a *temporary* flag.

Clustering. Because users can find and label the same accessibility problem from different panoramas, we needed to develop an algorithm to aggregate labels for the same target together. We do this by clustering. Each cluster refers to a single found problem (and may contain one or more raw labels). We use a two-stage clustering approach: *single-user* clustering followed by *multi-user* clustering. First, we consolidate raw labels for each individual user into intermediate clusters—this is necessary because some users choose to label a single problem from multiple viewpoints. Second, we combine these individual user clusters together to create our final cluster dataset. Both stages use the same hierarchical agglomerative clustering approach: the Vorhees clustering algorithm with the haversine formula to compute distances between labels and clusters.

For stage one, we cluster raw labels of the same type that are within a certain distance threshold. Because some label types are often legitimately close together—*e.g.,* two curb ramps on a corner—we use two different thresholds: 2 meters for curb and missing curb ramps and 7.5 meters for other label types. These thresholds were determined empirically by iteratively computing clusters at different threshold levels from 0 to 50 meters (*step size*=1 meter) and qualitatively analyzing the results. Stage two clustering is similar but uses the centroids of stage one clusters with slightly looser thresholds (7.5 and 10 meters, respectively).

4.4.4 Public API

To enable the use and broader study of our collected data, we developed and released an initial public REST API (http://projectsidewalk.io/api). The API has three endpoint types: *labels* for obtaining raw label data, *clusters* for obtaining label clusters, and scores, which provide computed scores for street and neighborhood accessibility. Each API requires a lat-long bounding box to specify an area of interest for input and returns data in the *GeoJSON* format. For the score APIs, we developed a simple scoring model that incorporates the number of problem labels and returns an accessibility score between 0 and 1. Providing a robust, personalizable, and verifiable scoring algorithm is ongoing work.

4.5 Deployment Study

In August of 2016, we launched an 18-month deployment study of Project Sidewalk. Washington DC was selected as the study site because of its large size (158 km^2), diverse economic

	Volunteers		Turkers	Researchers	Total	Total
	Anon (N=384)	**Registered (N=243)**	**(N=170)**	**(N=28)**	**Labels**	**Clusters***
Curb Ramp	9,017	27,016	88,466	18,336	142,835	51,098
M. Curb Ramp	1,085	3,239	13,257	1,138	18,719	7,941
Obstacle	934	2,799	16,145	1,498	21,376	12,993
Surf. Prob.	620	1,885	3,213	2,591	8,309	5,647
No Sidewalk	1,185	6,192	28,167	7,919	43,463	23,468
Occlusion	47	310	462	438	1,257	953
Other	62	147	1,137	34	1,380	928
Total Labels	**12,950**	**41,588**	**150,847**	**31,954**	**237,339**	**103,028**

Table 4.1: The total amount of data collected during our deployment. *Total clusters refers to filtered data only. All other columns are the full dataset.

and geographic characteristics, and substantial commuter population—many of whom take public transit and use pedestrian infrastructure [357]. Additionally, as the nation's capital, which draws ~20m visitors/yr [375], there is increased pressure to follow and model ADA guidelines.

We recruited two types of users: *volunteers* through social media, blog posts, and email campaigns, and *paid crowd workers* from Amazon Mechanical Turk (turkers). We further divide volunteers into *anonymous* and *registered* groups; the former was tracked by IP address. For comparison, we also show data from 28 members of our research lab, who voluntarily contributed to help test the tool and received in-person training on *how* and *what* to label. We paid turkers a base amount for completing the tutorial and first mission ($0.82) and a bonus amount for each mission completed thereafter ($4.17/mile). These rates were based on US federal minimum wage ($7.25/hr), assuming an expected labeling rate of 1.74 miles/hr, which was drawn empirically from our data. In practice, our turkers earned

\$8.21/hr on average (*SD*=\$5.99), which increased to \$12.76 (*SD*=\$6.60) for those 69 turkers who audited at least one mile. Turkers could see their earnings in real-time via the mission panel. We posted a total of 298 assignments over a 6-month period.

4.5.1 Results

Overall, Project Sidewalk had 11,891 visitors to the landing page, of which 797 (627 volunteers; 170 turkers) completed the tutorial and audited at least one street segment in the first mission. In total, these users contributed 205,385 labels and audited 2,941 miles of DC streets (Table 4.1). Below, we analyze user behavior, contribution patterns, and responses from a pop-up survey given to turkers. We examine worker and data quality in a separate section.

User behavior. On average, registered users completed more missions (5.8 *vs.* 1.5), contributed more labels (171.1 *vs.* 33.7), audited faster (1.93 mi/hr *vs.* 1.22), and spent more time on Project Sidewalk (55.8 mins *vs.* 18.3) than anonymous users (Table 4.2). Registered users also took longer on onboarding (6.9 mins *vs.* 3.8) and left more open-ended descriptions (10.0 *vs.* 1.6). Paid workers, however, did significantly more work on average than either volunteer group: 35.4 missions, 887.3 labels, and spent 4.4 hrs using the tool. If we examine only those users who passed our "good" user heuristic, we filter 28.2% paid, 23.7% anonymous, and 22.6% registered workers; however, relative user behaviors stay the same. Similar to [189], user contribution patterns resemble a power law distribution: the top 10% anonymous, registered, and paid workers contributed 56.7%, 86.6%, and 80.2% of the labels in their group, respectively. By the top 25%, contribution percentages rise to 77.4%, 93.6%, and 94.8%.

User dropoff. To examine user dropoff, we analyzed interaction logs for the last eight months of our deployment (after we added comprehensive logging to the tutorial). User dropoff was steep. While 1,110 users started the tutorial, only 568 finished it (51%), 479 (43.2%) took one step in their first mission, and 328 (29.5%) completed at least one mission.

	Anonymous		Registered		Turkers		Researchers	
	All	**Filtered**	**All**	**Filtered**	**All**	**Filtered**	**All**	**Filtered**
Num. users	384	293	243	188	170	122	28	21
% Filtered	–	23.7%	–	22.6%	–	28.2%	–	25.0%
Tot. miles	155.5	79.9	535.6	391.6	2,248.9	1,016.4	238.5	211.7
Avg (SD)	0.4 (1.2)	0.3 (1.0)	2.2 (8.2)	2.1 (9.1)	13.2 (37)	8.3 (32)	8.5 (19)	10.1 (22)
Tot. missns	576	316	1,406	1,044	6,017	2,953	690	604
Avg (SD)	1.5 (3)	1.1 (2.5)	5.8 (20)	5.6 (22)	35.4 (95)	24.2 (87)	24.6 (53)	28.8 (62)
Tot. labels	12,950	10,760	41,588	35,923	150,847	103,820	31,954	30,488
Avg	33.7	36.7	171.1	191.1	887.3	851.0	1,141.2	1,451.8
Lbls/100m	8.0	10.5	5.8	6.8	7.1	8.9	6.0	7.1
Avg speed	1.22	0.74	1.93	1.58	1.68	1.14	2.76	2.57
Avg time	18.29	17.59	55.83	57.88	266.20	225.22	195.81	233.84
Avg desc	1.6	1.9	10.0	12.1	47.2	58.1	28.1	37.0

Table 4.2: The total amount of data collected during our deployment. Averages are per user. Avg. speed is in mi/hr, time is in mins, lbls/100m is median labels per 100m, and 'avg desc' is the average number of open-ended descriptions.

Of those 328, a majority, went on to finish their second mission (59.8%; 196 users) and then dropoff dampened substantially. For example, 74.0% of the users who completed *Mission 2* also completed *Mission 3*. When splitting the 1,110 users by group—846 volunteers and 264 turkers—we found different patterns of behavior. While only 43.9% of volunteers finished the tutorial and only 19.1% finished the first mission, turkers were far more persistent: 74.6% finished the tutorial and 62.9% completed the first mission.

Pop-up survey. To begin exploring why users contribute to Project Sidewalk, we developed a 5-question survey shown to users after their second mission. The first three questions asked about task enjoyment, difficulty, and self-perceptions of performance via 5-point Likert scales while the last two questions were open-ended asking about user motivation and soliciting feedback. A single researcher analyzed the two write-in questions via inductive coding. Though the survey is now given to all user groups, it was only available to turkers during our deployment study—which we analyze here.

In all, 123 turkers completed the survey. Of those, 110 (89.4%) stated that they enjoyed using Project Sidewalk (*Mean*=4.4; *SD*=0.7). For task difficulty, the responses were slightly more mixed: 83 turkers (67.5%) selected *easy* or *very easy* and 5 selected *difficult* (*M*=3.9; *SD*=0.9). When asked to self-rate their performance, 81 turkers (65.9%) felt that they did at least a *very good* job and none reported *poor* (*M*=4.0; *SD*=0.9). For the first open-ended question (required) about user motivation, 74 (60.2%) mentioned that the task was interesting or fun—"*It was an interesting and unique change to my day*" (U111); 48 (39.0%) felt that the task was important/helpful—"*I think it is important for those who are using wheelchairs to be able to safely navigate streets.*" (U223); and 20 (16.3%) mentioned money—"*It was interesting work and good pay*" (U61). The last question was optional and asked for feedback: 68 turkers chose to answer, mostly to thank us for the task (55 of 68): "*Good & interesting task. Thank you*" (U96). Six suggested features, five asked questions about labeling, and two reported bugs.

4.6 Data Validation Study

To investigate data quality and compare performance across user groups, we performed a data validation study using a subset of DC streets. This study occurred approximately halfway into our public deployment. Because pedestrian infrastructure can differ based on neighborhood type (*e.g.,* commercial *vs.* residential), age, and density, we first divided DC into four quadrants based on official geographic segmentation data [93]. We then sub-divided each quadrant into land-use zones using DC's open zoning regulation dataset [95]. Finally, we randomly selected the first two or three mission routes completed by individual volunteer users. This resulted in a test dataset of 44 miles (625 street segments) from 50 registered and 16 anonymous users across 62 of the 179 DC neighborhoods. We then verified that the selected routes had similar geographic and land-use distributions compared to all streets in DC.

To compare volunteer *vs.* paid worker performance, we posted the selected missions in our test dataset to Amazon Mechanical Turk. Other than payment, we attempted to carefully mimic the volunteer work experience: individual turkers completed onboarding and then were implicitly assigned either an *anonymous* user's mission set (two) or a *registered* user's mission set (three). To control for experience and learning effects, we did not allow deployment turkers to participate. We paid workers based on US federal minimum wage drawn from median volunteer completion times: $2.00 for the tutorial + two missions (~2,000ft) and $3.58 for the tutorial + three missions (~4,000ft). Unlike the deployment study, turkers could not choose to complete additional missions for bonus payment. To examine the effect of multiple labelers on performance, we hired five turkers per mission set for a total of 330 turkers.

To create ground truth, we first developed a labeling codebook based on ADA guidelines [358–360], which was then vetted and refined by a person who has used a wheelchair for 20 years. Following iterative coding [171], three researchers began labeling the same subset of data: one randomly selected mission set for an anonymous user and one for a registered user. For each round, the researchers met, resolved disagreements, and updated the codebook accordingly. After seven rounds, the average Krippendorff alpha score was 0.6 (*range*=0.5-0.8) and raw agreement: 85.4% (*SD*=4.1%). The three researchers then split the remaining 52 mission sets equally and a final review was performed. In total, ground truth consists of: 4,617 clusters, including 3,212 *curb ramps*, 1,023 *surface problems*, 295 *obstacles*, and 87 *missing curb ramps*. Though laborious, we note that this ground truth approach allows us to more deeply examine labeling performance compared with verifying placed labels—as the latter does not allow us to calculate false negatives.

Analysis. We examine accuracy at the street-segment level. We first cluster all labels from anonymous, registered, and paid workers using *single-user* clustering. We then use haversine distance to associate label clusters to their closest street segment. To compute our accuracy measures, we sum the number and type of label clusters for each segment and compare the result to ground truth. This produces counts of true/false positives and true/false negatives at each segment, which we binarize for final analysis. In total, 89.6% (560/625) of the street segments contained accessibility labels in ground truth. Unlike the four other label types, the *no sidewalk* label is not used for single-point targets but rather targets that extend multiple panoramas. Thus, we exclude this label from our analysis.

We report on *raw accuracy* (number of segments that match ground truth), *recall*, and *precision*. Here, recall measures the fraction of accessibility targets that were found (labeled) compared to those in ground truth while precision measures the correctness of those labels. Ideally, each measure would be 1.0; however, similar to other crowdsourcing systems (*e.g.,* [161]), we prefer *high recall* over precision because correcting false positives is easier than false negatives—the former requires verification while the latter requires users actually re-explore an area. Except for the multiple labelers per segment analysis, we use only the *first* hired turker for each mission (rather than all five). For statistical analysis, we use binomial mixed effects models with user nested in mission route id and a logistic link function with accuracy, recall, and precision modeled as binomials. We assess significance with likelihood-ratio (LR) tests and use post-hoc Tukey's HSD tests to determine statistical orderings. Our analysis was performed using the *R* statistical language.

4.6.1 Results

We examine overall performance across user groups, the effect of label type, label severity, and multiple labelers on accuracy, and common labeling mistakes.

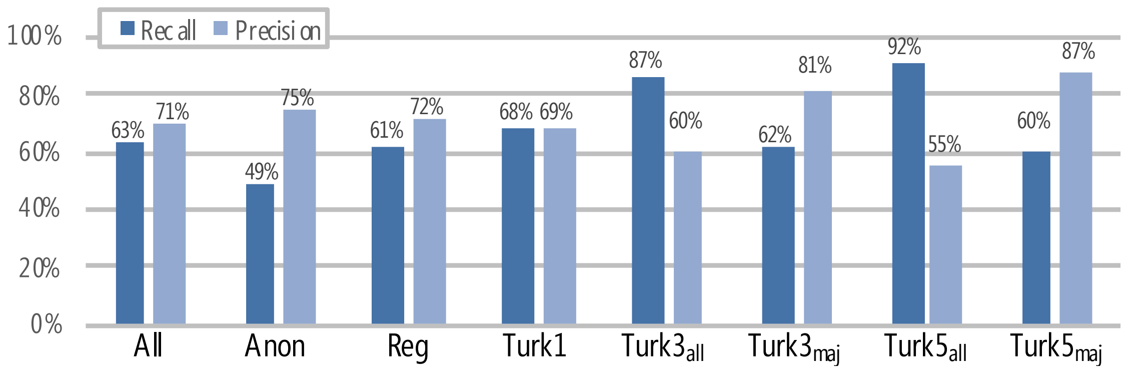

Figure 4.5: Average recall and precision for all user groups.

User performance. The overall average raw accuracy was 71.7% (*SD*=13.0%) with all three user groups performing similarly (~70%). Because of the high true negative rates in our data—that is, most panoramas do *not* have accessibility issues and were correctly labeled that way—recall and precision are more insightful measures (Figure 4.5). Turkers found significantly more issues than registered and anonymous users (*recall*=67.8% *vs.* 61.4% *vs.* 48.8%, respectively) at similar precision levels (68.8% *vs.* 72.2% *vs.* 74.5%). With an LR test, user group had a statistically significant association with recall (lr=21.6, df=2, n=132, p<0.001) and precision (lr=7.1, df=2, n=131, p=0.028) but not raw accuracy. Pairwise comparisons for recall were all significant but none were for precision.

To explore the effect of multiple labelers on performance, we hired five turkers per mission set. We examine *majority vote* for each group size (3, 5) as well as treating each contribution individually (*e.g.,* $\text{Turk3}_{\text{maj}}$ *vs.* $\text{Turk3}_{\text{all}}$). We expect that Turk_{maj} will result in higher precision but lower recall as it requires more than one user to label the same target and just the opposite from Turk_{all} (*i.e.,* higher recall, lower precision). Indeed, this is what we found: from Turk1 (baseline) to $\text{Turk5}_{\text{all}}$, recall rose from 67.8% to 91.7% but at a cost of precision (from 68.8% to 55.0%). In contrast, for majority vote, recall fell from 67.8% to 59.5% for Turk1 to $\text{Turk5}_{\text{maj}}$ but precision rose from 68.8% to 87.4%. We found turker group had a statistically significant association with recall (lr=498.96, df=4, n=330, p<0.001) and precision (lr= 374.88,

	Gnd Truth Clusters	Raw Acc.	Recall	Precision
Curb Ramp	3,212	83.7 (23.1)	86.0 (25.7)	95.4 (7.5)
No Curb Ramp	87	72.9 (21.9)	69.3 (43.5)	20.5 (31.7)
Obstacle	295	71.2 (18.8)	39.9 (36.9)	47.5 (37.4)
Surface Problem	1,023	59.0 (24.8)	27.1 (30.5)	72.6 (35.4)

Table 4.3: Accuracy by label type. All pairwise comparisons are significant.

df=4, *n*=330, $p<0.001$). All pairwise comparisons for recall and precision were significant except for $\text{Turk5}_{maj} < \text{Turk3}_{maj}$—for recall only.

Label type. To examine accuracy as a function of label type, we analyzed labeling data across users (Table 4.3). *Curb ramps* were the most reliably found and correctly labeled with *recall*=86.0% and *precision*=95.4%. In contrast, while *no curb ramps* had reasonably high recall at 69.3%, precision was only 20.5% suggesting an incorrect understanding of what justifies a *no curb ramp* label. The other two label types, *obstacle* and *surface problem*, had lower recall (39.9% and 27.1%) but comparatively higher precision (47.5% and 72.6%), which mirrors our experience with ground truth—these accessibility problems are hard to find and require diligent exploration. In addition, these two label types can legitimately be switched in some cases (*e.g.,* a patch of overgrown grass could be marked as either an *obstacle* or *surface problem*). We explore labeling mistakes in more detail below.

Effect of severity. We hypothesized that high-severity problems would be easier to find. To explore this, we partitioned ground truth labels into two groups: *low severity* (<= 2 rating) and *high severity* (>= 3 rating). The low severity group contained 1,053 labels and the high 352 labels. As expected, we found that high-severity labels had significantly higher recall (*M*=83.3%; *avg*=69.8%; *SD*=35.5%) than low-severity labels (*Mdn*=56.3%; *M*=57.0%; *SD*=32.3%). To determine significance, we created a binomial mixed effect model with *severity* (high or low) as the fixed effect and *user* nested in *mission route id* as random effects. Result of LR test (*lr*=10.6, *df*=1, *n*=246, *p*=0.001).

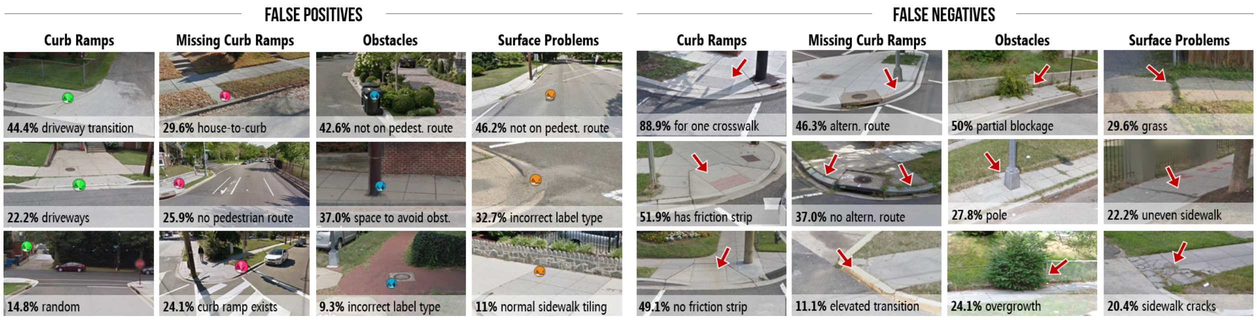

Figure 4.6: An overview of false positive and negative labeling mistakes ordered by frequency (taken from 432 error samples in the data validation study).

4.6.2 Common Labeling Errors

To better understand labeling errors and to contextualize our quantitative findings, we conducted a qualitative analysis of labeling errors. We randomly selected 54 false positives and 54 false negatives for each label type, which resulted in 432 total error samples from 16 anonymous, 43 registered, and 80 paid workers. A single researcher inductively analyzed the data with an iteratively created codebook. We show the top three errors with examples in Figure 4.6.

In analyzing false positives, we observed that most mistakes were understandable and either easy to correct with better training or innocuous. For example, 66.6% of incorrect *curb ramp* labels were applied to driveways, nearly half of *obstacles* and *surface problems* were potentially legitimate issues but not on the primary pedestrian route (*e.g.,* middle of street *vs.* crosswalk), and almost 30% of incorrect *missing curb ramps* were on extended residential walkways. Moreover, 32.7% of *surface problems* and 9.3% of *obstacles* were correctly labeled as problems but with a different label type from ground truth—*e.g.,* a surface problem marked as an obstacle.

For false negatives (*i.e.,* a user did not label a problem when one exists), it is harder to discern clear patterns—at least for some label types. For *obstacles* and *surface problems*—both of which had the lowest recall and thus can be considered hardest to find—salience appears to be a contributing factor: 50% of missed *obstacles* were only partially blocking the pedestrian path and nearly 30% of *surface problem*s were grass related. For *missing curb ramps*, 46.3% of missed labels were at a corner where at least one other curb ramp exists though the second most common error was more egregious: a pedestrian path to a street had no curb ramp and no alternative accessible route (37.0%). We discuss potential solutions to address labeling errors in the Discussion.

4.7 Semi-Structured Interview Study

To complement our deployment and data validation studies and to solicit reactions to Project Sidewalk from key stakeholders, we conducted an interview study with three DC-area groups (N=14): six *government officials* (G), five *people with mobility impairments* (MI), and three *caregivers* (C). G included state and city transportation employees with oversight of pedestrian infrastructure, MI participants used a mobility aid such as a wheelchair or cane, and caregivers took care of a person with a MI either as a professional, family member, or friend. Participants were recruited via mailing lists, word-of-mouth, and social media.

The three-part study began with a semi-structured interview about participants' current perceptions of and problems with urban accessibility. We then asked participants to use Project Sidewalk while "thinking aloud." Finally, we concluded with a debrief interview about the tool, including its perceived utility, concerns, and design ideas. Sessions lasted between 60-65 minutes, and participants were compensated $25. One government session was a group interview with three participants (coded G3); all other interviews were individual. Sessions were audio- and screen-recorded, which were transcribed and coded to find emergent themes using peer debriefing [86, 332]. Using deductive coding, one researcher created an initial codebook for the interviews, which was refined with the help of a peer. A randomly selected transcript was then coded, which was reviewed by a second researcher using peer debriefing. To resolve conflicts and update the codebook, the two researchers met after each review process. The final codebook was produced after three iterations (with one transcript coded per stakeholder group) and 46 conflict resolutions over 305 excerpts and 1,466 applied codes. The remaining data was then coded by the initial researcher.

4.7.1 Results

We describe findings related to the perceived value and usability of Project Sidewalk as well as design suggestions and concerns. For quotes, we use (participant group + id).

Perceived value. Overall, all three stakeholder groups felt that Project Sidewalk enabled rapid data collection, allowed for gathering diverse perspectives about accessibility, and helped engage citizens in thinking about urban design. Government officials emphasized cost savings and community involvement envisioning Project Sidewalk as a triaging tool before sending out employees to physically examine areas: "*It's really good for a starting point. This is a first observation, and when you send somebody out in the field, they can see those observations and pick up more information. It's just neat*" (G4). The MI and caregiver groups focused more on personal utility, envisioning accessibility-aware navigation tools that could incorporate Project Sidewalk data: "*I might take advantage of more opportunities knowing that, okay, if I could rely on the data and knew I could anticipate how difficult it was going to be for me to get around*" (MI1). Six of the seven MI and caregiver participants mentioned that Project Sidewalk data could enhance their independence, give them confidence to explore new and unfamiliar areas, and/or help them achieve the same pedestrian rights as everyone else.

Usability. Participants across groups felt that the tool was easy-to-learn and fun to use. G3, for example, stated: "*I think it's awesome. [. . .] It's a lot of fun*" and reported "*feeling good*" contributing data to a social purpose while also being motivated by the game design elements:

"*we're looking at the 71 percent complete, and we're pretty excited!*" Three participants appreciated relying on a familiar technology like GSV, "*You're not introducing like yet another platform that somebody has to relearn—that was helpful*" (G3). Almost everyone (13/14) found the labeling system comprehensive as captured by MI3: "*the labeling is pretty all-inclusive.*"

Concerns. Key concerns included outdated GSV imagery or labels (*N*=6), data reliability (3), and conflicting data (4). Towards outdated imagery and labels, C1 asked "*if a street light was marked as an obstacle and if it was replaced or moved, would the labels reflect that?*" While this is one limitation of our virtual auditing approach, four participants mentioned that they would rather be aware of a potential issue even if it no longer existed. For example, C2 stated: "*if there was a label, I'd rather be aware of it.*" For data reliability, G4 suggested that each road be audited by multiple people: "*I would have more confidence if different people did it, did the same street.*" Four participants (2 Cs, 2 MIs) were concerned about how labelers may differ in interpreting problems compared with their needs and experiences. For example, MI1 said: "*my concern as a user . . . someone said this was accessible and I got there and it wasn't accessible, because everyone has different opinions on accessibility.*"

Suggestions. Participants suggested developing mechanisms to keep information up-to-date (4)—for example, by adding a complementary smartphone-based data collection app, adding verification interfaces (3), and surfacing data age (2). All government officials were interested in ways to export and visualize the data; one suggested integrating directly into their service request backend. At a more detailed tool level, seven participants suggested adding new label types, including for crosswalks, the presence of sidewalks, access points (such as driveways), and construction.

4.8 Discussion

Through a multi-methods approach, our results demonstrate the viability of virtually auditing urban accessibility at scale, highlight behavioral and labeling quality differences between user groups, and summarize how key stakeholders feel about Project Sidewalk and the crowdsourced data. Below, we discuss worker and data quality, future deployment costs and worker sources, and limitations.

4.8.1 Label quality

Our data validation study found that, on average, users could find 63% of accessibility issues at 71% precision. This is comparable to early streetscape labeling work by Hara *et al.* [160], where turkers labeled at 67.0% and 55.6% for recall and precision, respectively; however, our tasks are more complex, contain more label types, and are evaluated at a larger scale. Like [160], we also show how assigning multiple labelers can improve results and describe tradeoffs in aggregation algorithms—*e.g.,* by combining labels from five turkers per street, recall rose to 92%; however, precision fell from 69% to 55%. We believe our findings represent a lower bound on performance and provide a nice baseline for future work.

To improve quality, we envision four areas of future work: first, a more sophisticated workflow pipeline that dynamically verifies labels [34, 299], allocates the number of assigned labelers per street based on inferred performance, and integrates other datasets (*e.g.,* top-down imagery). Second, though not explored in this work, our mission-based architecture supports a large variety of diverse mission tasks—*e.g.,* verification missions and ground truth seeding missions, both which will enable us to more reliably identify poor-quality workers. Third, Project Sidewalk currently relies solely on manual labeling; we are experimenting with deep learning methods trained on our 240,000+ image-based label dataset to detect problems automatically (building on [161, 336]), triage likely problem areas, and/or aid in verifications. Finally, our results suggest that many *false positives* could be corrected via improved training (*e.g.,* a driveway is not a curb ramp) and by using simple automated validation (*e.g.,* check for labels in unlikely areas).

4.8.2 Data age

Our interview participants raised two concerns about data age: GSV image age and label age. Towards the former, prior work has found high agreement between virtual audit data of pedestrian infrastructure compared with traditional audits [28, 76, 157, 161, 304, 384]. Google does not publish how often their GSV cars collect data; however, in a 2013 analysis of 1,086 panorama sampled across four North American cities, the average age was 2.2yrs (*SD*=1.3) [161]. In our dataset, workers labeled 74,231 panoramas, which at the time of first label, were also *M*=2.2yrs old (*SD*=1.5). As a comparison, the official opendata.dc.gov curb ramp dataset [94] was captured in 1999 and last updated in 2010 (nine years ago) but this only covers curb ramps (no other label types are included). Our general approach should work with any streetscape imagery dataset, including *Mapillary* [189], *CycloMedia*, or *Bing StreetSide*—many of which are exploring high-refresh methods via automated vehicles and crowd contributions. In terms of maintaining labels over time, one benefit of our scalable approach is that streets can be periodically re-audited and old labels can be used to study historical change (*e.g.,* as initially explored in [269]).

4.8.3 Cost

While future deployments could rely solely on paid workers, ideally Project Sidewalk would also engage online and local communities who are concerned with urban accessibility. Based on our deployment study, we estimate that auditing DC with 100 paid workers alone would cost $34,000 and take 8 days (assuming five labelers/street, 8hrs of work per day, and that 72 of 100 met our "good" user quality threshold). If one-third of DC was audited by volunteers, costs fall below $25,000. However, DC is a large city and has a reasonably well-resourced transportation department with full-time ADA compliance staff; small-to-medium sized cities often lack ADA budgets and could particularly benefit from Project Sidewalk. Indeed, we have been contacted by more than a dozen cities in the US and Canada about future deployments.

4.8.4 Increasing user engagement

While ~63% of turkers who started the tutorial went on to complete one mission, this value was 3x lower—19.1%—for volunteers. To increase user engagement, we plan to explore: (1) supporting smartphones, which will increase the reach of the tool and allow any-time access (*e.g.,* users can complete missions while on the bus or subway). This will hopefully result in more repeated visits and higher mission completion rates (our web logs show nearly 25% of traffic is mobile); (2) providing users with visual feedback about the impact of their contributions (*e.g.,* via accessibility visualizations like [221]); (3) incorporating more gamification principles such as additional mission types (*e.g.,* rapid data validation mini-games, scavenger hunt missions), badges, and leaderboards—all of which have been shown to improve retention in VGI systems [122]; and (4) and better engaging the local community through outreach efforts to pedestrian and accessibility advocacy organizations.

4.8.5 Limitations

There are three main limitations with crowdsourcing virtual audits: panorama age, label quality, and the ability for crowdworkers to see and assess sidewalks from GSV. We addressed the former two points above. Towards the latter, users could mark areas as occluded in our tool (*e.g.,* a truck blocking a sidewalk); however, *occlusion* constituted only 0.4% of all applied labels in our deployment suggesting that most sidewalks are visible. For study limitations, we employed a multi-methods approach to mitigate the effects of any one study technique. Still, longitudinal deployment studies are messy and ours is no exception: we lost over two months of deployment time due to changes in the GSV API, maintenance upgrades to our servers, and personnel changes. For the data validation study, we were unable to consistently reach high α agreement for *obstacles* and *surface problems* during our seven iterative rounds of coding; these label types are challenging and can be legitimately conflated (*e.g.,* marking overgrown grass as a surface problem *vs.* an obstacle). Our performance results for these label types may have been impacted.

Finally, while our studies take place in the US, accessible infrastructure is a global problem. Project Sidewalk should, ostensibly, work wherever GSV and OSM are available. That said, Project Sidewalk's label types were drawn from US ADA standards [358–360], prior work [246, 254], and our previous experience working with US-based stakeholders. While we believe that these label types constitute primary accessibility barriers for people with mobility impairments and are likely relevant to most North American and European cities, more work is necessary to explore mobility barriers in other regions. As we plan future deployments, we will work with local stakeholders to better understand regional contexts, socio-cultural concerns, and unique, localized infrastructural accessibility issues. Project Sidewalk can be updated per region to, for example, add specific label types or instructions for a city.

4.9 Acknowledgements

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4.10 Chapter Conclusion

This chapter introduced a scalable data collection approach for sidewalk accessibility using online streetview imagery and crowdsourcing. For validating this approach, we conducted three studies, including a city-wide public deployment in Washington DC, a data validation study to evaluate data quality, and an interview study with multiple stakeholders to understand their perceived data utility, concerns, and future tool improvements. We also generated the first city-wide tech enabled sidewalk accessibility dataset. Finally, this work forged the path for future deployments in the United States and abroad.

5 AccessVis: Modeling and Visualizing Urban Accessibility

This chapter explores the first application category for utilizing urban accessibility datasets: interactive visualizations. I present a multi-stakeholder analysis of diverse data and assessment needs and sensemaking practices of understanding urban accessibility datasets, with the goal of exploring how interactive visualizations can support stakeholder decision making. I call this project *AccessVis*, named after the preliminary prototype I built for visualizing sidewalk accessibility that inspired this work (Figure 5.1).

For this investigation, I conducted a three-part interview study with 25 participants across five stakeholder groups using map visualization probes. In this chapter, I elaborate how stakeholders' varying levels of familiarity with accessibility, geospatial analysis, and specific geographic locations influences their sensemaking needs. Further, I present 10 design considerations for geovisual analytic tools for urban accessibility communication, planning, policymaking, and advocacy. Finally, I apply this design space to existing urban accessibility visualization tools such as *AccessMap* and *WheelMap*.

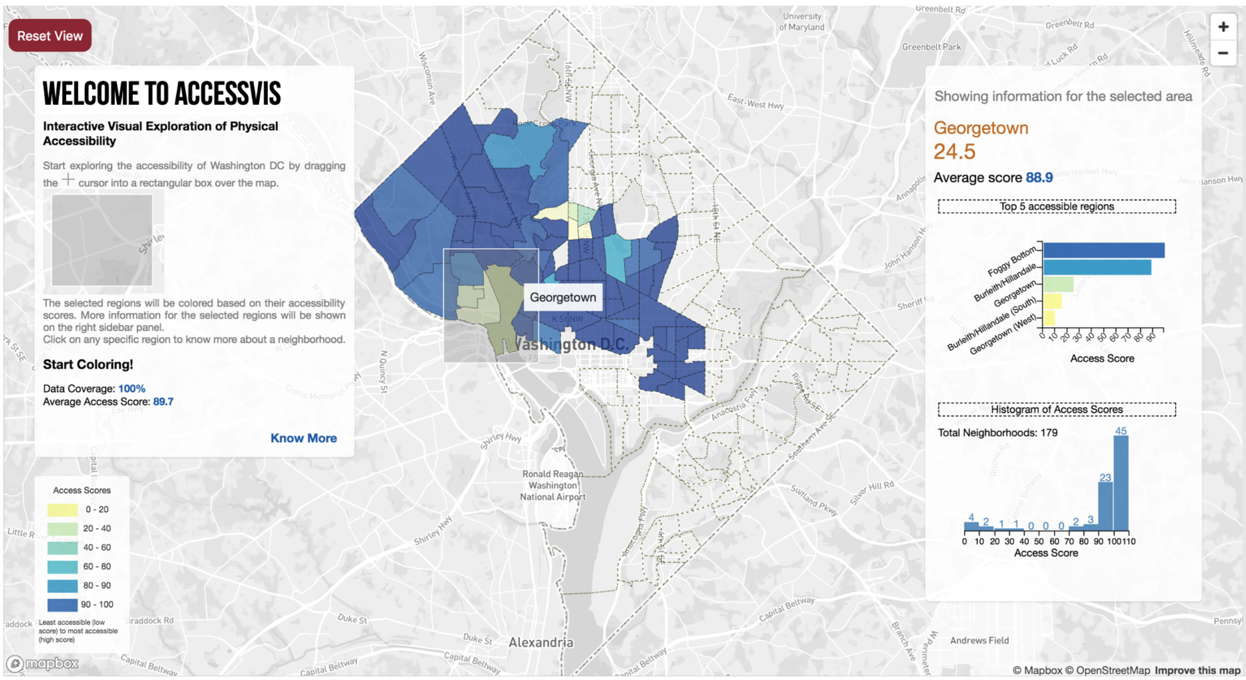

Figure 5.1: AccessVis, a geospatial visualization interface for sidewalk (in)accessibility. AccessVis provides exploration at the high-level via city-wide accessibility visualizations and allows drilling down to explore the raw label data using semantic zoom. The figure shows Washington DC's accessibility at the highest level through a neighborhood based choropleth. The tool allows 'coloring' *i.e.,* drawing a box over an area to find and color based on the neighborhood accessibility score. The complementary sidebar visualizations dynamically respond to user interactions, such as zooming, panning, brushing, linking, hovering, and clicking, to show detailed information on neighborhood(s).

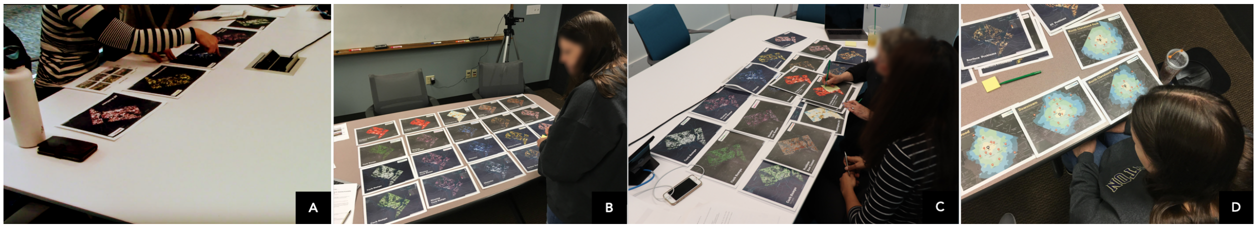

Figure 5.2: Interview setup and three-part study process. Part 1 presents visualization probes with seven map types. Row-by-row we gradually build a 5 x 5 map grid (A & B), where each row shows a different map type. Part 2 involves performing three sensemaking tasks. In (C), a participant completes a task using the map grid. (D) illustrates a task involving three ego-centric isochrone maps. Part 3 critiques map types and gathers opinions for future interactive visualization tools.

5.1 Introduction

A recent UN report notes a *"widespread lack of accessibility in built environments, from roads and housing to public buildings and spaces"* and this lack contributes to and further reinforces systemic inequalities in economic opportunity and access to basic services such as transportation, medicine, and education for people with disabilities [176]. While the open data movement has enabled new types of urban analytics and insights for transportation [349], climate change [77, 78], and public health [165], similar efforts in urban accessibility have been hampered by a lack of data [124]. Towards addressing this problem, new data collection tools such as *Project Sidewalk* [238, 310] and *WheelMap* [380] as well as open data initiatives such as *OpenSidewalks* [341] and *Accessibility Cloud* [6] have emerged, spurring new urban access visualization and mapping tools [51, 220, 319, 380]. While this progress is commendable, little work has characterized how best to visualize urban accessibility datasets across different stakeholders: what are the key visual analytic tasks and data needs (**RQ1**) and how might key stakeholders' sensemaking practices differ (**RQ2**).

To begin addressing these questions, we first developed 24 urban accessibility visualization design probes across seven map types using Project Sidewalk's Washington DC dataset [239, 310]: point visualizations, severity point visualizations, grid maps, heatmaps, choropleth, street visualizations, and ego-centric isochrones. Our designs were informed by prior work in urban accessibility visualizations [51, 124, 158, 380] and support a range of questions and tasks from *"Where are key (in)accessible hotspots in my city and why might this be?"* to *"How does neighborhood X compare to Y?"*. Using the probes to ground discussion and solicit feedback, we then conducted a three-part interview study (Figure 5.2) of five stakeholder groups (*N*=25): local transit officials, policymakers, accessibility advocates, caregivers, and people who use a mobility aid such as a cane or wheelchair (MI individuals). In Part 1, we observed how participants reacted to and made sense of the visualizations while in Part 2, they used the maps to complete specific sensemaking tasks. In Part 3, participants critiqued and reflected on their experience.

Through iterative coding and thematic analysis of the interview recordings, we present findings on urban accessibility tasks and data needs across stakeholders and share observations of the influence of professional role and/or life experience on their sensemaking process. Specifically, personal experience with accessibility, geographic location, and data analysis influenced their sensemaking processes. We find that participants analyzed maps based on personally relevant assessment factors and preferred maps that aligned with their mental model for assessing accessibility. For example, MI/Caregivers preferred localized views of the data (*e.g.,* street level), while policymakers and department officials preferred city-scale views. Participants built confidence when they could personally verify their assessments with other maps. Finally, establishing trust with the data was crucial to confidently interpret and draw insights from the visualizations.

Our contributions, which are situated at the intersection of the accessibility and visualization literature, are three-fold: (1) a multi-stakeholder data and task characterization within a multi-layered task model for urban accessibility visualizations, (2) elaborating the influence of individual differences on sensemaking processes, and (3) a set of 10 design considerations for implications and opportunities for future interactive geovisual analytic tools to support advocacy, policymaking, city planning, and daily living.

5.2 Background and Related Work

I present a background on urban accessibility assessments, metrics, and stakeholders' needs for urban accessibility decision-making followed by prior work in visual analytics and sensemaking.

5.2.1 Urban Accessibility Assessments

Urban accessibility seeks to enable access to opportunities and services while ensuring comfort and quality of experience to people of all abilities [92, 306, 371]. Physical access includes pedestrian infrastructure (*e.g.,* sidewalks), transit (*e.g.,* buses, trains), and Points of Interest or POIs (*e.g.,* buildings and facilities) [109, 154, 306, 326]. In this chapter, we use sidewalk accessibility data to study visualization-based urban accessibility assessment needs. Physical access issues to sidewalks include the presence and absence of curb ramps, surface problems, sidewalk path obstacles, and the availability of sidewalks themselves. The Americans with Disabilities Act (ADA) [360, 361] together with US Access Board [363] provides standards for accessible sidewalks by specifying design requirements. For example, sidewalks must be a minimum 1.5m (5ft) passing width, a maximum 5% grade, and have curb ramps at intersections. Governments conduct field measurements by taking physical instruments such as digital scales to check for ADA compliance.

Beyond physical assessments, digital assessments widely utilize maps for analyzing and communicating urban issues due to their spatial arrangement, visual impact, and perceived credibility [197]. Existing accessibility assessment tools are largely map-based [6, 51, 54, 220, 260, 380] with street- and sidewalk-level views. While these tools offer information on

POI accessibility [6, 380] and customized views of sidewalk accessibility based on mobility needs [51, 220], these tools and visualization types have yet to be studied across different stakeholders. Closest to our work is a design probe-based study that envisioned future accessibility-aware location-based tools for MI individuals [158], where maps played a central role in the resultant designs. We extend that work [158] by studying sensemaking processes and visualization needs across five stakeholder groups using map-based paper prototype probes. We contribute to urban accessibility task and data characterization [268] by elaborating stakeholder goals, tasks, and needs for future geovisual decision support tools.

5.2.2 Quantifying Accessibility: Models, Indexes, and Metrics

For representing multiple assessment factors, map visualizations often aggregate raw data with other factors using models, indexes, and metrics. In this section, I will review some of these accessibility measures from the transportation, urban design and planning, and urban informatics literature.

Accessibility metrics allow benchmarking cities [38, 75, 119], mitigating urban problems (*e.g.,* traffic accidents and pollution emissions [223]), and exploring relationships between urban planning factors such as land-use [129, 156, 373], social equity [67, 222, 377], and sustainability (*e.g.,* use of green transportation [68]). For example, identifying food-deserts for underrepresented communities (*e.g.,* elderly populations) in diverse socio-economic regions (*e.g.,* low-income areas) [323] is a common usage of accessibility-based planning and assessment.

Due to the many definitions of accessibility (discussed in Chapter 2), defining a single precise metric is a widely debated subject [30, 37, 377], resulting into numerous types of metrics and classes [90, 129]. While Geurs *et al.* [129] categorize metrics across four groups—infrastructure-based, location-based, person-based, and utility-based, Bhat *et al.* [37] categorize across five classes: spatial separation, cumulative opportunity, gravity, log-

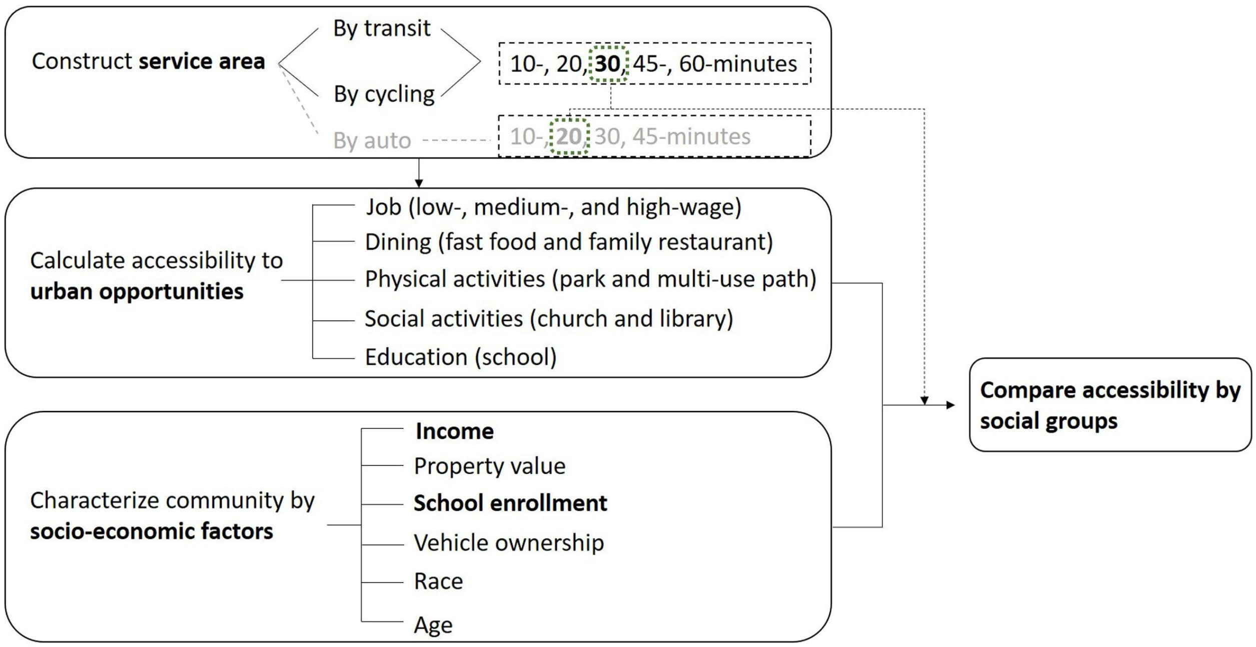

Figure 5.3: Chen *et al.*'s Accessibility Framework [68]. Illustration shows the four components of this model, namely, constructing service area, calculating accessibility to urban opportunities, characterizing by multiple socio-economic variables for comparison with different social groups; with the goal of assessing transportation equity for disadvantaged groups.

sum/utility, and time/space models. According to the Bhat *et al.*'s taxonomy, these models vary by the accounted factors, such as travel mode (*e.g.,* auto, transit), trip purpose (*e.g.,* access to employment, public facilities), time of day (*e.g.,* peak period, average week day), level of service (*e.g.,* Euclidean distance, travel time), and spatial granularity (*e.g.,* zone, node, household, individual).

All these models follow the traditional conceptual framework of accessibility—studying the effects of land-use and transportation systems on access to destinations and services. However, more recent models [38, 67, 186, 222, 223, 377] have looked beyond to socio-economic (*e.g.,* promote equity) and environmental considerations (*e.g.,* promote sustainability) and towards creating 'accessibility profiles' [162]. For example, Chen *et al.* [68] proposed an accessibility framework to evaluate transportation equity using diverse socio-demographic variables for disadvantaged groups, where accessibility is defined as the "number of urban opportunities falling inside each service area" (Figure 5.3). Biazzo *et al.* [38], through the use of isochrones, proposed metrics such as *velocity score*, *sociality score*, and *cohesion score* to measure the performance of transport systems, rank cities according to their overall accessibility, and highlight inequalities across populations; their results are accessible via an interactive vis platform, *CityChrone* [75]. Finally, toolkits such as MIT's Urban Network Analysis [258, 259, 325], part of the ArcGIS toolbox, have made using accessibility indexes more accessible; giving access to graph analysis indexes on spatial networks such as Reach, Gravity, Betweenness, Closeness, and Straightness. These models and metrics enable accessibility visualizations highlight global patterns and differences across cities and relationships to human well-being and environmental impact (*e.g.,* forest loss) [377].

Despite the long history of accessibility indexing of over six decades [37], accessibility metrics considering disability needs are scarce to-date. Within this context, past models' foci were on auto and transit accessibility [316]; however, pedestrian accessibility models are extremely limited [53, 282, 370]. They have ranged from mapping wheelchair users' needs with binary values [282] to pre-defined user profiles for limited user groups [370] to more comprehensive pedestrian mobility profiles [53]. The latest work from Bolten *et al.* [53] propose sidewalk accessibility metrics based on pedestrian mobility profiles within a personalized pedestrian network analysis framework. However, for conducting more comprehensive analysis of pedestrian accessibility within the disability context (*e.g.,* across socio-economic and demographic factors), much more work is warranted.

In this chapter, we present and use AccessScore, a simple parameterizable model to show the impact of sidewalk inaccessibility on the mobility for people with and without mobility disabilities. This model scores regions based on the impact of physical barriers to access important destinations, called as *accessible reach* (described in more detail later). While not as comprehensive as the ones mentioned earlier, the model was sufficient for creating visualizations such as choropleth (Section 5.3.1) and ego-centric isochrones (Section 5.3.2) for the purposes of the design probe study described in this chapter.

5.2.3 Stakeholders and their Decision Making Perspectives

Urban accessibility stakeholders include, people with disabilities, caregivers, occupational therapists, advocates and activists, policymakers, department officials, transit agency officials, and other professionals [209, 306, 366]. These groups, each with their own accessibility perspective, can be divided into two overlapping categories: people who are affected by accessibility issues and people who make or support infrastructure planning decisions and improvements. In Chapter 3 [306], I discussed the decision-making process and needs of five stakeholder groups: policymakers, department officials, accessibility advocates, MI individuals, and caregivers. We found that MI individuals and caregivers prioritize travel safety and quality, and therefore, have localized questions such as *"Is it doing to be a smooth ramp?"* or *"Is the entrance accessible?"*. Policymakers and department officials are concerned with more macro-scale questions related to planning and resource distribution: *"what are the highest priority sidewalks?"* or *"do we invest in new sidewalks or in repairing existing sidewalks?"*. Finally, advocates often act as an intermediate representative body between the government and the citizens to communicate needs and concerns to push for change. The nature of their questions are both investigative and exploratory to aid them in (a) understanding the extent and impact of the problem and (b) analyze effectiveness of remediation approaches to ensure accountability (*e.g.,* investigating a non-compliant curb ramp: *"When was this curb ramp installed? Was it part of this administration?"*). With these needs and perspectives in mind, we study these stakeholder groups' visualization needs for analyzing urban accessibility data.

5.2.4 Making Sense of Visualizations

Russell *et al.* [305] define sensemaking as the *"process of searching for a representation and encoding data in that representation to answer task-specific questions"*. Within geovisual analytics, sensemaking focuses on how people perceive information in geovisualizations and make sense of their inferences [302]. While past work in visual analysis research [291] typically focused on understanding analysts' sensemaking processes, a recent body of work has started studying how non-experts understand, process, and construct visualizations [218, 287]. With the proliferation and wide-scale consumption of visualizations in mass media, especially during the ongoing COVID crisis [217, 396], emerging research is examining visualization use in real world contexts, especially the social and political contexts of visualizations [102, 217, 287]. Our work fits within this growing body of work, where we study visualization use within the urban accessibility context, studying sensemaking processes of multiple stakeholders and the influence of stakeholder differences on their interpretation process of making accessibility assessments.

In this work, we develop an understanding of the sensemaking processes of diverse non-expert stakeholders while performing geovisual analysis for urban accessibility. We specifically study people with little or no professional data analysis experience but have data questions for assessing accessibility. They have indirect interactions with such data-driven visual analyses. For example, policymakers are usually consumers of the visualizations (rather than an analyst) while advocates, who are not analysts by profession, are often involved in geovisual analysis as part of their job.

5.3 Design of Map Visualization Probes

To structure our visualization design work, we drew on common urban accessibility questions identified in the literature [158, 310]: *"where are the most (in)accessible parts of the city?"*, *"which is the most accessible neighborhood to live?"*, and *"why is my neighborhood inaccessi-*

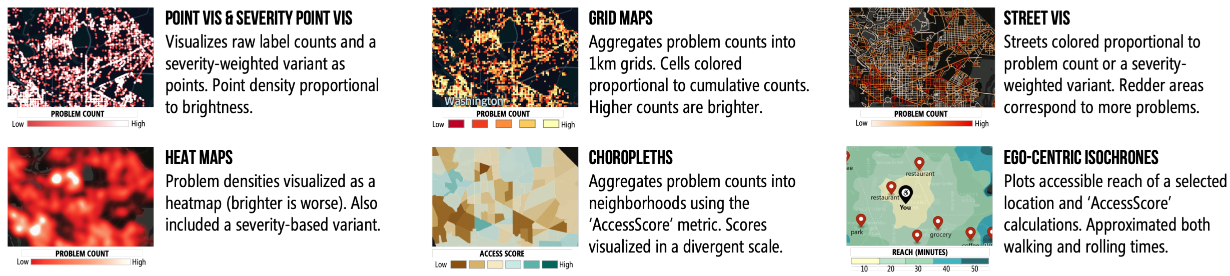

Figure 5.4: Design Probes. Seven map types used in the study. PointVis and SevPointVis are represented in one sub-figure.

ble?". We attempted to create a diverse visualization set that enabled both micro-assessments of urban accessibility such as via point- or street-level visualizations similar to AccessMap [51] as well as more holistic analyses via heatmaps using Inverse Distance Weighting method for spatial interpolation and Gaussian distributions [169], choropleths using *AccessScore* metric [220] and ego-centric isochrones using *BarrierTimePenalty* metric described next.

Dataset. All visualizations were created using Project Sidewalk's open sidewalk data from Washington DC [239, 240, 310]. The DC repository consists of 250,000+ geo-located sidewalk annotations identifying and assessing curb ramps, missing curb ramps, obstacles, and surface problems. Each label is annotated with a severity assessment on a 5-point Likert scale (5 – most severe) and optional open-ended descriptions.

5.3.1 Access Score

When creating *AccessScore*, we had three key design tenets. First, while urban accessibility visualizations would be useful to urban planners, government workers, and other audiences, our primary target community are MI individuals. Second, based on our formative work [158], the system must adapt to individual mobility needs. Finally, the visualizations and underlying model should incorporate the proximity to and priority of destinations (similar to *walkscore.com*).

The *AccessScore* model discretizes a city into a grid of equally-sized rectangular cells. For each cell, we compute an accessibility score by, first, using the Google Maps Directions API to find the n nearest points of interest corresponding to p categories (*e.g.,* library, park, restaurant). We then request a pedestrian route to each destination ($n * p$ destinations in total) from the cell's center and score these routes based on the accessibility data from Project Sidewalk. For each accessibility feature along the route (*e.g.,* curb ramp), we add a weight c and for each sidewalk barrier (*e.g.,* missing curb ramp), we subtract a weight d. The two weights can vary depending on the given accessibility feature, severity, and end-user customizations. We also apply a cost penalty as a function of distance (from [331]). Finally, accessibility scores are normalized based on route length.

5.3.2 Barrier Time Penalty

Barrier Time Penalty is a delta time estimate for a person in a wheelchair to reach a particular destination or travel within a neighborhood given the sidewalk barriers. This penalty score is used to create ego-centric isochrones showing physical access differences between people with and without mobility disabilities. The same set of pedestrian routes to destinations from the *AccessScore* algorithm is used as the origin route pool. The sidewalk problems identified via Project Sidewalk and elevation changes along a route are incorporated to compute this score. In theory,

$$ActualTravelTime = EstimatedTravelTime + \boldsymbol{BarrierTimePenalty}$$

where, $BarrierTimePenalty = ProblemPenalty + ElevationPenalty$.

Problem Penalty. If there are n sidewalk problems within a collection $\{p_i\}$ (*e.g.,* within 12 meters of a route or street segment) then p_i is a problem of some type that has significance w_i and severity s_i. The *Problem Penalty* for a route or collection of problems in a neighborhood is given by

$$ProblemPenalty = \sum_{i=1}^{n} w_i * s_i$$

Elevation Penalty. Elevation changes along a route are computed at point locations along the street centerline every 100 meters. If e_i is the elevation in meters at point i along a route, then $slope_i = (e_{i+1} - e_i)/100$ is the slope between consecutive points. Then the *Slope Cost* for a slope in $\{slope_i\}$ is given by

$$SlopeCost_i = \begin{cases} 0, & if slope_i \leq 0.05 \\ 4 * (3 + 100 * |slope_i - 0.05|), & if slope_i > 0.05 \end{cases}$$

The value 4 was selected as the significance of slope changes greater than 5% (based on ADA requirements [47, 48, 114]), and 3 was selected as the base severity level. Notice that severity level increases by one for each percentage point the slope is above 5%. For example, if a given segment had a slope of 0.07, then the actual severity of the slope of this segment would be $3 + 100 * |0.07 - 0.05| = 5$. However, the severity of a segment with slope less than 0.05 (*e.g.,* 0.04) would be 0.

These slope costs are aggregated by summing the slope costs of each segment j along a route. If there are m segments along a route, then the *Elevation Penalty* is computed as

$$ElevationPenalty = \sum_{j=1}^{m} SlopeCost_j$$

Finally, to compute $BarrierTimePenalty$, we sum $ProblemPenalty$ with $ElevationPenalty$,

$$BarrierTimePenalty = \sum_{i=1}^{n} w_i * s_i + \sum_{j=1}^{m} SlopeCost_j$$

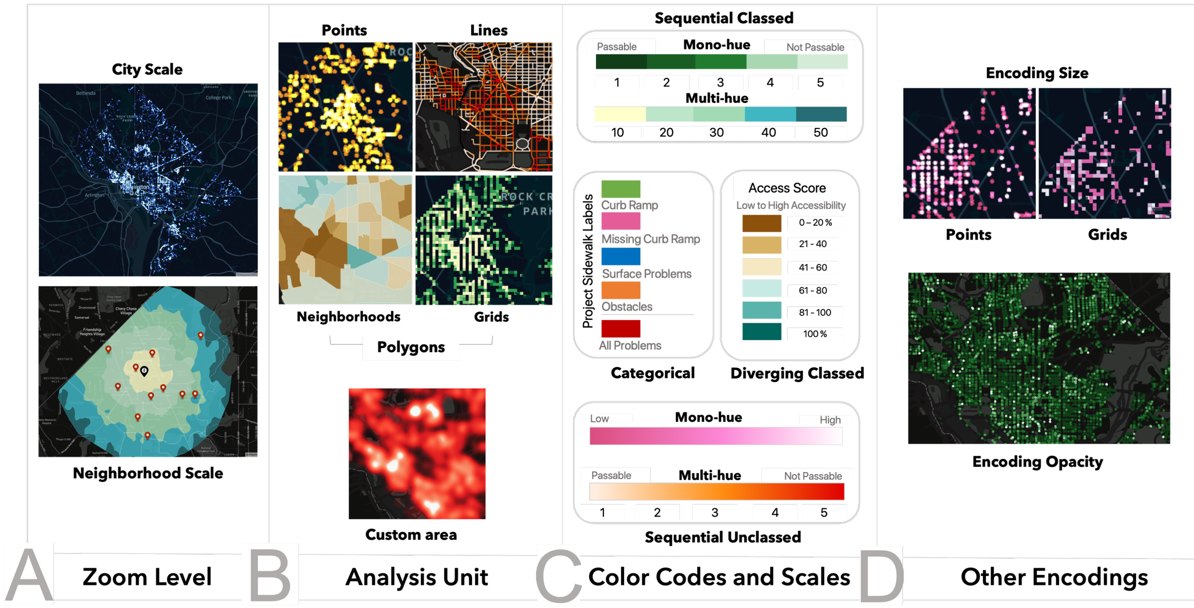

Figure 5.5: Design Dimensions of Map Probes. A. Zoom Level, B. Analysis Unit, C. Color Codes and Scales and D. Other Encodings (*e.g.,* size and opacity). For the accessibility label categories, we used Project Sidewalk's color palette [239, 240, 310] as color codes.

5.3.3 Design Space Dimensions

Through iterative design amongst our cross-disciplinary team and informed by the geovisualization and cartography literature [15, 57, 97], we distilled a guiding set of design dimensions (Figure 5.5): *zoom level*, *analysis unit*, *color codes and scales*, and *other encodings*.

Zoom level describes map data at two different zoom levels: *city scale*, which are full maps of DC, and *neighborhood scale*, which visualize a zoomed-view of a specific neighborhood.

Analysis unit refers both to how the underlying sidewalk data is aggregated as well as how it is expressed on a map. For example, point visualizations render the frequency of a sidewalk label as small as 2px circles, grid maps and street visualizations render cumulative aggregated counts, and heatmaps visualize density clusters.

Color codes and scales. To visualize raw problem counts and severity-weighted variants, we used mono-hue gradients. Aggregated views such as grid maps and choropleths used discretized multi-hue color schemes denoting low-to-high problem areas. For some map types, we created multiple visualizations—one per sidewalk assessment type. Here, we used Project Sidewalk's color palette [239, 240, 310]: curb ramps (green), missing ramps (pink), surface problems (orange), and obstacles (blue). To emphasize problematic areas, we used a black background with bright problem clusters [251, 315].

Other Encodings. The size of map elements such as points or grids were chosen to facilitate comparison across map types. For point maps, where overplotting is common, we used opacity to convey point density.

5.3.4 Final Urban Accessibility Design Probes

For our interview study, we ultimately created 24 map-based visualizations across seven map types (Figure 5.4 and Figure 5.6): point (*PointVis*), severity point (*SevPointVis*), grid (*GridMaps*), heatmaps (*Heatmaps*), choropleth (*Choropleth*), street (*StreetVis*), and egocentric isochrone (*Isochrones*). The maps are situated in different points in our design space utilizing unique aggregation models, visual encodings, and zoom levels and also reflect emerging prior work in urban accessibility visualizations [51, 124, 158, 380]. For *PointVis*, *SevPointVis*, and *GridMap* visualizations, we created five individual maps—one map for each label type (*e.g.,* obstacles, surface problems) as well as an aggregate map for all problems. To create the visualizations, we used Project Sidewalk's DC API [1] and geospatial mapping tools–Mapbox, kepler.gl, and QGIS [195, 242, 295]. To simplify technical map names, in the interviews, we used the terms "area map" for choropleth and "time plot" for Isochrones. While all designs were presented as paper prototypes, our findings are intended to inform the design of future interactive visualizations.

[1] dc.projectsidewalk.org/api

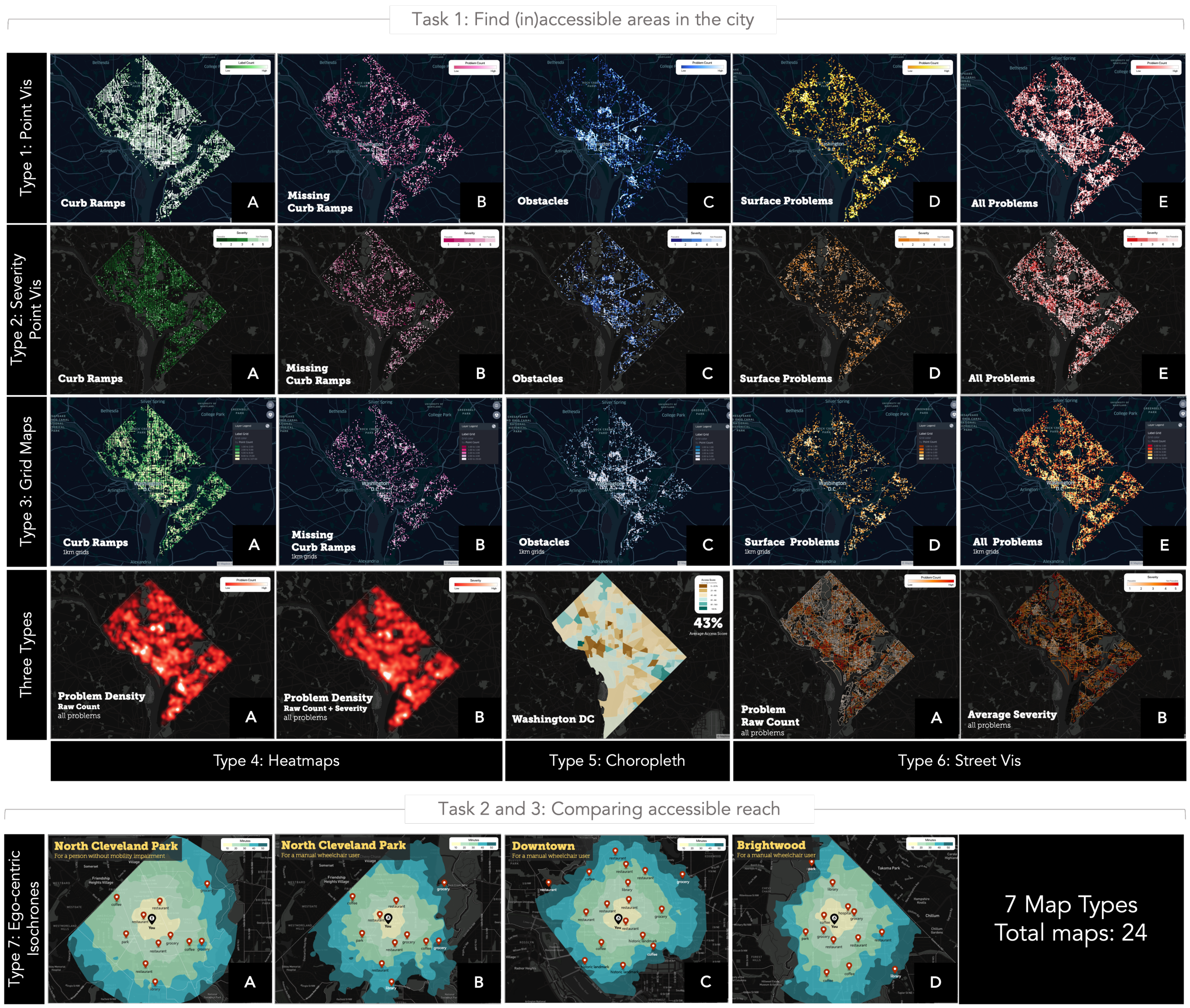

Figure 5.6: Illustration showing the 5x5 map grid of 24 prototypes across seven map types. High-resolution images are available in Appendix A.

5.4 Interview Study

5.4.1 Study Methodology

To investigate our primary research questions on understanding visual analytic tasks and data needs (**RQ1**) and individual differences in sensemaking processes across stakeholder groups for urban accessibility (**RQ2**), we conducted a three-part interview study with the 24 paper-based map visualizations (Figure 5.2). In Part 1, we observed how participants reacted to and made sense of the visualization; in Part 2, they used the maps to complete specific sensemaking tasks; in Part 3, participants critiqued and reflected on their experience. Study sessions lasted 1.5–3 hours and were audio and video recorded. We provided compensation of US$25/hour and up to US$30 for transportation costs. Interviews were conducted by the first author, and the study was conducted as part of a larger interview study with the same participants. During all study parts, participants were asked to "*think aloud*."

Part 1: Initial Exploration of Visualizations. In Part 1, we studied cross-stakeholder similarities and differences in how participants initially reacted to and interpreted the map visualizations. Specifically, we studied *exploration*, *sensemaking*, *interpretation* practices, and solicited feedback on perceived *usefulness* and *desired features*. A secondary goal was to familiarize participants before the sensemaking tasks in Part 2. To begin, we first introduced Project Sidewalk and the collected data then sequentially introduced each map type by building a row-by-row visualization grid (Figure 5.6) on a large table surface. For each row, participants were asked: *"What do you learn from these visualizations?"*. While the order of the seven map types was kept the same across all participants, the rows closest to the participant (Figure 5.2) were randomly changed across participants.

Part 2: Visual Sensemaking Tasks. Next we sought to understand *sensemaking* processes with respect to a task: how do participants use the visualization(s) to answer task questions and why use specific visualizations? We asked participants to perform three sensemaking tasks: one *"find"* task and two *"compare"* tasks. These tasks, which were derived from the literature [158], require participants to assess overall city accessibility, compare accessibility of regions (such as neighborhood/locale), and compare the accessible reach of individuals. They represent common tasks for assessing and prioritizing infrastructure improvements and/or for informing travel decisions.

In Task 1, we asked participants to "find the *three most accessible* and *three most inaccessible* areas in the city" using any of the city-level maps (Figure 5.6: Types 1–6). Participants marked identified areas using Post-Its (Figure 5.2: sub-figure C) and were asked to explain their rationale. For Tasks 2 and 3, we used Isochrones (Type 7 in Figure 5.6). Here, participants compared the *accessible reach* of an individual [2]. In Task 2, participants compared the accessible reach of individuals with and without mobility impairments (Figure 5.8). In Task 3, participants compared selected neighborhoods (Figure 5.9) and were asked to select the most accessible neighborhood for a family member using a manual wheelchair. After each task, we asked: (1) What aspects of the selected visualization helped answer the question? (2) Was there any missing information? (3) How did they envision using these visualizations in their personal or professional lives?

Part 3: Critique and Reflections. Participants critiqued and reflected on their experience by discussing the perceived utility and limitations of the map types, rated the usefulness and trustworthiness of each, and stated their map preferences. We then solicited design recommendations for interactive visualization tools.

5.4.2 Participants

We recruited 25 people (11 female) aged 25–72 (*Mean*=48.3, *Median*=45, *SD*=14.5) across five stakeholder groups: six department officials (D), eight accessibility advocates (A), four policymakers (PM), seven people with mobility impairments (M), and five caregivers (C). Five participants identified with two stakeholder roles (*e.g.,* P4 and P20 both identified as advocates and caregivers) and were interviewed from both perspectives. Department officials included employees from city departments of transportation (DOTs) and other related government organizations. Policymakers were either elected officials or their legislative staff members. Advocates worked as active disability rights advocates either as paid employees or

[2] For tasks 2 and 3, *accessible reach* is defined as an area that can be covered by a person within the existing sidewalk barriers, specifically characterized as POIs that are within reach and how far are they from a given location

volunteers. MI participants used a mobility aid such as a wheelchair or a cane, and caregivers took care of an MI individual either as a professional, family member, or friend. During recruitment, we asked MI participants if they used a mobility aid and to describe their disability. We provide a description of all participants in Appendix A. Only one participant had a professional data analysis background. Participants were recruited from three cities: Washington DC (N=5), Seattle (N=19), and New York (N=1) via mailing lists, word-of-mouth, social media, and directed emails. All interviews were conducted in person in the participants' respective city. We refer to participants by 'P' suffixed by their participant number and stakeholder group [D | A | PM | M | C].

5.4.3 Analysis Method

We audio and video recorded the interviews and analyzed the data in two phases: (1) through iterative coding and thematic analysis [56] to identify common themes and (2) through video analysis to study how the five groups performed the sensemaking tasks.

For the first phase, four researchers independently open coded two participants' data—interview transcript and video—to generate initial codes. Next, we used affinity diagramming [211] on these codes to create a codebook followed by collaboratively coding the videos and transcripts of one participant using it. Codes covered the sensemaking practices used, insights learned, envisioned usage of those insights, confusions and challenges faced, map inspired new analysis questions, and desired features for future interactive tools. We coded nine participants across all coders to form the codebook before splitting the rest to code independently. During the process, new codes were added if required and all coders were updated.

For the second phase, the first author went through all the videos and conducted a part-by-part analysis of the study sections. The researcher made notes on the sensemaking processes and their responses to individual interview questions and conduced a stakeholder analysis analysing the similarities and differences between stakeholder groups. The sensemaking process analysis involved going over the study video to notice how they used the maps such as combining maps to answer questions, pointing at certain areas of the maps, and reasoning about them. For the analysis and reported findings, we combine MI individuals and caregivers (MI/Caregivers) into one group as their data/tool needs were similar.

5.5 RQ1: Task and Data Needs

To address *what are the key visual analytic tasks and data needs* (RQ1), we summarize participants' comments across the study on desired data and map usage for different decision contexts. The analytic task and data needs are represented and combined in a multi-layer task model for urban accessibility analysis (Figure 5.7).

Across stakeholders, participants wanted to use interactive maps for planning travel, city planning and policymaking, supporting civic interactions, and advocacy. While MI/Caregivers primarily talked about *navigability*, policymakers, department officials, and advocates talked about sidewalk network *connectivity* and *livability* for investment decisions. To inform resource prioritization, stakeholders wanted to perform *impact analysis*—impact of (in)accessibility on quality of life such as healthcare, jobs, and housing and *equity analysis*—equitable access to resources and physical infrastructure across diverse populations and geographic regions. An example analysis question was *how does accessibility of low-income areas compare with high-income areas?*. Beyond prioritization of resources, department officials described using maps for communication and citizen engagement, while advocates envisioned them as a persuasion and accountability tool to visualize equity issues: *"You know that not all neighborhoods are created equal, so being able to show that view of the world is a useful tool, especially when places have goals that say they want to do the right thing"* (P11A). These analytic tasks are represented as macro goals, analysis strategies, and micro tasks in Figure 5.7: Analysis Task Needs.

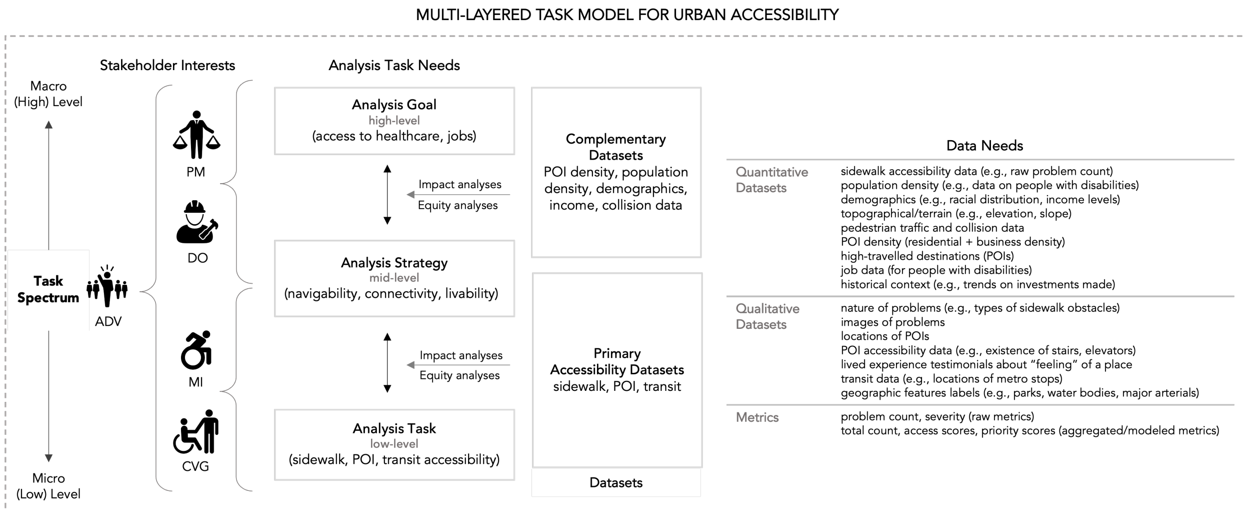

Figure 5.7: Mapping Stakeholders' Analysis Task and Data Needs into a Multi-layered Task Model for Urban Accessibility. The analysis needs are on a task spectrum, spanning from low-level micro tasks such as determining sidewalk (in)accessibility to high-level analysis tasks such as assessing healthcare access based on physical infrastructure conditions. The analyses occur at specific levels or across multiple levels (*e.g.,* equity analysis). 'Stakeholder Interests' represent stakeholders' primary focus and overlapping task needs: MI/Caregivers (MI/CVG) operate at low to mid levels, policymakers (PM) and department officials (DO) at mid to high, and advocates (ADV) across the spectrum. Note: The represented needs are not an exhaustive list, but reflect our participants' key tasks, strategies, and data needs. Icons from the Noun Project [275–279].

Participants mentioned various assessment factors have to be balanced across these decision-making contexts: *"I feel like I understand the map. The question is what am I willing to compromise?"* (P4C, a caregiver). The assessment factors ranged from disaggregated sidewalk problems (*e.g.,"I want to know how many of these obstacles are parking signs? Utility poles?"*–P23PM) to destinations, transit, and routes (*e.g.,"What this isn't telling me is where I can and cannot get through"*–P21D) to experiential (*e.g.,* travel safety) and socioeconomic factors. For example, policymakers and advocates wanted to perform equity analysis and analyze correlations with socioeconomic factors such as demographics (*e.g.,* where people with disabilities lived), population, and business density: *"I want to be able to look at it by tract or zip code or some other defined district and probably in multiple ways. I want to look at population data. These [all maps] are fantastic for outreach with our programs and our advocacy. They also are suggestive of solutions."* (P24A). These factors are categorized across quantitative and qualitative measures (Figure 5.7: Data Needs).

We map the identified analytic tasks and data needs into a multi-layer task model to demonstrate the observed analysis workflow and how these needs overlap across stakeholders (Figure 5.7). Participant tasks are mapped on a spectrum as high-level (macro) analyses goals, mid-level strategies, and low-level (micro) tasks. Depending on the task, analyses occur at either a specific level such as the low level task of determining sidewalk (in)accessibility and associated causes or across levels such as equity analysis using mid-level assessment strategies such as connectivity analysis and complementary data such as regional income levels. For example, an advocate requested: *"I would want to look at home ownership income and education level by zip code, and see if those zip codes intersect with where the problem counts are high, and the severity is the least passable, or perhaps see if there is an intersection there"* (P15A). The stakeholder groups' primary tasks are at specific levels with some overlapping (shared) tasks (Figure 5.7: Stakeholder Interests). MI/Caregivers' primary tasks were between low to mid level, policymakers and department officials were usually at high-to-mid level, and advocates' were across the entire task spectrum. For example, policymakers and department officials talked about sidewalk network connectivity breakdowns as assessment strategies to perform impact analyses.

5.6 RQ2: Sensemaking Practices

To examine *how sensemaking practices differ across stakeholders* (RQ2), we summarize observations across the open-ended map explorations (Part 1) and targeted visual analytic tasks (Part 2). We describe map use and present contributing factors for map preferences and trust in visualizations, supplemented with participants' Likert Scale ratings on each map type's utility and trustworthiness.

5.6.1 Task Analysis: Open and Targeted

Across both open exploration and targeted tasks, we report on participants' sensemaking processes for map understanding and usage for addressing the task prompt, challenges, and desired information.

Participants followed the sensemaking loop model. During open exploration, participants utilized the *bottom-up* processes of Pirolli *et al.*'s model [291] by building theory from data where sensemaking processes involved reading and extracting patterns and building a case for determining (in)accessibility. In contrast, participants employed *top-down* processes [291] for Task 1, namely searching for relevant information, relations across maps, and supporting evidence for self-evaluating assessments. Further, participants used 'tasks' as a sensemaking framework during Task 1: *"I'm trying to think of what my task is. Whether it's like to live there or to be there"* (P4C, a caregiver). Using a higher-level task as a "frame" to determine an area's (in)accessibility aligns with Klein *et al.*'s [201] data-frame theory of sensemaking, where the selected task is the mental frame within which sensemaking processes are performed. Policymakers and department officials adopted a prioritization of resources and investment decisions framing while MI/caregivers and advocates used navigability and livability. This layered approach is captured in the previously described task model (Figure 5.7).

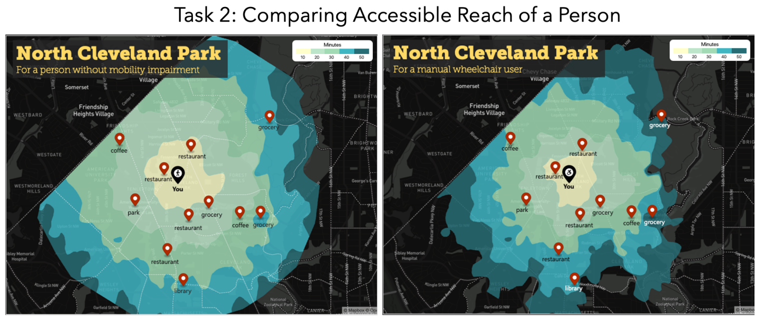

Figure 5.8: Isochrones used for Task 2: Comparing accessible reach of a person. The task is to compare the accessible reach of two individuals: one with a mobility disability (in this case, a manual wheelchair user) and an individual without mobility disability. Illustration shows the accessible reach for both individuals for a specific point in DC's North Cleveland Park neighborhood.

In line with prior work [217, 287], personal experiences drove sensemaking. We identified three influential factors: (1) a participants' relationship with sidewalk accessibility as a function of their lived and/or professional experience (*Accessibility Familiarity*); (2) previous experience with analyzing map-based visualizations (*Map Familiarity*); and (3) familiarity with the city (*Location Familiarity*)[3]. For example, those familiar with map types immediately started reasoning about the identified patterns (*e.g.,* causes of high inaccessibility) based off their prior knowledge: *"It looks like there's a high density of obstacles. I could imagine the sidewalks are really narrow in Georgetown, so I could imagine there being a utility pole or something in the middle of the sidewalk"* (P3GC, non-DC department official speaking based off prior visits to DC). Individuals with personal experience of disability analyzed maps based on their lived experience: *"From my perspective, even a severity of three, I can manage there. But once we get up to five, then that's a huge problem. So on this [PointVis], it looks really, really bad, and on this [SevPointVis], it still looks pretty bad"* (P1M, a motorized wheelchair user analyzing obstacle maps across both map types). Participants

[3]Six participants were Washington DC residents and three had visited or were otherwise familiar with DC.

familiar with map-based analysis focused on searching for specific insights: *"what I'm looking for here [StreetVis] is not just redness, but the distribution of redness across a particular area as it connects to other red markings."* (P7AC, an advocate analyzing connectivity).

Contextualizing patterns was a core sub-task and need. All groups wanted to know the *"why"* behind the patterns seen: *"I don't feel like I can say anything about what is the cause of having it take the person longer"* (P4C, a caregiver during Task 2). Participants suggested contextualizing identified problem hotspots with quantitative data such as problem count, demographics as well as qualitative information (*e.g.,* problem images): *"There is a lot of problems highlighted in this area. It makes me wonder if that area has a lot of people of color who are disabled."* (P15AM, a black advocate interested in assessing racial inequities). Participants emphasized showing *personally* relevant information: problem locations (geo-context), problem types (identity context—*e.g.,* identifying utility pole from a water hydrant), reason for problems (root cause context), and what is harder to repair (remediation context): *"Adding a curb ramp is changeable. [...] [In contrast,] moving a telephone pole is really hard. [...] There are many, many agencies that have to approve that. So it would be interesting to find a way to assess the remediation possibility."* (P2M, an MI individual who assisted government agencies on accessible infrastructure). Unfamiliarity with the city's geography, makeup, and history with accessibility investments hindered analysis for policymakers as these external geo-contextual factors played key roles in drawing conclusions and making funding decisions. For Tasks 2 and 3, participants requested information on land topography (*e.g.,* elevation), underlying street grids, and important POIs.

Participants weighed metrics to determine *personally* relevant assessment factors. To pick (in)accessible areas in Task 1, participants weighed metrics such as problem count and severity based on what accessibility meant to them. An advocate explained her preferred quality of travel experience with her choice of low severe problem count over high problem count: *"I'd rather have the one big leech bite [high severity, low problem count] than the 100 mosquito bites [low severity, high problem count]"* (P15AM). Similarly, participants weighed label types against each other: missing ramps are a prime candidate for repairs (*e.g.,* for department officials) while obstacles are dealbreakers for navigation (*e.g.,* for MI/Caregivers). Depending on one's relation with accessibility, the metric combination varied.

Accounting for the diversity of accessibility needs across MI individuals was key. Accessibility assessments being a deeply personal problem manifested as participants found existing qualitative measures like severity useful but limited. While some participants expressed that severity added a nuanced information layer (*e.g.,* more problems does not always lead to an inaccessible path), others pointed out that severity is a subjective measure: *"Severity is in the eye of the beholder, or the eye of the traveler"* (P7AC, a caregiver) and *"people will have different ideas on what severity means to them"* (P10M, a cane user). During tasks 2 and 3, participants noted differences in accessible reach depending on a person's mobility profile, such as their pace and and functional status: *"I bet it's [accessible reach] even smaller than this when you consider functional status, meaning one uses a manual chair, but one is in excellent condition and doesn't have any other limitation in terms of upper body or fatigue. Because then what looks like 10 minutes is way longer because you've got to stop and rest."* (P24A, an advocate).

5.6.2 Map Types: Usefulness and Preferences

All groups wanted access to multiple map types to view the data from different perspectives and serve diverse audiences and decision contexts. Participants evaluated maps based on comprehensibility, comprehensiveness, and perceived utility for different contexts. In terms of self-reported usefulness, the top three map types were StreetVis (*Median*=5, *SD*=1.16), Isochrones (*Median*=4.5, *SD*=1.2), and SevPointVis (*Median*=4, *SD*=1.22). StreetVis and Isochrones were useful—especially preferred by MI/Caregivers and advocates—for their ability to inform travel decisions and equity advocacy. Below, we unpack contributing factors to a map's interpretability, utility, and preference.

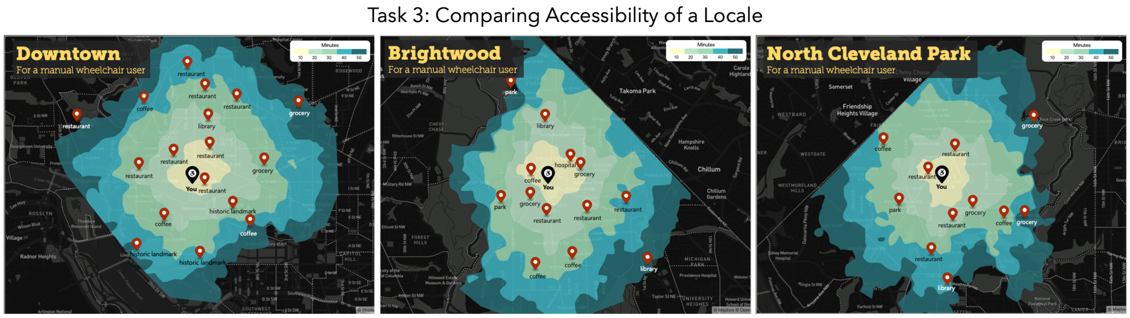

Figure 5.9: Isochrones used for Task 3: Comparing accessibility of a locale. The task is choosing the neighborhood with the most accessible neighborhood in terms of accessible reach for a manual wheelchair user. Illustration shows the three neighborhood maps used for comparing accessible reach.

Perceived utility aligned with how well a map supported existing mental models. Department officials preferred GridMaps and StreetVis because of the maps' close alignment with their mental model of sensemaking: GridMaps for its normalized data representation and StreetVis for streets as an analysis unit, both of which were commonly used in their jobs. MI/Caregivers focused on highly-localized problems such as the navigability of routes confined to specific areas (*e.g.,* neighborhoods, streets): *"I'm kind of wrapping my head around the fact that this is a global assessment versus usually my needs are very localized. And so from that perspective, this feels more like a data analysis task than really a problem assessment task. Because whenever I'm going someplace, it's highly context specific"* (P4C).

Stakeholder's decision context influenced map choices. A department official summarized a map's usefulness with respect to the ease of making individual decisions: *"What's most useful about the point maps, or the street map, or the zoomed in area map, is it allows me to begin to make individual choices about where I'm going to walk or route today. Or where I'm going to choose to make investments."* (P3DC). An advocate (P14A) preferred Heatmaps when acquiring investments and StreetVis when convincing MI/Caregivers with granular information like routes between A to B. Choropleth with access scores brought a sense of competitiveness that is useful as a persuasive political tool. Policymakers and advocates discussed Isochrones' wide utility from analysis to communication: understanding the impact of socioeconomic factors on MI individuals' navigability and neighborhood liveability, identifying points of change (*e.g.,"translating general feeling that we know to be true into [...] actual points of change"*—P23PM), and communicating with policymakers and civic groups. In contrast, all department officials acknowledged Isochrones' usefulness in guiding others while expressing limited personal utility due to insufficient specificity for city planning.

The analysis unit influenced map usefulness based on information granularity. Extending past work [158], the analysis unit (*e.g.,* points *vs.* grids *vs.* neighborhoods), referred as "location precision" in Hara *et al.* [158], influenced the information granularity and eventual usefulness towards decision-making tasks. For example, P3DC gave low ratings to Heatmaps, Choropleth, and GridMaps because of lower information granularity. Despite the ease of use, Choropleth was not preferred because of conflicting insights relative to other map types. The difference was due to the chosen analysis (aggregation) unit of neighborhoods *vs.* a much smaller area (*e.g.,* 1km grids) for PointVis, SevPointVis, HeatMap, GridMaps, also known as the Modifiable Areal Unit Problem (MAUP) [389, 390].

Participants preferred maps with experiential context. Policymakers preferred maps that conveyed the experiential context such as what an accessible path would look/feel like. For example, Isochrones to *"get a more dynamic change of what you're seeing [on the ground]"* (P17PM) and StreetVis as *"it is just more visceral because you can see the grid. [...] I want a presentation to be able to put someone in the mindset of someone who's in a wheelchair or blind or having a special mobility need"* (P18PM). A policymaker (P17PM) suggested showing PointVis coupled with the GSV problem image and associated severity as an effective way of visualizing experiential data.

Stakeholder Task	Primary Unit of Analysis	Low Level data		High level data	Context of Use (envisioned usage)
		Quantitative	Qualitative	Metrics / Trends	
Equity analysis	city neighborhood street	problem count income data past investments	demographics	temporal trends historical trends equity scores	Investment decisions Persuading public officials
Connectivity analysis	neighborhood street	problem count	severity POI locations issue images	priority scores distribution of "badness"	Informing policy Guiding MI individuals Persuading public officials Resource prioritization
Navigability of routes	street	problem count	severity issue images	temporal trends priority scores	Finding accessible routes Guiding MI individuals Persuading public officials Resource prioritization
Livability of neighborhoods	neighborhood street	pop. density business density	POI locations	historical trends	Guiding MI individuals Persuading public officials Resource prioritization

Policymakers · Department Officials · Advocates · MI/Caregivers

Table 5.1: Characterizing key stakeholder tasks. We adapt the design space dimensions of Schulz *et al.* [317]. Individual task cells are marked with stakeholder color markers to show tasks shared across groups. Note: This is not an exhaustive list; we represent a selected set of tasks mentioned by participants.

5.6.3 Trustworthiness of Map Visualizations

Overall, *trust in the underlying data* and participants' *ability to interpret the metrics and maps* primarily drove trustworthiness. Participants who rated trustworthiness low (≤ 3) or refused to rate it (N=2), wanted to know more about how the data was collected, how it was aggregated and modeled, and desired to personally confirm learned insights with on-the-ground reality (*e.g.,* field work). Some participants were skeptical about relying on crowdsourced data: *"I don't know who did this"*—P20AC who rated 1 for all maps. In contrast, participants rating high (≥ 4) talked about having belief in the researcher, work, and the scientific methods used to generate the data and maps.

Information on the visualized data establishes trust. In line with the *disclosure* principle [102], participants suggested showing stronger ties to the underlying data to establish trust in the data, visualization, and gained insights. For example, algorithmic understanding of access scores, data collection method (*e.g.,* relative to ADA standards) and frequency, and impact of user bias on collected data: *"Did they annotate all the issues or just the ones they happen to care or know about, [...] but then didn't bother with other things?"* (P7AC). Underlying numbers and quantities such as sidewalk measurements (for ADA compliance) increase trust in the resultant analyses for decision-making and communication: *"As a district, state and local government, we need to be clear because the requirement by the law is to have the numbers. [...] Even though you can see it's wrong, you still need the numbers [sidewalk feature measurements] to confirm."* (P22D, a department official).

Ability to triangulate across map types and reaffirm inferred insights helped establish trust. Participants mentioned the ability to confirm their insights from other maps (*e.g.,* maps agreeing with each other) and prior knowledge: *"The areas that I am personally familiar with and I know to be problems in general showed up as problems here. So that makes me trust the areas that this highlights as problems that I'm maybe not so familiar with."* (P23PM). Corroborating prior work showing progressive disclosure via semantic zooming to assess data trust [71], participants suggested using interactivity to probe the raw data: *"If you have a heat map and you click in and it changes to, "Cool, I see streets." And you can click on a street segment and you can see what the problems are, maybe it shows you the three missing curb ramps and the obstacles and stuff. Something like that would allow me to trust it."* (P14A).

Influence of data/information granularity on trust varied based on relevance to the individual. For example, P24A trusted StreetVis because *"of how granular it is"* and PointVis for its strong association with the raw data: *"when you show a dot it's a specific problem. When you show a cluster of dots, it's very specific"*. In contrast, a policymaker P17PM did not trust PointVis because of lack of *desired* information granularity to understand the *"why"*: *"I just don't know what this is telling me. I feel more comfortable at this scale [city level] aggregating things"*. However, aggregation in GridMaps reduced trust for an advocate P7AC:

"amassing all of that[data] into some kind of generalized area, not score, but cumulative, is even more opaque. I'll reduce the trustworthiness for that reason".

5.7 Discussion

Our interview study indicates that assessing urban accessibility requires multi-faceted analysis across diverse factors, ranging from quantitative measures (*e.g.,* problem count and severity) to qualitative concerns (*e.g.,* POI accessibility and lived experiences). We explored stakeholders' sensemaking processes through both open-ended and targeted exploration of map-based accessibility assessments. Through these tasks, we learned about individual differences in stakeholders' sensemaking processes and visualization needs. We reflect on these findings and present design implications for future interactive geovisual analytic tools for urban accessibility.

5.7.1 Assessing and Quantifying Accessibility

Q1: *How do we handle the diverse assessment factors needed across varied decision-making contexts for urban accessibility? Do we need separate tools for each context?*

Earlier, we mapped our participants' key analytic tasks into a multi-layered task model (Figure 5.7) where tasks ranged from low-level tasks such as assessing sidewalk accessibility to high-level tasks such as analysing access to healthcare. Table 5.1 breaks down these tasks at various levels into their individual data needs and envisioned use. Since these high level analyses can be performed in different ways, Table 5.1 represents one possible task analysis breakdown. For example, a policymaker's task of assessing the impact of sidewalk (in)accessibility on connectivity helps evaluate the impact on other aspects of life such as employment or healthcare. These interdependencies serve as a useful tool for policymaking, advocacy, daily living, and subsequently impact prioritization of resources by city departments. The task model (Figure 5.7) helps guide the design of tools to support complex analyses of urban accessibility: *"I think a lot of these visualization types as graphics are helpful, but then playing around with different overlays helps people to begin making decisions or understand what all this means."* (P3DC, department official).

We also found that many mapped tasks are shared across stakeholders (Table 5.1). For example, an advocate and a policymaker both care about equity analysis. To support these shared tasks, we envision a single geoanalytic tool that can be personalized towards a particular stakeholder and a specific decision-making context while providing access to perform other shared multi-level tasks. This could prevent siloed analysis in existing task workflows of city governments and foster better cross-stakeholder interactions.

To complement these analysis tasks, we also need varied computational models to develop accessibility metrics (*e.g.,* access scores [220]) and account for the diversity of factors and analyses. A set of metrics supplemented by qualitative data such as lived experiences is needed to allow for comprehensive analyses. For example, an *Access Equity Score* to model the correlation of physical accessibility factors with socioeconomic factors, similar to the Tree Equity Score [249, 353] used by city governments to evaluate tree cover with respect to income and race. An extension of sidewalk accessibility metrics by Bolten *et al.* [53] with the expressive accessibility framework by Chen *et al.* [68] introduced earlier could be another way forward. As one of the grand challenges in accessible visualizations, modeling accessibility is a rich open research problem for future work [124].

5.7.2 Stakeholders' Sensemaking Processes

Q2: *How did individual differences in stakeholders' needs and experiences impact sensemaking processes?*

Urban accessibility assessments are challenging because they are *deeply personal* and *deeply political* [306]. In our study, we saw how this dual nature manifests in the stakeholders' sensemaking and assessment processes of urban accessibility. We argue that engaging with the subjective nature of accessibility assessments, infused by the different stakeholders' analytical lenses and lived experiences, will be crucial for designing visualizations (and tools) for this application context.

Stakeholders' experiences with accessibility and disability (*Accessibility Familiarity*), either professionally and/or personally, introduced subjectivity in assessments. We saw differences in sensemaking processes in stakeholder's preferred information granularity, map types based on preferred unit of analysis (*e.g.,* streets or neighborhoods), and personally relevant assessment factors, metrics, and tasks. In line with prior work [287], we saw participants use 'personal relevance' to guide their process, from choosing a personally relevant task to weighing metrics based on the assessment factors that mattered the most (*e.g.,* severity more important than problem count). Further, a mismatch between a user's mental model of accessibility and the visualization made assessment challenging. For example, city-scale maps did not meet MI/Caregivers' localized needs. Similar to prior work [287], our findings suggest that an 'overview-first' model of visualization [329] is not suited for these participants, further suggesting a clear need to support varied accessibility tasks across stakeholders.

Relatedly, participants' personal experience with maps and geo-spatial analysis (*Map Familiarity*) influenced interpretation: maps that did not align with participant's mental model of map analysis were harder to use. Not all participants were familiar with these maps, imposing a learning curve. For example, a caregiver found PointVis overwhelming *vs.* a policymaker that found Heatmaps too abstract. These observations complement past work [217, 287] that finds personal ties with the data and visualization can supersede design dimensions for assessing usefulness based on *relatability*: if the user can relate to their own perspective or goal using the maps.

Finally, participants' personal experience with the city or location in question (*Location Familiarity*)—either lived, visited, or having prior knowledge—also influenced how they interpreted, used, and drew value from the maps. We found that a lack of geographic con-

	Design Considerations (C)	Example Application of Design Considerations
Establishing Data Trust	C1: Make clear where the data comes from (Data Provenance)	Document data sources and collection information
	C2: Make clear how data is modeled (Analytic Provenance)	Provide explanation of the algorithms/models used
Handling Diverse Assessment Factors	C3: Support for adding diverse datasets	Advocates can add their personally collected data in their desired format (e.g., Excel, CSV)
	C4: Support multivariate analysis: both analyzing across accessibility assessment factors and visualizing diverse datasets	Policymakers assess the impact of inaccessible infrastructure on MI individuals to reveal inequities
Supporting Shared Stakeholder Tasks	C5: Support for varied, often conflicting, stakeholder group needs	MI/Caregivers assess navigability of a neighborhood Department officials assess equity in distribution and prioritization of resources and investments
	C6: Support for individual differences (e.g., familiarity with maps, accessibility, location)	MI/Caregivers' view tailored to localized data and neighborhood and street level maps (e.g., Isochrones)
	C7: Support for adjusting to visualization user needs as an analyst or target consumer	
Supporting Comparisons	C8: Make it easy to compare between multiple data, map, and geo-contextual views (e.g., providing historical context on accessibility investments across locations)	Department officials comparing accessibility of multiple locations within and across cities
Building Persuasive Stories	C9: Support for audience-driven message framing by adding relevant contextual data	Framing for policymakers: show impact of investments on citizen's quality of life
	C10: Support for exporting audience-driven stories in multiple visualization formats	Framing for MI/Caregivers: show impact of inaccessibility on their personal life

Table 5.2: Design Considerations for Interactive Visualization Tools in Urban Accessibility. The highlighted design considerations for 'Supporting Shared Stakeholder Tasks' play a central role across other design considerations.

text hindered comprehensive analyses and participants requested more location-oriented information (*e.g.,* neighborhood name, street name, historical context). As we expect urban accessibility visualizations to be consumed by a variety of end-users, including those unfamiliar with the represented city (*e.g.,* when planning a trip), it is important to surface geographic contextual information to facilitate sensemaking.

In conclusion, our findings suggest the need to support stakeholders' personal differences and preferences, reaffirming Peck *et al.* [287]'s open question, *how can we design [visualization] systems that align with the personal experiences of our audience?*

5.7.3 Visualizing Urban Accessibility: Design Considerations

Q3: *Given these challenges, how might we utilize interactive visualizations to support communication and decision-making needs for urban accessibility?* Here, we discuss selected design implications for visualizing urban accessibility across diverse stakeholders and tasks. Table 5.2 lists ten corresponding design considerations.

5.7.3.1 Establishing Data Trust

We found that trust in the underlying data influences trust in the visualizations and insights. Hara *et al.* [158] emphasized the importance of *data quality* with five features: granularity, relevance, credibility, recency, and coverage. We extend this work by adding two data features for establishing trust: data and analytic provenance. Elaborating Hara *et al.*'s credibility feature, *data provenance* describes where the data is coming from and how was it collected. *Analytic provenance* refers to how models and metrics (*e.g.,* access scores [220]) are calculated. We suggest that future interactive urban accessibility visualizations should include features to provide both data and analytic/algorithmic provenance. While recent discussions around trust building in visual analytic systems has been in terms of describing and calibrating the trust continuum [155], *how we design these interactions to effectively support trust building* remains an area for future research.

5.7.3.2 Handling Diverse Assessment Factors

Diverse assessment factors require integration of numerous data sources, ranging from publicly available datasets from city governments to independently collected datasets by academic and advocacy organizations. The data formats vary and may be unstructured. Future visual analytic tools for urban accessibility could account for this diversity by making it easier to blend datasets and facilitate multivariate analysis. However, *how do we provide interactive visual support for these multivariate analysis tasks?* For example, assessing the impact of sidewalk inaccessibility on connectivity for MI individuals living in largely black neighborhoods requires multi-level analyses across four dimensions, namely—sidewalk accessibility, connectivity, population density for MI individuals, and race. Visualizing such multivariate geographic patterns effectively is a known challenge [145]. Current state-of-the-art geovisual analytic tools utilize linked views and layering to convey multivariate patterns, with a primary focus on univariate or bivariate patterns. Recent work for multivariate analysis [191] explored self-organizing maps [205] and parallel coordinate plots [179] to visualize high dimensional data. However, using such complex visualization techniques for non-expert users like our stakeholders seems ill-advised. We hope to explore the rich space of visualizing complex multivariate patterns for non-expert users in future research.

5.7.3.3 Supporting Shared Stakeholder Tasks

Previously, we characterized stakeholder tasks in a shared multi-layered task model (Figure 5.7), where tasks overlapped across stakeholder groups (Table 5.1). To account for group differences and support the rich shared task ecosystem for diverse stakeholders, future work is needed to explore tool designs that uses task characteristics as a configuration parameter. Do we design a full-featured analytic tool and have a derivative tool for MI/Caregivers? Is there a middle ground that serves all stakeholders? How easily could we customize such shared tasks based on stakeholder needs and differences?

5.7.3.4 Building Persuasive Stories

All groups envisioned using visualizations as a storytelling medium to spark engagement and dialogue with other stakeholders (*e.g.,* push agendas to decision makers) while driving awareness (*e.g.,* educating the general public). Crafting persuasive stories for cross-stakeholder interactions (*e.g.,* between policymakers and advocates for new policy/change [306]) requires tailored data stories for the target audience that consider their background while appropriately framing and contextualizing the data. Participants suggested adding and representing contextual information pictorially (*e.g.,* accessibility problem images, animations), textually (*e.g.,* lived experience stories), and quantitatively (*e.g.,* accessibility statistics). Future tool designs might explore a combination of visualization authoring techniques (*e.g.,* Lyra and others [314]), visualization recommenders (*e.g.,* Voyager 2 [180, 391]), and narrative visualization techniques [322] to provide interactive story-building support to produce artifacts such as story maps [374]. Handling existing biases by balancing maps with enough context such that false information is not percolated will be crucial [396]. An official said people came

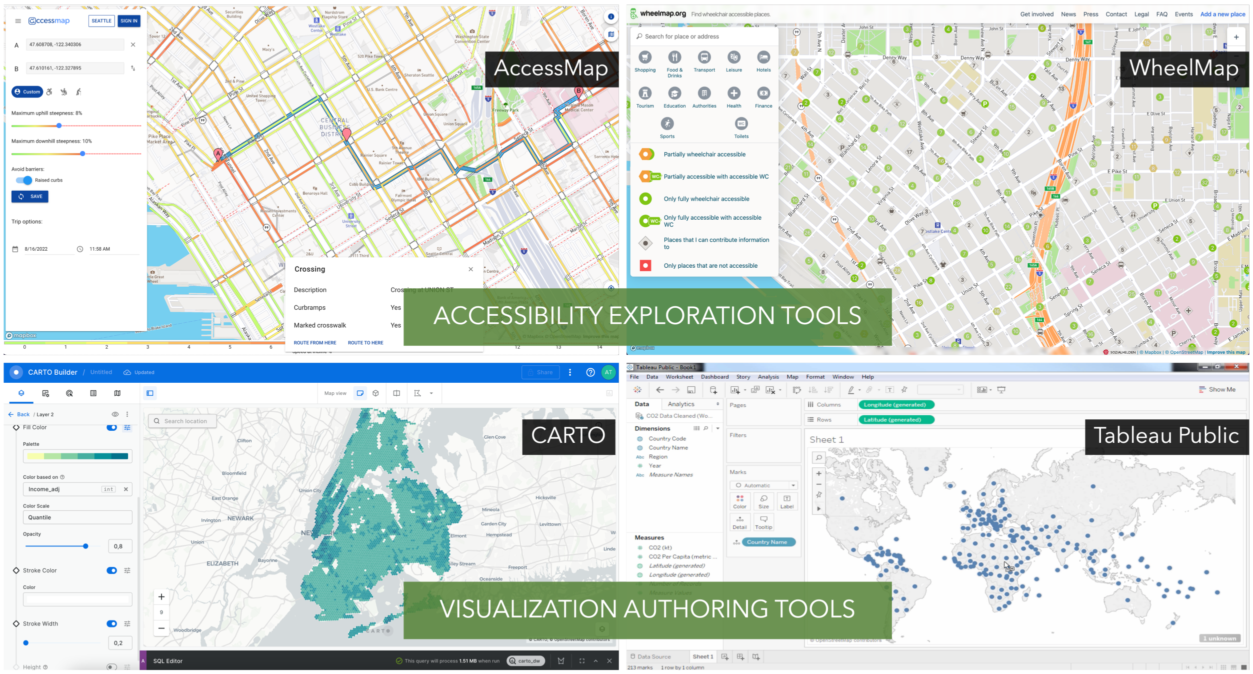

Figure 5.10: Interactive Visualization Tools used for AccessVis Design Space Analysis. The top row are the Accessibility Exploration tools: AccessMap and WheelMap. The bottom row are the Visualization Authoring Tools: CARTO and Tableau Public.

biased wanting to show their area in the worst light, corroborating an advocate's views on preferring maps showing problems in the worst way possible for a strong impact.

Comparative Analysis of Interactive Vis Tools using AccessVis Design Space

In this section, we apply the above design space to conduct a comparative analysis of some map visualization tools used by accessibility communities across decision-making contexts of daily living and advocacy. The goal is to demonstrate the utility of this design space in evaluating existing mapping tools for missing functionalities and features and potential enhancements.

	CHARACTERISTICS			
	Category	Decision-making Context	Primary Datasets	Features / Tasks
TOOLS				
AccessMap	*Custom*: Accessibility Exploration	Daily Living: Navigation and Trip Planning	Sidewalk Network, Elevation	Finding personalized accessible routes between destinations
WheelMap			POI	Finding and rating wheelchair accessible places
Carto	*General Purpose*: Visualization Authoring	Communication and Advocacy	customizable	creating map visualizations, exporting visualizations, advanced GIS features
Tableau Public			customizable	creating map visualizations, data stories, exporting visualizations, advanced data prep features

Table 5.3: Tool Characteristics for Design Space-based Tool Analysis. The table highlights the tool context, namely, their decision-making usage context, datasets used, and supported features/tasks.

Tools. We review two tool groups (Figure 5.10): (1) *Custom* Accessibility Exploration Tools–*AccessMap*[4] [51] and *WheelMap*[5] [380] and (2) *General Purpose* Map Visualization Authoring Tools—*CARTO*[6] [63] and *Tableau Public*[7] [338]—both are commonly used by social advocacy organizations [61, 339]. AccessMap and WheelMap are for visualizing accessibility needs, sidewalk and building respectively, to make trip planning decisions by MI/Caregivers. CARTO and Tableau Public allow end-users to create interactive visualizations and provide comprehensive features such as storytelling and exporting data in diverse visualization formats. They are not tailored for specific stakeholder groups. More details in Table 5.3.

Method of Analysis. Given the tools were made with specific needs and tasks in mind, each tool group is analyzed separately within the scope of the primary purpose of the tools for

[4] accessmap.io

[5] wheelmap.org

[6] carto.com/platform Figure 5.10 image taken from CARTO User Manual: Tutorials

[7] public.tableau.com Figure 5.10 image taken from Tableau Public Resources

a fair comparative analysis. Further, we also analyze whether each design dimension is applicable to the tool. We do not argue that every tool should provide full support across each dimension. Rather, supporting additional dimensions would result into a richer decision-making tool, providing *actionable* insights with applicability across stakeholder groups and decision-making contexts. The specific design consideration from Table 5.2 is denoted by C followed by the index number. For example, C1 refers to 'Data Provenance' consideration from the first dimension 'Data Trust'. The order of the dimensions presented is changed for clarity and readability.

Shared Stakeholder Tasks. This dimension is about providing multi-stakeholder support by accounting for user differences: group specific tasks [C5], individuals' prior experience or background with accessibility, data/map analysis, and location [C6], and customized vis end-user support (*e.g.,* vis consumer *vs.* analyst) [C7]. Through these considerations, the goal is to provide a customizable task support for the end-user. Currently, both tool groups have inadequate customizable support for diverse stakeholders within a shared task ecosystem. The accessibility exploration tools are designed specifically for the MI/Caregivers group, with limited task support for urban-scale decision-makers (*e.g.,* policymakers, advocates). The visualization authoring tools can be used to design decision-making interfaces tailored to a specific stakeholder's needs. However, for providing true multi-stakeholder support within the shared task ecosystem, we would need to reimagine tools' inherent support by taking task as a configuration parameter within the visualization authoring interface.

Diverse Assessment Factors. In this dimension, we examine whether the tools allow adding [C3] and analysing multiple datasets and assessment factors with respect to each other [C4]. Both accessibility-infused tools allow investigating a single physical accessibility factor *i.e.,* sidewalk elevation and building accessibility for an MI individual. While these tools' intended purpose do not need performing multivariate analysis, the tools can be extended to support other stakeholder groups (*e.g.,* policymakers, advocates) to analyze socio-demographic patterns. On the other hand, CARTO and Tableau have inherent support for adding and

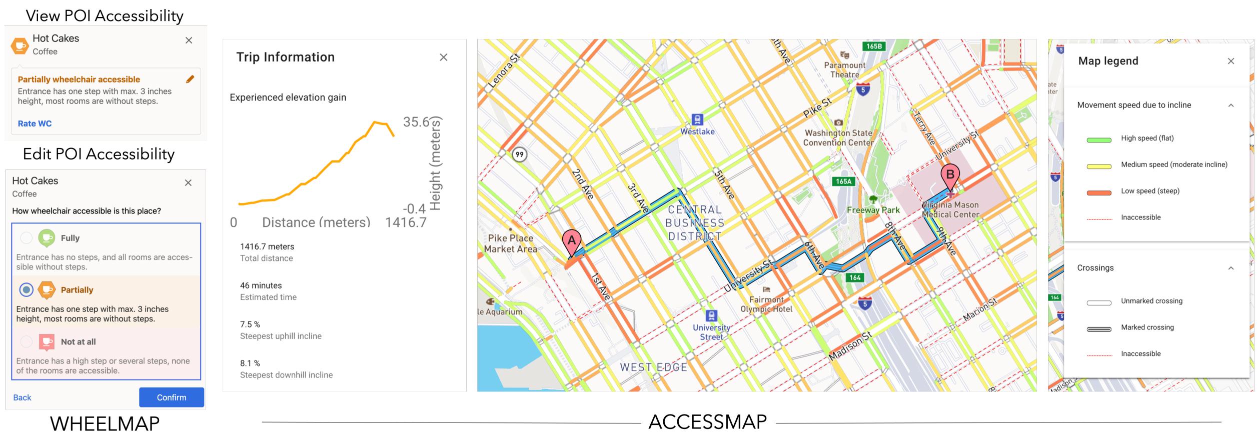

Figure 5.11: WheelMap and AccessMap Data Trust Analysis. The left illustration shows the data explanations provided during viewing and editing a POI's accessibility rating. The right illustration shows the data explanation—*i.e.,* trip information and map legend—to explain the route accessibility map in the center.

analysing multiple datasets to multivariate analysis. However, further interactive guidance would be needed to assist technically novice users to analyse and extract actionable insights.

Comparisons. This dimension requires support for comparing across different data, map, and geo-contextual views (*e.g.,* historical context) [C8]. Currently, the accessibility exploration tools provide examining accessibility of individual routes or destinations across filterable data views based on specific parameters. However, accessibility comparisons are not possible. On the other hand, the authoring tools have inherent support for showing different views. CARTO, in particular, has advanced GIS features for supporting geo comparisons (*e.g.,* diverse map views) [62].

Data Trust. This dimension pushes for providing appropriate explanations about the underlying data and their sources [C1] and metrics/models used for data aggregation [C2] to establish trust. WheelMap provides detailed explanation of a POI's wheelchair accessible rating (Figure 5.11). While adequate, adding metadata about the data collection process would further strengthen data trust. AccessMap provides explanations about the route accessibility through trip information and map legend. However, providing real-time interactive support (*e.g.,* on hover) to examine the route and its characteristics would allow closer engagement with the data. Further, a simple text explanation on why the route was chosen would also engender more trust in the underlying routing algorithm. For the authoring tool group, both tools provide features to design static and dynamic data interactions to provide data context.

Persuasive Data Stories. For building persuasive data stories, this dimension suggests having interactive tool support for contextualizing and framing data stories [C9] and ability to export these data stories in formats specific to a stakeholder's individual and decision-making context [C10]. Both visualization authoring tools support exporting the analysis results in different data formats (*e.g.,* png, jpeg, gif). However, neither of them provide advanced story framing support during creation stage (*e.g.,* pull relevant data for the intended audience's perspective) and export stage for framing the results to a target audience (*e.g.,* for policymaker's political interests). The two accessibility exploration tools were not designed to create data stories. However, we argue that providing a data story support would transform them into powerful advocacy tools for not only MI/Caregivers' self advocacy needs, but also larger NGOs/non-profits for communicating with city officials.

CONCLUSION. Existing tools do not provide full support for urban accessibility needs based on the AccessVis design space analysis. We would need to reimagine existing data analysis and communication workflows in interactive data-driven tools for supporting diverse stakeholders and their decision-making needs. The ultimate goal is moving beyond siloed analysis, towards true cross-stakeholder decision-making tools keeping the stakeholder's context as the core element.

5.7.4 Limitations

We conducted this work in large US cities. While local government structures influence the decision-making processes, we argue that our findings would apply to most developed countries with similar structures and existing accessibility regulations. Second, we had very few participants from DC (*N*=6). Therefore, the map interpretation differences based on location familiarity may not hold as strongly in a dedicated local context. Future work could systematically study how location familiarity impacts one's interpretation process. Third, due to overlapping roles of some participants, both roles impacted their map interpretation and use, making it hard to identify the perspective they spoke from. Finally, the visualizations were not designed to support people with different visual abilities. Making accessible visualizations is an important and active area of research [196, 230], which we plan to draw upon in the future.

5.8 Acknowledgements

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5.9 Chapter Conclusion

As an early work in understanding sensemaking processes using urban accessibility visualizations, this chapter developed an understanding of how different stakeholders from diverse backgrounds and professions analysed urban accessibility. Through an interview study with 24 map visualizations as design probes, we studied the stakeholder groups' similarities and differences in map interpretation and urban accessibility assessment needs. We found that personal ties to data, task, and maps played a primary role in driving sensemaking processes.

Based on our findings, we mapped stakeholders' data and analysis needs into a multi-layered task model and proposed 10 design considerations for designing future geovisual tools for urban accessibility. While we map the visualization task space based on our focused lab study, future longitudinal design studies with interactive tools are needed to closely engage with stakeholders and extend the visualization task space for urban accessibility.

6 Landmark AI: Designing for the Last-Few-Meters Wayfinding Problem

This chapter explores how the need for personalization is manifested on tool design for a second group of MI individuals: people with visual disabilities and problem context: in-situ navigation in the last few meters of a destination.

Despite the major role of Global Positioning Systems (GPS) as a navigation tool for people with visual impairments (VI), a crucial missing aspect of point-to-point navigation is the *last-few-meters wayfinding problem*. Due to GPS inaccuracy and inadequate map data, systems often bring a user to the vicinity of a destination but not to the exact location, causing challenges such as difficulty locating building entrances or a specific storefront from a series of stores. In this work, we study this problem space in two parts: (1) A formative study (N=22) to understand challenges, current resolution techniques, and user needs; and (2) A design probe study (N=13) using a novel, vision-based system called *Landmark AI* to understand how technology can better address aspects of this problem. Based on these investigations, we articulate a design space for systems addressing this challenge, along with implications for future systems to support precise navigation for people with visual impairments.

6.1 Introduction

According to the World Health Organization [381], there are 285 million people with visual impairments (VI), of which 39 million are blind. For this group of people, navigation can be difficult due to challenges such as obstacles, crowds, noise, or complex layouts of physical spaces [26, 100, 394]. Among the many navigation tools that have been developed to cater to the needs of this community, GPS-based systems [25, 43, 255, 342] are the most popular. This presents a challenge, in that smartphone-based GPS has a horizontal accuracy of about ±5m at best [139], with potential for much worse accuracy in areas like urban canyons [257].

This means that smartphone GPS can guide a user to the vicinity of their destination, but not to the precise location (*e.g.,* to the front of a building, but not to the actual door). This gap of a few meters is acceptable for people who can rely on their vision to identify their destination but creates confusion and uncertainty for people with VI. In addition to GPS inaccuracy, location-based systems rely on map data that is often inadequate to guide the user to their intended destination due to lack of granular information. Together, these imprecisions can limit blind users' sense of independence. We call this challenge the *last-few-meters wayfinding problem* (also known as the "last 10-meters/yards" problem [134, 224]).

In this chapter, we investigate the problem of navigation for people with VI from the lens of the last few meters to a destination and use landmark recognition as the central strategy for navigation, building on the typical landmark-based navigation strategy taught to people with VI by Orientation and Mobility (O&M) specialists [227]. We conducted a formative study to understand the characteristics of this problem including the challenges faced, current resolution techniques (and where they fall short), and how an ideal system might fill the gaps left by existing navigation aids. We then developed *Landmark AI*, a computer vision system intended as a design probe for understanding how technology could be employed to help users answer three common questions surfaced by participants in our formative study: (i) *"What is around me?"*, (ii) *"What does this sign read?"*, and (iii) *"Is this the place I am looking* *for?"*. Using this design probe, we conducted a user study to elicit feedback and opinions on the design of applications to address some of the last-few-meters challenges that blind pedestrians' experience.

As the first work to comprehensively investigate the last-few-meters wayfinding challenge, our contributions include:

1. An investigation into the problem via a formative online survey with 22 participants
2. A qualitative study of our Landmark AI design probe with 13 visually impaired users
3. A description of the design space resulting from the two studies capturing the relationship between use of landmarks and other information types with a person's mobility skills, residual vision, and situational context
4. Design implications for future camera-based AI systems targeting the last-few-meters problem

6.2 Background and Related Work

Onset of VI impacts a person's ability to perform day-to-day activities, and traveling independently is a core skill that must be developed [292]. As a key part of rehabilitation training, O&M specialists teach people with VI how to safely navigate indoors and outdoors. The basic O&M techniques for navigating independently include performing systematic search and trailing [292], as well as skills based on locating and using a series of physical landmarks between locations [227]. Some commonly used landmarks to ascertain location include contrasting floor textures and coverings (*e.g.,* carpet to tiled surface or concrete sidewalk to grass pavements); using sounds (*e.g.,* refrigerator humming, birds chirping, church bells, traffic) and smells (*e.g.,* laundry room odors, kitchen smells, perfume store aromas) [178]. An O&M specialist teaches a route by breaking it down into small sections and helps the VI person identify useful landmarks along them. Using the identified set of landmarks as a checklist, the person moves from one section of the route to another by taking an action at each section endpoint marked by a landmark. For example, trailing a building line until it ends (landmark) and then taking a right turn (action). In this work, we aim to address the last-few-meters challenge by complementing these existing mobility skills with technology that supports the discovery and use of landmarks.

6.2.1 Navigation Systems for the Blind

Navigation systems for the blind is a well-studied field for both indoor and outdoor navigation. Outdoor GPS-based systems [25, 43, 255, 342], are the most widely deployed, providing features such as announcing nearby Points of Interests (POIs) and street intersections, and providing directional guidance via turn-by-turn directions [43, 342] and spatialized audio [25, 255]. Although they allow a user to navigate large distances, the localization accuracy is ±5m [139], preventing users from getting very close to their target POI.

Information on locating landmarks such as doors, elevators, or stairs can play a crucial role in getting to a destination successfully. However, most systems lack such granular information. Some recent work on indoor navigation systems [29, 113, 126, 127, 288, 313] have looked into providing information on such semantic features of the environment[289]. For example, NavCog3 [313] uses a BLE beacon network to provide sub-meter localization accuracy indoors and information on nearby landmarks. Such systems demonstrate the usefulness of the landmark-based navigation approach; however, they require (i) additional deployment and maintenance effort to augment the physical environment (*e.g.,* with RFID sensors [126], NFC tags [127], or Bluetooth beacons [313]), (ii) significant bootstrapping cost for setting up databases of floor maps [113] and landmarks [29, 113, 127, 270] [126], or (iii) require a user to carry an additional/specialized device [126]. These issues reduce the scalability and applicability of existing systems in diverse environments (*e.g.,* outdoors). The BlindWays [44] smartphone app is a system that aims to address the last-few-meters challenge without augmentation; using crowdsourced clues to assist in finding transit stops. In this work, we investigate the full breadth of the last-few-meters wayfinding challenge and evaluate a camera-based (rather than crowdsourced) solution to find landmarks. This approach could work in tandem with outdoor or indoor navigation systems without requiring custom infrastructure.

6.2.2 Camera-based Systems for the Blind

Camera-based applications serve a wide array of purposes for VI users, including simple object recognition [8, 321, 397], text recognition [192, 203, 321], and search tasks [39, 40]. Object recognition systems either use computer vision [8, 321], human-assistance [9, 32, 35], or a hybrid of the two [340]. Human-in-the-loop systems' latency (ranging from several seconds [79, 340] to several minutes [35]) may be unacceptable for many navigation tasks; hence, our focus with Landmark AI is on automated approaches.

Coughlan *et al.* [85] used a phone camera for wayfinding by utilizing computer vision to locate and read aloud specially designed signs. Subsequent systems have looked into combining phone and wearable cameras (*e.g.,* [29, 354, 392]) with other sensors (*e.g.,* smartphone and motion sensors [204, 301, 354]), or augmenting a smartphone camera [167, 173]. Using computer vision and sensor fusion techniques, these systems localize, keep track of the user's path, and provide precise corrective heading instructions. However, these systems require a time-consuming and laborious process of creating a database of likely locations, landmarks, or paths and augmenting the physical environment, making them unsuitable for exploring infrequent and unknown destinations, and unscalable for open-world exploration in natural environments. In contrast, our design probe uses only a smartphone camera without augmenting the environment and provides in-situ feedback for both familiar and unfamiliar environments.

6.3 Formative Study

We conducted an online survey on how people with VI currently navigate to understand: (i) challenges they face in the last few meters, (ii) how they resolve them, and (iii) what information would aid them in resolving these challenges.

Informed by O&M literature [227, 292] and a discussion with an O&M specialist, we grouped commonly used landmarks into five categories—structural, sound, tactile, air, and smell. Some landmarks may be included in multiple categories (*e.g.,* an elevator is both a structural and a sound landmark). Structural Landmarks are part of the physical structure of the built environment and are usually detected either via residual vision, vision of the guide dog, or haptic resistance through a cane (*e.g.,* doors, stairways, elevators, and dropped curb edges). Sound Landmarks such as fountains, bell towers, and elevators generate noise. Tactile Landmarks have a distinct texture that is easily recognizable either through direct contact or through aids such as canes (*e.g.,* carpeted surfaces, tactile domes on curb ramps). Air Landmarks produce some form of heat or cool air that is felt through the skin, such as HVAC units or fans. Smell Landmarks have a distinct aroma (*e.g.,* perfumeries, tobacconists, bakeries).

6.3.1 Method

Participants. We recruited 22 blind participants (9 female): 15 were between the age of 31–50, four were between 18–30, and three were above 50. Participants had varying levels of residual vision: 15 were totally blind and seven had some degree of light or color perception. 13 participants used canes as their primary mobility aid, six used guide dogs, 1 used a sighted guide, and one used other aids. Most described themselves as independent travelers (16) with varying self-confidence levels (*Mdn*=4, *SD*=0.9), ranging from Not at all Confident (1) to Extremely Confident (5).

Procedure. The survey was conducted over three weeks in August 2018. It took 30 minutes to complete and participants were compensated US$25. The survey used a recent critical incident approach [117] in which we asked participants to think of a specific recent episode in which they had experienced a last-few-meters navigation challenge. We used affinity diagramming [211] to analyze open-ended responses and identify themes. For the rest of the chapter, survey participants are referred to by "S" suffixed by the participant number (*e.g.,* S1) and the counts of the responses are included in parenthesis.

6.3.2 Findings

Challenges in the Last Few Meters

Participants described challenging situations including tasks such as getting to an apartment, visiting the doctor's office, and finding specific buildings within large areas like business complexes. For instance, S19 explained *"I was dropped off at a college campus and I was unable to locate the building of my scheduled interview."* Amongst all participants, visiting the doctor's office in a medical center was the most common scenario (6). In addition, the challenge of navigating open spaces where there is a lack of helpful environmental cues was a clear theme. Examples included indoor open spaces such as airports and malls (8), spaces with complex and varied paths like parks or universities (5), and open parking lots (5). These challenges are commonly encountered, with two-thirds of participants reporting at least some degree of familiarity with problematic destinations.

In most cases, the hardest part of traversing the last few meters was finding the intended doorway (11). Participants reported this was caused by: (i) failure of existing guidance systems such as the inaccuracy of navigation technology, the limitations of guide dogs, or missing or inaccessible signage (9); (ii) finding the right door from a cluster of doors (5); (iii) transit drop-off points being far away from the actual destination (5). S8 gave an example situation where these reasons get intermixed: *"The entrance to the building was off the* *parking lot rather than at the end of a sidewalk and the inside was a series of doors off a long hall."*

Resolution Techniques

Participants responded to these challenges by using sighted assistance (17), O&M skills (11), trial and error (7), technology (2), or completely giving up (2). Though participants described sighted assistance as the most common and effective technique, it was not always useful: *"We resolved it by asking people, whoever could understand English, which was not too many at the airport at that time of the morning (S9)."* Almost everyone (21) received O&M training for navigating physical spaces (known techniques included counting steps, finding landmarks, and using sensory clues such as aromas, sounds, or tactile surfaces). Trial and error was also quite common (7) as indicated by S3: *"It's a matter of feeling around until you find the actual handle of the store."* Participants often combined these techniques: *"I usually ask for assistance from a passing pedestrian. If no one is around, I simply try all the doors until I locate the right one. It's easier if it's a restaurant or coffee shop or any store that has a distinct aroma that I can use to pinpoint the exact location. (S11)"*

Technological Limitations

All participants mentioned using technological solutions during navigation to access information like turn-by-turn directions (9), nearby streets, intersections and POIs (9), and human assistance (*e.g.,* Aira [9]) (1). Despite these benefits, participants reported many types of failures: *"Mainly the accuracy with it not putting me exactly at my location instead putting me a few yards away. (S12)"* The most important concern with current technology (16) was imprecision in terms of localization and granularity of information (*e.g.,* floor number of the location): *"Sometimes the GPS gets really thrown off and I end up walking in circles."* (S3). Other issues included lack of indoor navigation (3), intermittent GPS signal (2), use of headphones blocking ambient noise (2), and battery power drain (2).

Useful Information in Resolving the Challenges

Given the recent critical incident participants reported, we asked them to rate the categories of landmarks previously defined in terms of usefulness in that situation. Across all participants, tactile landmarks (*Mdn*=5, *SD*=1.1) were most preferred (11). For example, S2 *"...used the grass on the [entrances] to the apartment buildings."* Structural landmarks (*Mdn*=5, *SD*=1.3) and sound (*Mdn*=4, *SD*=1.4) were next. Smell (*Mdn*=3, *SD*=1.5), and air (*Mdn*=3, *SD*=1.1) landmarks were least mentioned amongst all participants. S11 summarized the use of the landmark types based on the usage scenarios and their primary mobility aid, *"Because I travel with a guide dog, I mostly rely on smell and sound cues when traveling, with tactile landmarks being useful if they are under my feet, and structural landmarks being helpful if I know they are there and can give my dog the command to find the landmark such as 'find the stairs'."* When asked about missing information that would be useful in these situations, knowing about the layout of indoor and outdoor spaces was the most popular request (9).

Participants also wanted to know more about existing signage (5): *"If something could identify a sign, i.e., text/logos that identify a business then that would be very helpful."* (S6) Several participants indicated they would like to receive ego-centric layout information about nearby things (4): *"Imagine being able to walk down the hallway of an office building and hear 'men's bathroom on your left.' (S15)."* Other examples of desired information were precise auditory guidance on a smart mobile or wearable device (*e.g.,"approaching apartment building entrance"*), granular map information (*e.g.,* location of parking lots), and creating personal landmarks (*e.g.,* an arbitrary location like a bench in a park).

6.4 Design Probe Study

Based on our formative study's findings, we developed a vision-based app called Landmark AI as a design probe. We designed Landmark AI to demonstrate how landmark recognition could work, with the goal of helping participants imagine how they might use such technology combined with their existing mobility skills to overcome wayfinding problems. Because we were interested in broad questions of potential utility and context, Landmark AI was not rigorously optimized for accuracy. Rather, our probe identified categories of information for which AI developers might gather large, robust training sets such that more accurate recognition algorithms could be trained. While we do not wish to minimize the importance of accuracy and precision for such systems, these questions are out of scope for this work. Based on this investigation, we developed a set of design considerations for future systems addressing navigation challenges in the last few meters.

6.4.1 Landmark AI System

Landmark AI (Figure 6.1) is a camera-based iOS app that allows users to gather information about the space around them once they get close to a destination. It is designed to provide information that supports their existing mobility skills to aid in decision-making during navigation. We modeled our app's design on Microsoft Seeing AI [321], an iOS app that provides users with visual information via so-called channels (*e.g.,* reading short text, scanning bar codes, and reading currency notes). Basing our design probe on Seeing AI allowed us to minimize user training, to segregate different information types (via the channel metaphor), and to provide the user with an appropriate mental model of the feasible capabilities of current and near-term AI solutions (*i.e.,* computer vision can succeed at specific, scoped tasks such as recognizing doorways, but open-ended description of unpredictable scenes is not currently accurate). In Landmark AI we provide three new channels—Landmarks, Signage, and Places—to provide visual information that is relevant in navigating the last few meters. The app is operated by either panning the phone's back-facing camera or taking a picture (depending on the channel) to get auditory callouts.

6.4.1.1 Landmark Channel: *"What is around me?"*

Given landmarks that were indicated as useful in our formative study and prior literature on critical landmarks for navigation [289], we designed the Landmark channel to recognize

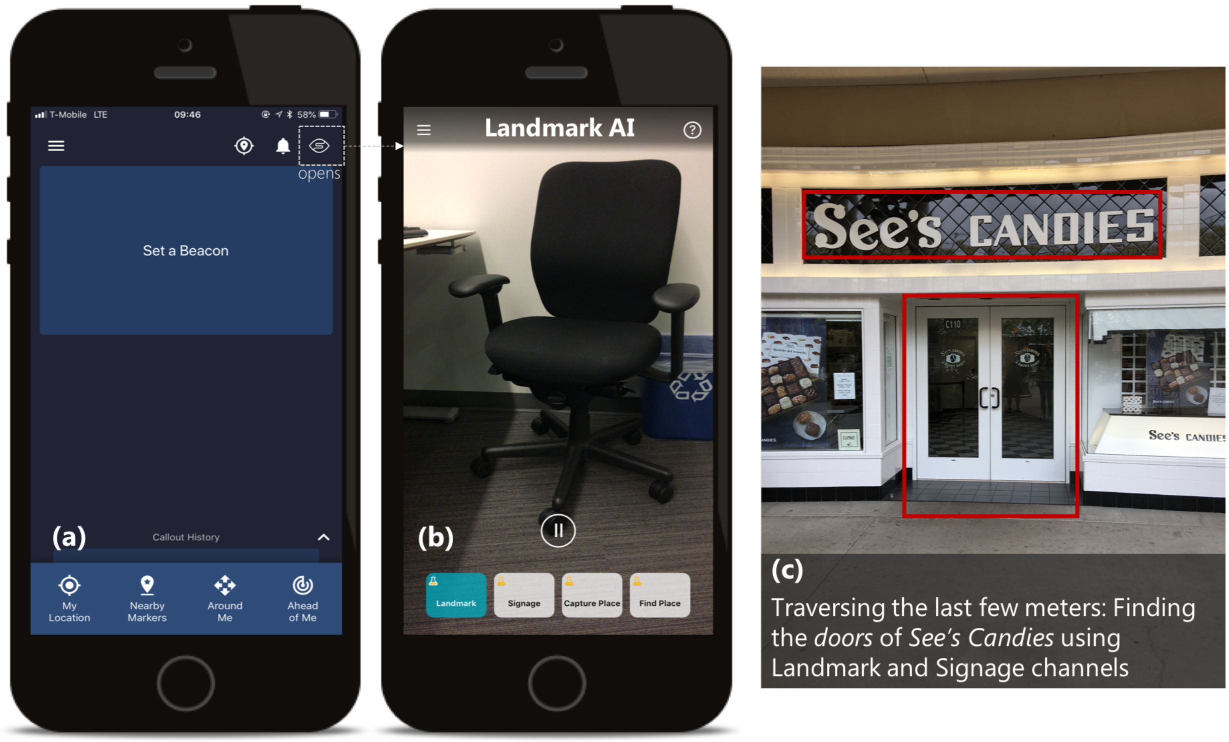

Figure 6.1: Landmark AI is a vision-based app that is modeled on Seeing AI iOS app. The app is fully operable non-visually via the VoiceOver screen reader, but we show the visual UI here for clarity. (a) The Soundscape iOS navigation app helps the user get near the location. In this case, it's outside See's Candies. The top-right button is included to switch to Landmark AI once near the destination. (b) The Landmark AI app has three channels: Landmarks, Signage, and Place (a pair of Capture Place and Find Place functions). (c) Using the Landmark and Signage channels, the user can locate the entrance of See's Candies once close to the store

structural landmarks (*e.g.,* doors, stairs, windows, elevators, and pillars) and obstacles (*e.g.,* tables, chairs, and benches) around the user as they scan the environment. Instead of choosing computationally heavy methods [66, 324, 343], we used a light-weight pre-trained object recognizer with reasonable accuracy (F1 = 69.9 at a 99% confidence threshold for recognition) to run on commodity smartphones. The recognizer is based on the SqueezeNet [136] deep neural network model, and trained on 2,538 randomly selected images from the ImageNet database [96]. As the user pans the phone's camera, the channel announces landmarks when first recognized and every two seconds the landmark remains in the camera's view. While a real-world system would likely need to detect a much larger set of landmarks and at a much higher accuracy, constraining the detected landmarks to features common in our study location was sufficient for the purposes of a design probe demonstrating the landmark recognition concept.

6.4.1.2 Signage Channel: *"What does this sign read?"*

In our formative study, participants indicated that knowing more about nearby signage would be helpful in navigating the last few meters to a destination (*e.g.,* finding store names or signs with directions), so we designed a channel to read signage in static images the user captures with Landmark AI. An ideal implementation of this channel would perform recognition on-device in real-time [226, 327], but implementing such an algorithm was out of scope for our design probe, so we used Microsoft's cloud-based Cognitive Services [80] to implement the recognition. These services require several seconds to process a frame, preventing a fully real time interaction for this channel. Despite this limitation, the signage channel gave us the opportunity to test different feedback mechanisms and study the utility of signage versus other cues when traversing the last few meters.

6.4.1.3 Place Channel: *"Is this the place I am looking for?"*

We designed the place channel to allow users to define and recognize custom landmarks. To use the channel, a user first saved a picture of a specific place they wanted to find in the future either by taking a picture themselves using Capture Place function or saving a picture sent from a friend (*e.g.,* a meeting place like the box office window at a theater or a specific table outside a storefront, Figure 6.2). The user could then use the Find Place function to search for the location in the captured image. Due to the complexity of this scene matching task, we simulated this functionality in our design probe via a Wizard of Oz [194] approach,

Figure 6.2: Examples of places for the Place Channel. (a) “box office counter of a theater” (b) “benches outside the ice-cream store” (c) “gummy bear outside the storefront of Margo’s Sweet Shop”

whereby a researcher would trigger customized feedback (*“<X> place found”*) when users of the design probe scanned the phone running Landmark AI over a visual scene that matched the stored scene.

6.4.2 Study Method

We conducted a three-part study using a scenario-based design [303] involving three tasks, each highlighting a last-few-meters challenge. Before using the Landmark AI design probe, users completed a set of short tutorials demonstrating the use of each channel. Each task involved getting close (~2–5ft) to a particular business using a popular GPS-based iOS navigation application called Microsoft Soundscape [255] and then using Landmark AI to cover the last few meters. For every task, the participants were asked to think aloud as they made navigation decisions. We solicited feedback on their experience including perceived utility, limitations, and design recommendations for future systems. Tasks took place within a large, outdoor two-story shopping center in the U.S. Study sessions lasted about 90 minutes, and participants also completed a demographic questionnaire. Participants were compensated US$75.

Task 1. Find the elevator near the restrooms and ice-cream store. First, participants were asked to locate the store using the GPS app and then find the elevator using their own mobility skills. Then participants were asked to walk back to the location where the GPS app stopped being useful and switch to Landmark AI to locate the elevator again. The goals of this task were to contextualize the use of Landmark AI after experiencing challenges in the last few meters when navigating on their own, and to study the use of Landmark AI in a familiar place (familiarization after completion of the first sub-task).

Task 2. Find a table near the entrance of the candy shop. In this task, participants were guided to the second floor of the shopping center and asked to use the GPS app to locate a candy shop. Participants were informed that they could switch to Landmark AI at any time. We observed how they used the two apps together, when they switched between the two, and when and why they chose to use particular channels in Landmark AI. The goal of this task was to test the usefulness of Landmark AI in visiting an unfamiliar place.

Task 3. Find the box office counter for the theater. For this task, participants were asked to imagine a scenario where they are meeting with a friend (in this case, the researcher) at the box office counter of the theatre, which the friend had sent a photo of. Their task was to locate the counter using the Place channel in Landmark AI after using the GPS app to get near the theater. The goal of this task was to understand how participants would use the more open-ended scene recognition of the Place channel.

6.4.3 Participants

We recruited 13 people with VI (4 female) aged 24–55 (*Mean*=39, *SD*=11). Six participants used guide dogs, six used white canes, and one had low-vision (P3) and used magnifiers to read text. During the study, two guide dog users switched to using their canes, as they felt canes were better suited for the tasks. Participants had varying levels of functional residual vision: color perception (3), visual acuity (2), contrast sensitivity (3), peripheral vision (4), central vision (6), no vision (5), and others (2). On a 5-point Likert scale ranging from Not at all Confident (1) to Extremely Confident (5), participants had varying self-confidence levels for navigating on their own (*Mdn*=4, *SD*=0.86), and on a 4–point Likert scale ranging from Not at all Familiar (1) to Very Familiar (4), most participants were users of both Soundscape (*Mdn*=3, *SD*=0.86) and Seeing AI (*Mdn*=3, *SD*=0.75). Only 5 participants had some familiarity with the study location (*Mdn*=1, *SD*=0.85), and amongst them, none were familiar with the specific task locations.

6.4.4 Data and Analysis

We audio recorded, transcribed, and coded the sessions to find general themes using deductive coding [56]. We transcribed 12 audio files; one participant's (P7) transcript was unavailable due to audio recording device failure. One researcher prepared an initial codebook based on the formative study findings and our research questions, which was later refined by a second researcher. Both researchers coded a randomly selected transcript. We used Cohen's Kappa [367] for establishing inter-rater reliability (IRR) which was 0.42 for the first iteration of the codebook, suggesting a need for more iterations [367]. We conducted three such iterations, resolving disagreements and removing or collapsing conflicting codes, before establishing IRR (κ =0.69, *SD*=0.23) with the final codebook. The remaining transcripts were divided and coded independently.

6.5 Findings

6.5.1 Existing Wayfinding Strategies

Participants first described their wayfinding strategies included employing their O&M training, mobility aid, and residual vision (if any) to either discover what is around them or search for a specific target when they get close to their destination, depending on their familiarity with the space. Guide dogs are particularly useful in search tasks (*i.e.,* looking for a known object that the dog can recognize in the last few meters), whereas canes are more suitable for discovery tasks via O&M techniques like building trailing and structured discovery. P10 described using their residual vision to search for geometric and photometric properties of a landmark (*e.g.,"I can see the gleam off the metal"* or *"It looks like a big blob of colors so I think I'm in the area"*) and falling back to technology when their residual vision is not sufficient: *"I usually have a monocular. [...] I visually try to look around. If I get really confused, I'll go into Google Maps and zoom."* (P10).

6.5.2 Information Utility

All participants valued the information provided by Landmark AI, as the app gave access to information they might not have otherwise. They listed several reasons: ability to know what's around them, faster mobility by speeding up their search and discovery tasks, and increased independence. Participants identified several situations where they would use a system like Landmark AI: common places such as transit stops (most commonly mentioned), airports, pedestrian crossings, universities, and malls; unfamiliar places with confusing layouts such as conference centers or theaters; finding specific objects such as trash cans; and avoiding obstacles.

6.5.2.1 Channel-Specific Utility

The Landmark channel was viewed as the most useful due to instant access to contextual information and most likely use in day-to-day life: *"I like the real time feedback. Even if it's not perfect, it's so cool because it gives you kind of a quick sense of what's around you. That's something that, as a blind person, you usually have to be pretty slow, careful, and rigorous about exploring your environment. This gives you a chance to be a little freer, or a little more spontaneous."* (P6) Participants saw the potential to use it in different contexts by expanding the list of landmarks recognized by the system such as including restrooms and transit stops or recognizing rideshare cars' make and model. P10 described using a gummy bear statue outside the candy shop to confirm the store location; the use of residual vision with landmark detection in this case suggests that landmark detection should be designed to work in combination with users' residual vision (*e.g.,* identifying color and shape of an identified landmark) to support future visits even without the system.

The Signage channel was used to get confirmation when participants reached their destination. It was especially liked by those who had enough residual vision to detect, but not read, signs: *"I like the fact that they can pick up signage that might be too far away to see."* (P10). The channel also provided a way to be independent, especially where Braille is unavailable. In spite of the benefits, many (5) participants found it hard to use because of difficulty in knowing when to look for signs (*"I didn't visually see a sign, so I didn't have a trigger to switch to sign [channel]"*—P3) and where to point the camera (*i.e.,* both framing the view and conceptually knowing where signs could be). To remedy this, four participants suggested detecting existence of signs in the Landmark channel and providing more guidance to capture the signs as they scan the environment.

The Place channel was the most liked channel (9) because of the ability to capture and share an uncommon location (*e.g.,"Meet at the bench outside Baskin Robbins in the mall"*), simplicity of usage, the wide potential of usage scenarios, and increased feeling of independence. People with residual vision found utility where their vision was inadequate: *"Because I don't have* *any peripheral vision, I wouldn't have noticed it [box office counter], but now that I've been there, if you said, 'Okay, go find a box office at that place.' I'd go right straight to it. It's a good learning tool."* (P10). Participants liked the channel's social focus: *"Being able to be precise and to share landmarks and to connect with people in that way, there's fun there, right?"* (P3).

6.5.2.2 Importance of Landmarks

Amongst the landmarks currently identified by Landmark AI, the popularity of detecting doors was unanimous. Additionally, the differentiation between a door and a window was appreciated since (i) people with residual vision often have a hard time differentiating between the two due to the similarity of materials used (glass) in large shopping complexes and commercial buildings, (ii) guide dogs, who are usually good at finding doors, often get confused and lead the VI individual to a full-pane window, and (iii) cane users have trouble finding the door since they have to manually feel the door handle (*"You don't have to do that weird fumbling thing."*—P8).

6.5.3 System Design Considerations

6.5.3.1 Seamless User Experience

Six participants liked the instantaneous feedback from the Landmark and Place channels since it gave a *"quick sense of what's around you."* Several participants (4) felt the need for less information as it incurred cognitive load while walking. *"I really don't wanna hear everything that's coming in my way. That's too much information to process."* (P9). They expressed the need to filter irrelevant information based on the task at hand (*e.g.,* finding the building entrance), or the situational context (*e.g.,* entering a restaurant *vs.* looking for a table) by either manually or algorithmically *"determining the importance of putting the landmark with respect to where you wanna go and what you're trying to do"*—P9.

In the design of Landmark AI, users had to switch between channels to access different types of information. Multiple participants (4) indicated the need for a simpler design favoring a merged channel to enable efficient interactions and transitions between the different types of information. Participants suggested the system should intelligently ascertain the information need based on the situational context such that the cognitive load of *"where to point and having to pick the category"* (P3) is reduced. For example, if looking at a sign, read the sign automatically instead of switching to the channel to trigger the feedback.

Physical form factor was an important consideration that was noted by several participants (4). Hands-free use was desired so as to not disrupt their navigation routine and pace. Having to hold the phone out is not ideal due to safety concerns and the difficulty of managing it along with their primary mobility aid [393]. Participants suggested using wearables such as head-mounted devices (*e.g.,* Google Glass) or wearing on-body cameras *"Because you have to hold the phone for the camera to work, I would be very limited if I wasn't using my guide dog, because she works on my left side. I can only hold the phone with my right hand. If I was using my cane, I would not be able to use this app."* (P12). In addition to the awkwardness of using the phone, holding the phone straight was another issue. If not held straight, some participants had difficulty in understanding what was around them and where items were with respect to them; holding a tilted phone was the likely reason for their confusion.

6.5.3.2 Accuracy

Accuracy was one of the most important concerns amongst all participants (13) as it forms the foundation for establishing trust and confidence in the system. Factors that influenced accuracy were either system-oriented or user-oriented. System oriented factors included presence of false positives in the object recognizer and lack of robustness in handling a variety of materials. For example, false positives from objects located across the glass window and false negatives caused due to environmental conditions (*e.g.,* lighting and color contrasts causing inability to read signs). User-oriented factors included difficulty in framing a well-focused image, handling users' walking pace, and perceived inaccuracy caused by not holding the phone straight and in line with their body's position. Despite the current object recognizer's inaccuracy, participants explained even with inaccurate information, they would rely on their mobility skills to support them when technology fails. An instance was confirming the information provided by the application (*e.g.,* checking a table's existence with their cane).

Closely tied to the accuracy of the object recognizer is accurately capturing the scene and receiving usable feedback. For example, participants were concerned about being too far away or too close while taking a picture. Similarly, some participants were concerned whether the system could handle the variability in the perspectives of a captured location in the Place channel. Participants liked that the system was able to recognize landmarks from a distance as that didn't require them *"to be up close and personal with [the] building"* (P8). However, they were frustrated when the system failed to recognize landmarks from a distance, which happened for a few participants due to variability of phone usage. Getting feedback at the right distance is important when the feedback is crucial to be received ahead of time (*e.g.,* detecting obstacles). Participants wanted to hear the feedback as *"further out it can tell"* —P10 or periodically when moving towards their target (*e.g.,* in decrements of *"50 feet, 25 feet, 10 feet"* —P10).

6.5.3.3 Future Design Enhancements

Participants wanted access to more information with both more granularity and variety. For example, recognizing objects such as trash/recycling bins and drinking fountains, or landmarks such as pedestrian signals and restrooms. They wanted to identify objects that cannot be detected with their primary mobility aid such as railings when using a cane, empty tables when using a guide dog, and if there are people in the way when capturing a picture. In addition to the feedback about the environment, participants wanted precise directional guidance to reach their intended target as well as in situ guidance to use the system better. Precise directional guidance included providing information on the VI person's spatial orientation, ego-centric directions, and distance from the object of interest. In situ guidance included: (i) how to hold the phone and manipulate the camera: *"I don't know if a sighted person would look down to find the table. So, does that mean I have to angle the phone* *down?"* (P5—congenitally blind participant); and (ii) identify and prompt the user when to use the system: *"I keep forgetting that sometimes there are signs that hang out perpendicular to the building; [...] signs are things that we avoid as blind people because they hurt."* (P6). They also suggested using earcons to help them capture a picture better (*e.g.,* a beeping sound to guide the user in capturing the full sign). Additionally, participants mentioned varying directional instructions depending on an individual's residual vision, *e.g.,* using more visual instructions *vs.* more directional feedback. As P10 explains, *"I would give her [a friend with residual vision] more visual instructions because I know she can see that to a point."* For a completely blind person, much more granular information is needed such as precise ego-centric directions to the object of interest (*e.g.,"men's bathroom 10 feet to your left"* or *"door 20 feet ahead"*).

Finally, participants envisioned how such a vision-based system could be integrated or could work in tandem with other existing applications. Some examples included using it with native phone apps (*e.g.,* Photos), GPS-based apps such as Soundscape (*e.g.,* being able to set a beacon on the landmark of interest), using images from messaging applications or Google Street View as *"places"* to find, and mapping applications such as Google Maps: *"Collaboration is really an important thing when it comes to AI. If you could have the landmark feature integrated into [...] Google Maps for indoor navigation, that would be really nice in big hotels."* (P11).

6.6 Design Space For Landmark-Based Systems

As articulated by Williams *et al.* [383], individual differences play an important role in a VI person's use of navigation technology. Based on our studies' findings, literature on O&M training, and prior studies of VI peoples' navigation behaviors [7, 292, 382, 383], we articulate a design space for creating adaptive systems using landmarks as the primary wayfinding strategy. Systems designed according to these principles would provide personalized information relevant to the user and the situational context. The need for tailored information based on the user's specific abilities is a key aspect in O&M training and the proposed principles strongly comply with the Ability-based Design paradigm [388].

As described earlier, landmarks have varied sensory properties such as having distinct colors, shapes, sizes, aromas, sounds, or textures. Landmark preferences depend on the landmark's availability, the mobility aid individuals use, residual vision, and the presence of other senses (*e.g.,* hearing). Based on these factors, the relevance of a particular landmark in a given situation may differ. We define a design space to capture this relationship by mapping a person's mobility need to the different affordances of a landmark and its environmental context. We break the design space into four components: (i) Visual Abilities, (ii) Mobility Aid, (iii) User Personality and Preferences, and (iv) Context.

6.6.1 Visual Abilities

Adapting a system to VI user's visual abilities requires accommodating a person's use of their residual vision (if any) to navigate and how their navigation strategy impacts the choice of landmarks. During O&M training, an instructor assesses a user's residual vision to determine which landmarks would be usable. Relevant visual indicators include user's color perception, contrast sensitivity, visual acuity, and presence/absence of peripheral and central vision. As we saw from our study, landmarks are chosen based on their color, shape, size, and the location with respect to the user. For completely blind users, providing granular directional guidance is key. For people with residual vision, using visual instructions (*e.g.,* by describing visual features of the environment) is more appropriate. For example, for a person with color perception, an adaptive system should identify landmarks with distinct colors (*e.g.,* a bright red mailbox). Wayfinding apps could also be personalized in ways that best augments users' existing capabilities, *i.e.,* focusing only on calling out landmarks in the periphery if someone's central vision is intact. Alternatively, as suggested by one of our participants, a user may wish to specify in their profile that they would like an app to focus only on identifying landmarks in the region they can detect with their residual vision, so that they can then learn to attend to these landmarks in the future without the aid of the app.

6.6.2 Mobility Aid

An adaptive system should consider the differences in the information received from a person's mobility aid. Mobility aids such as guide dogs and white canes have different affordances. For example, a guide dog is mainly used to avoid obstacles and is most suitable for search tasks, while a cane is effective for detecting obstacles and is most suitable for discovery tasks. These differences impact an individual's navigation strategy [383], as we saw VI individuals' ability to use our system differed depending on their primary mobility aid. For example, finding doorways is easier for guide dog users while it is a laborious and a manual process for cane users. On the other hand, guide dog users do not receive any tactile information of objects and surfaces around them. This suggests adaptive systems should make discovery of landmarks dynamic depending on a user's mobility aid [7, 143]. For example, technology to assist in detecting tactile landmarks would be beneficial for guide dog users while systems that find structural landmarks such as doors and elevators would benefit cane users.

6.6.3 User Personality and Preferences

An individual's confidence traveling independently is a major personality trait that influences how they wish to use guidance systems [7]. Confidence may depend on years of mobility training received and/or the number of years of sight loss. Such differences could inform the level of support and guidance needed from a wayfinding system. For example, a person with recent sight loss might need constant feedback while a person who has never had vision may be more confident and may only need specific informational cues depending on what they want to achieve. In our study, we found that some participants were very task-oriented and only cared about the information relevant to the current context. In contrast, some participants wanted a full report on every landmark or object in the environment to get acclimatized and build a more complete mental model. Systems could support both pull and push interactions, allowing users to explicitly set their personal preferences.

6.6.4 Context

Complementing prior work [3, 7, 190], the fourth aspect of adaptation relates to the contextual factors that determine landmark choices when on-the-go. Depending on a VI individual's situational context (*i.e.,* familiarity with the space, noise level, crowd density, weather, and time of day), the usefulness of a landmark will vary. For example, a user's familiarity with the location changes the navigation task from discovery (for unfamiliar spaces) to search (for familiar spaces). Certain landmark types may not be useful based on the environment (*e.g.,* sound landmarks when the environmental noise is high) or may not be available (*e.g.,* "ding" sounds if the elevator is out of service). When a location is crowded, navigation becomes slower and use of mobility aids becomes difficult (*e.g.,* guide dogs losing line of sight to targets such as doors); in such scenarios, detection of obstacles would be important to provide for a clear path to the user and their mobility aid. Finally, lighting conditions, depending on the time of day and weather, may affect computer vision technologies and users' residual vision.

6.7 Discussion

Using two exploratory studies, we investigated the characteristics of the last-few-meters wayfinding challenge and explored specific user needs in this space. From these studies, we articulated a design space for creating adaptive systems providing tailored feedback to VI pedestrians. This design space is not only limited to the last-few-meters problem but can also be applied to traditional point-to-point navigation applications where the primary means of navigation is walking.

In the last few meters, we found that the spatial relationship between the person and the surrounding landmarks and/or obstacles needs to be established (*e.g.,* elevator is 10 feet away from the user at their 2 o'clock). Amongst landmark categories, we found discovering structural landmarks was the most preferred across all participants. Usefulness of landmark categories depended on the user's situational context and personal preferences based on their vision level and mobility aid, and we captured this relationship in our proposed design space. Our findings demonstrate how Landmark AI can be useful in complementing a VI individual's mobility skills, *i.e.,* how the system would be used with their primary mobility aid and residual vision. We reflect on these findings and present implications for designing and developing camera-based AI tools for accessibility, and present limitations and future work.

6.7.1 Implications for Camera Systems for VI Pedestrians

In this work, we demonstrated the feasibility of using a smartphone camera-based system that provides near-real time information about the world within the accessibility context when the user is mobile. Within the three interaction paradigms we observed, *i.e.,* real-time scanning (Landmark channel), image capture (Signage channel), and hybrid—combining capturing images and real-time scanning (Place channel), participants preferred real-time scanning as it was fast, simple, and easy to use on-the-go. Capturing a good image was a frustrating experience [184, 185]. Partial coverage or misfocus in capturing images of signs were common reasons for difficulty in using the channels. Applying blind photography principles [33] could help guide users to capture accurate pictures, though this remains a challenging area for further research. Additionally, participants preferred a simpler interaction than switching channels. Even though channels are an artifact of Seeing AI, this system design allowed us to analyze the implications and impact of these interaction paradigms: while channels simplify a system's technical implementation, they add overhead for the end user, and we recommend avoiding them.

Consistent with prior work [113, 241], some participants had difficulty positioning the phone while walking. This caused misinterpretation of the app's feedback. Implementing camera guidance mechanisms [184, 365] to handle hand-body coordination could resolve such difficulties. Alternatively, participants suggested using a wearable camera to allow hands free usage when they are mobile—critical for many participants due to either situational or motor impairments. Prior work [115] and industry solutions (*e.g.,* [181, 182, 387]) have looked into wearables for VI users. However, further work is required on wearable solutions to study scene capture accuracy and its impact on users' understanding and knowledge of the environment; Manduchi *et al.*'s investigation of blind users' ability to use smartphone object recognizers [241] is an important step in this direction.

6.7.2 Implications for Vision Algorithms for Accessibility

On-device Recognition. In this work, we looked at the application of deep neural networks (DNNs) for recognition tasks on mobile devices [170, 175, 395]. Use of fast and light-weight recognizers are crucial for providing real-time feedback when the user is mobile. We used a fast on-device recognizer based on SqueezeNet [175] to identify landmarks, making instantaneous response a possibility. However, a contributing factor to the signage channel being least preferred was the slow processing time due to dependence on cloud-based API calls. Current on-device recognizers lack the robustness in handling the variety of font styles encountered in the open world, particularly stylized logos common in commercial spaces. Future work from the vision community to develop on-device text recognition algorithms will be crucial in making signage recognition real-time. In addition to enabling real-time information, on-device recognition would also preserve privacy, especially for people captured in the scene.

Need for Material Recognition. Our design space highlights the importance of identifying a landmark's photometric and geometric properties to support varied vision levels in order to customize landmark detection. For this to happen, materials and texture recognition [33, 74, 172, 318] would play a critical role, for example, detecting the material of the landmark and detecting changes in surface texture (for tactile landmarks). However, current computer vision algorithms [33, 74, 172] are not accurate enough, warranting an effort in improving their speed and accuracy. Combining material recognition with object recognition could also improve landmark recognition accuracy. In addition to materials, determining the color, shape, and size of landmarks is important when integrating them with object recognition.

Implementing Place Recognition. Landmark AI's place channel, which used a Wizard of Oz approach, was popular among study participants. Participants expressed interest in knowing whether the system would support recognizing the place if the original angle of capture differed from angle of the real-time feed. Prior work in robotics has looked into using deep learning approaches [69, 228, 337] and traditional computer vision techniques [89] for performing place recognition [137]. Future work in implementing a real-time place recognizer that is both viewpoint invariant and time invariant will be crucial in making this demonstrated experience a reality. Within the accessibility context, the place recognition problem can be constrained at two stages: (i) at the image capture stage, where unique landmarks are captured in the scene along with the location, and (ii) at the recognition stage, where performing a fuzzy match between the previously stored image and the current scene could be sufficient, thus circumventing the need for semantic scene understanding. This approach would be particularly useful for scenes for which specific classifiers have not been trained or that contain unusual uncommon objects.

Achievable Accuracy. We found that participants preferred certain types of landmarks such as doors over others. This suggests that we may not need general-purpose recognizers that classify a wide range of possible objects, a daunting task for current computer vision algorithms. Instead, collecting a large and realistic dataset of common landmarks and objects (*e.g.,* doors of different types), combined with counterexamples of objects that are similar and confusable with the object of interest (*e.g.,* full-pane windows) would be a priority. Building a robust recognition model for a smaller (but important) set of objects could have a significant impact on VI users' daily navigation abilities. Our design decision of using simpler vision models with preset landmarks was guided by this fact to maintain a reasonable level of accuracy.

In our system, we cared more about precision (low false positives) than recall (low false negatives). Ideally, there should be a balance between the two. However, realistically there are high chances of the results being skewed. In those cases, low precision causes more harm than low recall. In our study, we found participants getting frustrated with false positives, making it hard to rely on the system. Participants did understand that a system cannot be perfect, and they valued access to rich contextual information. However, the system cannot *"provide the user too much of wrong information, because that will directly confuse the user more than really help them out."* (P9). DNNs have been found to get easily "fooled" even with a high confidence threshold [274]. For a deployable level of accuracy, using computer vision techniques alone may be insufficient. Potential solutions relying on humans to use their own judgment to reason about the inference (*e.g.,* using explainable AI techniques [144]) or using heuristics and sensor fusion techniques to supplement the vision results could help establish more confidence in AI-based navigation aids.

6.7.3 Limitations and Future Work

Two main limitations may impact our findings. First, due to Landmark AI's high rate of false positives, participants were often frustrated and confused. While we believe that accuracy should have been better, this allowed us to understand the implications of poor accuracy, a likely scenario in the open world in the near-term with state-of-the-art AI. Studying how people learn to adapt to system inaccuracies will be valuable for understanding usage of fault-prone AI systems [3]. Second, Landmark AI did not provide navigational guidance to reach the landmark target once it was identified, an important characteristic for a wayfinding system [241, 392]. However, this gave us an opportunity to investigate the guidance needs in the last few meters. Indeed, we observed that the system does not have to be hyper-accurate with such guidance, as one's existing mobility skills (through O&M training or otherwise) plays an important role of being independent. As participant P10 summarizes, *"At some point, you got to leave something out to the user to use their brain. Some people want to be spoon-fed every single little bit of information, but how do you learn if you don't find the stuff out for yourself?"*.

6.8 Chapter Conclusion

In this chapter, we looked at the second application category—in-situ navigation—targeting a second group of MI individuals: blind and low-vision travellers. Specifically, we investigated the last-few-meters wayfinding problem for this target community. Our formative study identified common challenges faced in the last few meters, how VI users currently overcome them, and where current technology falls short. Based on these findings, we designed *Landmark AI* and elicited feedback on the usefulness of the system design via a design probe study. Using qualitative data analysis, we found that an individual's choice of mobility aid (*e.g.,* guide dogs or white canes) and their visual ability impacted the manner in which they used the system and the provided feedback. We captured this rich relationship between the information types and an individual's mobility needs in a design space for creating adaptive systems and presented a set of design implications for future camera-based AI systems for people with visual disabilities.

7 Discussion: What Lies Ahead?

Building inclusive cities requires understanding the lived experiences of diverse communities. Beyond acquiring qualitative accounts of their experience, data can play an important role in understanding and quantifying the accessibility needs of the city and its people. In this dissertation, my goal was to identify those data-driven opportunities for tools and technological interventions. I took a holistic approach by understanding the larger landscape of urban accessibility problems, going beyond the physical accessibility barriers that exist to reveal the underlying causes. Specifically, the human factors that influence the physical (in)accessibility of urban infrastructure. Through my research, I studied a mix of stakeholders who had the power for influencing change in terms of accessibility improvements and those affected by inaccessible infrastructure. I studied how their needs differed and sometimes conflicted. Finally, I developed interactive tools for urban-scale data collection, navigation, and visualization, and generated design guidelines for future interactive data-driven applications for this domain.

In this chapter, I review these contributions, present limitations of the work, and lay out a vision for future interactive data-driven tools for urban accessibility.

7.1 Review of Thesis Claim and Contributions

In the Introduction (Chapter 1), I presented the following thesis claim:

> Interactive data-driven tools for urban accessibility that incorporate the social, political, and individual contexts of varied stakeholders lead to multi-faceted decision-making tools providing actionable insights.

Below, I describe how my dissertation research supports this claim through a review of the contributions.

Multi-stakeholder analysis as a method

Throughout the dissertation, I took a multi-stakeholder approach by studying five different stakeholder groups with respect to each other to understand their individual perspectives on urban accessibility, data needs, and decision-making practices. Building this foundation allowed us to understand the socio-political complexities of a civic ecosystem where infrastructure development decisions are made (Chapter 3). Further, using this approach to study human-data interactions with accessibility datasets, allowed us to understand how their individual perspectives affected their understanding of urban accessibility and the consequent implications towards designing for those specific perspectives (Chapter 5).

Civic Interaction Space

Through the multi-stakeholder approach described above, I identified the roles of individual stakeholders, the different goals and tasks they carried out, and the required cross-stakeholder interactions for accomplishing those goals (Chapter 3). Mapping these interactions revealed the varying decision contexts within which the tasks are performed. Understanding these points of interactions are crucial for designing tools catering to these stakeholders and facilitating collaborations through technology.

Project Sidewalk, a tool for remote data collection of sidewalk accessibility at scale

One of the primary reasons for the lack of these comprehensive accessibility-aware tools is the lack of urban scale datasets that help answer wide range of decision-making questions. Project Sidewalk addresses this concern for collecting sidewalk accessibility data at scale. We chose sidewalks as they form the backbone of the pedestrian infrastructure and is crucial for MI individuals' day-to-day travel. In this dissertation (Chapter 4), I described a scalable approach of combining crowdsourcing, GSV imagery, and gamification techniques, to design, deploy, and evaluate a data collection tool for labeling sidewalk accessibility issues such as missing curb ramps, surface issues, sidewalk obstacles, and no sidewalks. We evaluated the tool with a deployment study in Washington DC, where we remotely collected the first-ever city-wide sidewalk accessibility dataset. We also identified common labeling errors made by crowdworkers, which has led to further development of Project Sidewalk, active till date. Since the initial deployment in DC, the Project Sidewalk team has increased in size and the tool itself (Figure 7.1–top) has an improved interface design, new label types (*e.g.,* crosswalks, pedestrian signals), new features (*e.g.,* public leaderboards – Figure 7.1–bottom), and complementary tools for data validation (Figure 7.2–top) and data exploration (*e.g.,* Sidewalk Gallery [1] [105]) (Figure 7.2–bottom).

Publicly available urban-scale sidewalk accessibility datasets

Through this dissertation work, we generated first-ever tech-enabled and publicly available city-wide sidewalk accessibility datasets with over 260,000+ labels from the pilot deployment in Washington DC. This has led to significant real-world impact, including inspiring (i) 10+ cities around the world to deploy Project Sidewalk [232–238] for informing policymaking (*e.g.,* Mexico City's Pedestrian Master Plan), (ii) research efforts in universities to develop automated data collection approaches using our datasets [376, 378], and (iii) data enthusiasts visualizing these datasets for their personal context and needs [263, 264].

AccessVis: Design guidelines for interactive geovisualization tools for urban accessibility

Towards designing novel multi-faceted decision-making tools for varied stakeholders and diverse contexts, the first was interactive visualizations of urban accessibility. Through analysis of how different stakeholders interpreted map visualizations of the DC dataset, I uncovered how the alignment with their existing mental models of accessibility and sense-making processes influenced their perceived usefulness of the visualizations. Specifically, I

[1] https://sidewalkgallery.io/

Figure 7.1: Project Sidewalk Developments. This illustration shows some of the developments made to Project Sidewalk (top) since the initial Washington DC deployment, namely improved interface design, new label types (*e.g.,* crosswalks, pedestrian signals), and new features (*e.g.,* public leaderboards - bottom).

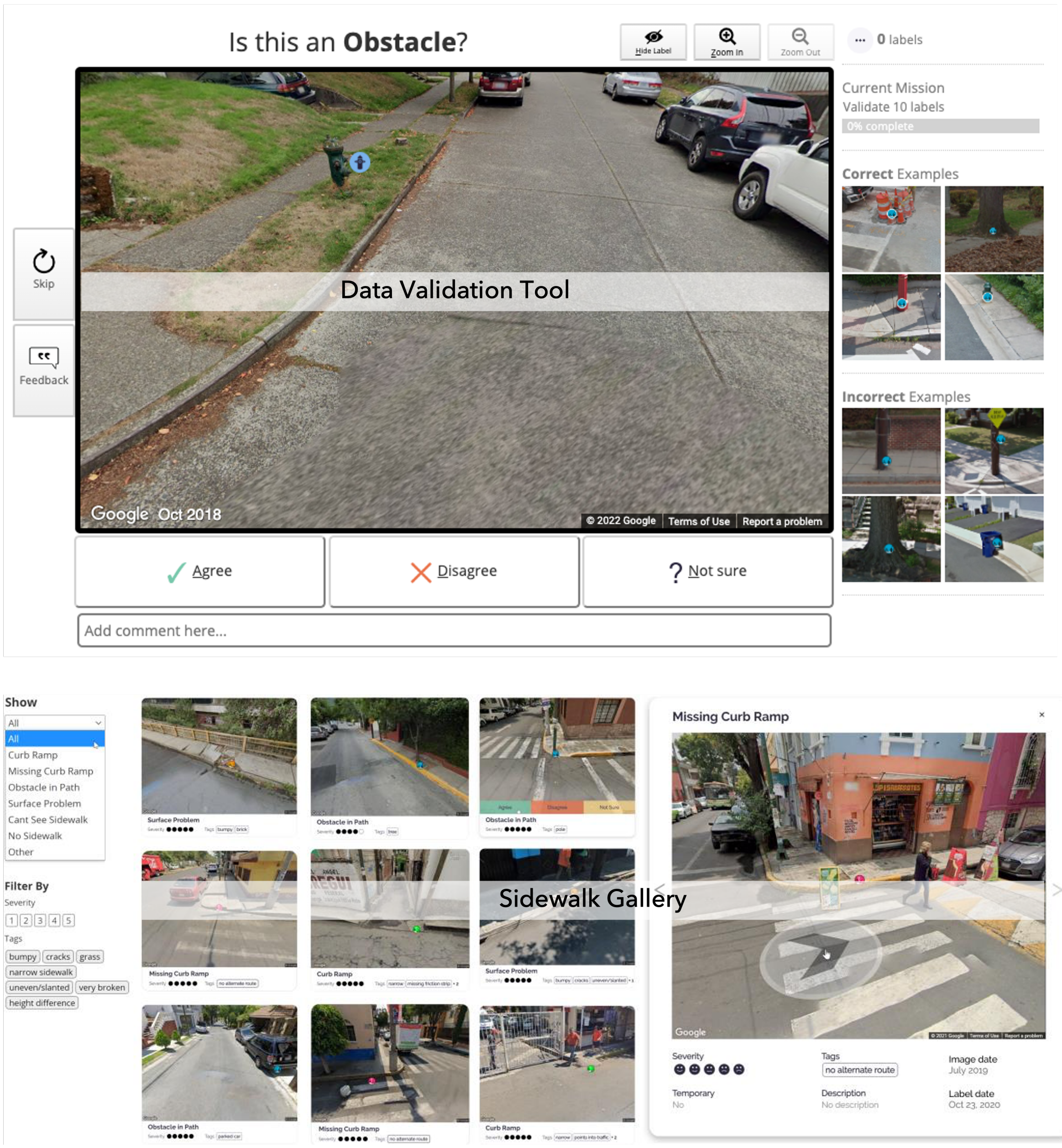

Figure 7.2: Project Sidewalk Developments – Complementary Tools. Illustration shows two complementary tools. First is a data validation tool (top) that allows crowdworkers to review and correct data from other crowdworkers. The second is a data exploration tool called *Sidewalk Gallery* (bottom) that allows exploring the collected dataset by label types and their attributes such as severity and tags (*e.g.,* “bumpy surface”).

found that an individual's relation to accessibility through lived or professional experience, familiarity with the location being visualized, and familiarity with map-based analysis influenced their sensemaking process as well as the insights gained. As discussed in Chapter 5, these findings suggest significant implications for future geovisualization tools to provide actionable insights to such diverse audiences. More specifically towards personalizing data analytics, which I will discuss in the future directions section later in this chapter.

Landmark AI, a computer vision based navigation tool for addressing the last-few-meters wayfinding challenge of people with visual disabilities

The second application I explored was for supporting people with visual disabilities in navigating the last-few-meters of a destination where GPS fails. Through several formative studies, I designed and evaluated the feasibility of using computer vision with audio-based AR to provide relevant navigational guidance for covering the last-few-meters to an actual destination (*e.g.,* a building entrance). Landmark AI explored three interaction paradigms providing real-time feedback, server-processed feedback, and a hybrid information channel. I then presented how the system worked in tandem with an individual's mobility skills, the mobility aid used (*e.g.,* guide dogs, canes), and on-the-go travel. Beyond the system design contribution, I also generated a design space for future landmark-based navigation systems and implications for computer-vision based navigation tools. Specifically, I found that personalized information delivery tailored to their specific context, residual vision, mobility aid, and personality will be key for designing for this population. Finally, the ideas explored and the findings from this work are now available as accessibility features in Apple iPhones (May 2022 feature release) [18].

7.2 Assumptions and Limitations

Urban Accessibility is a global problem. At the beginning of this dissertation, I set my larger vision towards mapping the physical accessibility of the world. Towards this goal, this dissertation investigated the accessibility of US cities, where relying on technologies such as Google Street View is easier due to abundance of data across cities, as compared to other countries where regulatory troubles can limit use of these technologies [166]. In addition, in the US, comprehensive accessibility regulations and policies exist, but non-compliance with these standards is the issue. However, cities around the world, where these regulations do not exist, might have completely different implications for tools needed. Similarly, the presence of accessible infrastructure features cannot be assumed in many parts of the world either. Our recent initial investigations of these socio-cultural and geographical differences on urban accessibility demonstrates this fact [123]. However, the impact on tool design accounting these differences is an unexplored area. Despite the specific geographic context of this dissertation, the core findings around how stakeholders' perspectives, needs, and interactions with one another impact urban accessibility, can be extended across different geographic locations and communities, thus, providing the foundation to pursue future research.

Defining (in)accessibility for diverse disability communities. (In)accessibility means different things to different groups. Tools presented in this dissertation operated on the definition most closely relevant to a wheelchair users' perspective. For simplicity, I used this definition through the dissertation. However, my research also revealed how personal perspectives change the definitions for an individual based on their lived and/or professional experience with accessibility. Thus, for addressing the broader range of accessibility needs, we need to expand the definition and create a broader taxonomy. For example, as we saw in Chapter 6, sidewalk features such as water hydrants can serve as landmarks as opposed to 'obstacles' for guiding people with visual disabilities. Presence of tactile strips are beneficial to a person with a visual disability but might be a sidewalk barrier for a new wheelchair user. This suggests that we need to work towards making tools and their underlying taxonomies inclusive and customizable to an individual's personal context.

7.3 Future Directions

The primary theme of this dissertation is the impact of the stakeholders' diverse needs on tool design. Considering the challenges presented by this diversity, I present some future directions for the next generation of interactive data-driven tools along the previously defined three-pronged problem space of urban accessibility: people, data, and tools.

7.3.1 *People*: Catering to Diverse Audiences

We saw a mix of audiences with diverse data/technical skills and physical abilities. Accounting for these differences would require personalized interfaces across task domains such as urban data analytics and navigation. I call these applications '*Accessible Data Tools*', where accessibility is defined across two spectrums: data skills and physical abilities. Below, I describe two personalization spaces: *personalized accessibility profiles* and *personalized data analytics*. Accessible visualizations for people with visual disabilities is an example application that sits at the intersection of the two.

Personalized Accessibility Profiles. Chapter 5 and Chapter 6 demonstrated the need for personalized information feedback depending on the individual's personal context. For example, accessibility for a manual wheelchair user *vs.* a powered wheelchair user *vs.* a cane user would be significantly different. Therefore, acknowledging these differences in tools for audiences with varied accessibility needs is crucial. Recent work has looked at creating personal mobility profiles for providing navigation information [51]. However, a broader set of accessibility profiles would be needed for different task domains (*e.g.,* visualizations), warranting further research.

Personalized Data Analytics. Complementing the above need is addressing the lack of accessible data tools catering to varied data skills. Currently, the power of using data remains in the hands of the few with technical expertise. For example, in the public and non-profit sector, the stakeholders are advocates and government officials who often work together to develop policies. The non-profit sector often have individuals with deep data questions but lack necessary technical skills. Additionally, they are often financially constrained to hire dedicated in-house data support. To support these individuals in their pursuit for data-driven advocacy, we would need to reimagine data analysis workflows that cater to their existing data skills. I call these individuals, the '*novice data scientist*'. So the question is *how do we make cognitively challenging analytics accessible to novice data scientists? how do we make considerations around their sensemaking processes?* I call future researchers to work towards '*Personalized (Novice) Data Analytics*'.

Combining the two personalized spaces would be a step towards the larger vision for future accessible data tools: *Designing intelligent information systems that consider the abilities of the end-users–both physical and technical–to guide them in the data-oriented tasks*.

7.3.2 *Data*: Crowdsourcing and Maintaining Diverse Datasets

This dissertation presented a scalable approach to crowdsource sidewalk accessibility data. However, as seen in Chapter 3 and Chapter 5, stakeholders require numerous types of datasets, some being more challenging to collect through manual methods than others. One of them is *experiential data*. Policymakers had noted that being able to understand what the on-the-ground experience feels like could be beneficial on the decision-making table. Another example of experiential data are non-visual cues such as smell and sound, which are used by people with visual disabilities as landmarks for navigation (Chapter 6). These types of data can also be used for other map-based applications such as Smelly Maps [297, 298] to find enjoyable travel paths. But *how do we gather such experiential data i.e., non-visual cues at scale?* Quercia *et al.* proposed using geo-referenced social media posts. However, data for the accessibility context would require more granular data attributes and descriptions such as temporality, quality, and reliability of these non-visual data. Future work is warranted towards extending the existing approaches and/or innovating new approaches for the accessibility context.

Data collection efforts are important but they are only the first step. For long-term use of such location-based applications, datasets need to be kept updated. Project Sidewalk addresses an important issue of the lack of urban-scale accessibility datasets, however, the problem of data age and update is an open problem. In-person approaches suffer from being slow and tedious and generating sparse datasets [101]. Could a hybrid model where people traveling in cities update the existing remotely collected data work? Google Maps uses this approach to collect transit crowd data. Could this be applied to an accessibility context without leading to data sparsity? I call researchers towards more investigations for this challenging, yet crucial problem of data maintenance.

7.3.3 *Tools*: Facilitating Cross-stakeholder Interactions

While I explored applications for three main tasks—data collection through crowdsourcing and online streetview imagery, data exploration through interactive visualizations, and navigation through computer vision and mobile applications—this dissertation also revealed a vast set of tasks and problems where urban accessibility tools are missing. Specifically, tools for facilitating civic interactions between stakeholders is especially lacking. Below, I describe directions for tools supporting two communication tasks–storytelling and collaboration–within the urban accessibility context.

How do we enable data-driven interactions and collaborations between different stakeholders? Chapter 3 laid out the different cross-stakeholder interactions that take place for urban-scale decision-making. Some examples of these interaction goals are raising awareness, setting priorities, acquiring community input, and issue resolution. For accomplishing these goals, variety of stakeholders with diverse backgrounds need to collaborate to make large- and small-scale decisions. Recent work has started looking into participatory approaches for enabling civic discourse and civic action [31, 187]. Within the urban accessibility context, recent work by Bolten *et al.* [52] proposed a community-based participatory action framework and present how data-driven technologies can show inequities in data collection processes in cities. More work will be needed for designing tools that facilitate such collaborative decision-making processes.

How do we support building persuasive data stories for cross-stakeholder communication? Chapter 5 emphasized the importance of combining quantitative data with qualitative emotional context to build a story. This work reaffirms prior findings that emotions can often drive decisions [107]. This is especially true for politically and emotionally charged issue domains beyond accessibility such as climate change and police violence [262]. Past work have used 3D videos, simulations, and citizen testimonials for appealing to a person's emotions [311, 356]. However, more work is needed to facilitate building data-driven stories via interactive tools. Specifically, investigations on the type of interactive storytelling support needed for combining data-based facts with emotional and historical context of the people involved. Immersive technologies such as VR could be a space for exploration for showing the experiential data augmented with statistical data facts. Situated urban visualizations [261] through interactive displays or AR and place-based digital storytelling approaches [243] could be another avenue of exploration.

7.4 Concluding Remarks

With the growing need for inclusive walkable/rollable cities, new interactive data-driven tools will be needed to enable and support decision-making for accessible infrastructure development, policymaking, advocacy, and daily living. In this dissertation, I studied the issue of urban accessibility by studying stakeholders across these decision contexts: their data, sensemaking, and tool needs. Based on those findings, I designed and evaluated multiple tools from data collection to data visualization to navigation. I further demonstrated the importance of keeping stakeholders and their specific contexts central during tool design. I hope the findings from the tool and stakeholder analyses presented in this dissertation will form the foundation for future researchers and technologists to study and design tools not just for urban accessibility, but any socio-political domain that share similar characteristics (*e.g.,* diverse stakeholders, complex decision-making and organizational structures).

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A For Chapter 3: Socio-political Environment Analysis and Chapter 5: Visualizing Urban Accessibility

Participant Description

Group: M=MI individuals, C=caregivers A=advocates, D=department officials, PM=policymakers. Five participants self-identified into two groups.

P#	Group	Affiliation	Role(s)	Additional Notes
P1	M			Powered Wheelchair User Ehlers Danlos Syndrome
P2	M			Powered Wheelchair User Osteogenesis Imperfecta
P3	D & C	DOT	Sidewalk Repair Program Manager	Father under care
P4	C			Husband under care
P5	M			Powered Wheelchair User Complete Quadriplegic
P6	C			Daughter under care
P7	A & C	Tech-based Disability Adv. Org.	Director	Daughter under care
P8	D	DOT	Asset Management Strategic Advisor	
P9	M			Manual Wheelchair User Incomplete Quadriplegic
P10	M			Cane User
P11	A	Walkability Adv. Org.	Vice Pres., Policy Committee Chair	
P12	D	DOT	ADA Coordinator	
P13	A & M	Disability Adv. Org.	Senior official	Manual Wheelchair User Lumbar sacralagenesis
P14	A	Neighborhood Adv. Group	Co-lead	Former Mayoral Candidate
P15	A & M	City Commission for Disabilities	Member	Cane User POTS Syndrome
P16	A	Law Firm	Partner, Lawyer	
P17	PM	City Council	Policy Analyst	Assists all city council members; Liaison between DOT and the council
P18	PM	State Legislation	Ex-State Representative	Former Mayoral Candidate
P19	D	Office of Disability Rights	ADA Architect	
P20	A & C	City Commission for Disabilities	Volunteer	Husband under care
P21	D	DOT	Chief Performance Officer	
P22	D	DOT	ADA Coordinator	
P23	PM	City Council	Analyst	
P24	A	Disability Adv. Org.	Executive Director	
P25	PM	City Council	Elected Official	

Interview Script for Chapter 3 and Chapter 5

Data from **Part 1** of the interview script was analyzed and presented in **Chapter 3**: Urban Accessibility as a Socio-Political Problem

Data from **Part 2 – 4** of the interview script was analyzed and presented in **Chapter 5**: Visualizing Urban Accessibility

Participant ID: ______________________ Date: __________________________ Time: __________

Formative Study on Visualizing Urban Accessibility

Semi-structured Interview Session

Introduction:

[READ TO PARTICIPANTS] – 5 min

Hi, I am Manaswi Saha, a PhD Student at UW. Thanks for coming in today.

Before we begin the study, let me give a brief overview of our project. I am going to read out from my script so that we present the same instructions to all participants.

Our goal is to design new methods and tools to inform people about inaccessible areas of a city. For example, places could be inaccessible due to lack of sidewalks, absence of curb ramps at intersections and so on. Our long-term research agenda is to develop tools that enable people like yourself (and others such as city governments, advocates) to utilize this data in the form of novel applications, support open data initiatives, and increase transparency. Some examples of applications include smart routing for people with mobility impairments and interactive visualizations of city's accessibility.

The goal of this study is to understand the sensemaking process of assessing accessibility through visualizations. The study will be in four parts:

1. The first part is an interview study, where the questions will be to understand on how you assess accessibility and what are your **current practices** of doing so?

2. The next two parts are geared around a set of paper prototypes visualizing urban accessibility data. We will use a **think aloud protocol** i.e., as you make sense of the visualizations, you will say your thoughts out loud such that in understanding your thought process in making assessments using those visualizations.

3. Finally, the last part is a short **debrief interview**, to reflect back on the previous part. We will ask questions about your overall experience of the study and future accessible mapping tools.

The whole study session should take about 90-120 minutes. Your data will be kept anonymous. We will be audio/video recording. For the video recording, your face will not be captured and we do not intend to take identifiable images of you. You have the right to stop participating in the study at any time. Before we begin the interview, we need to you sign the consent form and complete the background questionnaire [if the participant hasn't already].

Do you have any questions?

Begin Interview:

INSTRUCTIONS FOR RESEARCHER:

Keep these handy for the entire session:

- Pre-Study Questionnaire (optional- if participant hasn't filled it out) (5 minutes)
- Consent form
- Interview Script
- Paper Prototypes
- Prototype Overview Sheet
- Label Guide Sheet
- Payment form and cash

[Start recording once the participant signed the consent form and filled out the questionnaire.]

I have just started the recorder and we will begin the interview. Please feel free to say whatever is on your mind and to ask me questions at any time. Are you ready to begin?

Part 1 – Interview Session – Current Practices for Assessing Accessibility

Main goal: Understand **current practices** for assessing accessibility data and understand the **metrics** they use.

INSTRUCTIONS FOR RESEARCHER:

Have the questionnaire ready for reference. Note the timing of any interesting comment the interviewee mentioned.

Stakeholders:

1. Government Officials (GOV)
2. People with Mobility Impairments (MI) and Caregivers (CVG)
3. Accessibility Advocates (ADV)

General Questions

About Participants – 5 minutes

1. GOV + ADV: What is your role in your organization?
2. ADV: What is the role of your organization towards city's urban development efforts specifically with regards to accessibility?
3. CVG:
   a. Who do you care for as a caregiver?
   b. Which aid do they use?
   c. Do you travel with him/her/them in the city? How often?
4. MI/CVG:
   a. Could you recall a situation where they (CVG) OR you (MI) faced a challenge while moving around in the city using sidewalks? What were the biggest obstacles while traveling?

Assessing Accessibility – 10 minutes

1. How do you currently assess sidewalk accessibility? Prompt: Familiar vs non-familiar neighborhoods
2. Do you rely on any metrics to quantify accessibility? If yes, what are they?
3. GOV: What do you look for specifically when making an accessibility assessment of a region?
4. Do you use any digital tools to make these assessments?
   a. Yes: What are some of the tools you use?
   b. No: How do you make assessments?
5. GOV: What types of data sources do you rely on?
6. [MI, CVG: Consider you (and the person under your care) are moving to a new neighborhood.]
   a. What types of questions would you ask when assessing a new neighborhood in terms of mobility? Example:
      i. GOV: For fixing sidewalks
      ii. ADV: For pushing policies/making a change
   b. Do you factor in points of interests (POIs) when you assess accessibility? For example, transit stops, groceries, hospitals, restaurants.
      i. Yes: How do you factor them in? For e.g., do you use any tools?
7. GOV, ADV: Do you work with citizens during your assessments? If so, who are they (demographics)?

--- TURN ON VIDEO CAM ---

Part 2 – Paper Prototype Study: Part A - Assessing Overall City Accessibility (60 min)

Main goal: To understand their sensemaking process using visualizations.

[READ TO PARTICIPANTS]

Let's begin the second part of the session—the think aloud activity—using paper prototypes. In this part, you will be asked to do a set of sensemaking tasks using the visualizations we created. Let's introduce you to the data and the corresponding visualizations.

DATA INTRODUCTION

[show the PS video: https://www.youtube.com/watch?v=YZZK9mcH4Hc]

The data that we use for these visualizations is a tool called Project Sidewalk, a crowdsourcing based tool that is based on Google Street View where volunteers virtually explore city streets via SV images to find and label accessibility problems such as surface problems, curb ramps and missing curb ramps, sidewalk obstacles, or absence of sidewalks. Each applied label has a location associated with it and a severity rating ranging from low **in**accessibility (level 1) to high **in**accessibility (level 5). We collected data collected in Washington DC and you will be looking at maps of DC.

Here is a guide for your reference to see what severity of each problem type looks like.

Finally, in some of the visualizations, we incorporate street elevation data as well.

Part 2a: Initial Understanding (45 min)

PROTOTYPE INTRODUCTION

We have created six types of visualizations based on this data. Let's go over them one by one.

1. **Point Visualizations**: This shows the geo-located accessibility problems segregated by label types. Brighter areas are denser.
2. **Severity Point Visualizations**: These set of visualizations break down the point visualizations by their individual severity ratings ranging from 1 to 5 or low to high inaccessibility.
3. **Grid Maps**: This visualization breaks down the city in 1km grids. Each grid is colored by the label count in those regions. So higher the concentration, brighter is the grid color.
4. **Heatmaps**: This visualization highlights the density of problems by total point count and by severity i.e. highlighting regions with more severe issues.
5. **Area Map**: Based on the different problem types, we created an "access" score for measuring accessibility of regions (such as neighborhoods). They are calculated by assigning penalty to each problem type. Some types have more penalty than others. For example, missing curb ramps is given more over penalty than other problem types. The scores are on a scale 0 – 100 % from low to high accessibility. Note: The scale is now on ***accessibility*** and **not** inaccessibility as previously seen. To simplify, blue is good, and brown is bad.
6. **Street Visualizations**: We now move to streets and visualize the raw problem count and average severity of streets based on the problems associated with each street. Exception: High count/severity is the darker color and low is the brighter color.

[Ask after each visualization intro] Questions:

1. What do you understand/learn from these set of visualizations? [Prompt]: Do you notice any patterns?
2. Could you summarize your findings from these visualizations?
3. [MI: For severity point viz]: Rate the significance of problem types based on their importance to you on a scale of 1-5, Not at all Significant to Extremely Significant [Prompt]: Which problem types are more important to you? **[**Give label guide sheet**]**

Part 2b: Sensemaking task (15 min)

Task 1 Prompt: *Identify the three most **accessible** and **inaccessible** areas of the city.*

Clarification:

What is an area?

'Area' can be chosen by you based on how you define. Examples could be an area around a location of choice, a neighborhood, a district etc.

Post-task questions:

1. <Answer to the prompt asked>
2. What about the selected visualization(s) helped you answer this question?
3. Was there any information missing from the visualizations to answer this question? If yes,
    a. Follow-up: What types of information would have helped in answering the question?
4. How do you envision using these visualizations?
5. Do you trust the insights from these visualizations?
    a. [Yes] What helped you in establishing this trust?
    b. [No] What would you need to establish trust in the findings you learn from these visualizations?
6. Are there any other ways in which you would like to compare neighborhood accessibility? If so, what are they? Goal: What are the factors for the basis of comparison?
7. [Optional] Other than Project Sidewalk's severity scale, how would you want to define or measure severity of regions?

Interviewer Notes:

--- Break: 5 min ---

Part 3 – Paper Prototype Study: Part B- Assessing Accessibility of a Neighborhood/Locale (15 min)

Main goal: To understand their sensemaking process using visualizations.

[READ TO PARTICIPANTS]
In this part, you will look at a new visualization type, we call **time plots**, for assessing accessibility with respect to a location of your choice. Similar to the previous part, this will be a think aloud activity.

Part 3a: Initial Understanding (5 min)

[Show the ego-centric isochrones for person **without** mobility impairment for only one neighborhood]

[**Meta Task**] This visualization shows the accessible reach of a location: what points of interests (or POIs) are accessible to your location and how far are they from your location? [Point at the visualization] For example, the innermost circle shows what is accessible within 10 minutes of your location. In other words, this map shows how easily a certain point of interest can be reached by walking.

[Ask after showing visualization] Questions:

1. What do you understand from this visualization?

Part 3b: Sensemaking tasks (10 min)

[Show the ego-centric isochrones with access vs no access]
Task 2 Prompt: Here is the same visualization for a person on a manual wheelchair. Your task is to compare and identify the differences you notice in terms of accessible reach for each person.

Post-task questions:

1. <Answer to the prompt asked>
2. What about the selected visualization helped you answer this question?
3. Was there any information missing from the current visualizations to answer this question? If yes,
    a. Follow-up: What types of information would have helped you in making this decision faster or easier?

Interviewer Notes:

[Show the ego-centric isochrones which incorporates accessibility]

Task 3 Prompt: Here is the same map for two other neighborhoods for a manual wheelchair user. Consider a situation where a family member who is in a wheelchair wants to move into a new neighborhood. Which neighborhood looks the most accessible in terms of accessible reach?

Post-task questions:

1. <Answer to the prompt asked>
2. What about the visualizations helped you answer this question? [Prompt]: What helped you in making the inference?
3. Was there any information missing from the current visualizations to answer this question? If yes,
    a. Follow-up: What types of information would have helped you in making this decision faster or easier?
4. What entities (other than POIs) would be useful for you to assess the accessibility of the neighborhoods using such visualizations?
5. How else do you envision using this visualization?
    a. What value do you want to get out of it?

Interviewer Notes:

Part 4 – Concluding Debrief Interview Session (10 min)

Time allotted: 10 Minutes

Main goals: To understand the participant's decision-making process in doing the sensemaking tasks in Part 2 of the study. Have the participants reflect upon (1) their experience during the course of the activity, (2) their likes, dislikes and desired additions/changes to the visualizations.

INSTRUCTION FOR RESEARCHER:

Write the timing in the notes of any interesting comment the interviewee mentioned.

[READ TO PARTICIPANTS]

The last part of the study is having a discussion around your experience of doing the sensemaking tasks in the previous parts.

Questions:

[Ask only if not answered]

1. In your assessments, what were the factors of region's (in)accessibility you were looking for?
2. Were you able to find them with the current set of designs? If not, what was missing?

[Compulsory]

1. Rate the **importance of each task** on a scale of 1-5, 1 being Not at all Important to 5 being Extremely Important and **why**:
    a. Task 1: Assessing overall accessibility
    b. Task 2: Comparing accessibility of regions
    c. Task 3: Assessing accessibility of a neighborhood/locale
2. For each visualization type, rate the **usefulness** and **trustworthiness** on a scale of 1-5, 1 being Not at all Useful/Trustworthy to 5 being Extremely Useful/Trustworthy and **why**: [Give the visualization overview sheet]
    1. Point Distributions
    2. Severity Point Distributions
    3. Grid Maps
    4. Heatmaps
    5. Area Map
    6. Street Visualizations
    7. Time Plots
3. Do you see value in having the different types of visualizations in increasing your understanding of city accessibility or would you prefer a single type of visualization? [If single type preferred] Which would one that be?
4. Which visualizations would you like to see in an interactive tool? An interactive tool would let you zoom, filter, drag/pan a map, switch between different visualizations.
5. What more would you want to know about urban accessibility through visualizations? [Prompt]: What would you want to learn?
6. What other types of visualization types would you like to see?
    a. Prompt: What other types of data would have liked to visualize and how (read: new visualization types)?

Chapter 3 Interview Study: Codebook

Below is the list of the codes used during the thematic analysis of the interview data.

Research Question(s):

What are the information needs and challenges for assessing and making decisions around urban accessibility?

What role does data and technology play in their decision-making practices?

This is getting at what do they care or want to learn about around urban accessibility, and how do they do currently assess sidewalk accessibility?

Code	Description	Notes/Remarks
Participant Roles	What roles did stakeholders have as an official in their organization towards accessibility development? Applicable only to advocates, policymakers, and department officials	
Barriers for Travel	What do stakeholders look for when assessing state of accessibility and needs? Describes the barriers that people with mobility disabilities face.	
Personal Barriers	Talks about barriers due to limited personal health and mobility e.g., upper body strength, poor vision, hearing etc. This includes describing the use of mobility aids as well. For example, manual vs power-assisted manual wheelchair.	Clarified during round 2
Physical Barriers	E.g., sidewalks heights, curb cuts, elevation, presence/absence of sidewalks, uneven sidewalks, severity of issues, natural (e.g., tree roots) vs man-made (bikes on sidewalks).	Updated code name and description – round 2
Type of Surface Material	E.g., Bumpiness/smoothness, brick, gravel, concrete	
Pedestrian Signaling Features	E.g., presence/absence of tactile strips, timing of pedestrian signals	
Building Accessibility	E.g., Steps, elevators	
Miscellaneous Barriers	Any of the codes that don't fit cleanly above. E.g., crowd/rush of people, absence of benches, number of lanes	

Method of Assessment	Describes the assessment method for accessibility (e.g., "field studies", "hazardous intersection reviews")	
Visual Inspection	Inspecting visually by going out physically which doesn't involve taking any measurements. This is a more informal process. When participant says things like "we look around and eyeball problems". Other terms would include "visual inspection", "foot on the ground", "drive-by".	Clarified in round 2
Experiential	Person says they try it out and see if they can navigate it (if not, they improvise). E.g., "trial and error"	Modified name and clarified code after coding all
Taking Pictures	Go out in the field and take pictures	
Physical Audits	By physical going out and taking measurements for **accessibility only**. This is a formal audit. E.g., "neighborhood walk audits", "accessibility audits", "taking measurements with or without using tools".	Clarified in round 2
Surveys	E.g., rider survey	Changed the name after round 2
Ask People	When the participant says "ask people" or indicating verbally asking people through conversations. This isn't surveys that are done with a large group of people.	
Other Methods	Any method that hasn't been mentioned before.	
Data Sources	What data do they rely on for making these assessments? "**raw data**"	
Citizen Provided Data	E.g., 311 service requests, phone calls, rider surveys, complaints, "people's lived experiences", "people contacting me and telling their story"	
Internal Data Sources	With respect to the participant's position, whether the data source is internal or external. Participant talks about how they collect and maintain data internally collected within the organization either	Expanded after round 3; Clarified description after round 2

	hiring consultants or teams within the organization. E.g., "SDOT has two teams that gets this data", "our internal teams have an inventory of items" – the data they have, not always specific or clear.	
External effort/agency data	With respect to the participant's position, whether the data source is internal or external. City wide effort programs/initiatives, data from transit agencies and others (e.g., Office of Aging, Pierce transit). E.g., "we relied our own data around transit stops"	Clarified description after round 2
Open data	Readily available datasets – open to the public. E.g., By the city, transit agencies (e.g., WMATA), data provided by other government departments (e.g., WSDOT)	Clarified description after round 2
Miscellaneous data sources	Other types of data sources and types that they utilize but are not categorized above E.g. ???	Clarified after round 1
Desired Data Types/Sources	Any data that they **would like** to rely on. For example, if the participant says "We would like to have X"	Clarified after round 1
Digital Tools Used	What digital tools do participants use (if any) for making accessibility assessments?	
No use of tools	When the participant says they don't use any tools	
Online street view imagery	E.g., Google Street View	Clarified code
Imaging equipment	Tools used to take pictures e.g. digital camera	Updated code
Satellite imagery	E.g., Google Earth, Bing Maps	
GIS and Mapping tools	E.g., ESRI, simple maps, Google/Apple/Bing Maps	
Analytical Tools	E.g., Tableau	
Other Tools	Any other type that was mentioned e.g. digital levels, smart levels	Clarified after round 1
Accessibility Metrics	How did stakeholders quantify accessibility? "**what factors are used**"	
Building Features Measurements	E.g., width of doorways	

Sidewalk Feature Measurements	Slope of curb ramps, height of curb ramps	
Priority Index	Models created to determine severity of issues	
Travel Time	When the participant talks about travel time e.g., time to walk "three blocks", proximity to destinations.	Added after round 1
Other Metrics	Any other type of metric that was mentioned e.g., number of lanes	
No Metrics	If the participant says they don't use any metrics	Added during coding
Prioritization Practices and Factors	What parameters/factors are considered when making assessments and decisions? How do they or would want to prioritize when making decisions (e.g., for resource investments, policy making, advocacy efforts, choosing a neighborhood to live in)? "**How will the factors be used**"	
Limitations of Current Practices	Talks about the different limitations that exist in current practices around prioritization and decision-making processes. Ranges from low level details such as tools and methods to higher level elements such as policy.	Added after round 1; Clarified after round 2
Decision Making Questions	Includes the specific questions that participants ask to make decisions whether it be policy decision, repair decision, or personal living situations. E.g., "How do we make X efficient", "Where should curb ramps be installed", "Who are the people living there? I want to know that"	Added after round 2
Infrastructure utilization	E.g., frequency of use, pedestrian count, "highly travelled walkways", "high need repair and retrofit places", "busy-ness of transit"	Clarified after round 2
Population density	Within neighborhood or an area, how many (specific population) live there?	
Area demographics	Who are the people living or using the infrastructure?	
POI Related	Everything around POIs and destinations - both factors and practices.	Round 2 - Updated code name and clarified description

	Practice would be around questions that they ask. For e.g. "What is around me or where do/can people get to?" "What is in the proximity of the POIs". The other part is individual factors. What are the POI people are interested in? E.g., businesses, parks, public spaces, restaurants, post offices, government facilities	
State of accessible infrastructure	Severity of inaccessibility of curb cuts, sidewalk quality, obstructions. Also, includes characteristics of the infrastructure e.g., height of the sidewalk, cross slope of the curb ramps, pedestrian signals etc.	
Capital Projects	Participants talks about development (construction) projects that leads to updates (e.g., repairs) to sidewalk infrastructure. E.g., "private development", "redevelopment".	Added after round 1
Social support	Presence of local people to support / help. E.g., being able to "ask people"	
Citizens' Voice	Anything that relates to **how** citizens impact the decision-making process—individual needs, personal stories, service requests, and/or their support. E.g., participant talks about listening to people's lived experiences / issues and prioritizing based on that. E.g., "listening to my constituents to know how bad the situation is" OR relying on age or count of the requests. OR "Do constituents in the area support this".	Changed the code name and clarified code description
Nature of fixes	Type and number of fixes. For example, simple/small fixes vs more elaborate or large fixes (e.g., concrete pavements vs flexi-pave, repairs vs new curb cuts).	
Support of leadership/ management	Due to upper management's interests in funding/prioritizing accessibility	

Incongruent / Differing Responsibilities	When participants talk about differing responsibilities which may not always align between agencies or between citizens and the city – "who is responsible for what?". That leads to lack of incentive to prioritize and having to coordinate/negotiate between agencies	Added after round 1; Clarified during coding
Costs and Funding	Talks about anything related to costs and funding. E.g., availability of funds through "local levies", "How do we make the funding pie bigger? ", "coming up with a dollar amount"	
Political Interests and Constraints	Participants talk about how political motivations dictate what are the priorities. E.g., "often times what gets done is a political discussion instead of a policy driven one"	
Effects of Bills, Policy, and Advocacy	Participant talks about specific outcomes from policy decisions and advocacy efforts e.g. "It would create new plans and pipelines for accessible lanes …"	Added after round 2
Equity	Participant talks about equity/inequity – how resources are not distributed to all areas equally or how they aim for achieving equity. E.g., "like more shade which is an equity issue on better sidewalk access", "the eastern half historically had been disinvested from more historically black neighborhoods."	Added after round 2
Availability of transit connections	Does transit exist and, if so, how often? Presence/absence of multi-modal options, type of transit available, presence/absence of transit hubs (e.g., Westlake Center), and frequency of transit. This **doesn't talk** about whether it is close to you or not.	Clarified after round 2
Type of Analysis	When participant talks about the type of analysis to take decisions E.g., using comparative analysis e.g., comparing between proposals or comparing cities-- "If we're very different than what they're	Expanded code after round 2; Added after round 1

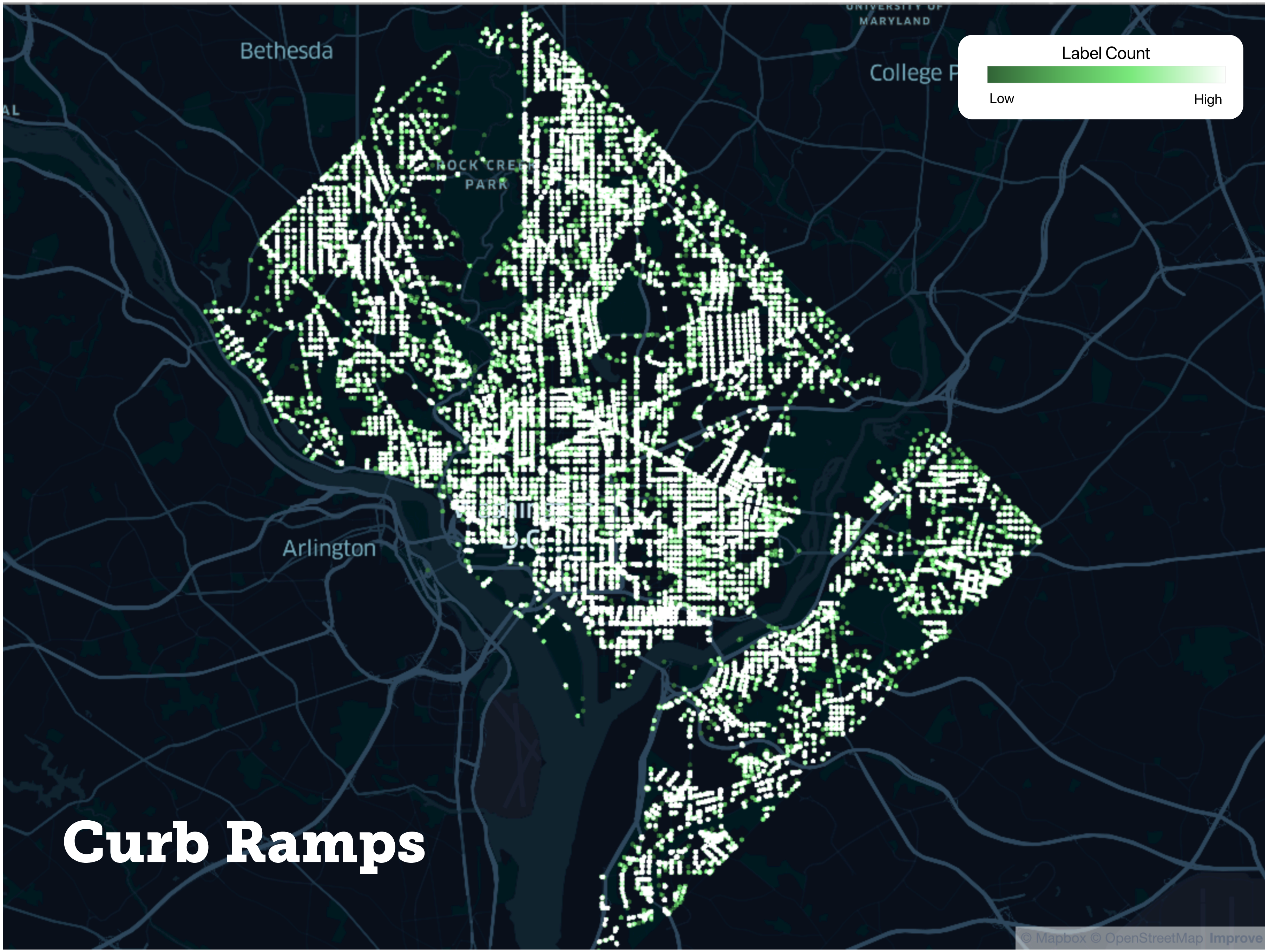
	doing in Portland or somewhere else, why is that?", "root-cause analysis"	
Other Factors or Practices	Any other type of practice/factors that was used to prioritize or take decisions.	

Map Visualization Prototypes

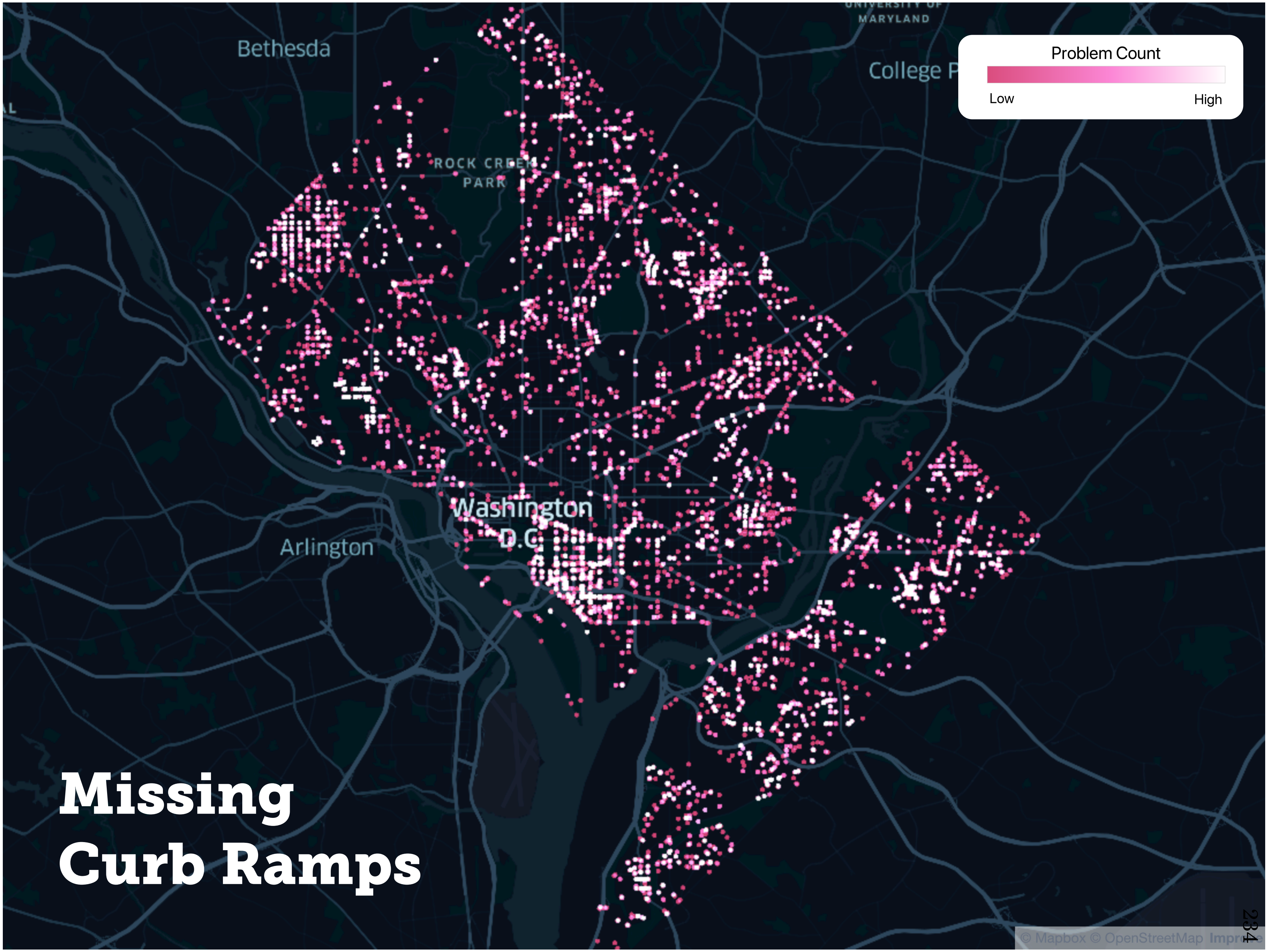
Paper Prototype Design Probe Study

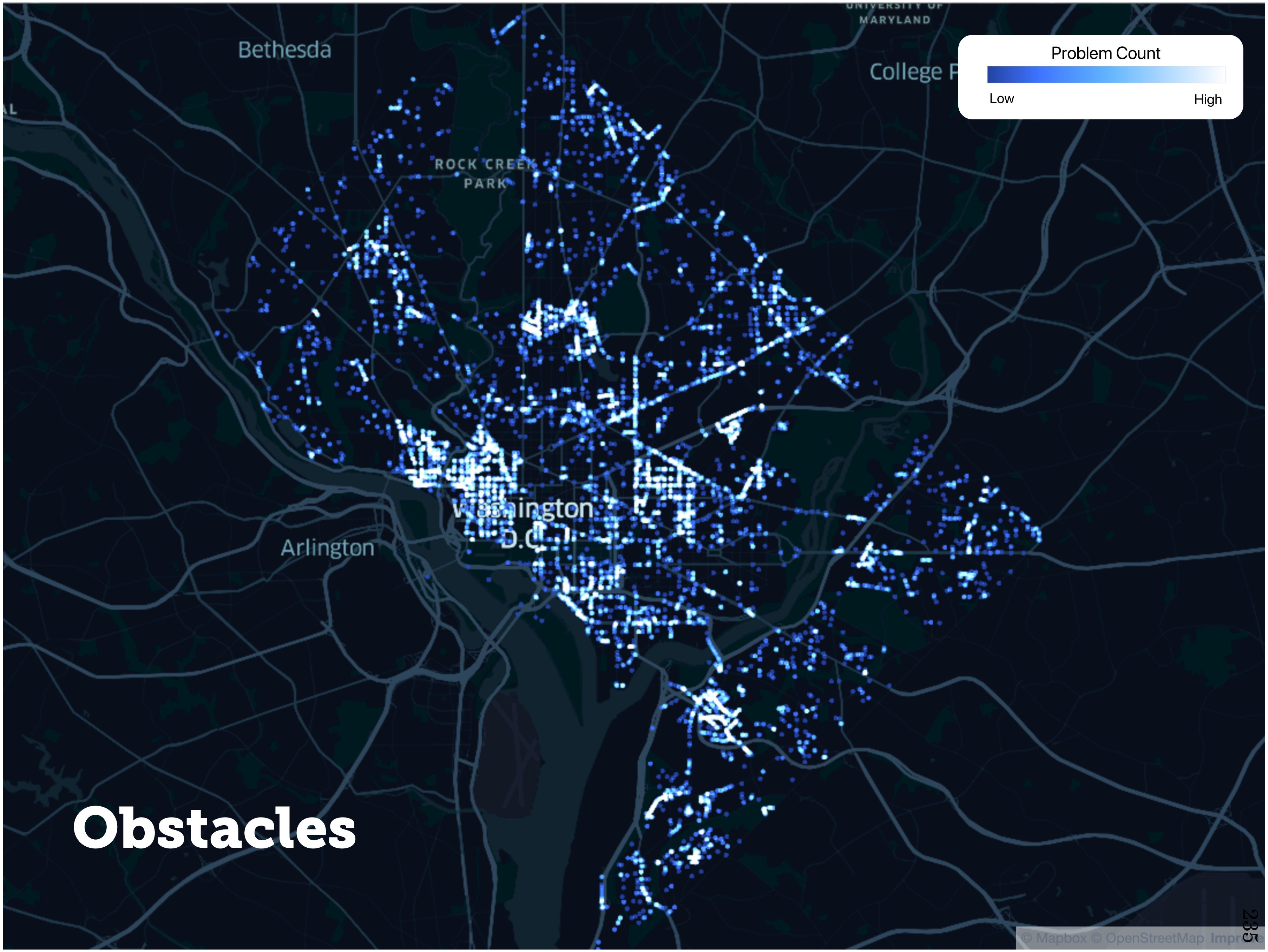
1. Point Visualizations
2. Severity Point Visualizations
3. Grid Maps
4. Heatmap Visualizations
5. Choropleth or Area Map
6. Street Visualizations
7. Ego-centric Isochrones or Time Plots

Point Visualizations

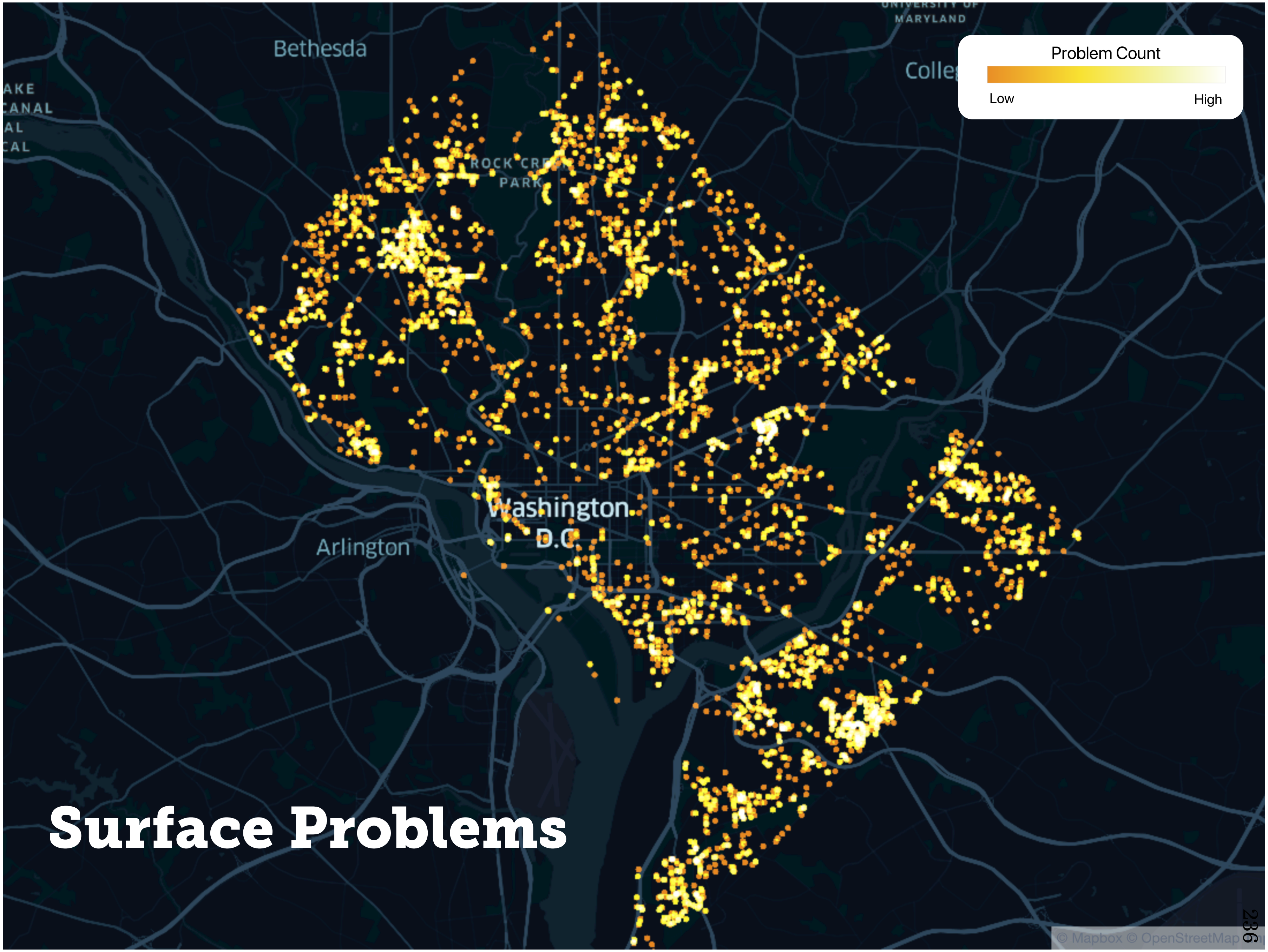


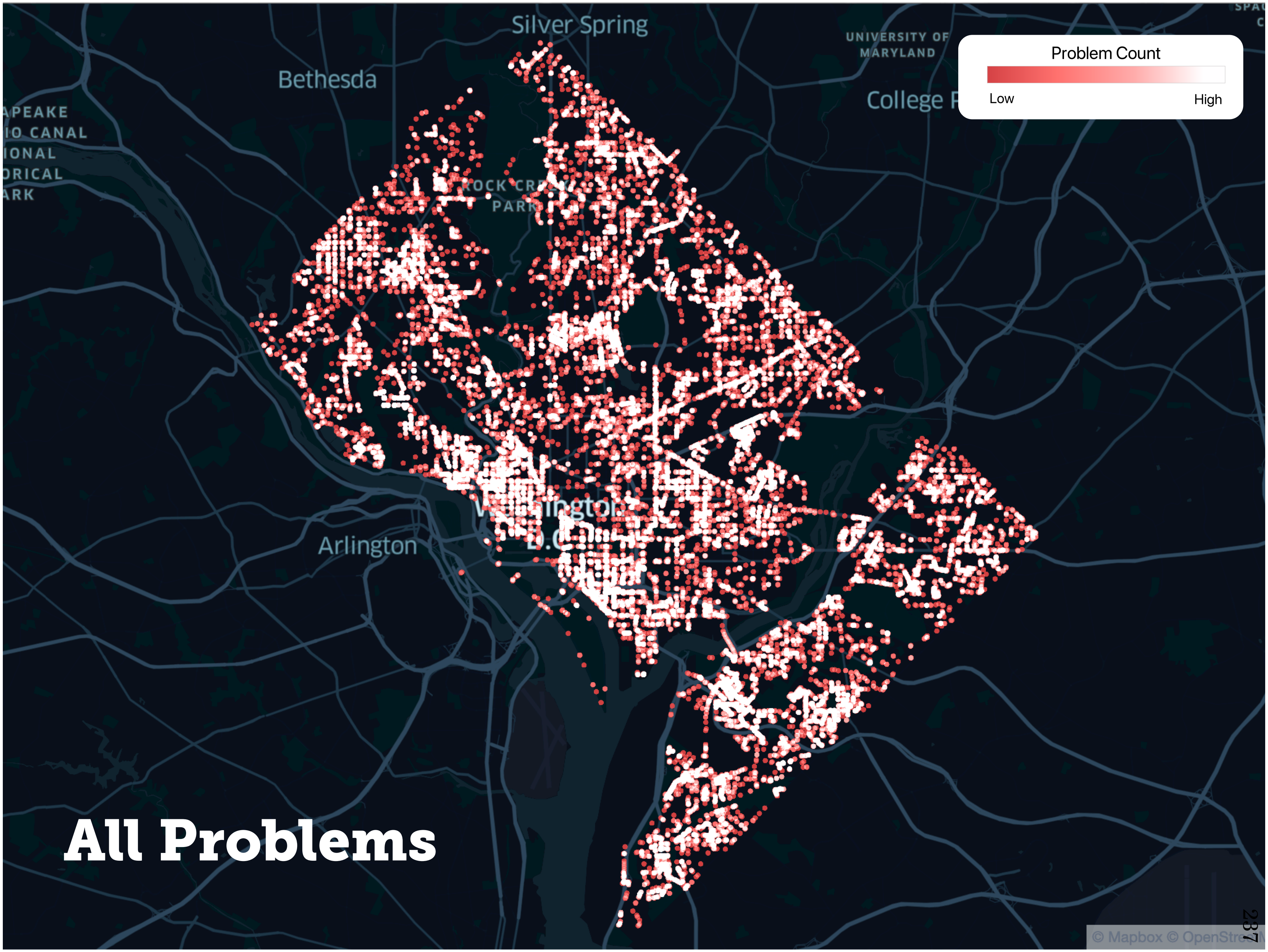
Curb Ramps
Label Count
Low
High
Bethesda
College P
UNIVERSITY OF
MARYLAND
ROCK CREEK
PARK
Arlington
© Mapbox © OpenStreetMap Improve


Missing
Curb Ramps
Problem Count
Low
High
Bethesda
College P
UNIVERSITY OF
MARYLAND
ROCK CREEK
PARK
Washington
D.C.
Arlington
© Mapbox © OpenStreetMap



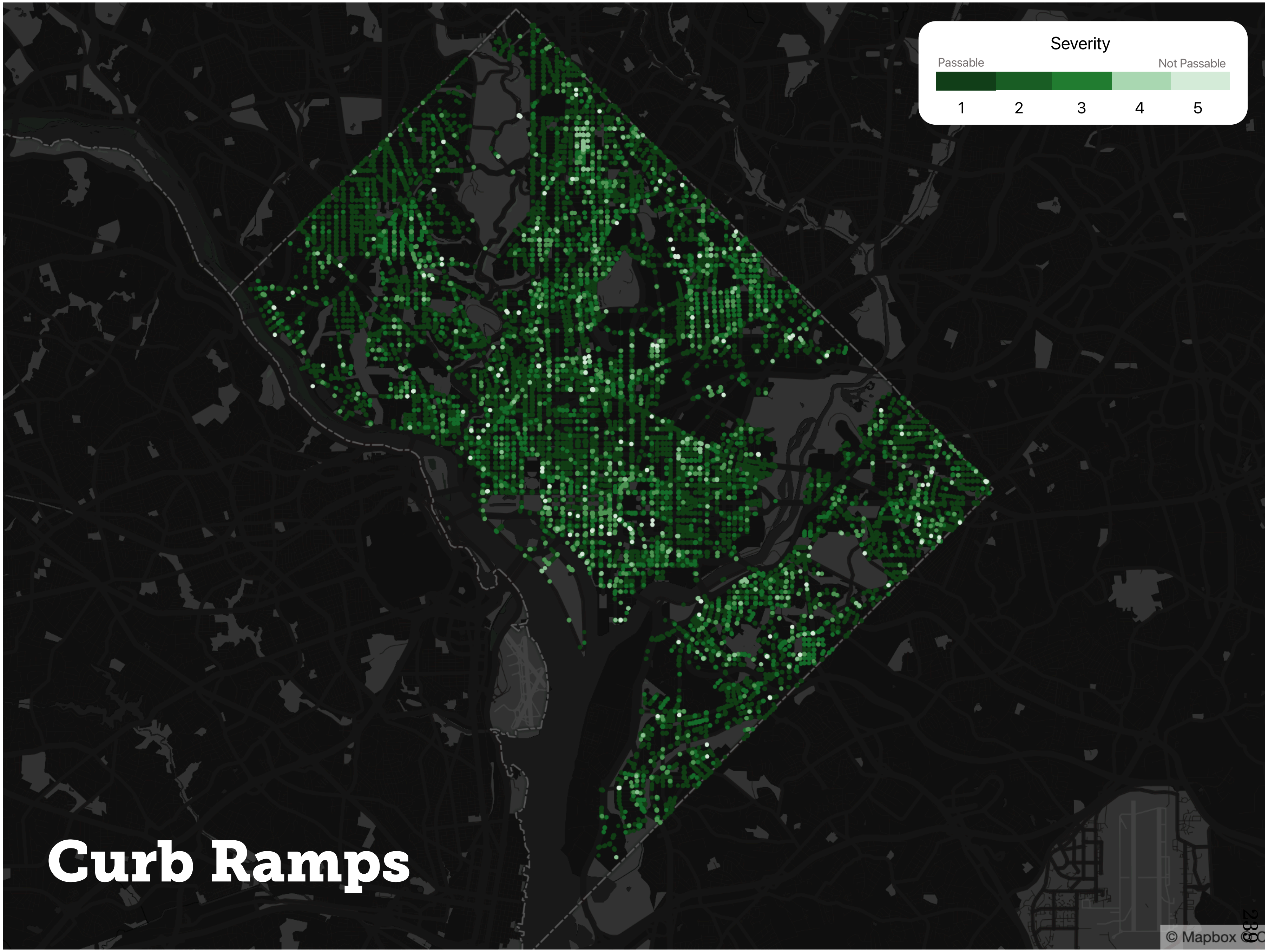
Bethesda
UNIVERSITY OF MARYLAND
College P
ROCK CREEK PARK
Problem Count
Low
High
Washington D.C.
Arlington
Obstacles
© Mapbox © OpenStreetMap Impr


Surface Problems
Problem Count
Low
High
Bethesda
ROCK CREEK PARK
Washington D.C.
Arlington
UNIVERSITY OF MARYLAND
© Mapbox © OpenStreetMap

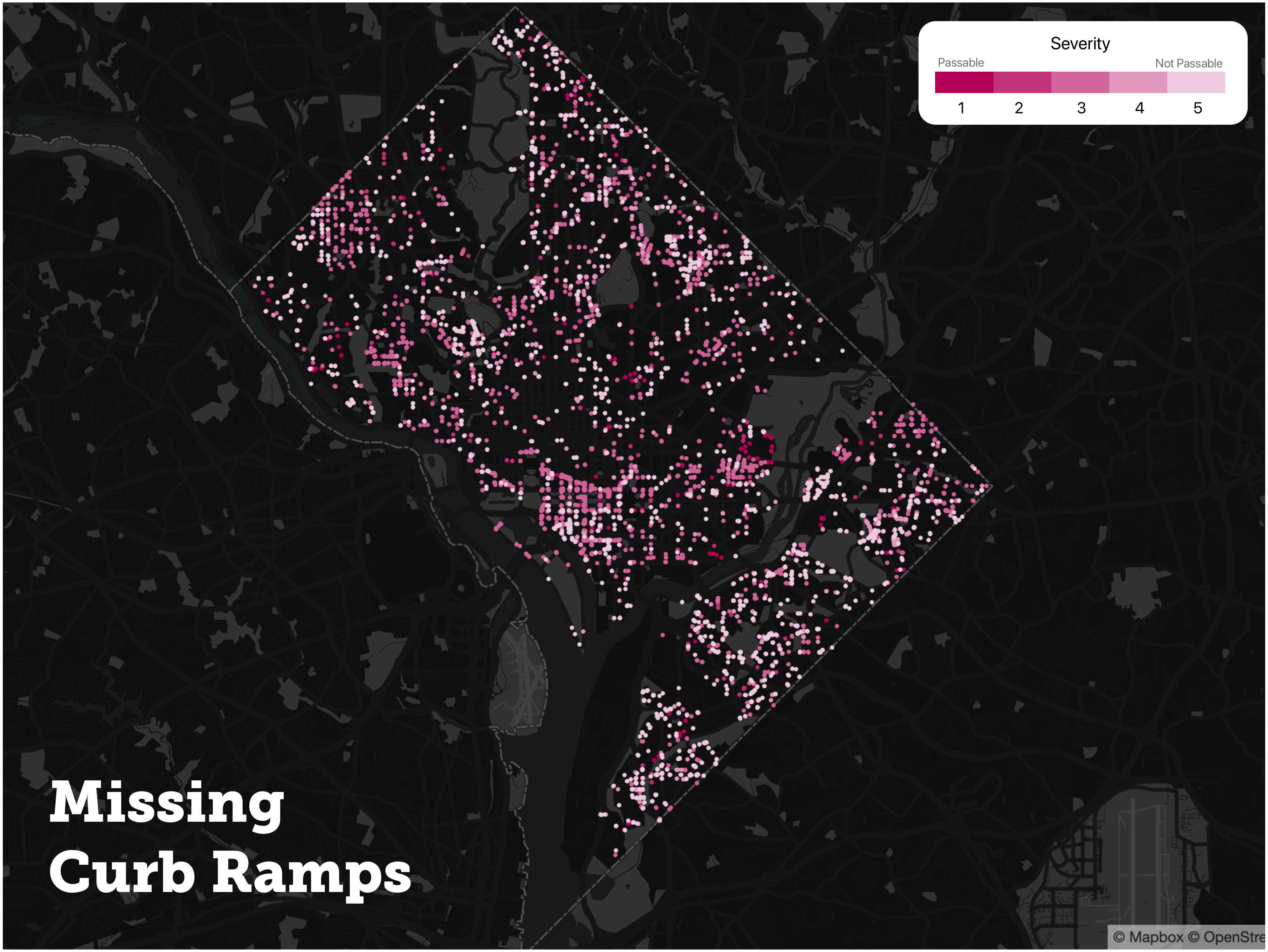


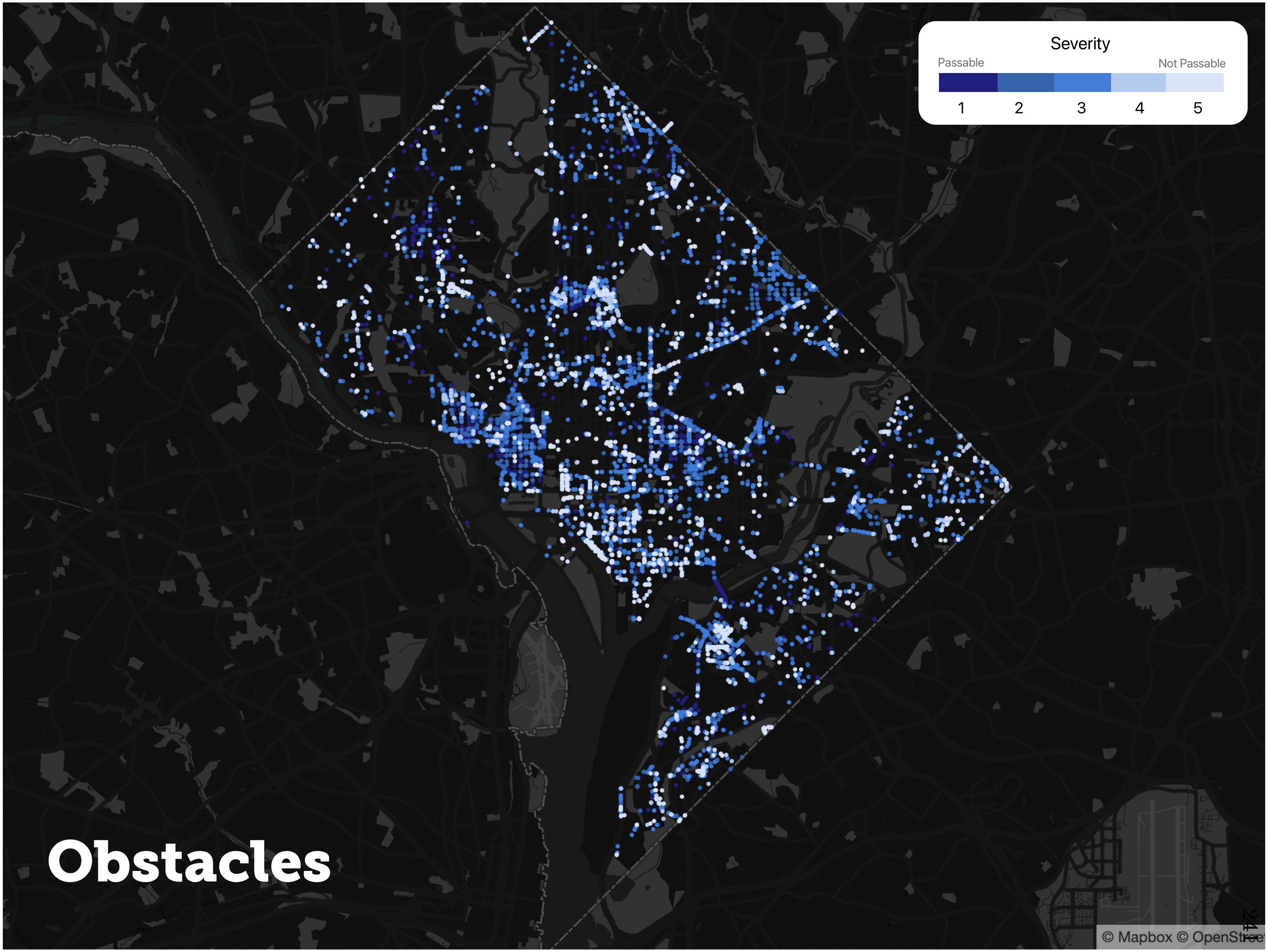
All Problems
Problem Count
Low
High
Silver Spring
Bethesda
University of Maryland
College P
Arlington
Washington D.C.
Rock Creek Park
© Mapbox © OpenStre

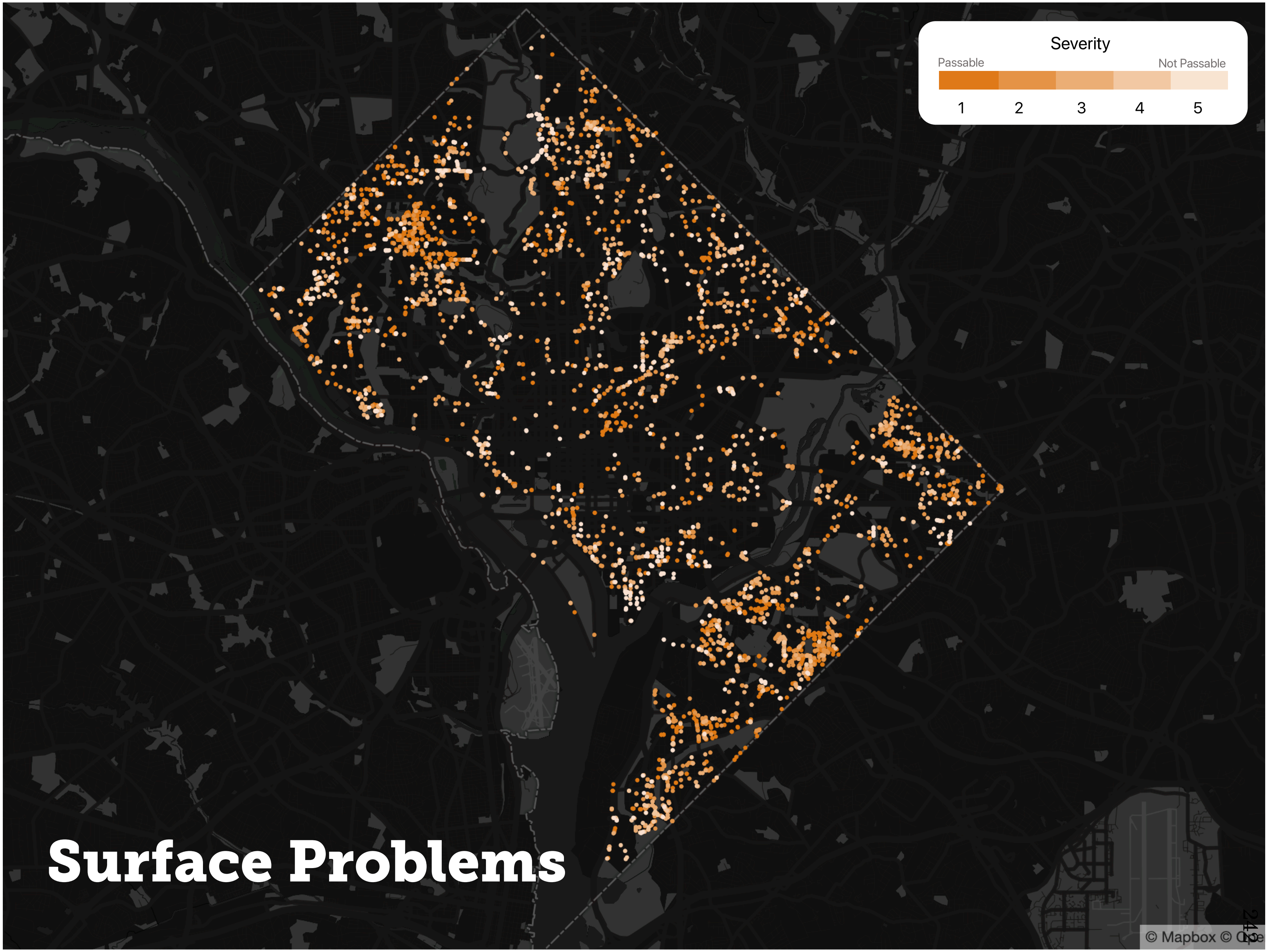
Severity Point Visualizations

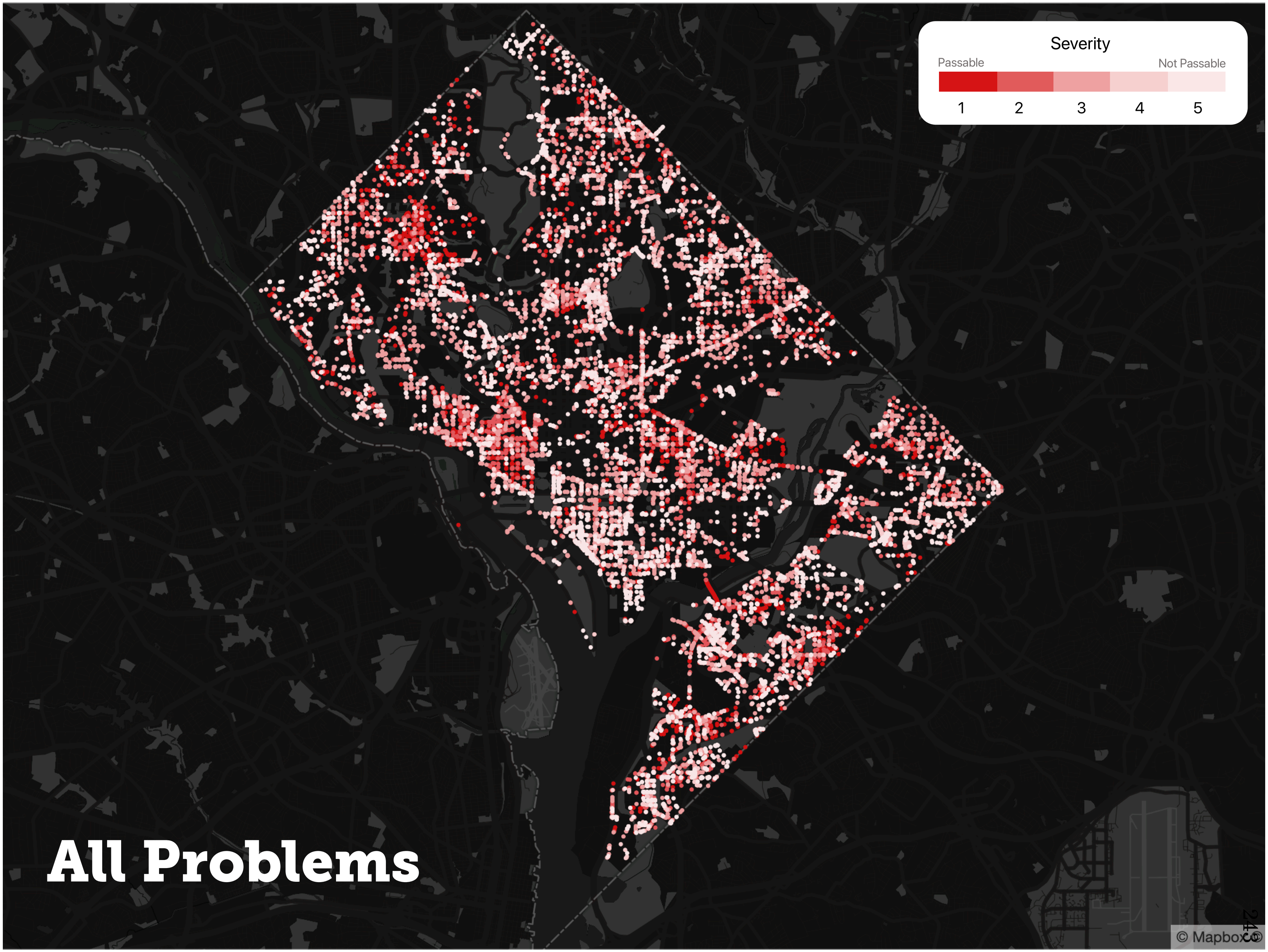


Severity
Passable
Not Passable
1
2
3
4
5
Curb Ramps
© Mapbox ©


Missing
Curb Ramps
Severity
Passable
Not Passable
1
2
3
4
5
© Mapbox © OpenStre

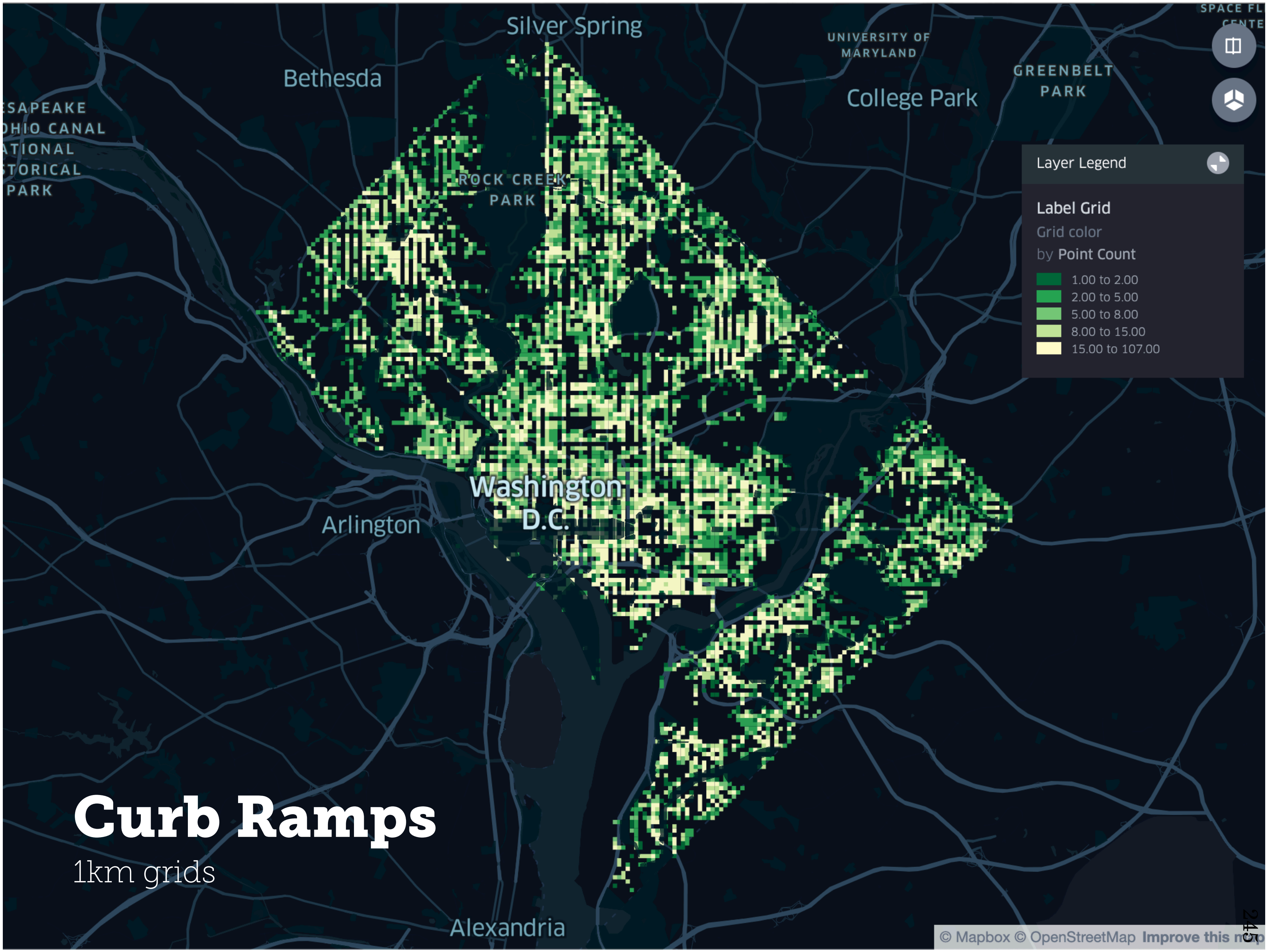

Severity
Passable
Not Passable
1
2
3
4
5
Obstacles
© Mapbox © OpenStree

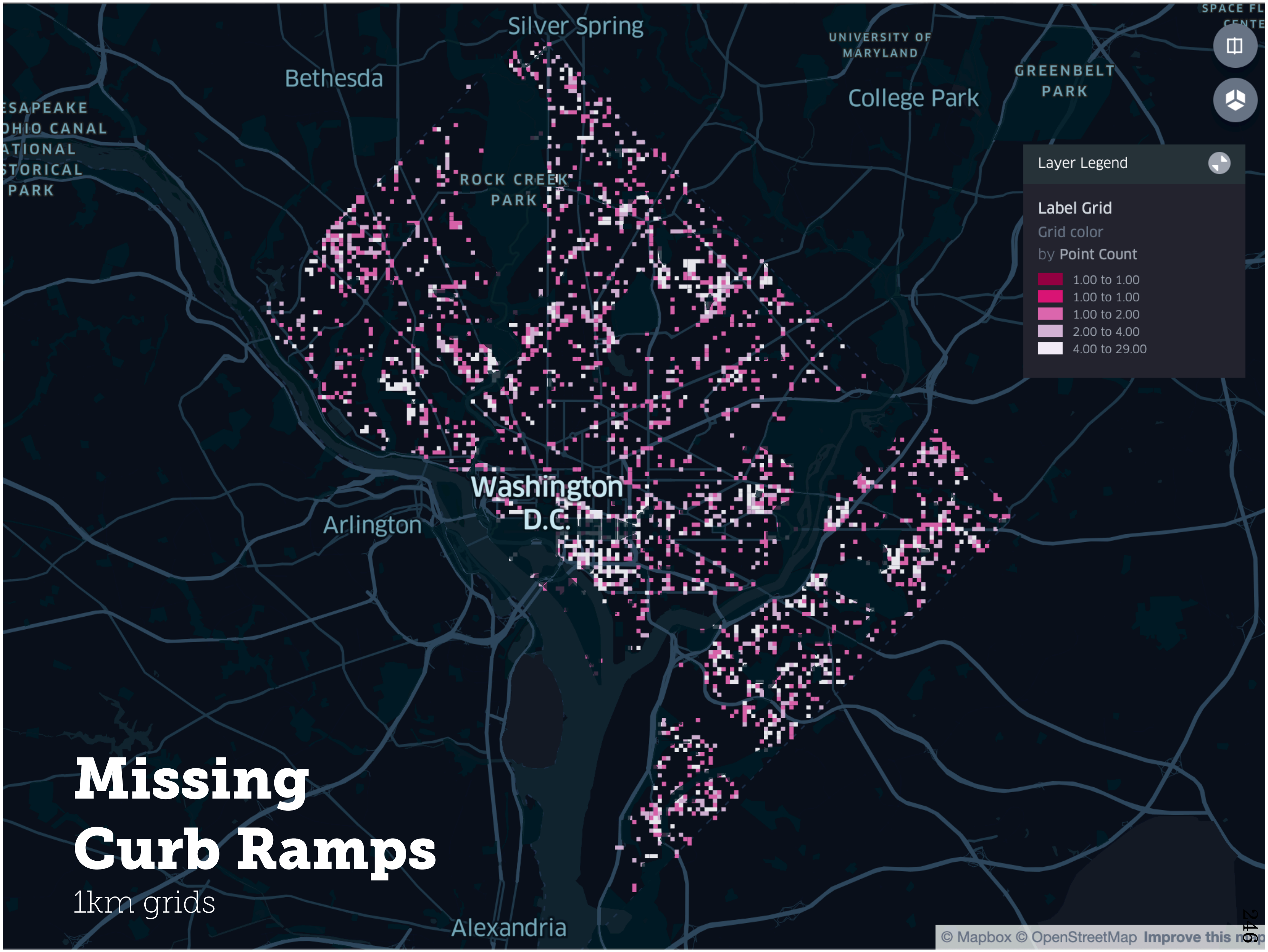

Surface Problems
Severity
Passable
Not Passable
1
2
3
4
5
© Mapbox



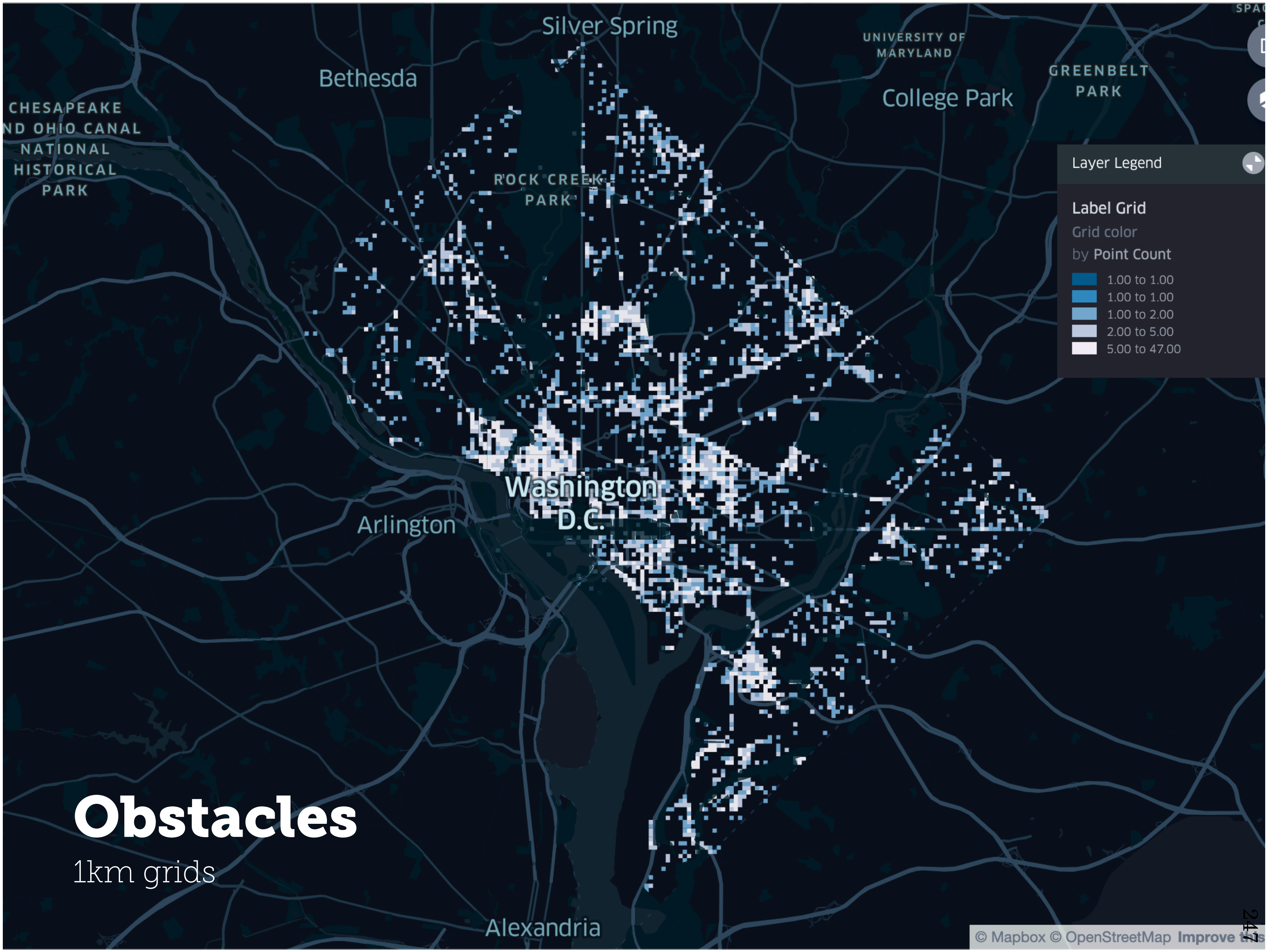
Severity
Passable
Not Passable
1
2
3
4
5
All Problems
© Mapbox ©

Grid Maps

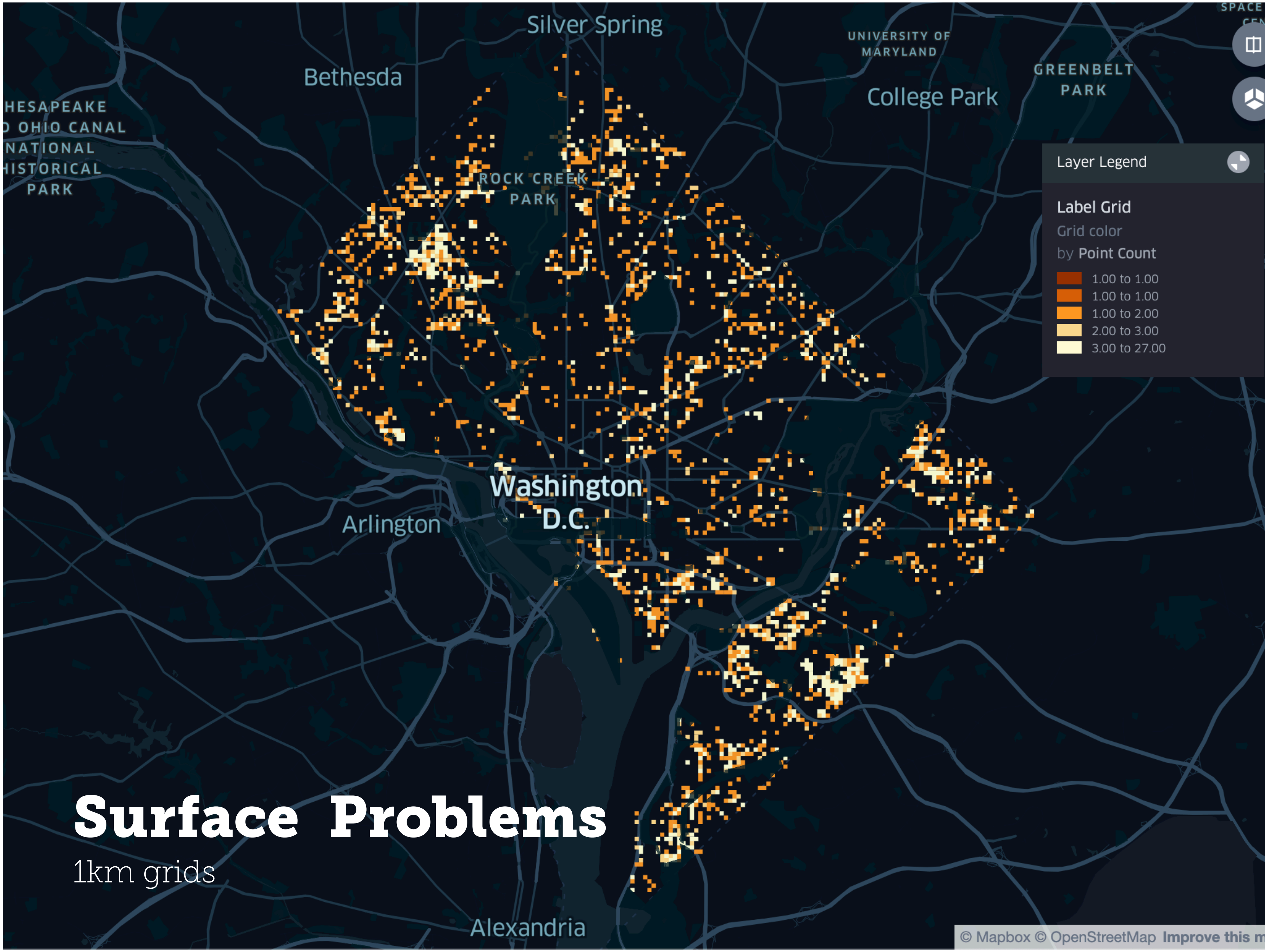

Curb Ramps
1km grids
Silver Spring
Bethesda
College Park
UNIVERSITY OF MARYLAND
GREENBELT PARK
ROCK CREEK PARK
Washington D.C.
Arlington
Alexandria
Layer Legend
Label Grid
Grid color
by Point Count
1.00 to 2.00
2.00 to 5.00
5.00 to 8.00
8.00 to 15.00
15.00 to 107.00
© Mapbox © OpenStreetMap

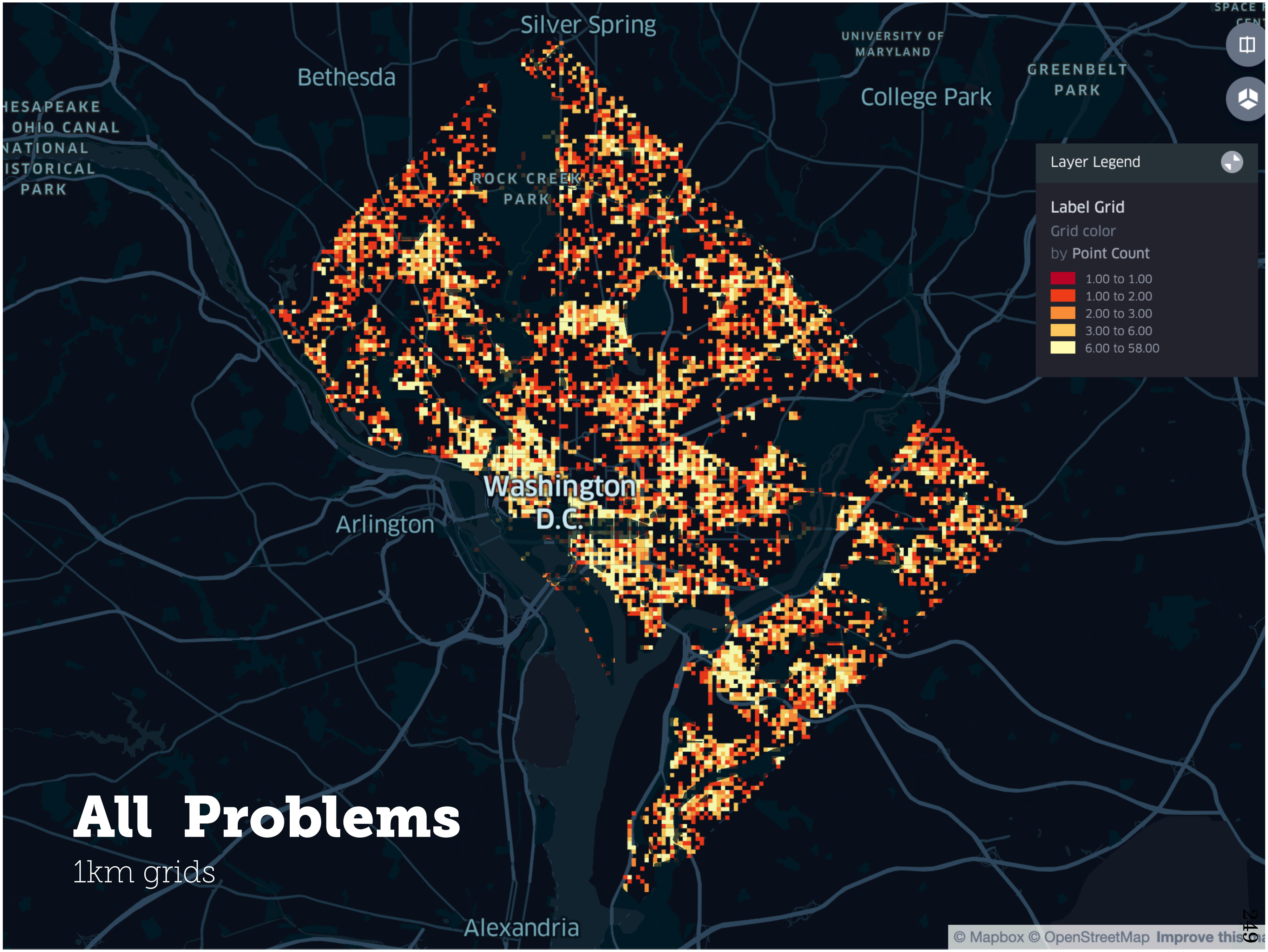


Missing
Curb Ramps
1km grids
Layer Legend
Label Grid
Grid color
by Point Count
1.00 to 1.00
1.00 to 1.00
1.00 to 2.00
2.00 to 4.00
4.00 to 29.00
Silver Spring
Bethesda
University of Maryland
College Park
Greenbelt Park
Rock Creek Park
Washington D.C.
Arlington
Alexandria
© Mapbox © OpenStreetMap Improve this map

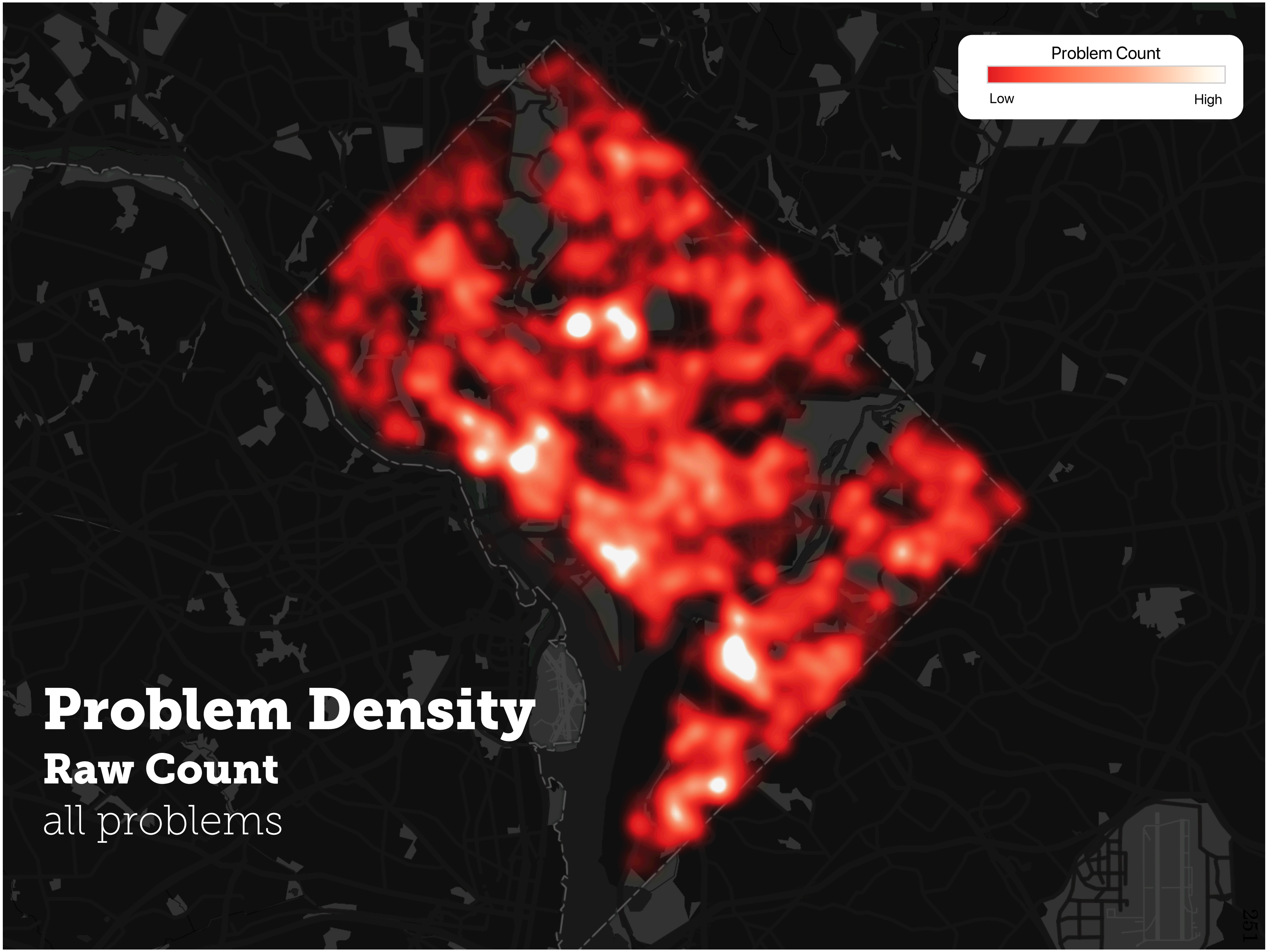


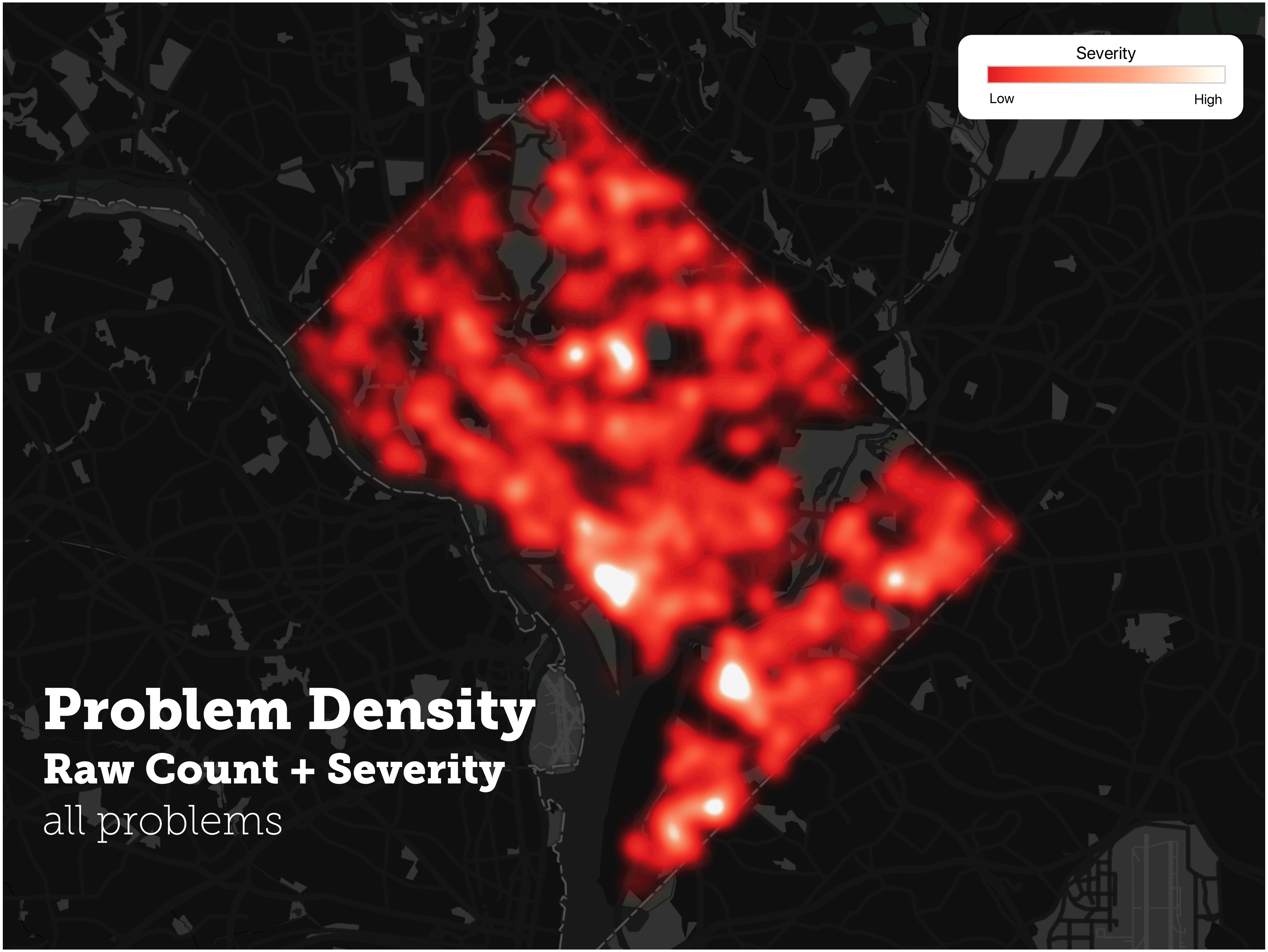
Obstacles
1km grids
Silver Spring
Bethesda
University of Maryland
College Park
Greenbelt Park
Chesapeake and Ohio Canal National Historical Park
Rock Creek Park
Washington D.C.
Arlington
Alexandria
Layer Legend
Label Grid
Grid color
by Point Count
1.00 to 1.00
1.00 to 1.00
1.00 to 2.00
2.00 to 5.00
5.00 to 47.00
© Mapbox © OpenStreetMap


Surface Problems
1km grids
Silver Spring
Bethesda
College Park
UNIVERSITY OF MARYLAND
GREENBELT PARK
ROCK CREEK PARK
Washington D.C.
Arlington
Alexandria
Layer Legend
Label Grid
Grid color
by Point Count
1.00 to 1.00
1.00 to 1.00
1.00 to 2.00
2.00 to 3.00
3.00 to 27.00
© Mapbox © OpenStreetMap

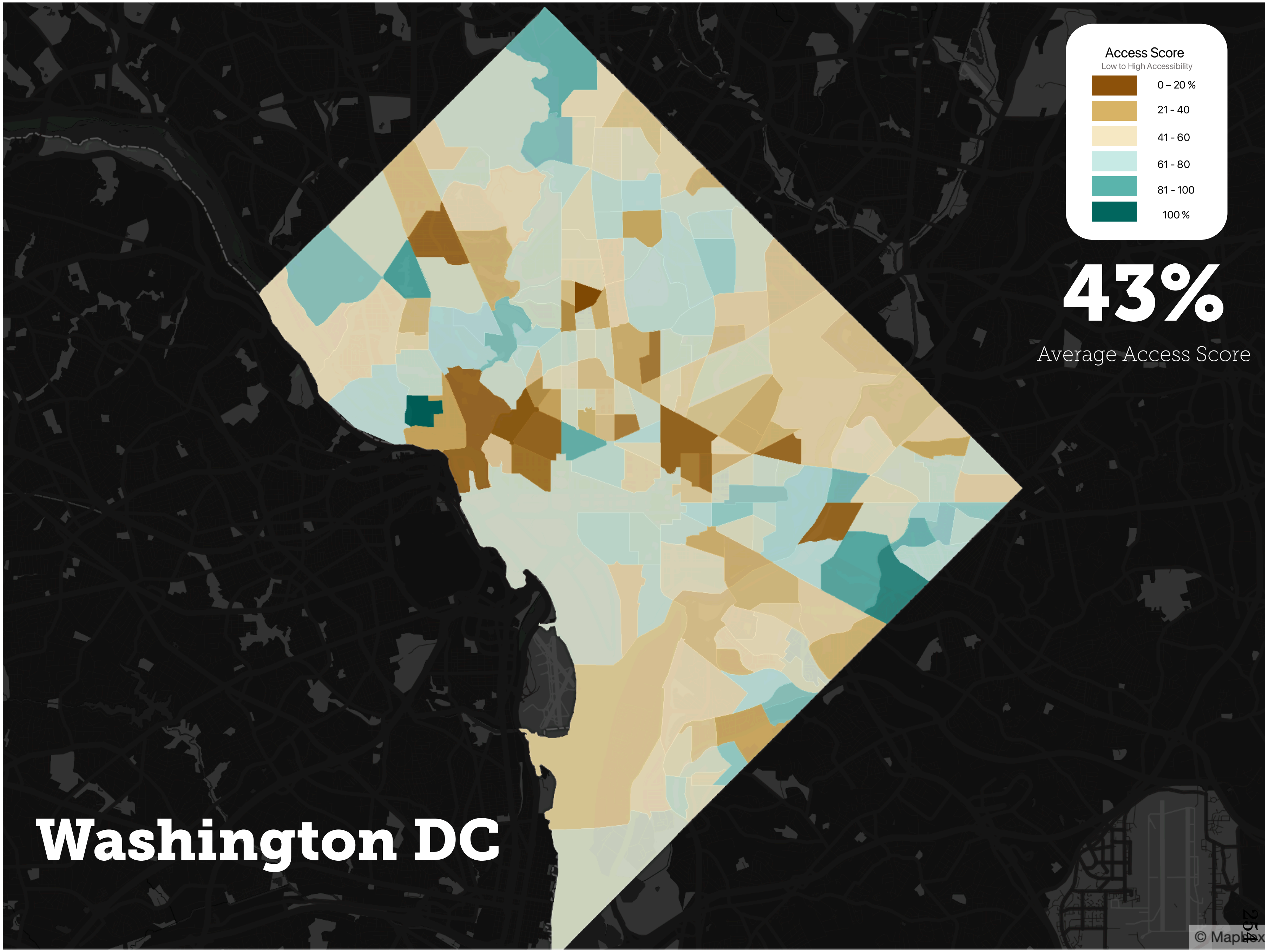

All Problems
1km grids
Silver Spring
Bethesda
University of Maryland
College Park
Greenbelt Park
Rock Creek Park
Washington D.C.
Arlington
Alexandria
Layer Legend
Label Grid
Grid color
by Point Count
1.00 to 1.00
1.00 to 2.00
2.00 to 3.00
3.00 to 6.00
6.00 to 58.00
© Mapbox © OpenStreetMap Improve this

Heatmap-style Visualizations

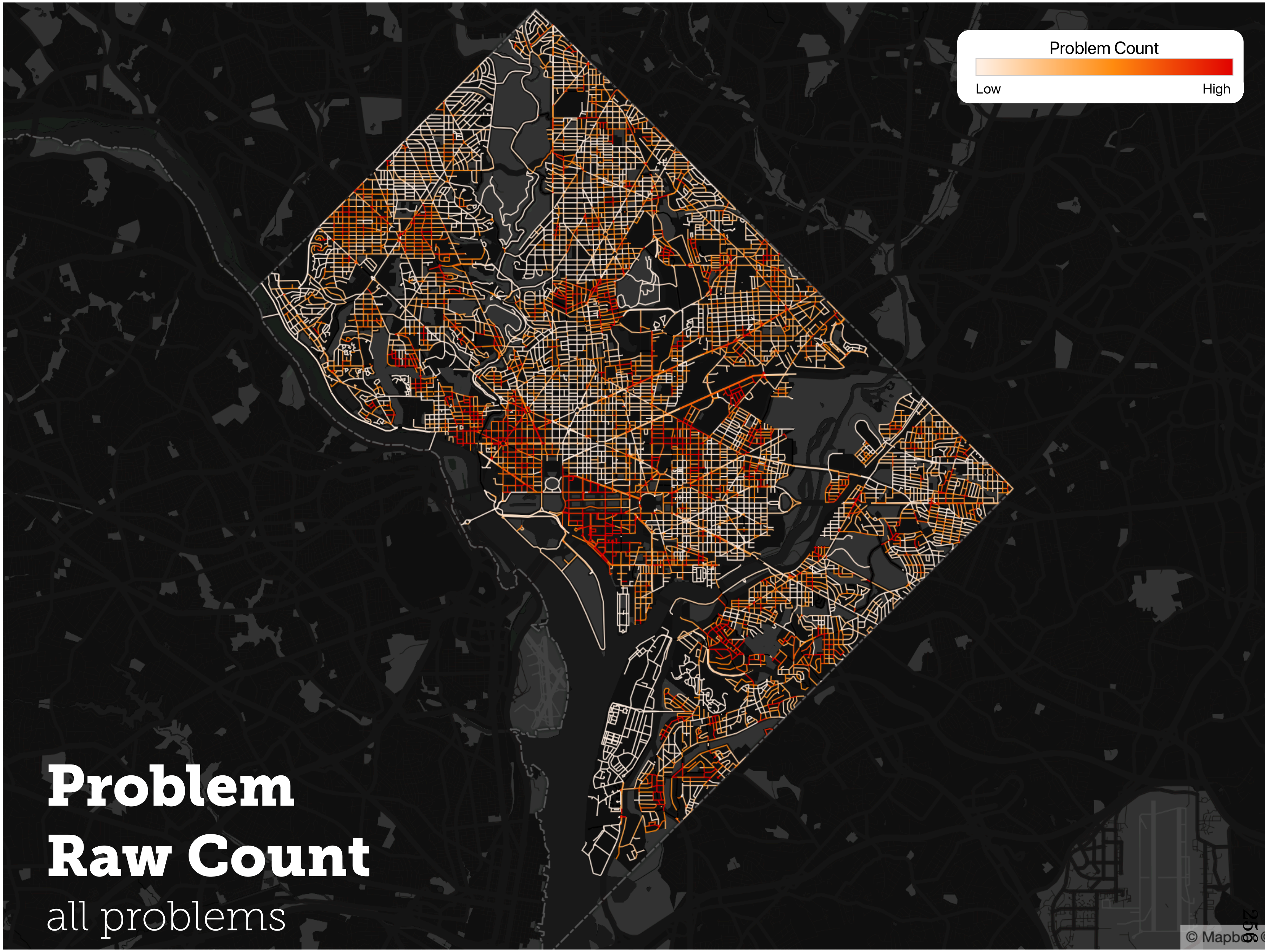

Problem Count
Low
High
Problem Density
Raw Count
all problems

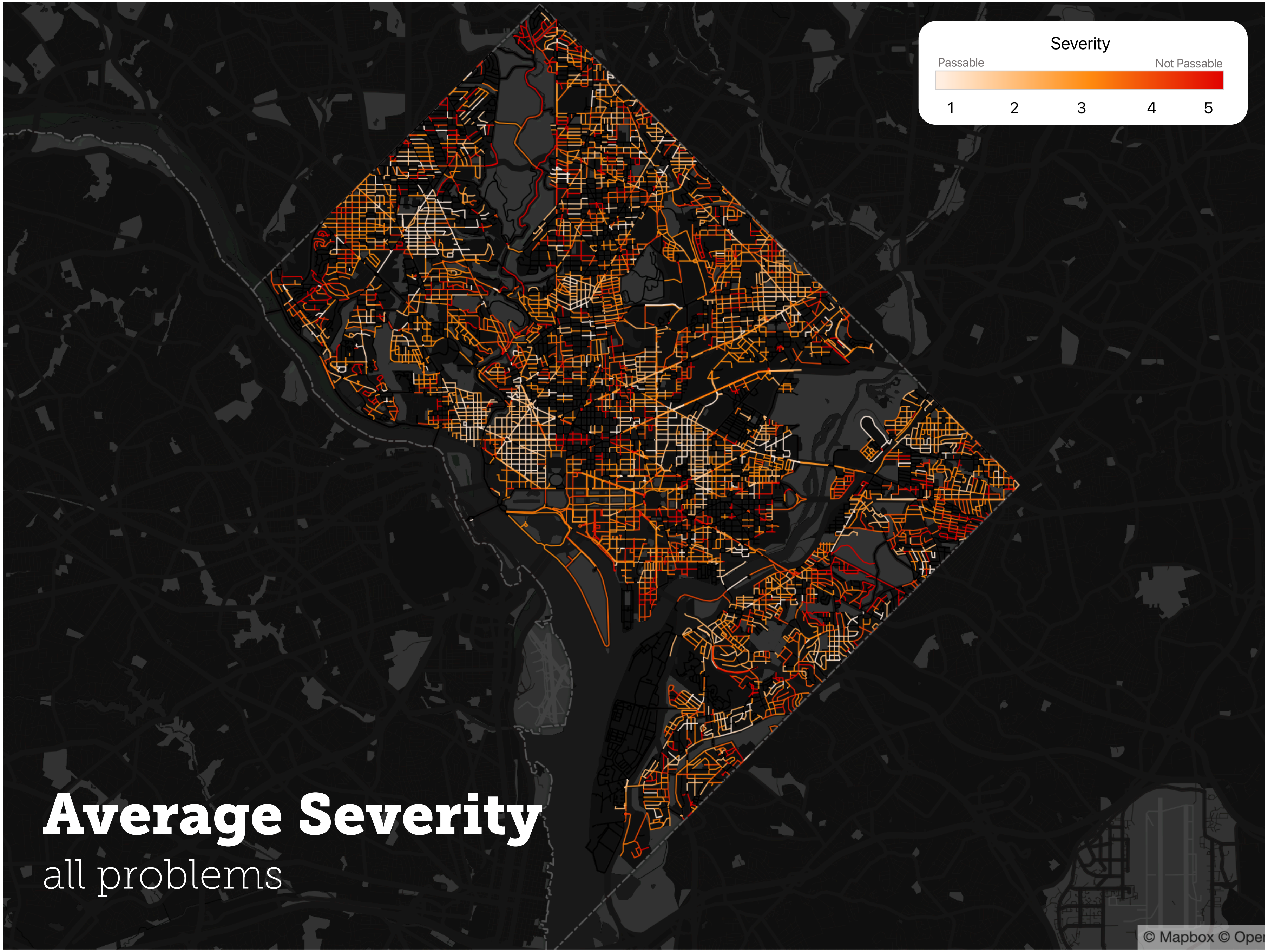

Severity
Low
High
Problem Density
Raw Count + Severity
all problems

Area Map

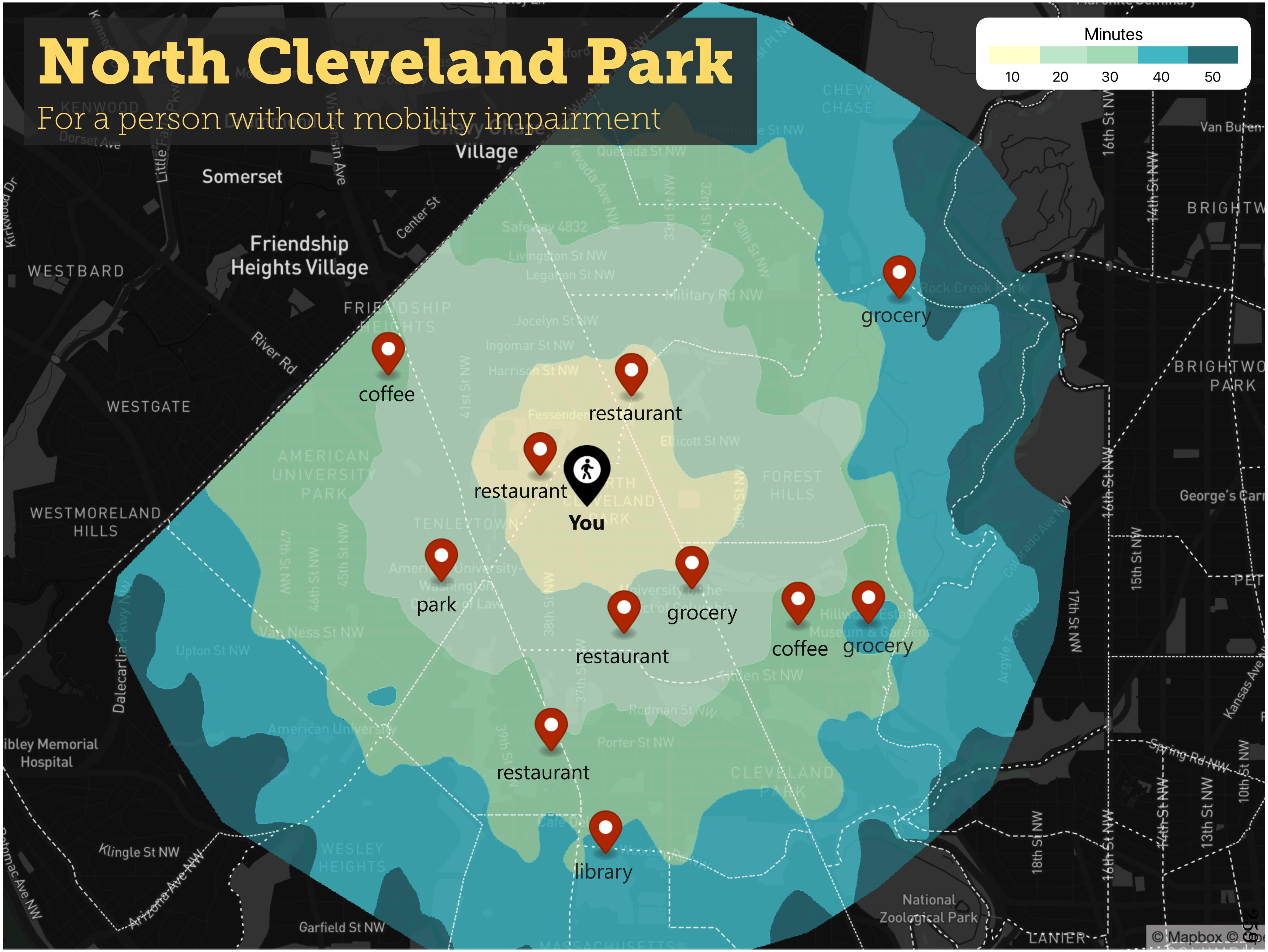

Access Score
Low to High Accessibility
0 – 20 %
21 - 40
41 - 60
61 - 80
81 - 100
100 %
43%
Average Access Score
Washington DC
© Mapbox

Street Visualizations

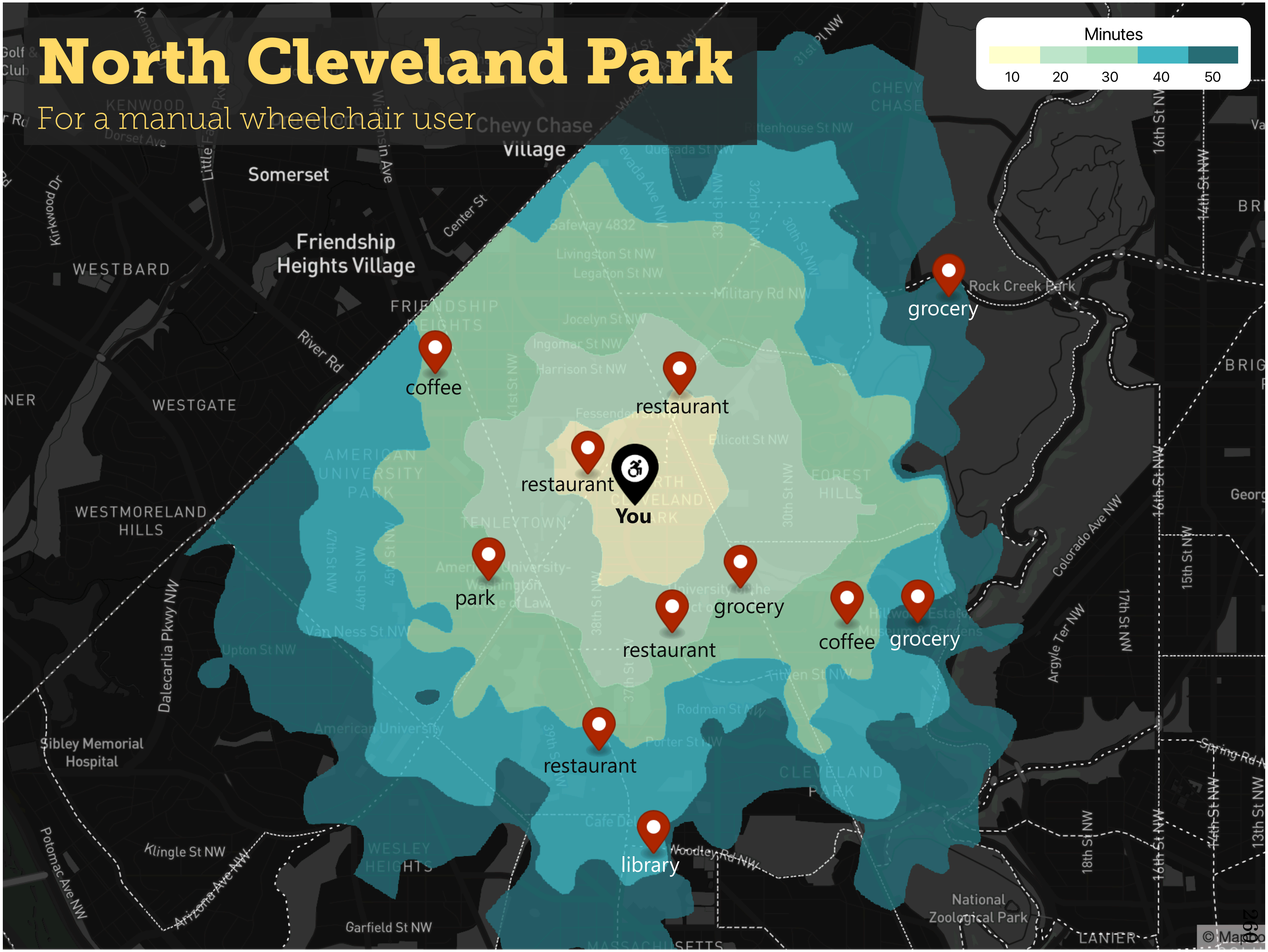

Problem Count
Low
High
Problem
Raw Count
all problems
© Mapbox

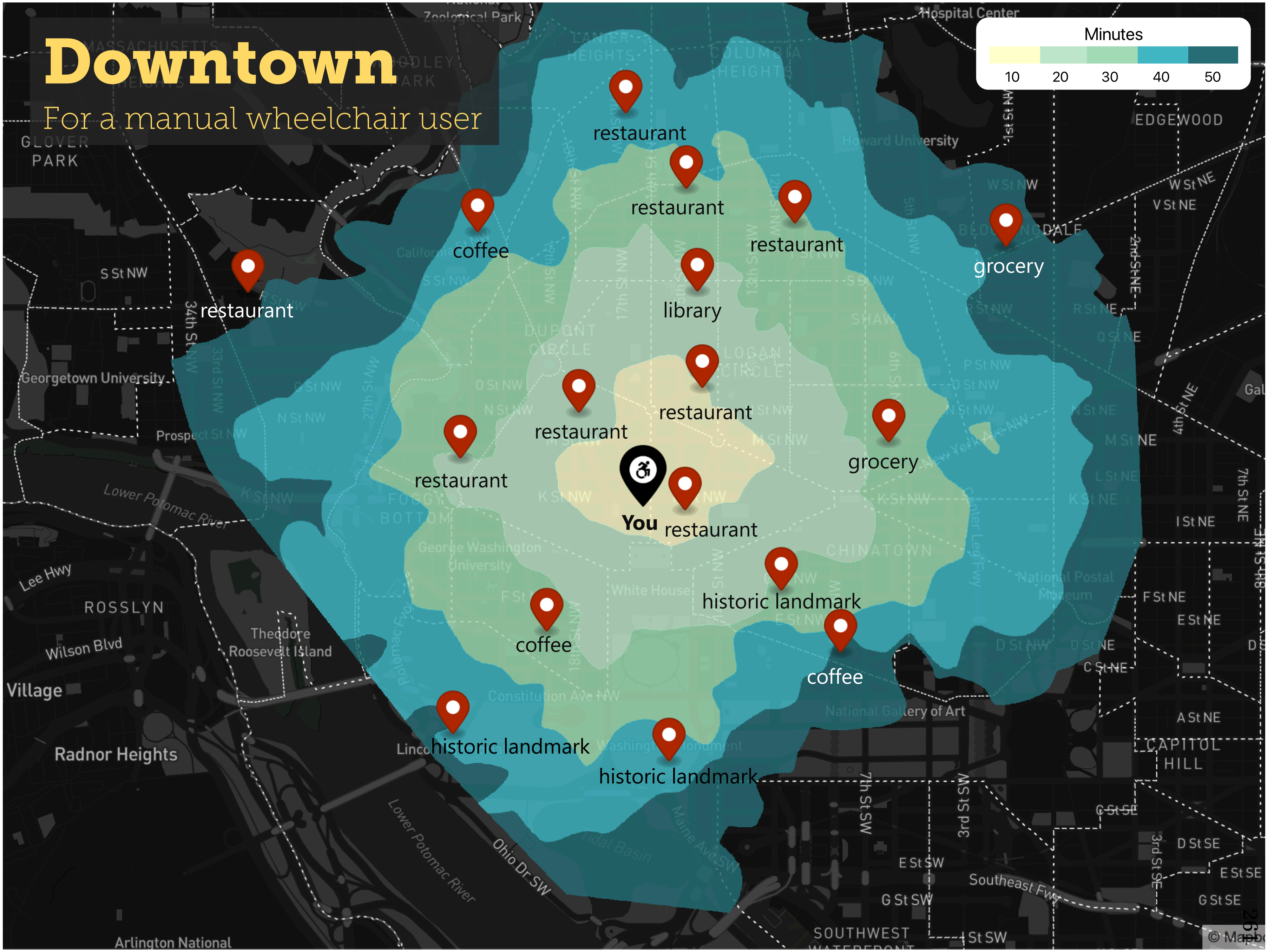

Severity
Passable
Not Passable
1
2
3
4
5
Average Severity
all problems
© Mapbox © Ope

Ego-centric Isochrones



North Cleveland Park
For a person without mobility impairment
Minutes
10
20
30
40
50
You
restaurant
restaurant
restaurant
restaurant
restaurant
grocery
grocery
grocery
coffee
coffee
park
library
Friendship Heights Village
Somerset
WESTBARD
WESTGATE
WESTMORELAND HILLS
AMERICAN UNIVERSITY PARK
TENLEYTOWN
FOREST HILLS
CLEVELAND PARK
WESLEY HEIGHTS
CHEVY CHASE
BRIGHTWOOD PARK
National Zoological Park
© Mapbox


North Cleveland Park
For a manual wheelchair user
Minutes
10
20
30
40
50
grocery
coffee
restaurant
restaurant
You
park
grocery
restaurant
coffee
grocery
restaurant
library
Somerset
Friendship Heights Village
Chevy Chase Village
WESTBARD
WESTGATE
WESTMORELAND HILLS
FRIENDSHIP HEIGHTS
AMERICAN UNIVERSITY PARK
TENLEYTOWN
FOREST HILLS
CLEVELAND PARK
WESLEY HEIGHTS
Sibley Memorial Hospital
National Zoological Park
Rock Creek Park



Downtown
For a manual wheelchair user
Minutes
10
20
30
40
50
restaurant
restaurant
restaurant
coffee
grocery
restaurant
library
restaurant
restaurant
restaurant
grocery
You
restaurant
historic landmark
coffee
coffee
historic landmark
historic landmark
GLOVER PARK
Georgetown University
ROSSLYN
Theodore Roosevelt Island
Village
Radnor Heights
Arlington National
Lower Potomac River
Ohio Dr SW
SOUTHWEST
CHINATOWN
White House
George Washington University
FOGGY BOTTOM
DUPONT CIRCLE
LOGAN CIRCLE
SHAW
Howard University
EDGEWOOD
CAPITOL HILL
National Gallery of Art
Hospital Center
Zoological Park
© Mapbox

Brightwood
For a manual wheelchair user
Minutes
10
20
30
40
50
You
coffee
hospital
grocery
library
park
park
grocery
restaurant
restaurant
restaurant
coffee
coffee
library
Takoma Park
Hampshire Knolls
Chillum
Chillum Gardens
Carole Highland
CHEVY CHASE
FOREST HILLS
MICHIGAN PARK
UNIVERSITY HEIGHTS
Providence Hospital
Hillwood Estate, Museum & Gardens
Military Rd NW
Rittenhouse St NW
Beech St NW
Aberfoyle Pl NW
31st Pl NW
Ellicott St NW
Tilden St NW
Taylor St NE
12th St NE
1st St NE
Eastern Ave NE
Chillum Rd
New Hampshire Ave
Sargent Rd
Piney Branch Rd
Tulip Ave
Lee Ave
Holly Ave
Lincoln Ave
Boyd Ave
Larch Ave
Elm Ave
Poplar Ave
4th Ave
© Mapbox © Open

B For Chapter 4: Project Sidewalk

Initial Launch Advertisement – August 2016

Help make Washington DC more accessible!

City streets, sidewalks, and businesses in the US remain inaccessible for people who use wheelchairs, scooters, or walkers to travel. Curb ramps and well-maintained sidewalks don't just help people with mobility impairments, they support all of us—when we're pulling luggage, pushing strollers, etc. However, there are currently few, if any, mechanisms to determine accessible areas of a city easily and comprehensively. We are trying to change this.

Project Sidewalk is a revolutionary new tool that empowers anyone—from motivated citizens and caretakers to government workers and urban enthusiasts—to remotely and quickly label accessibility problems by *virtually* walking through city streets. Our vision is to transform the way accessibility information about the built environment is collected and visualized. Imagine, for example, maps that show the accessibility of our cities at-a-glance or a navigation app on your smartphone that provides accessible routes for people with mobility impairments.

Join us! Visit http://sidewalk.umiacs.umd.edu to get started! Click "Participate" and complete a few short missions! In private beta testing, 126 users mapped the accessibility of over 245 miles of DC streets--that's nearly 25% of all streets in the city (and greater than the distance from DC to New York!). With just 10-15 minutes, you can make a difference!

DC is just the beginning. Our long-term vision is to deploy Project Sidewalk in every city in the world that has Google Street View!

Be a part of this revolution!

Help us make the world a better place for ***everyone***!

Project Sidewalk Team
University of Maryland
PS You don't have to live in DC to contribute—people from all over the world can participate to make DC accessible!

Email Advertisement

PROJECT SIDEWALK

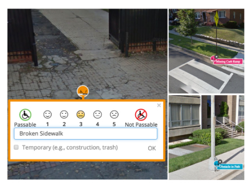
Let's create a more accessible world

Sidewalks benefit all of us. They help improve walkability, increase physical activity, and provide a safe, accessible path for people with disabilities. However, there is a severe lack of information about the location and quality of sidewalks in cities. Our research team at the University of Maryland is trying to change this. **And we need your help.**

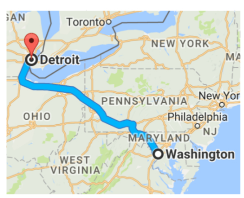
Introducing Project Sidewalk

Help improve Washington DC's sidewalks by virtually exploring the city in Project Sidewalk.

Project Sidewalk is a new online tool that enables anyone—from motivated citizens to government workers—to virtually walk through cities to help locate, label, and assess sidewalks. User-contributed labels are shared with local governments and used to model and predict sidewalk problems in cities.



Example sidewalk problems found in DC with our tool

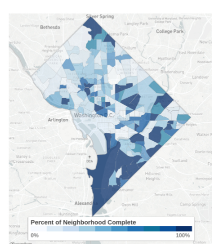


Together, We Are Making a Difference

Since our beta launch in Fall 2016, over 580 users have already contributed **72,000 labels** across 504 miles of DC streets—that's nearly **50% of the city** (and the distance from DC to Detroit).

Help Us Reach 100%

But we are not done. Our goal is **100%** coverage. To help us get there, we are proud to announce a **new version** of Project Sidewalk that makes it easier and faster to explore DC neighborhoods and find sidewalk problems! Try it out by clicking the 'Start Mapping!' button below. You can also help out by sharing this email with your colleagues, family, and friends.



DC neighborhoods colored by completion rates.

Let's make the world more accessible one curb ramp at a time.

Five minutes of your day could make someone else's.

Start Mapping Now!

Project Sidewalk is a research project at the University of Maryland.
Thank you for participating.

Project Sidewalk Data Collection on Amazon Mechanical Turk

Interfaces showing the first screen of a HIT

Instructions

HIT Objective: We are researchers at the University of Maryland developing new ways to track and study city accessibility for people with disabilities. This HIT will consist of completing game-like missions in our custom tool called Project Sidewalk. In a mission, you will virtually walk through Washington DC streets to find and label sidewalk accessibility issues. These issues include missing curb ramps, sidewalk obstacles, and surface problems (see image below).

Curb Ramps | Missing Curb Ramps | Sidewalk Obstacles | Surface Problems

Reward Payment:

- **Initial reward**. A confirmation code will be generated for you after completing the mandatory tutorial and the first mission. You can submit the code below at any time to qualify for the initial HIT reward of $0.82. You can continue working on as many missions as you like, even after submitting the code, until the time when your assignment *would* have expired. The payment for any additional completed missions will be in the form of bonuses.
- **Bonuses.** The bonus amount is proportional to the length of each mission completed after the initial one. You will be paid at the rate of $4.17 per mile. For example, you will be paid $2.08 for completing a 1/2 mile mission. However, you need to complete the entire mission to qualify for a bonus; you will not be paid for partially completed missions.
- **End Time for Bonuses**: You will only be paid for work completed *before the time when your assignment would have expired (which is 45 minutes after you accepted the HIT)*. This includes the time when the HIT was in your queue. Although the tool may show your bonus amount increasing after that time, you will not be paid for work completed after the allotted time, so we ask that you keep track of when you need to stop working, and suggest stopping early to be safe.

Start HIT

Provide the confirmation code below

e.g. ABC123

MTurk Interface for First-time Turker

Instructions

HIT Objective: We are researchers at the University of Maryland developing new ways to track and study city accessibility for people with disabilities. This HIT will consist of completing game-like missions in our custom tool called Project Sidewalk. In a mission, you will virtually walk through Washington DC streets to find and label sidewalk accessibility issues. These issues include missing curb ramps, sidewalk obstacles, and surface problems (see image below).

Curb Ramps | Missing Curb Ramps | Sidewalk Obstacles | Surface Problems

Reward Payment:

- **Assignment Approval:** A confirmation code will be available in the orange "Mturk Code" button on the interface. Submit the code in this window at any time before your assignment expires. You can continue working on as many missions as you like, even after submitting the code, until the time when your assignment *would* have expired. The payment for any additional completed missions will be in the form of bonuses.
- **Bonuses:** The bonus amount is proportional to the length of each mission completed. You will be paid at the rate of $4.17 per mile. For example, you will be paid $2.08 for completing a 1/2 mile mission. However, you need to complete the entire mission to qualify for a bonus; you will not be paid for partially completed missions.
- **End Time for Bonuses:** You will only be paid for work completed *before the time when your assignment would have expired (which is 1 hour after you accepted the HIT)*. This includes the time when the HIT was in your queue. Although the tool may show your bonus amount increasing after that time, you will not be paid for work completed after the allotted time, so we ask that you keep track of when you need to stop working, and suggest stopping early to be safe.
- **Don't remember how to use Project Sidewalk?:** You can click on the "Retake tutorial" button on the top-right of the tool to refresh your memory!
- **Do you have any longer HITs I can do?:** Yes! You are able to do this HIT because we gave you the "sidewalk_quality_unsure" qualification. We will be manually reviewing the work that you submit, and if we think it is of the highest quality, we will give you the "sidewalk_quality_verified" qualification, which lets you do much longer HITs! If you want to know how to do the highest quality work on Project Sidewalk, here is a 2 minute video showing an example of a very high quality worker: https://www.youtube.com/watch?v=tZS3IeYNq_k. Note that this is totally optional, but we hope it is helpful!

Go to Project Sidewalk

Provide the confirmation code below

e.g. ABC123

MTurk Interface for Poor Quality Turker

Instructions

HIT Objective: We are researchers at the University of Maryland developing new ways to track and study city accessibility for people with disabilities. This HIT will consist of completing game-like missions in our custom tool called Project Sidewalk. In a mission, you will virtually walk through Washington DC streets to find and label sidewalk accessibility issues. These issues include missing curb ramps, sidewalk obstacles, and surface problems (see image below).

Curb Ramps Missing Curb Ramps Sidewalk Obstacles Surface Problems

Reward Payment:

- **Assignment Approval:** A confirmation code will be available in the orange "Mturk Code" button on the interface. Submit the code in this window at any time before your assignment expires. You can continue working on as many missions as you like, even after submitting the code, until the time when your assignment *would* have expired. The payment for any additional completed missions will be in the form of bonuses.
- **Bonuses:** The bonus amount is proportional to the length of each mission completed. You will be paid at the rate of $4.17 per mile. For example, you will be paid $2.08 for completing a 1/2 mile mission. However, you need to complete the entire mission to qualify for a bonus; you will not be paid for partially completed missions.
- **End Time for Bonuses:** You will only be paid for work completed *before the time when your assignment would have expired (which is 45 minutes after you accepted the HIT).* This includes the time when the HIT was in your queue. Although the tool may show your bonus amount increasing after that time, you will not be paid for work completed after the allotted time, so we ask that you keep track of when you need to stop working, and suggest stopping early to be safe.
- **Can I see examples of high quality work?:** Yes! Here is a video that is an example of someone doing high quality work: https://www.youtube.com/watch?v=tZS3leYNq_k. It is only 2 minutes long, and is optional! We hope you find this useful!

Go to Project Sidewalk

Provide the confirmation code below

e.g. ABC123

MTurk Interface for Verified Turker

Online Pre-Study Questionnaire

Introduction

Hi! We would like to thank you for participating in our study.

Our team is designing new methods and tools to inform people about inaccessible areas of a city. For example, places could be inaccessible due to lack of sidewalks, absence of curb ramps at intersections, or inaccessible building entrance.

Before the day of the interview, we would like to ask you a few questions about your background to know you a little better. Please take a few minutes to complete the following survey. It will save time on the day of the interview study, and so we will be able to spend more time on other activities. Thank you very much for your time!

Background

- Age
- Gender
- Are you a:
    - Government Official
    - Person with a mobility impairment
    - Caregiver
- For government officials:
    - Which organization do you work for and at what capacity (state your designation)?
    - How long have you been working there?
    - What are the programs in your organization that are involved with accessibility?
    - Which program are you associated with?
    - Have you worked with people with mobility impairments?
        - If yes,
            - What types of mobility impairment did they have?
            - What kind of mobility aids did they use? (Manual wheelchair / Electric wheelchair / Manual assistive devices)
            - What are the means of transportation they used? (Private vehicle / paratransit / public transportation / chair or walk)
- For people with mobility impairments (MI):
    - What type of mobility impairment do you have? Describe your medical condition.
    - How long have you had the impairment?
    - What mobility aids do you use? (Manual wheelchair / Electric wheelchair / Manual assistive devices)
    - What is the main means of transportation to, for example, a grocery store? (Private vehicle / paratransit / public transportation / chair or walk)
    - How often do you travel in a week on an average? (once a week or less / 2-4 days a week / more)
    - Do you have any other impairments? (vision impairment / hearing impairment / none)

- For caregivers:
  - What is your role as a caregiver:
    - Nurse
    - Orientation <fill in>
    - <fill in>
    - Family member
    - Friend
  - For professionals,
    - How long have you been involved in this line of work?
    - Where do you work?
    - What type of mobility impairment patients have you worked with?
    - What kind of mobility aids did they use? (Manual wheelchair / Electric wheelchair / Manual assistive devices)
    - What are the means of transportation that you use with your patients? (Private vehicle / paratransit / public transportation / chair or walk)
    - How often do you travel in a week with them on an average? (once a week or less / 2-4 days a week / more)
  - For family members,
    - Who do you take care of? State your relationship with that person.
    - How long have you been taking care of them?
    - What type of mobility impairment do they have?
    - What kind of mobility aids do they use? (Manual wheelchair / Electric wheelchair / Manual assistive devices)
    - What are the means of transportation that you use with them? (Private vehicle / paratransit / public transportation / chair or walk)
    - How often do you travel in a week with them on an average? (once a week or less / 2-4 days a week / more)
- Do you use a computer?
  - If so, how often? (once a week or less / 2-4 days a week / more)
  - [ONLY for a person with MI] Do you use any assistive technologies to use a computer? For example, a trackball mouse?
- Do you use a mobile phone?
  - If so, what kind of a mobile phone do you use? (smart-phone / other (e.g., bar phone))
  - [ONLY for a person with MI] Do you use any assistive technologies to use a mobile phone?

Participant ID: ______________________ Date: ________________________ Time: __________

Project Sidewalk Interview Study

Semi-structured Interview Session

Introduction:

[READ TO PARTICIPANTS] – 5 min

Hi, I am Manaswi Saha, a PhD Student. Thanks for coming in today. Before we begin to talk about the interview session, let me tell you about our project. Our goal is to design new methods and tools to inform people about inaccessible areas of a city. For example, places could be inaccessible due to lack of sidewalks, absence of curb ramps at intersections and so on. This would be especially useful for people with mobility impairments as well as city governments.

The goal of this study is to better understand the opinions from the stakeholders of our tool like yourself. The study will be in three parts:

1. The first part is an interview study, where the questions will be to understand why accessibility is important to you and what are your **current practices** of looking up accessibility information?
2. The second part is a think aloud activity, where you will use the data collection tool that we have built using the **think aloud protocol**, which is you say your thoughts out loud while using the tool. We are interested in observing your reactions to the tool.
3. Finally, the last part is another interview, where the questions will be to understand your **perception and opinions** about the tool you used. For example, we are interested in knowing – your likes, dislikes and design ideas to improve the tool. Also, knowing what are your perceptions about the utility of the tool.

The whole study session should take about 60-65 minutes. Your data will be kept anonymous. We will be audio/video recording. For the video recording, your face will not be captured and we do not intend to take identifiable images of you. You have the right to stop participating in the study at any time. Before we begin the interview, we need to you sign the consent form and complete the background questionnaire (if the participant hasn't already).

Are there any questions?

Begin Interview:

INSTRUCTIONS FOR RESEARCHER:

Keep these handy for the entire session:

- Pre-Study Questionnaire (optional- if participant hasn't filled it out) (5 minutes)
- Consent form
- Part 1 Script: Motivation and Current Practices Interview (20 minutes)
- Part 2 Script: Think aloud usability study (20 minutes)
- Part 3 Script: Perceptions and opinions about the tool (20 minutes)
- Payment form and cash

[Start recording once the participant signed the consent form and filled out the questionnaire.]

I have just started the recorder and we will begin the interview. Please feel free to say whatever is on your mind and feel free to ask me questions at any time. Are you ready to begin?

Part 1 – Interview Session – Motivations and Current Practices

Time allotted: 20 Minutes

Main goals: (1) Understand participant's **motivation** towards accessibility. (2) Understand **current practices** around gathering accessibility data.

INSTRUCTIONS FOR RESEARCHER:

Have the questionnaire ready for reference. Note the timing of any interesting comment the interviewee mentioned.

Government Officials

Understanding Motivation Towards Accessibility (if any) – 5ish minutes

1. For non-DOT orgs: What is the role of your organization towards city's urban development efforts?
2. What kinds of data do you traditionally collect during city audits?
3. Do you perform accessibility audits for your city?
    a. If yes:
        i. Why is your city interested in performing accessibility audits?
        ii. How long have you been involved with accessibility projects for the city?
        iii. What is your role in the accessibility efforts?
    b. If no:
        i. Is accessibility taken into consideration during city audits?
        ii. Are there any ongoing initiatives that are being taken in this direction?
        iii. What are the motivations behind these efforts?
        iv. What kind of accessibility data do you have access to? If sidewalk/street-level data not mentioned:
            1. Do you have access to any street level accessibility data?

Current Practices for Audits

1. What is the frequency of audits in a year?
2. How many personnel is needed for these audits generally?
3. How do you perform city/accessibility audits? Follow-up:
    a. What method do you use? E.g. in-person audits or any kind of rapid audits.
    b. Do you take any help from volunteers/citizens to do neighborhood audits through organizations (e.g. AARP), or community events (such as bike day, audit the sidewalk day etc.)?
4. What tools do you use to perform your assessment activities?
    a. What kind of technology do you use during audits? E.g. Robotics, Use of maps (E.g. Cyclomedia) etc.
5. What do you look for when making an assessment? (asset tracking not just accessibility)
6. How long does it generally take to perform assessment activities?
7. What difficulties do you face in collecting this data?
    a. For accessibility audits: What is the most challenging aspect of assessing accessibility?
8. What kind of tool would be beneficial for making this process easier?
9. How is the collected data used?
    a. What form is this data stored in?
10. If you are comfortable to share, what is your annual budget for [city | accessibility] audits (a ball park estimate)?

People with Mobility Impairments

1. How long have you had the impairment?
2. How do you get around the city? [Modes of transport]
   a. Do you travel alone or with someone?
3. What is your usual strategy to navigate from point A to point B if the destination is in an unfamiliar area? [How they get to the new place] Supporting Question:
   a. What do you do before traveling to this unfamiliar neighborhood? For example, do you use paper maps or technologies like Google Maps' navigation to find a route?
4. What is the most challenging aspect of traveling within cities?
5. When you are choosing a place to go, do you factor in accessibility of the neighborhood (such as its sidewalks and streets)?
   a. If yes:
      i. Does it affect your decision to go there?
      ii. How do you look up the accessibility of a route?
   b. If no: why not?
6. Do you look up the accessibility of the building you are going to visit, for example, by calling them ahead of time?
7. Do you use any existing technologies/tools to find information about the accessibility of these places? For example, do you use Google Street View or a mobile app to look up accessibility of a neighborhood? If yes, could you list them?
   a. What is your preferred method to look up accessibility information – which has worked for you?
8. Have you ever had any problems because you did not check the accessibility of a place or a route beforehand? Could you explain?
9. Would you use an accessibility-aware navigation tool if there is one? For example, if Google Maps had an "accessible route" option in addition to driving/walking/biking routes.

Interviewer Notes:

Caregivers

INSTRUCTIONS FOR RESEARCHER:

Have the questionnaire ready for reference.

Refer to the questionnaire and set the tone of the interview by talking a single sentence about the person under their care (for family/friend) or get details about the person they would be talking about (for professionals).

1. For professionals: What motivated you to work in this field?
2. What is the most challenging aspect of caregiving for people with MI?
3. What are some of the key mobility challenges that have affected you and the people under your care?
    a. According to you, what makes a city accessible?
4. How do you plan trips for people under your care? Supporting Question:
    a. What do you look for when you plan trips/other activities?
    b. What tools do you use to plan their activities around the city?
    c. How easy is it to plan trips for them?
5. Do you factor in accessibility of a route when you are visiting an unfamiliar place?
6. What kind of technology do you use to know about the accessibility of a place or a route? [Metro transit is one of them] Supporting Questions:
    a. Which technology has worked for you? How well do they work for you? [General opinion]
    b. What do you like about them?
    c. What do you dislike/limitations about them?
    d. Could you describe a time when these tools were very useful and not useful?
7. How long does it generally take in planning these activities?
8. Do you know if other caregivers share similar situations/problems/concerns as you?
    a. How different is your perspective from other caregivers that you might know?

10. Would you use an accessibility-aware navigation tool if there is one? For example, if Google Maps had an “accessible route” option in addition to driving/walking/biking routes.
    a. What would you expect the tool to provide?
11. Do you have any additional comments that you would like to add?

Interviewer Notes:

Part 2 – Think Aloud Usability Study

Time allotted: 20 Minutes

Main goal: To observe their reactions towards the tool, Project Sidewalk.

[READ TO PARTICIPANTS]

Let's begin the second part of the session – the think aloud activity. In this part, you will use a tool that we built called Project Sidewalk, which enables any person to label problems and features of the built infrastructure of cities that affect accessibility for mobility impaired users. Problems include broken sidewalks, presence/absence of curb ramps and others.

[OPTIONAL: Our long-term research agenda is to develop tools that enable people like yourself to utilize this data in form of novel applications, such as smart route navigation for people with mobility impairments and interactive visualization of the city's accessibility, and support initiatives to bring about policy change.]

In this exercise, you will be first shown the home page of our website. You may explore that page if you'd like. From that page, you go to the tool by clicking "Start Mapping". As a new user, you will first be on-boarded into the experience with a tutorial. Once you finish the tutorial, you will start a *"mission"* of labeling the streets of DC. You will complete one mission of 1000ft in this session. During the whole exercise, we would like you to state **out loud** what you are thinking as you are interacting with the tool e.g., the decisions that you make while labeling, your choices and so on. We want to understand your thought process when you use the tool and also, if the design decisions we made make sense to you. Please note we are NOT judging you; we are only observing your reactions towards the tool.

INSTRUCTIONS FOR RESEARCHER:

General Protocol:

- Keep the Project Sidewalk landing page open in the browser in the incognito mode.
- Ask them to "explore the page, and when done click Start Mapping". Observe what they look at, which sections they pay attention to.
- If they don't open the audit page in a minute of exploration of the landing page, then prompt them to 'Start Mapping' – "Why don't you now know go ahead and click Start Mapping?"
- Observe their actions while using the tool. Prompt them to keep saying what they think while taking any action.

Note the timing of any interesting comment the interviewee mentioned.

General Prompting Questions:

1. Why did you select X?
2. What made you click X?

Part 3 – Interview Session – Perceptions and Opinions on the Tool

Time allotted: 20 Minutes

Main goals: To understand the participant's reactions towards the tool based on the usage in Part 2 of the study. Have the participants reflect upon (1) their experience during the course of the activity, (2) their likes, dislikes and desired changes to the tool, and (3) understand their perceptions and expectations from Project Sidewalk.

INSTRUCTION FOR RESEARCHER:

Write the timing in the notes of any interesting comment the interviewee mentioned.

[READ TO PARTICIPANTS]

The last part of the study is having a discussion around your experience of using this tool, understand your likes/dislikes, and understand your perceptions and expectations from the tool.

1. What did you think of the tool?
2. What are the features that you liked and why?
3. What are the missing features that you would like to have and why?
4. Do you have any concerns about the collected data?
5. What would Project Sidewalk enable you to do? Supporting Questions:
    - How do you see this tool being used to, for e.g., "find neighborhoods that need most work"? Prompting Question:
        - Can this tool be used for triaging issues for city governments to work on?
    - How useful do you perceive the tool to be to explore accessibility of neighborhoods? Please answer in a 1-to-5 scale where 1 is not useful at all and 5 is very useful.

Interviewer Notes:

C For Chapter 6: Landmark AI

Participant Demographics

ID	Age	G	Aid	Self-described vision level
P1	52	M	WC	Totally blind
P2	34	M	GD	Left eye = no vision Right eye = no peripheral, central vision only, large shapes and colors - can tell if it is a car or building, can tell what general color the car is
P3	32	M	M	20/80 in my left eye with correction 20/200 in my right eye with correction ocular albinism light sensitivity
P4	52	F	GD	Light perception legally blind
P5	36	M	WC	Totally blind
P6	55	M	GD	I have light perception in my right eye. I am completely blind in the other.
P7	27	M	GD	I am totally blind (no light perception)
P8	25	F	WC	I can see better in light. I can see larger objects, but cannot make out finer details
P9	24	M	WC	I am blind (no vision at all)
P10	42	F	WC	I am completely blind in my left eye and have severe tunnel vision in my right with near-sightedness.
P11	54	M	GD	Blind
P12	32	F	GD	I can see light, dark, and shadow. I can sometimes see movement if it is close enough and within one of my small blurry islands of visibility. I cannot read any size font. I cannot identify shapes. I can sometimes tell when I am near a tall/large object using echolocation. My vision can fluctuate from day to day. I have moderate light sensitivity.
P13	38	M	WC	I have loss of peripheral vision in both eyes, my visual acuity is extremely poor in my central vision in both eyes. I have light sensitivity and diminished color perception.

Table 1. Participant Demographics.
Gender (G) = Male (M)/ Female (F). Primary Aid = White Cane (WC), Guide Dog (GD), Magnifier (M).

Codebook Used for Analysis of the Design Probe Study

Themes	Code#
Existing Mobility	
Existing Navigation Strategy	1
Use of Mobility Aid	2
Use of Residual Vision	3
Wayfinding Challenges	4
Information Useful at the Last-Few-Meters	
New Types of Information	5
Channel Information Utility	6
Confirmation of Pre-Existing Knowledge	7
Channel Preference	8
Usage Scenarios	
Time and Location (Situational)	9
Method of Usage (Operational)	10
Factors influencing information preference	
Mobility aid	11
Visual ability	12
System Considerations	
Physical Form Factor	13
Accuracy and Precision	14
Limitations	15
Feedback mechanism	
Timing and speed of output	16
Frequency	17
Seamlessness/Ease of Use	18
Design Ideas/Recommendations	19

Table 2. Codebook Used in the Analysis