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EVALUATING SIDEWALK INFRASTRUCTURE & PRIORITIZING INVESTMENT

Final Report

by

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Disclaimer

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Executive Summary

This project leverages advances in technology and increasing access to high-resolution remote sensing and spatial data to develop methods for inventorying sidewalk characteristics and static obstructions across an entire major city. In part 1 of this effort, we analyze city-scale sidewalk availability, width, and land coverage calculated from spatial data from aerial imagery (planimetrics). We then determine how much of a difference accounting for static obstructions makes when measuring the clear width of sidewalks in one city. Part 2 then combines planimetric sidewalk data with vehicle and pedestrian trip big data to develop a methodology to prioritize city areas in need of pedestrian infrastructure attention.

The results show an overall deficiency of sidewalks and indicate that deriving sidewalk availability, average width, and minimum clear width are feasible at the city scale. Moreover, the results suggest a significant decrease in the average clear width of sidewalks when accounting for static obstructions. Not accounting for static obstructions could lead to a gross overestimation of seemingly adequate sidewalks and an unrealistic assessment of sidewalk infrastructure and pedestrian accessibility. We then present a feasible and efficient method to prioritize pedestrian infrastructure in a city.

Primarily due to a lack of data, academic literature has scant research on sidewalks. In this project, we leveraged advances in remote sensing to bridge the data and research gap on pedestrian infrastructure in cities. These results will help cities that are lacking information rectify an unprecedented backlog of deteriorating pedestrian infrastructure.

Section 1. Sidewalk Static Obstructions and the Impact on Clear Width

Chapter 1. Introduction

Walking provides a vital mode of transportation in cities, and sidewalks offer a conduit to reach destinations such as work, school, activities, or other modes of transportation. Cities have seen an increase in populations and a reinvigorated desire for active modes of transportation (FHWA, 2017a; UN Department of Economic and Social Affairs 2018; UN Department of Economic and Social Affairs 2014; USCB, 2012). In addition, cities have developed pedestrian plans – some for the first time – and sidewalks provide a critical component to those efforts (City and County of Denver, 2004; City of Boulder, 2019; City of Durham, 2006; City of Philadelphia, 2012; City of Portland, 2019). However, the existing research suggests an overwhelming lack of sidewalk data (FHWA, 2006, 2015, 2018; Park, Bang, & Yu, 2015; Zhang & Zhang, 2019).

Advances in geospatial technology have begun to help fill the sidewalk data gap. Planimetric data, for instance, typically consists of physical features on the ground, including transportation infrastructure such as street edges and trees (Montgomery & Schuch, 1993). Planimetric data can also include sidewalk polygon data, but that polygon data usually only reveals the extents of the sidewalks. It is uncommon for such data to account for static obstructions – such as street furniture, signs, or trees – within the sidewalk. Static obstructions will narrow the clear width within the extent of the sidewalk for pedestrians to walk. Clear width is described in the Americans with Disabilities Act (ADA) Chapter 4 "Accessible Routes", subsection 403.5.1, as the minimum measured width of walking surfaces (USDOJ, 2010). To elaborate, clear width does not pertain to other sidewalk characteristics, such as the ground surface condition or slope, which the ADA describes in separate subsections, 403.2 and 403.3, respectively (USDOJ, 2010). This dimension does not refer to a measurement based on pedestrian flow nor characteristics such as speed, flow, density, space, free-flow speed, or jam density; rather, it refers to the physical space required for persons with disabilities (FHWA, 2020; Gupta & Pundir, 2015; USDOJ, 2010). For example, Figure 1 depicts the physical dimensions of a typical wheelchair user and the minimum clear width requirement of three feet (0.91 meters), as displayed in Figure 403.5.1 of the 2010 ADA Standards (USDOJ, 2010). In addition, Figure 1 depicts a utility pole in the middle of a five foot (1.52 meters) sidewalk, which narrows the sidewalk clear width to only two feet (0.61 meters). This becomes the narrowest point a pedestrian encounters in the extent of the sidewalk, otherwise called the clear width.

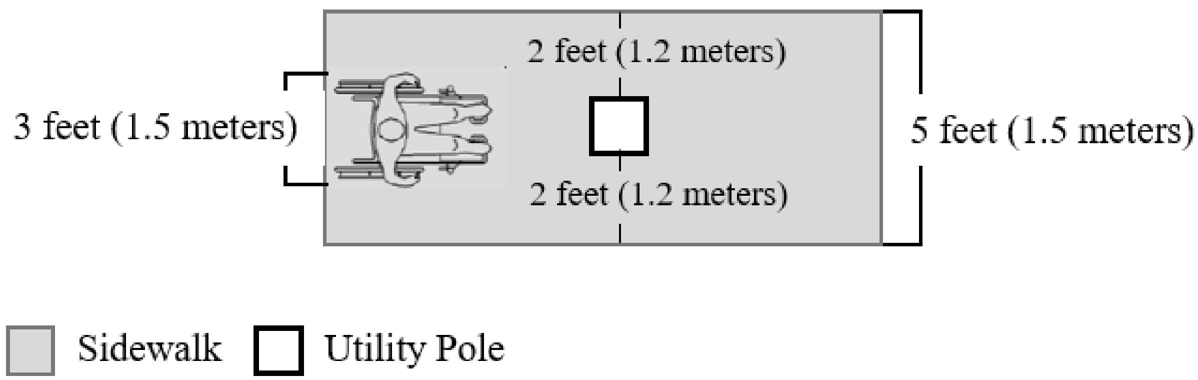


Figure 1. Sidewalk Clear Width (Plan View)

Static obstructions may influence route choice and force pedestrians to walk in the street or impede sidewalk accessibility, which emphasizes a safety concern and the importance of understanding clear width (Aghaabbasi, Moeinaddini, Asadi-Shekari, & Shah, 2018; FHWA, 2020; Odame & Amoako-Sakyi, 2020). "Accessibility" in this research refers to the ADA accessibility standards and the degree to which a sidewalk can be accessed by pedestrians (ITE, 2010; NACTO, 2013; USDOJ, 2010). Figure 1, for example, depicts a sidewalk with a utility pole narrowing the clear width and impeding access to a person in a wheelchair. This situation is not limited to people with disabilities, as it may similarly impede others from using the sidewalk such as a parent with a stroller or a delivery person with a dolly. In turn, this would result in the pedestrian needing to identify an alternative route, mode, destination, or foregoing their trip altogether. In addition, city agencies desire to know more about sidewalk clear width for compliance with ADA standards. The ADA standards, as well as many state and national guidelines, include static obstructions in their description of sidewalks. The ADA states that sidewalks are a "path of travel," which is defined as a continuous and unobstructed route for pedestrians (USDOJ, 2010). In addition, federal and national guidelines discuss geometric design in alterations to sidewalks where static obstructions impact accessibility. For example, the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) discuss the minimum clear width for pedestrian access and define it as a continuous route absent of static obstructions (AASHTO, 2018; FHWA, 2013). Nevertheless, only a couple cities have started removing select static obstructions from their planimetric sidewalk data. Cambridge, Massachusetts, for example, removes the MBTA subway head houses from their sidewalk layer, while Washington D.C. removes large concrete planters. Few other cities remove any static obstructions, and we did not find any U.S. cities that remove static obstructions such as light poles or fire hydrants. The problem is that we do not know how much of a difference accounting for static obstructions will make when measuring the clear width of sidewalks. In other words, does accounting for static obstructions in the sidewalk layer lead to a significantly different clear width?

Utilizing planimetric data, we analyzed sidewalk polygons with static obstructions to provide a more accurate depiction of sidewalk clear width and compared the results to ADA standards as well as national and federal sidewalk guidelines. In our study, we researched state, county, city, and other municipal websites in the U.S. for planimetric sidewalk data, and we identified Cambridge, Massachusetts as a suitable study city. We calculated the clear width for sidewalk polygons using Quantum GIS (QGIS) software. We then compared the results without static obstructions to the clear width when accounting for static obstructions.

This study utilizes advances in remote sensing data to calculate previously elusive information on sidewalk clear width with obstructions at the city scale. Prior studies have been limited to less accurate data at the city scale, using lines and points to represent infrastructure. Of the existing research that achieved greater infrastructure detail, researchers typically investigated significantly smaller geographic areas such as a single roadway. We expand upon the existing literature by analyzing sidewalk clear width at the city scale. This study begins to fill the sidewalk data gap, expands the current literature, and increases the understanding of how static obstructions in the sidewalk impact sidewalk clear width and pedestrian accessibility. Cities should be able to identify where sidewalks exist, the clear width of the sidewalk, and where static obstructions may hinder accessibility.

Chapter 2. Literature Review

Research on static obstructions in general are relatively prevalent. They include studies on utility poles (El-Halawany & Lichti, 2013; Lehtomäki et al., 2010), fire hydrants (Shadin & Tahar, 2015), street signs (Campbell et al., 2019), and street trees (Yadav et al., 2018). These studies, however, typically focus on collecting data of specific streetscape features rather than trying to understand how their presence might affect sidewalks or pedestrian accessibility (Campbell et al., 2019).

Studies on sidewalks in general – without accounting for static obstructions – are beginning to grow in numbers, but at this point, they tend to focus on a street, neighborhood, or similarly small geographic area. This is often attributed to a lack of existing spatial data and the need for time-intensive field-based data collection (Ai & Tsai, 2016; Bise et al., 2018; Brownson et al., 2009; Cheryl et al., 2007; Lowe, 2016). Analyzing portions of a city leaves potential for unintentionally skewed results and a misunderstanding of city sidewalk needs. Studies on sidewalks at the city level, or a similar geographic scale, often utilize linear roadway data to estimate sidewalks (Kang et al., 2015; Li et al., 2018). This presents two problems. First, the presence of a street does not necessarily equate to the presence of a sidewalk. Second, this leaves us with little information about the sidewalks themselves such as width or accessibility. Some researchers are trying to remedy these issues. For example, research by Li et al. developed an automated GIS process that creates a complete linear sidewalk network using roadway data. They then supplemented the automated work with manual edits based on field visits to verify sidewalk presence and conditions, including measuring sidewalk width. Although effective, the process was time consuming and difficult to accurately assess static observations. Some researchers have started to use remote-sensed planimetric data to extract sidewalk width characteristics (Coppola & Marshall, 2019, 2020). This facilitated expansion of sidewalk data sets to the city scale but was not yet able to account for static obstructions. Moreover, these papers were only able to measure average sidewalk width as opposed to identifying minimum clear width.

Studies that combine sidewalk spatial data with static obstructions are sparse. A study by Yairi and Igi developed a GIS model for pedestrian routing with sidewalk static obstructions to accommodate pedestrians with disabilities for Koganei City in Kyoto, Japan (Yairi, 2006). The data collection consisted of field surveys conducted by people with disabilities to categorize static obstructions and routes by type of disability. This study, however, did not measure sidewalk width; instead, static obstructions were represented by points snapped to a simple sidewalk centerline. Without measuring sidewalk width, it is difficult to understand how the obstructions may impact pedestrian accessibility. Another study by Ai and Tsai utilized mobile LiDAR data to automate the measurement of sidewalk width while accounting for static obstructions. This study collected data for one street at the Georgia Institute of Technology using four video cameras, two mobile LiDAR systems, and a global navigation satellite system (GNSS). However, there is no mention of cost of the equipment or time required for data collection, processing, and analysis. Moreover, this study has only been tested along one road with the authors mentioning a recommendation of another trial on a larger sidewalk network. Both studies present multiple obstacles, including time, money, and skilled staff to launch these studies at the citywide scale.

Prior literature on sidewalk audit methods to collect sidewalk width data generally include subjective data collection or varying measurement ranges (Aghaabbasi et al., 2018). For instance, the Walking and Biking Suitability Assessment includes a section to measure the sidewalk width "at a location that best represents the average width you observed." This introduces a high degree of subjectivity for an auditor to determine what may be deemed “best” or what is an “observed average width.” Regarding varying measurement ranges, the Analytic Audit Tool and the Pedestrian Environment Data Scan (PEDS) includes check boxes for: “does not apply, 0 to 3ft, >3 to < 6ft, >6ft” and “<4 feet, between 4 and 8 feet, >8 feet”, respectively (Brownson et al., 2003; Clifton et al., 2007). This introduces two issues: i) the measurements include a 3 feet or 4 feet range for each category, resulting in loss of detail; and ii) the audits include different sidewalk width ranges and therefore the results cannot easily be compared. In contrast to prior pedestrian audits, our research employs GIS to conduct continuous quantitative clear width measurements – including static obstructions – for every city sidewalk. This alleviates prior burdens such as the extreme time and cost necessary for a field survey, which also helps facilitate data collection at the city scale. Using this data, we are then able to identify and locate the minimum measured sidewalk clear width within each sidewalk polygon. This eliminates the need to convert raw data, potentially collected on paper, into digital format. Creating and storing data in GIS also enables further capabilities such as producing maps and conducting additional spatial analyses. Moreover, the data provides objective measurements and locations for every sidewalk as opposed to prior audits producing a subjective estimate or a measurement range. Overall, the prior research on sidewalks, sidewalk static obstructions, and sidewalks with static obstructions reveal a gap in detailed sidewalk data and the impact of static obstructions on sidewalks at the city scale.

Chapter 3. Methodology

One goal of this project is to continue to fill the sidewalk data gap and quantify the impact of static obstructions on sidewalk clear width. Prior research has shown that planimetric sidewalk data is starting to become available in some U.S. cities, but first we needed to determine if any of those cities also has enough data on sidewalk static obstructions (Coppola & Marshall, 2019, 2020). Thus, we first researched U.S. state, county, city, and other municipal websites. Next, we tabulated all sidewalk polygon data sets and identified cities covered within the data set extent. We then contacted the data originator (e.g. city GIS department) for each data set and requested: verification of the year when the data was collected, the accuracy level of the aerial imagery used to create the planimetric data, and if the data included coverage for the entire city. This information provided additional metrics to compare planimetric data sets, along with the obstruction data identified, to determine a study city for our research.

Of the cities with sidewalk polygon and obstruction data, Cambridge, Massachusetts, utilized the highest-quality aerial imagery, acquired at one inch (2.54 centimeters) = 300 feet (91.44 meters) scale photography, and provided the greatest number of obstruction data sets (City of Cambridge Massachusetts, 2020). Moreover, the city released planimetric data from a recent aerial photo flyover in April 2018, which was used by the city for the sidewalk polygon and all sidewalk obstruction data (City of Cambridge Massachusetts, 2020). With the Cambridge planimetric data, we utilized QGIS to extract and compare the clear width of sidewalk polygons against sidewalk polygons with static obstructions. We also evaluated the sidewalk minimum clear width results against ADA standards as well as national and federal sidewalk guidelines. These include guidelines from Federal Highway Administration (FHWA), American Association of State Highway and Transportation Officials (AASHTO), National Association of City Transportation Officials (NACTO), and Congress for the New Urbanism (CNU)/Institute of Transportation Engineers (ITE). Regarding minimum sidewalk width, Table 1 lists the specifics from each set of guidelines. The ADA requirement is a three foot (0.91 meters) minimum sidewalk width, but this measurement is exclusive of the width of the curb (USDOJ, 2010). Excluding the width of the curb would narrow the ADA minimum width requirement. However, the width of the curb varies depending on the configuration and the materials used (AASHTO, 2018). Therefore, we used three feet (0.91 meters) as the ADA requirement since the curb configuration, material type, and width may vary for sidewalks throughout a city, and this information is not typically accounted for in sidewalk data or able to be easily obtained.

Sidewalk obstruction data are defined in this study as spatial data sets – independent of the sidewalk data – provided by the City of Cambridge with point, line, or polygon (area) geometry detailing static (affixed) transportation infrastructure. To clarify, we are focusing on transportation infrastructure within the sidewalk, not sidewalk deficiencies such as vertical displacement, cracks, or gaps.

Table 1. Sidewalk Minimum Width Standards and Guidelines

Agency	Document	Width
ADA	2010 ADA Standards for Accessible Design[1]	3 feet (0.9 meters)
	Proposed Accessibility Guidelines for Pedestrian Facilities in the Public Right-of-Way[2]	4 feet (1.2 meters)
AASHTO	A Policy on Geometric Design of Highways and Streets[3]	
FHWA	Designing Sidewalks and Trails for Access[4]	5 feet (1.5 meters)
NACTO	Urban Street Design Guide[5]	
ITE & CNU	Design Parameters for Walkable Urban Thoroughfares[6]	6 feet (1.8 meters)

** The 2010 ADA Standards for Accessible Design provide enforceable guidelines based on legislation. All other minimum sidewalk widths provided are recommendations from agencies.*
[1] *(Mahoney, 2012)*
[2] *(USAB, 2011b)*
[3] *(AASHTO, 2018)*
[4] *(Kirschbaum et al., 2001)*
[5] *(NACTO, 2013)*
[6] *(Daisa & ITE, 2010)*

Data Preparation

We obtained planimetric sidewalk data and the 18 obstruction data sets listed in Table 2 from the City of Cambridge GIS website. The data sets needed to be prepared before conducting analyses in GIS. Sidewalk polygons included the following five-step preparation process, also displayed in Figure 2.

1. First, we dissolved the original Cambridge sidewalk polygon data to remove internal boundaries, which represented areas by material type (i.e. brick or concrete).
2. Second, we created a sidewalk centerline and a unique identification attribute matching each sidewalk polygon to the corresponding sidewalk centerline.
3. Third, we converted the sidewalk polygon to a polyline, which is required for GIS to measure the distance from the centerline to the sidewalk boundary edge.
4. Fourth, we created points along the centerline at one foot (0.30 meters) intervals, starting 10 feet (3.0 meters) from the beginning and terminating 10 feet (3.05 meters) from the end. Creating points along the centerline at 0.5 feet (0.15 meters) intervals considerably increased processing time, and the resulting difference in measurements were negligible with approximately .01 feet (0.30 centimeters) on average. Creating points along the centerline at 1.5 feet (0.46 meters) intervals had little impact on time and average measurements, but the maximum differences increased to two feet (0.61 meters). Therefore, to err on the side of caution, we continued with the one foot interval. The 10 feet (3.05 meters) spacing is because centerlines begin and end touching the sidewalk boundary. This results in a width measurement of zero feet. In addition, the 10 foot (3.05 meters) spacing accounts for some sidewalk centerlines generated by GIS that deviate off-center near the end of sidewalk segments, as displayed in Figure 2, step 4. We determined the use of the 10 feet (3.05 meters) distance by also creating centerline points at 1 foot (0.30 meters) intervals, starting at 9 feet (2.74 meters) and 11 feet from the beginning and end. We continuously conducted manual reviews, focusing on sidewalk polygons producing abnormally narrow widths at the beginning or end of sidewalk polygons (e.g. less than 1 feet). At 9 feet (2.74 meters), we identified incorrect narrow width measurements for sidewalk polygons due to centerlines deviating off-center. The results at 10 feet (3.05 meters) alleviated the errors identified at 9 feet (2.74 meters), and 11 feet (3.35 meters) indicated little to no difference from 10 feet (3.05 meters). We also joined the sidewalk polygon unique ID with each point.

5. For the final step, we created a line from each centerline point to the nearest sidewalk boundary edge for a distance measurement. Since the distance only accounts for half the width, we doubled the number to calculate the full width. We stored the full width measurement as an attribute with each centerline point. This will allow us to identify the width for each point and the corresponding sidewalk polygon by using the unique ID.

Table 2. Planimetric Obstruction Data

		Obstruction	Diameter *U.S. feet (meters)*	Measurement Source		Obstruction
Geometry Type	Point	Street Light (Not City Owned) [1]*	0.5 (0.2)	valmontstructures.com	Line	Bench
		Street Light [1]	0.5 (0.2)			
		Bike Rack[2]	1.4 (0.4)	theparkcatalog.com	Polygon	Buildings
		Fire Hydrant [3]	1.0 (0.3)	american-usa.com		Bus Shelter
		Litter Barrel [3]	2.3 (0.7)	trashcontainers.com		Decks
		Memorial Pole [3]	0.5 (0.2)	uncommonflagpoles.com		Misc. Structure
		Traffic Signal [3]	1.0 (0.3)	valmontstructures.com		Other Impervious
		Utility Pole [3]	1.0 (0.3)	blpole.com		Porch
		Street Tree [4]	Varies	caliper attribute		Stairs
						Subway Head House

** "Street Light (Not City Owned)" GIS metadata states the lights are owned by multiple organizations (City of Cambridge Massachusetts, 2016). However, information on the owner for each street light is not provided. In turn, we utilized the diameter from the City of Cambridge "Street Light" data.*

Identification Sources:
[1] City of Cambridge Electrical Department
[2] City of Cambridge Transportation Department
[3] Google Street View
[4] GIS Attribute

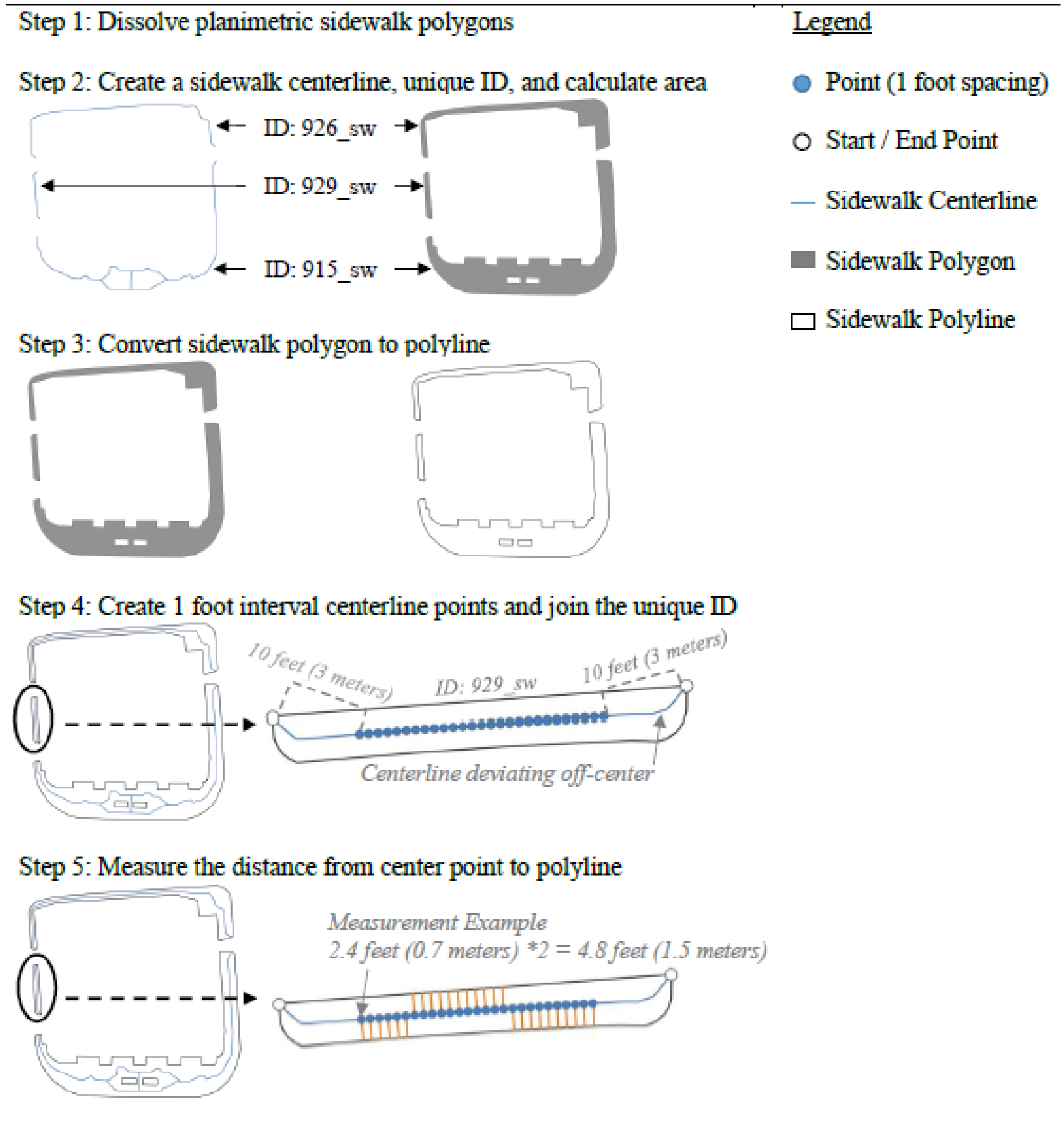


Figure 2. Sidewalk Polygon Minimum Clear Width Calculation Method

The planimetric obstruction data originated in three spatial data geometries: point, line, and polygon. Table 2 lists each obstruction data set and their geometry type. While points and lines represent the location of static obstructions, they fail to provide insight to the area occupied. In turn, we converted all line and point data to polygons to represent the area that each consumes. For example, the bench data (line geometry) represented the outline of a bench, so we converted it to a polygon. For static obstructions represented with a point, we contacted a city agency and/or identified a sample item through Google Street View. Once we identified an obstruction example, we researched dimensions online. Additional types of each static obstruction – other than the identified example – may exist in the city. Therefore, if multiple sizes were identified, we chose a conservative measurement by using the minimum reasonable dimensions. To identify the city light poles, for example, we contacted the City of Cambridge Electrical Department. The city electrician stated a 6.5 inch (16.51 centimeters) by 7 inch (17.78 centimeters) square base light pole produced by Valmont structures was a typical model used by the city. We also reviewed the company website provided by the city electrician and identified the Model 1907 with a 6 inch (15.24 centimeters) diameter base is the smallest available. One exception were street trees, which contained a GIS attribute with a caliper measurement for each tree. This measurement provided the information needed to buffer each tree point. A list of point planimetric data static obstructions, the buffered diameter, the source to identify a sample (Cambridge City Department or Google Street View), and the internet source to determine the area measurements are shown in Table 2.

Similar to the sidewalk polygon preparation, static obstructions located within 10 feet (3.05 meters) from the beginning and end point of the sidewalk centerline were not included in the analysis. The GIS process to measure the clear width with static obstructions requires the sidewalk centerline for reference. As we noted in the sidewalk polygon preparation, some sidewalk centerlines generated by GIS deviate off-center near the end of sidewalk segments. Thus, the resulting sidewalk width measurement would be incorrect. An example of the sidewalk centerline deviating off-center is displayed in Figure 2, Step 4.

Sidewalk Polygons

The city of Cambridge planimetric data resulted in 1,523 sidewalk polygons. A sidewalk polygon will often consist of a section of sidewalk along a city block. However, city blocks and sidewalk polygons can vary in size and shape. For the sake of clarity, Figure 3 provides summary statistics (min, max, and quartiles) for the sidewalk polygons. In addition, we provide a series of cartographic examples to help envision what a sidewalk polygon would look like for each of the summary statistic polygon sizes. For each example (min, max, and quartiles), we start at a larger geographic scale to help illustrate the example sidewalk polygon (Figure 3 - Area Map). The next cell down in Figure 3 provides greater detail displaying the city block where the example sidewalk polygon exists (Figure 3 - Detail Map). Lastly, Figure 3 depicts a close-up showing the dimensions of the example sidewalk polygon (Figure 3 - Close-up).

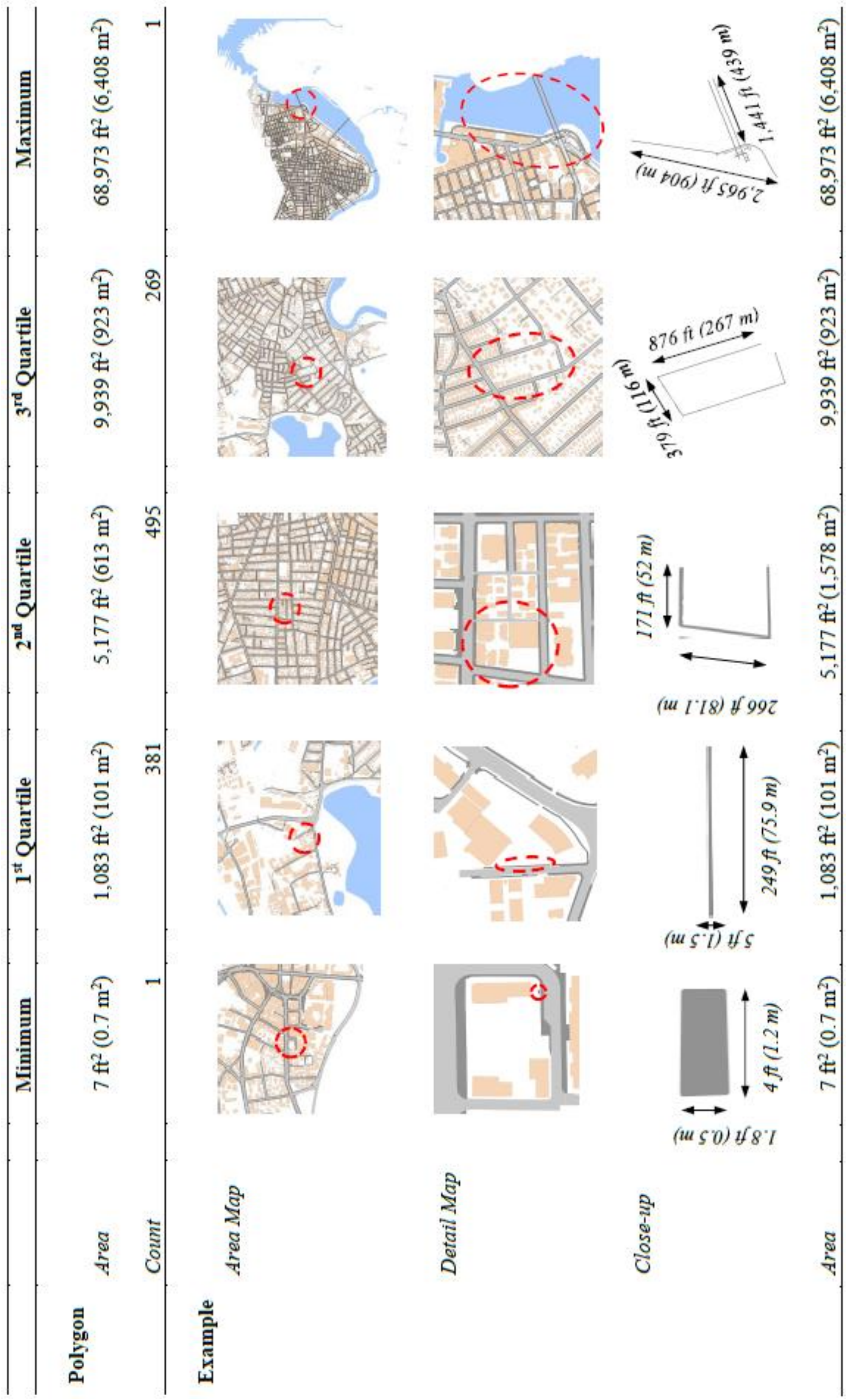


Figure 3. Sidewalk Data

Static Obstructions

We accounted for over 30,000 static obstructions within the sidewalk data. We provided a list of the static obstructions within sidewalks in Table 3, which includes: the count of each obstruction type, average obstruction polygon area, and polygon area standard deviation. Approximately 76% of the sidewalk polygons (1,151 of 1,523) contained static obstructions.

Table 3. Static Obstructions within Sidewalks[1]

Obstruction	Count	Mean		Standard Deviation	
		U.S. feet ^{2} (meters ^{2})			
Bench	205	11.4	-1.1	4	-0.4
Bike Rack	1,788	1.5	-0.1	0.2	(> 0.1)
Building	3,554	20.6	-1.9	126.4	-11.7
Bus Shelter	72	12.7	-1.2	30.4	-2.8
Deck	99	> 0.1	(> 0.1)	> 0.1	(> 0.1)
Fire Hydrant	1,383	0.8	-0.1	0.1	(> 0.1)
Impervious Other	909	1.1	-0.1	16.1	-1.5
Litter Barrel	489	3.4	-0.3	1.1	-0.1
Memorial Pole	511	0.2	(> 0.1)	> 0.1	(> 0.1)
Miscellaneous Structure	142	4.3	-0.4	20.3	-1.9
Porch	631	37	-3.4	100.7	-9.4
Stairs	914	> 0.1	(> 0.1)	> 0.1	(> 0.1)
Street Light	5,228	0.2	(> 0.1)	> 0.1	(> 0.1)
Street Light (Not City Owned) [2]	528	0.2	(> 0.1)	> 0.1	(> 0.1)
Street Tree	13,105	0.9	-0.1	1.4	-0.1
Subway Head House	24	> 0.1	(> 0.1)	> 0.1	(> 0.1)
Traffic Signal	2	0.8	-0.1	> 0.1	(> 0.1)
Utility Pole	839	0.8	-0.1	0.1	(> 0.1)
Total	30,423				

[1] Static obstructions within sidewalk polygons does not include those located within 10 feet (3.0 meters) of the sidewalk centerline beginning and end points.
[2] "Street Light (Not City Owned)" GIS metadata states the lights are owned by multiple organizations (City of Cambridge Massachusetts, 2016). However, information on the owner for each street light is not provided. In turn, we utilized the diameter from the City of Cambridge "Street Light" data.

Sidewalk Minimum Clear Width

Minimum sidewalk clear width provides information on the narrowest passage point within a sidewalk polygon. This provides information as to whether each sidewalk polygon is exceeding, meeting, or failing to meet sidewalk minimum width standards provided by the ADA as well as national and federal guidelines.

To determine the minimum clear width for each sidewalk polygon, we first imported the width measurements catalogued at each centerline point, as displayed in Figure 2 Step 5, into R software (R Core Team, 2018). Sidewalk centerlines with a length of 20 feet (6.10 meters) or less did not generate centerline points in GIS. As noted in step 4 of the sidewalk polygon data preparation, centerline points generated in GIS did not begin until 10 feet (3.05 meters) from the beginning point of the centerline and ended 10 feet (3.05 meters) before the end of the centerline. This equates to 20 feet (6.10 meters) of total length without centerline points being generated by GIS. In turn, for sidewalk centerlines 20 feet (6.10 meters) or less, we imported the sidewalk polygon area measurement and sidewalk centerline length measurement into R. We then divided the area by the width to calculate an average width, which we used to represent the clear width. Next, we joined the sidewalk width measurements from the centerline points and the sidewalk polygons with a centerline length of 20 feet (6.10 meters) or less into one table. For the final steps, we aggregated the sidewalk data, grouped by sidewalk polygon unique ID, and extracted the minimum clear width for each sidewalk polygon.

Sidewalk Minimum Clear Width Accounting for Static Obstructions

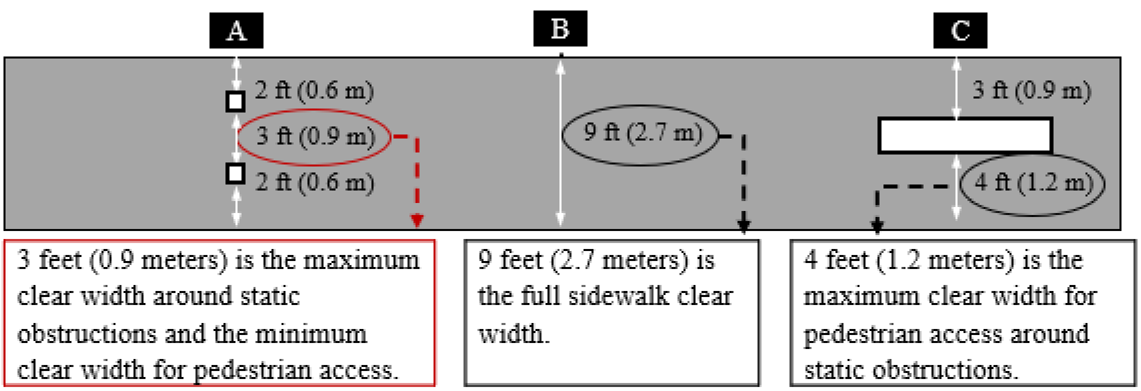
Sidewalk polygon minimum clear width provides information on the narrowest passage point, regardless of the number of obstructions, within a sidewalk polygon. Accounting for static obstructions identifies the area where static infrastructure exists and the impact this has on clear width for pedestrian access. This will provide information to measure if each sidewalk polygon with obstruction data is exceeding, meeting, or failing to meet sidewalk minimum width standards provided by the ADA as well as national and federal guidelines.

Determining the minimum clear width of a sidewalk segment with static obstructions included four steps, as displayed in Figure 4.

1. First, we identified the maximum width to navigate around obstruction(s) as shown in Figure 4A (the maximum width around obstruction(s) provides the most space for pedestrians to walk).

2. Second, we identified the minimum width among the maximum width measurements from step 1 at all obstruction locations along a sidewalk segment. For example, Figure 4 shows two obstruction locations in a sidewalk segment with a maximum width of three feet (0.91 meters) and four feet (1.22 meters) relative to positions A and C. The three feet (0.91 meters) passage at position A is the minimum width.
3. Third, we obtained the minimum width along the sidewalk segment where static obstructions do not exist, which is nine feet (2.74 meters) at position B in Figure 4.
4. For the final step, we compared the minimum width at obstruction locations to the minimum width along the sidewalk segment.

In Figure 4, the minimum width along the sidewalk segment is nine feet (2.74 meters), which is larger than the three feet (0.91 meters) measurement at obstruction locations. Therefore, the minimum clear width along this sidewalk segment is three feet (0.91 meters).



Legend

Sidewalk Polygon Sidewalk Static Obstruction

Figure 4. Sidewalk with Static Obstructions Minimum Clear Width Selection (Plan View)

Chapter 4. Results and Discussion

The results suggest a significant clear width difference when accounting for static obstructions. Table 4 presents the citywide summary, with the mean and quartile results on top, followed by sidewalk segment counts by width threshold at the bottom. On average, sidewalk clear width drops from 4.5 feet (1.37 meters) to 3.5 feet (1.07 meters). This is a 22% reduction in clear width for the average sidewalk segment. Looking at the 2nd quartile, we see than the median sidewalk width drops from 4.4 feet (1.34 meters) to three feet (0.91 meters). This is a nearly 32% reduction and puts our median sidewalk segment clear width – when accounting for static obstructions – right at the ADA threshold. This means that approximately half of all sidewalks in Cambridge do not meet the three foot (0.91 meters) ADA standard when we take into account static obstructions in the sidewalk. Not accounting for such obstructions, however, would have led us to believe that 78% of the sidewalk system met the threshold. Such a difference would considerably revise a transportation engineer or planner's understanding of citywide sidewalk needs and pedestrian accessibility.

By further examining the sidewalk segment counts by width threshold at the bottom of Table 4, we find differences that are even more drastic when we account for static obstructions. At the four foot (1.22 meters) clear width threshold – which is the proposed ADA standard as well as the AASHTO recommend minimum – the number of acceptable sidewalks segments is cut almost in half. The same can be said at the five foot (1.52 meters) clear width threshold, which represents the minimum sidewalk width recommended by FHWA and NACTO. At the four foot (1.22 meters) threshold, we would think that 59% of the system was acceptable, but accounting for static obstructions reduces that to under 31%. Measuring sidewalks for the five foot (1.52 meters) threshold – without accounting for obstructions – would leave us content with 36% of sidewalk segments; in reality, when we account for all the static obstructions, this would drop to just over 18% of sidewalks meeting that threshold.

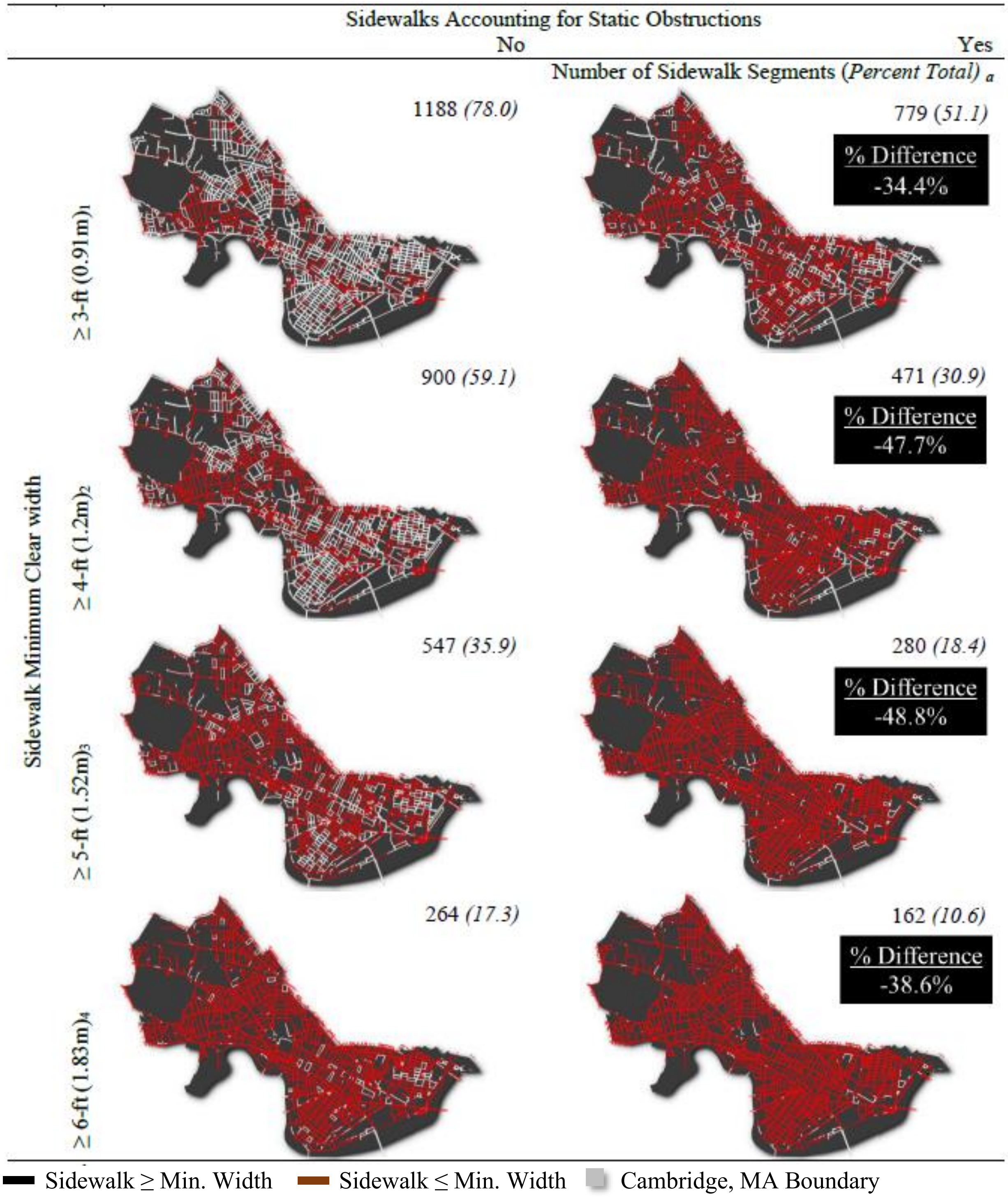
Table 4. Citywide Sidewalk Clear Width Summary

	Account for Static Obstructions? No	Yes	Difference
	U.S. feet (meters)		*(Percent Difference)*
Mean	4.5 (1.4)	3.5 (1.1)	-1.0’ (-22.2%)***
Minimum	0.3 (0.1)	0.0 (0.0)	-
1st Quartile	3.2 (1.0)	2.3 (0.7)	-0.9’ (-28.1%)***
2nd Quartile	4.4 (1.3)	3.0 (0.9)	-1.4’ (-31.8%)***
3rd Quartile	5.5 (1.7)	4.4 (1.3)	-1.1’ (-20.0%)***
Maximum	14.0 (4.3)	14.0 (4.3)	-
	Number of Sidewalk Segments (*Percent Total*) $_a$		*(Percent Difference)*
≥ 3-ft (0.91 m)$_1$	1188 *(78.0%)*	779 (*51.1%*)	*- 409 (-34.4%)****
≥ 4-ft (1.2 m)$_2$	900 *(59.1%)*	471 *(30.9%)*	*-429 (-47.7%)****
≥ 5-ft (1.52 m)$_3$	547 *(35.9%)*	280 *(18.4%)*	*-267 (-48.8%)****
≥ 6-ft (1.83m)$_4$	264 *(17.3%)*	162 *(10.6%)*	*-102 (-38.6%)****

$_a$ *Total number of sidewalk polygons (n) = 1,523*
Sidewalk segment minimum width agency: $_1$ *ADA,* $_2$ *ADA & AASHTO,* $_3$ *FHWA & NACTO,* $_4$ *ITE & CNU*
*t-test for Significance * p < .10; ** p < .05; *** p < .01*

To err on the side of caution and treat the data set more as a sample representation of the full sidewalk inventory, we performed a t-test to statistically compare the sidewalk clear width results with and without obstructions. This should help account for potential flaws in the imagery and/or methods used to create the sidewalk polygon data. All results in Table 4 are statistically significant with p-values less than 0.01.

Figure 5 illustrates the sidewalk results at each clear width threshold level. On the left, we see the city of Cambridge’s overall sidewalk network when not accounting for static obstructions, with the deficient sidewalks shown in red. On the right, we see the same thing, but we now account for static sidewalk obstructions when measuring clear width. This visual representation highlights how much of a difference static obstructions can make when trying to assess our sidewalk network. Transportation engineers and planners can go from thinking that more than three-quarters of their sidewalks meet the current ADA standard to quickly realizing that nearly half of the sidewalk network is deficient. The differences, again, are even more drastic at the four foot (1.22 meters) and five foot (1.52 meters) thresholds, but Figure 5 now presents those outcomes visually. At the six foot (1.83 meters) clear width threshold that is recommended in the ITE and CNU *Designing Walkable Urban Thoroughfares* manual, we can see how little (just over 10%) of the overall city sidewalk network is adequate (Daisa & ITE, 2010). As data collection continues to move more towards remotely-sensed, city scale or larger sidewalk data sets, it is clear that not accounting for static obstructions can easily lead to a misunderstanding of sidewalks needs and an overestimation of pedestrian accessibility.



[a] Total number of sidewalk polygons (n) = 1,523
Sidewalk segment minimum width agency: [1] ADA, [2] ADA & AASHTO, [3] FHWA & NACTO, [4] ITE & CNU

Figure 5. Before-and-After Static Obstructions Sidewalk Comparison

Chapter 5. Summary and Conclusions

Advances in remote sensing are beginning to grant municipalities and researchers with heretofore-unseen opportunities for sidewalk spatial data. Yet, this research demonstrates that not accounting for static obstructions in our sidewalk data may significantly misrepresent clear width and adherence to ADA standards or national sidewalk guidelines. In fact, we find that the number of ADA-accessible sidewalks can be cut nearly in half when accounting for static obstructions. In other words, not accounting for static obstructions can lead to a gross overestimation of city sidewalks that meet minimum clear width thresholds.

The major findings of this study are as follows:

- Analyzing sidewalk data without obstructions significantly misrepresents sidewalk clear width;
- The average sidewalk clear width reduces by 22% from 4.5 feet (1.37 meters) (without obstructions) to 3.5 feet (1.07 meters) (with obstructions);
- Sidewalk segments without obstructions meeting agency standards reduces by approximately 34% to 49% when accounting for obstructions;
- Including sidewalk obstructions helps to fill the sidewalk information gap at the city scale, but including deficiencies such as vertical displacement, cracks, and gaps would benefit in future research.

Future research could also delve deeper into these findings by disaggregating by obstruction count and/or type. It may also be useful to aggregate the results by block or block length or normalize them by area or length. Doing so would require altering the original data by splitting sidewalk polygons, but could help provide greater insight into problematic areas and the impact of static obstructions on pedestrians.

It is possible that Cambridge, MA, has more sidewalk obstructions than other cities, and that could be considered a limitation of this study. Cambridge is also a settlement that dates back to 1630, which could impact the urban design and city development as compared to more contemporary U.S. cities

(Marshall & Garrick, 2010). For example, modifications to streets to accommodate vehicles in the early 20th century may have resulted in narrow sidewalks due to significantly less public space available. Moreover, this could constrict the amount of space available for the city to place infrastructure for more modern needs such as traffic lights, transit stops, and signage. Nevertheless, accurate representations of sidewalk clear width is critical information for cities across the U.S. because many are facing increased scrutiny and pressure to meet ADA requirements. A lawsuit in Los Angeles, for example, resulted in the city agreeing to invest $1.4 billion dollars to upgrade their infrastructure for people with disabilities (City of Los Angeles, 2019). This problem is not limited to major cities. Colorado Springs recently settled two ADA lawsuits relating to poor pedestrian infrastructure (City of Colorado Springs, 2018; Colorado Springs Gazette, 2019). Beyond the legal liability, creating a pedestrian network with sidewalk infrastructure that is wide enough for wheelchairs and strollers – or simply wide enough for a parent to walk hand-in-hand with their child – is critical to health, safety, access to opportunities, and equity.

Sidewalk clear width is by no means the only consideration when evaluating pedestrian accessibility. Sidewalk deficiencies such as vertical displacement, cracks, and gaps are also discussed in the ADA standards and present a hindrance and safety issue to all pedestrians. Additional factors – including location and slope of ramps and crosswalks – also play an integral part. Expanding the conversation to include public footpaths or recreational paths would provide greater insight to pedestrian infrastructure as well. Furthermore, including the analysis to account for pedestrian flow characteristics – such as density, speed, and origin / destination – would further the understanding of how sidewalks accommodate pedestrian needs. However, a better understanding of the clear width of sidewalks is an important step in planning for pedestrians and pedestrian accessibility.

FHWA highlights that identifying sidewalk minimum width and including static barriers is an important component of sidewalk systems and ADA Transition Plans (FHWA, 2016). However, FHWA also identifies the burden of time, expense, and lack of sidewalk data, offering a hopeful future remedy through advances in aerial imagery (FHWA, 2016). This study turns this optimistic vision of FHWA into a reality. Using this sidewalk data, our methods also hone in on identifying sidewalks failing, meeting, or exceeding standards and guidelines, and the location *within* the extent of the sidewalk where the minimum clear width exists. This presents spatial information for cities to better understand where deficiencies in sidewalks exist. Moreover, it affords the opportunity to assist in prioritizing where to spend limited available funding.

Our research also highlights the data, tools, and expertise for a municipality to conduct similar analyses. For data, we used planimetrics, which included both sidewalk polygons and obstruction data sets. We identified that cities and counties often contract out planimetric data creation, which typically requires obtaining aerial imagery and extracting infrastructure data through manual data digitization or proprietary software algorithms. Furthermore, municipalities often acquire various infrastructure in addition to sidewalks and obstructions. In turn, it may benefit a municipality to collaborate with other government agencies in the region to acquire planimetric data. Regarding tools, we primarily used open-source software (QGIS), but one step – creating sidewalk centerlines – required the use of proprietary software (ArcGIS). Finally, expertise requires staff with a specialization in GIS.

Considering that our preliminary investigation identified multiple regions in the U.S. with access to planimetric data, there exists the potential for sidewalk research to expand much more broadly. However, our results also suggest that municipalities and researchers should attempt to account for static obstructions, as they play a critical role in defining sidewalk clear width. Without data on appropriate clear width, what is believed to be an accessible pedestrian route may fail. This could lead to safety problems with people needing to walk in the roadway or deciding that they cannot walk at all. This study only investigates one component of pedestrian infrastructure and accessibility. However, this research, and each additional step taken to fill the gap in sidewalk data, will provide greater insight and information for pedestrian planning.

Section 2. Prioritizing Pedestrian Infrastructure Using Big Data and Spatial Data

Chapter 6. Introduction

Missing or deteriorating sidewalk infrastructure makes pedestrians seem like an afterthought in many cities. Now, some cities are facing legal battles centered on the Americans with Disabilities Act (ADA). Atlanta, for example, is currently involved in a lawsuit regarding its failure to maintain sidewalks that are accessible to people with disabilities (Decatur Legal, 2018). Similar settled cases include Cedar Rapids, Colorado Springs, Seattle, Denver, and Los Angeles with some settlements totaling over $1B (City of Cedar Rapids, 2021; City of Colorado Springs, 2018; City of Los Angeles, 2019; Disability Rights Washington, 2018; USDOJ, 2018).

These cities, and many others, are facing an unprecedented backlog of deteriorating infrastructure and the difficult question of where to begin. Denver, for instance, recently started conducting inspections under their Neighborhood Sidewalk Repair Program; however, an audit revealed that it would take more than 50 years for the city to complete the program at its current pace (O'Brien, 2020). With recent advances in big data and spatial data, we aim to create a data-driven approach to assist cities in their efforts.

Transportation planners rely upon a plethora of data when working on automobile and transit projects. A scarcity of data has long made it impossible to do the same thing for active transportation modes. Slowly but surely, this is beginning to change via remotely-sensed pedestrian infrastructure efforts as well as cell-phone based origin-destination data. In this project, we seek to combine these data sources in an effort to locate areas with high levels of short driving trips that may be ripe for a pedestrian infrastructure intervention.

This effort first uses StreetLight big data, which processes records collected from smartphone and vehicle navigation systems (e.g. GPS) to create travel information on various modes of transportation such as vehicle, pedestrian, and bicycle. For example, StreetLight’s origin-destination trip data can help us identify where in Denver people are taking high numbers of short driving trips (e.g. less than one mile). So as not to overlook populations that may rely on walking as a primary or sole mode of transportation, we also consider pedestrian trip data. Next, we analyze remotely-sensed spatial data from aerial imagery (planimetrics) to identify sidewalk availability and sidewalk width throughout Denver (Coppola & Marshall, 2019, 2020, 2021; Lee & Sener, 2020). We then combine these data sources in an effort to figure out what might be causing such high levels of short driving trips in some neighborhoods. This analysis facilitated an initial neighborhood prioritization list that led to site visits where we could also identify locations that would seem to have adequate sidewalks given the planimetric data, but those sidewalks or curb ramps were in severe disrepair. The results provide cities a data-driven approach to prioritizing sidewalk improvements that does not require labor- and time-intensive, city-wide inspection programs.

Prior studies created sidewalk prioritization methods with limited or no data on trip volumes or infrastructure condition. We expand upon this literature by collecting and analyzing actual trip data to prioritize pedestrian infrastructure, supplemented by both remotely-sensed planimetrics and a limited number of field assessments. This study fills a gap in data, information, and methods to provide a feasible approach for cities to attend to their pedestrian infrastructure. The next section delves deeper into the literature review. This is followed by an overview of our data, methodology, and results.

Chapter 7. Literature Review

Prior research on pedestrian infrastructure prioritization often focuses on standards related to the American Disabilities Act (ADA) or disability rights legislation internationally rather than on methods to help with actual prioritization. Maciejko et al., for instance, researched design problems and accessibility issues for people with disabilities at a tourist site in Poland (Maciejko et al., 2019). In another example, Hartblay focused on community perception and business interests pertaining to ramp design and accessibility in Petrozavodsk, Russia (Hartblay, 2017). Yet, neither paper quantifies infrastructure measures or methods to prioritize the deficiencies.

Other researchers discussed infrastructure deficiencies but do so without any quantitative measure or prioritization methods. For instance, research by Seekins et al. delved into assessing and grading the accessibility of community infrastructure. The authors' methods included collecting and aggregating data based on factors observed and a rating scale. The authors identified one factor related to sidewalks, ramps, and crossings, but the rating scale descriptions were qualitative and overly generalized, such as "No accessible route to entry" (Seekins et al., 2012). Moreover, the resources and effort for the assessment required training observers and field collecting all data, which would be a monumental, if not impossible, task depending on the size of the city.

One of the few studies with quantitative measures relied upon extensive field work to collect pedestrian counts as well as citywide sidewalk infrastructure characteristics/condition. They then used this data to create an index that prioritized pedestrian corridors (Beiler & Phillips, 2016). Beiler and Philips developed this index based upon survey feedback from municipalities and professionals. The result was a weighted index that the authors identified as a means to prioritize "the pathway based on infrastructure need and pedestrian demand."

Another study by Qin et al. relied upon crowdsourced pedestrian usage and infrastructure data to determine prioritization (Qin et al., 2018). The idea was to encourage community engagement via a mobile and web-based application that allowed users to identify obstacles to people with disabilities and prioritize certain pedestrian routes. This approach has some advantages, but such community outreach efforts typically require extensive time, resources, and coordination. They can also introduce bias in terms of respondents (Piatkowski et al., 2017). The authors did not include specifics about what information the application collected from users nor how such information could be used to estimate pedestrian usage. Qin et al. then created a linear pedestrian network data set with the following attributes: priority, usage frequency, and material type of infrastructure (e.g. brick or concrete). While this represents a good start, it omits pertinent details such as sidewalk width, area, edge, and a defined perimeter of the infrastructure.

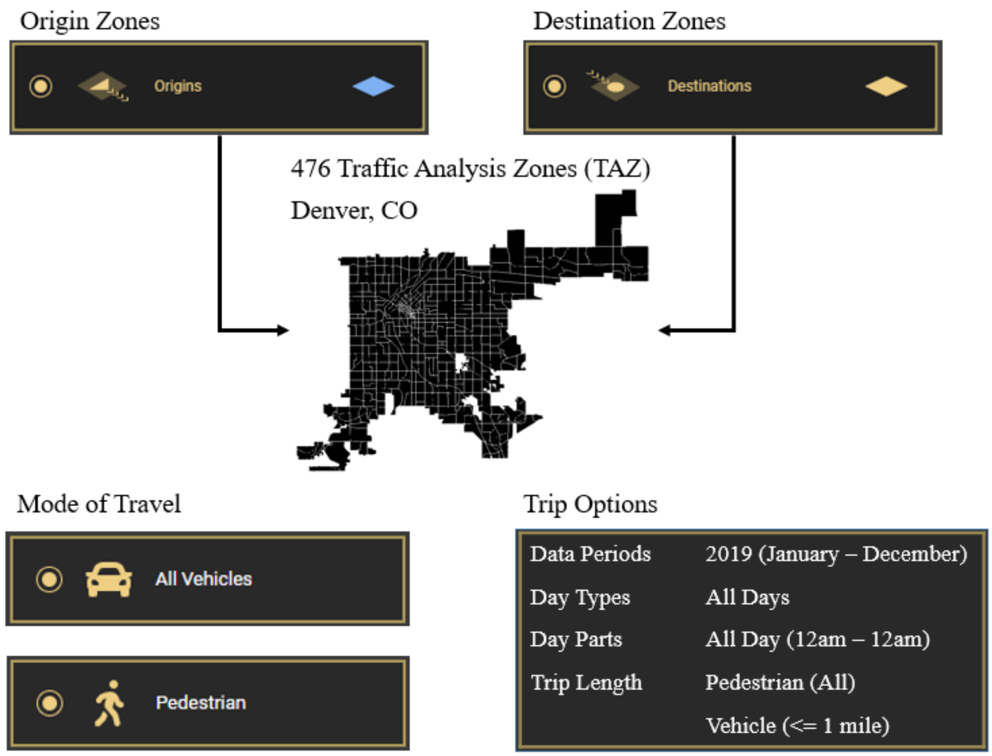
In contrast to prior pedestrian infrastructure prioritization papers, our research leverages data advances with both remotely-sensed sidewalk infrastructure spatial data as well as with cell-phone and vehicular GPS based trip data. This combination of initially assessing infrastructure and possible demand – prior to taking on extensive fieldwork – can help facilitate a quantitative, citywide approach that is missing from the existing literature. The next sections details our data and methods.

Chapter 8. Methodology

The goal of this project is to create a data-driven approach to prioritize pedestrian infrastructure by combining the following: i) trip data – locate and prioritize areas with high trip volumes for short-vehicle trips and pedestrian trips; and ii) infrastructure data - analyze sidewalk availability and width in the areas identified.

Trip Data

We obtained StreetLight's data for Denver, CO. StreetLight collects geographic location and other data metrics (e.g. speed) from smartphone application Location-Based Services and Navigation-GPS systems (StreetLight Inc., 2021). StreetLight then uses proprietary algorithms to calculate origin-destination trip volumes for various modes of transportation. We are interested in origin-destination average-daily trip volumes for short-vehicle trips (one mile or less) as well as origin-destination average-daily trip volumes for all pedestrian trips. Figure 6 displays an example overviewing our approach to obtain average-daily trip volume data from StreetLight. This included the following options: mode of travel, origin zone, destination zone, and additional options (data period, day type, day part, and trip length).



Source: Radio button screenshots obtained from StreetLight, Inc. website

Figure 6. Origin-Destination Trip Data

A trip consists of traveling one-way from one activity to another, which is also described as traveling from an origin to a destination (Levinson et al., 2017). Traveling from a person's house (origin) to a restaurant for dinner (destination), for example, constitutes a trip; traveling back home (destination) after eating dinner at the restaurant (origin) would constitute another trip. Regarding mode of transportation, our primary interest is short-vehicle trips (one mile or less) where the greatest potential for mode shift exists. According to the National Household Travel Survey (NHTS), a distance of one mile or less accounts for over 20% of vehicle trips, which is also the typical distance a pedestrian will walk for work, leisure, or other purposes (AASHTO, 2018; FHWA, 2017b; Yang & Diez Roux, 2012). Our secondary interest is all pedestrian trips. The intent is to identify where the highest volume of average-daily pedestrian trips are occurring, regardless of trip details such as distance.

Regarding origin and destination zones, traffic analysis zones (TAZ) are geographic regions created for and commonly used by transportation engineers and planners with the purpose of analyzing travel patterns, volumes, and demand (Pande, Wolshon, & Institute of Transportation, 2016). Accordingly, we used TAZs as the geographic boundaries, as shown at the top of Figure 6, to obtain average-daily origin-destination trip volumes. Our initial prioritization focus is the origin zone because the infrastructure (or lack thereof) can determine if a pedestrian can even begin a trip. Moreover, this may influence a person's mode choice decision. For example, if sidewalks do not exist where a parent with a stroller or a person using a cane resides, they may opt to drive instead. Once we identify the origin zones, we will also look at the associated trip destination zone(s).

At the time of our data collection, StreetLight allowed us to select any period of time for our trip data between 2018 through 2020. Considering the anomalous activity in transportation due to the pandemic in 2020, we opted to analyze data from the second most recent time frame of 2019. Regarding day type and day part, we researched all hours of the day, every day, for the entire year.

Because StreetLight limited the number of TAZ origin and destination entries to 200 (100 origin and 100 destination), we overlapped the TAZs for each new request with TAZs of a prior request by one mile (1.61 kilometers) or greater. This helped ensure that we obtained trip data for all TAZ pairs in the city of one mile or less while minimizing the number of data requests.

After collecting the vehicle and pedestrian average-daily trip data, we removed duplicate origin-destinations. Second, StreetLight provides documentation stating that if an origin and destination TAZ are the same, it represents a total volume of trips passing through this TAZ, without accounting for where the trip begins or ends (StreetLight Inc., 2020). In other words, this is not representative of a true origin-destination volume. Therefore, we also removed all origin-destination trips with the same TAZ.

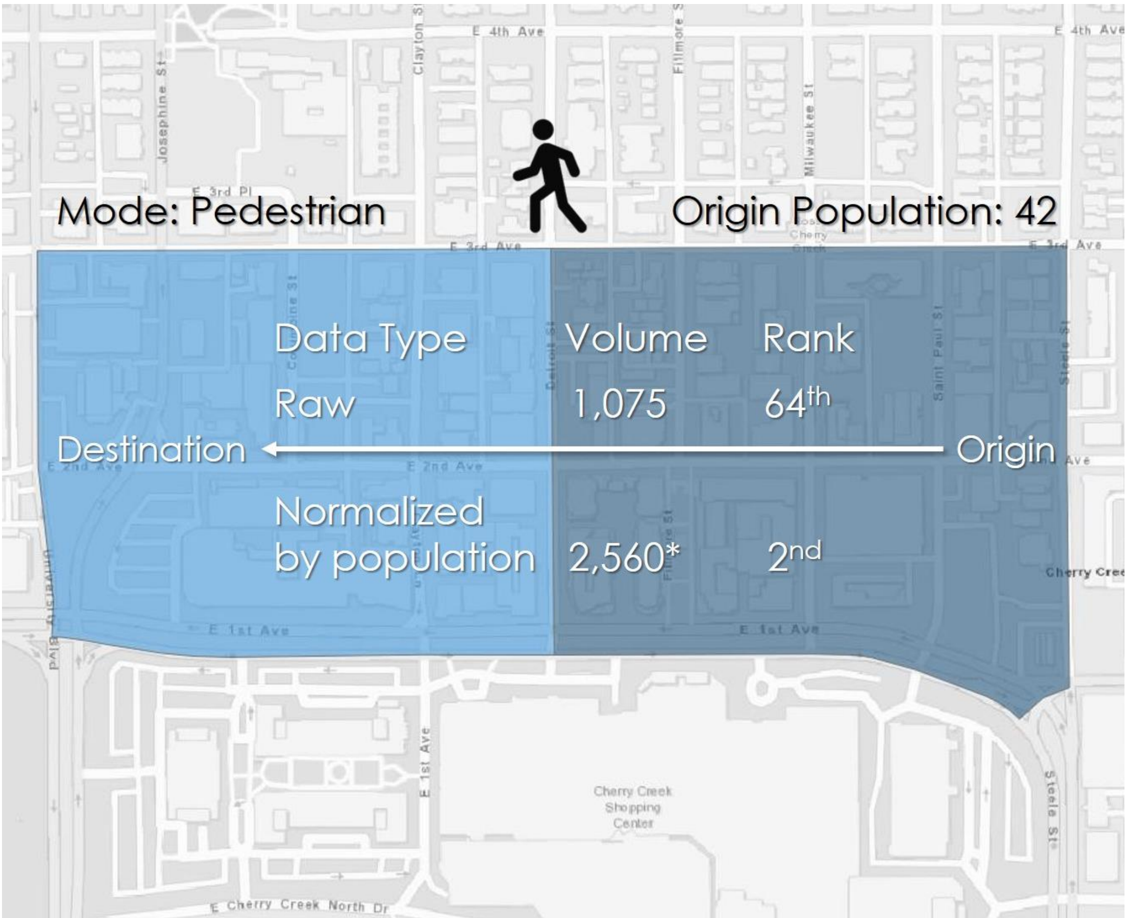
The original origin-destination trip data that we obtained, which we will refer to as the "raw data", provides information for the city of Denver to understand average-daily trip volumes. However, this may overlook residents in TAZs with the same issues but in less populated neighborhoods. Therefore, we also normalized the average-daily trip volumes by population per 100 people. Equation 1 divides the TAZ average-daily trip volume by the population and multiplies the result by 100. Figure 7, for instance, displays an origin TAZ in Denver with 42 residents and a raw data pedestrian average daily trip volume of 1,075 to a neighboring TAZ destination. The trip volume based on the raw data ranks this origin-destination trip volume as 64^{th} in the city. When we normalized the trip volume by population, the volume is 2,560, and it becomes the second-ranked origin.

Equation 1. Trip volume normalized by population per 100 people

$$\left(\frac{TAZ\ \text{average} - \text{daily}\ trip\ volume}{TAZ\ population}\right) * 100 = TAZ\ average\ daily\ trip\ volume\ per\ 100\ people$$

Infrastructure Data

The Denver Regional Council of Governments (DRCOG) acquires aerial imagery for Denver and the surrounding region as a reference to create a digital representation of the built environment, also known as planimetric data. Using this aerial imagery, specialists can then digitize different features such as buildings, parking lots, sidewalks, and roadways, as displayed in graphic 1 of Figure 8. From DRCOG's planimetric data, we obtained the 2018 planimetric sidewalk polygons and sidewalk centerlines, as displayed in graphic 2 of Figure 8. Sidewalk polygons are a delineated outline of the sidewalk boundary, and sidewalk centerlines are a delineated centerline. Both sidewalk data sets include adjoining driveway aprons (e.g. residential driveway) but omit alley and parking aprons (e.g. commercial parking lot driveway) (DRCOG, 2018).



$$* \left(\frac{TAZ\ Origin_{\ trip\ volume}}{TAZ\ Origin_{\ population}}\right) * 100 = TAZ\ average\ daily\ trip\ volume\ per\ 100\ people$$

$$* \left(\frac{1075}{42}\right) * 100 = 2560$$

Figure 7. Average daily trip volume comparison: raw data and normalized by population

According to a National Household Travel Survey (NHTS) survey, one of the most common reasons for not walking more includes no sidewalks or sidewalks in poor condition (FHWA, 2019). These infrastructure deficiencies present mobility barriers and safety concerns, which are an even greater issue for people with disabilities. In addition, cities are susceptible to legal challenges regarding compliance to the Americans with Disabilities Act (ADA). Using the vehicle and pedestrian trip information, we used spatial data to calculate sidewalk availability and width.

For sidewalk availability, our intent is to compare the length of the sidewalk to the length of the roadway for each TAZ. For sidewalk width, the intent is to measure an average sidewalk width for each sidewalk polygon and to calculate an overall mean width for each TAZ. With regard to sidewalk availability and width, we incorporated similar methods detailed in prior research conducted by Coppola and Marshall (Coppola & Marshall, 2020, 2021).

Sidewalk Availability

Sidewalk availability refers to the presence (or absence) of sidewalks alongside a roadway. Sidewalks should provide safety and a conduit for pedestrians to reach destinations. Moreover, providing sidewalks along both sides of roadways is highlighted in the ADA as well as other guidelines such as the Federal Highway Administration's (FHWA) *Designing Sidewalks and Trails for Access* (2001) and the American Association of State Highway and Transportation Officials' (AASHTO) *A Policy on Geometric Design of Highways and Streets* (2018) (AASHTO, 2018; Kirschbaum et al., 2001). In turn, we calculated sidewalk availability as a comparison of roadway and sidewalk length in cities, as depicted in Figure 9.

We used parcel data from the City of Denver to isolate sidewalks and roadways in the public ROW, as depicted in graphic 3, Figure 8. This was to control for sidewalks or roadways that fall within private land or on public parcels such as parks. City Park, for example, contains over 17 miles (27.36 kilometers) of sidewalks, but only seven miles (11.27 kilometers) of roads. This effort also required conversations with the Denver GIS department to confirm that areas outside of parcels denote the public ROW.

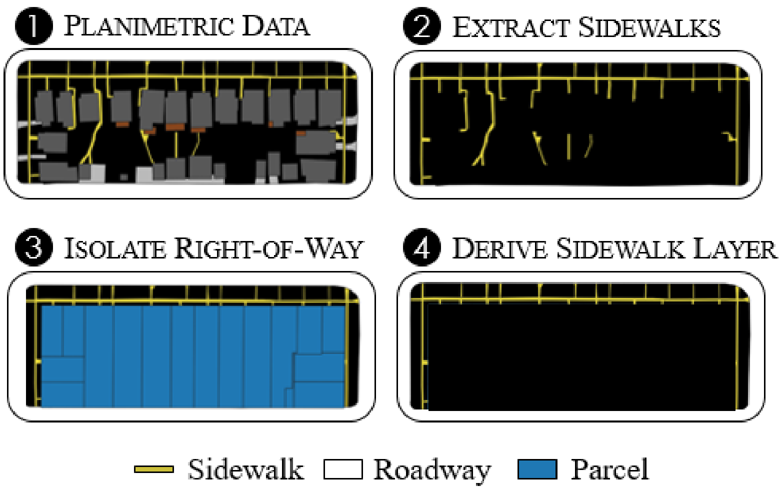


Figure 8. Planimetric Sidewalk Data Example

Sidewalk availability can be approach in one of two ways. First, we can consider one mile of roadway with two miles of sidewalk to equal 100% sidewalk availability. However, roadway centerlines often delineate census geographic boundaries in GIS data. This places the sidewalks on either side of the road in different TAZs, and a confounding situation where the sidewalks would be attributed to only the associated roadway TAZ. We can also view sidewalk availability from the standpoint that a roadway should theoretically exist on one side of the sidewalk. As a result, we chose this method, which evaluates the sidewalk independently in each TAZ. Via this approach, we consider one mile of sidewalk with one mile of roadway to have 100% sidewalk availability. For example, as displayed on the left side of Figure 9, if one mile (1.61 kilometers) of sidewalk paralleled one mile (1.61 kilometers) of roadway, this would equate to 100% sidewalk availability.

To measure sidewalk length, we used the DRCOG planimetric sidewalk centerline data. We first removed all "crosswalk" and "possible missing sidewalk" features, and we retained "sidewalks" and "best fit line", which indicates that a sidewalk is present (DRCOG, 2020). We also removed small lines unassociated with the public sidewalk before calculating sidewalks lengths from the centerline data.

To measure the corresponding roadway lengths, we first removed interstates and highways. We then combined all roadway lines to ensure overlapping roads were only measured once. Next, we created parallel copies of the roadway centerline. We then intersected the sidewalk and roadway lines with the

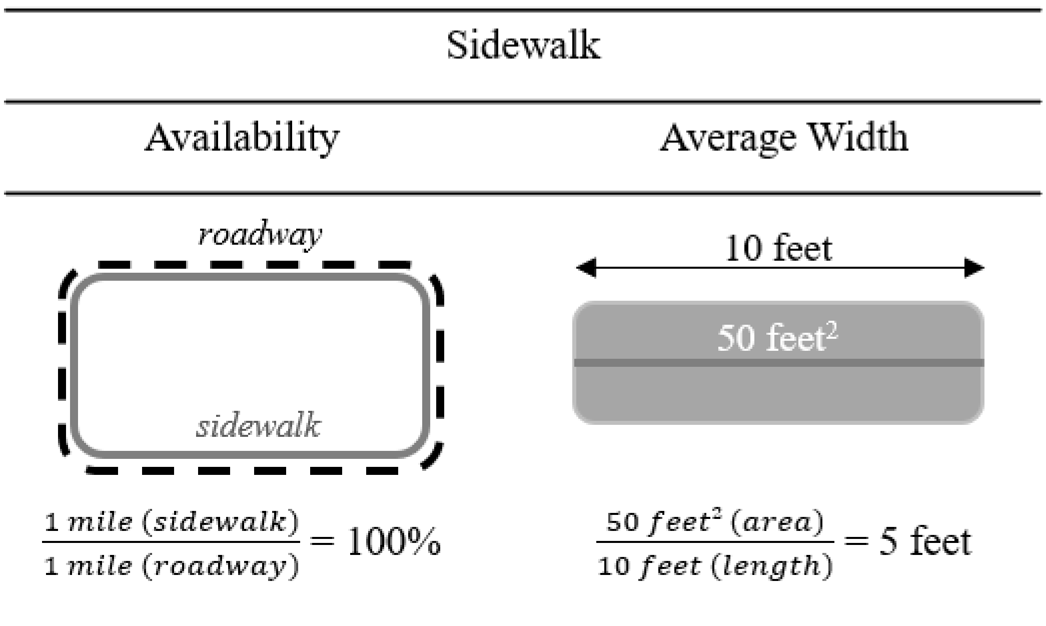
TAZs, which allowed us to measure the total sidewalk and roadway length for each TAZ. Finally, to calculate the sidewalk availability for a TAZ, we divided the TAZ total sidewalk length by the TAZ total roadway length.

Sidewalk Width

Sidewalk availability merely denotes the existence of sidewalks. Width is also an important characteristic for cities to understand their sidewalk infrastructure. Denver, for example, has many two feet (0.61 meters) wide sidewalk segments in the city. Accordingly, we measured the sidewalk average width for each sidewalk polygon, as depicted in Figure 9.

The ADA provides legal standards and proposed guidelines for sidewalk width. At present, the ADA stipulates a three feet (0.91 meters) minimum sidewalk width requirement, but this measurement is exclusive of the width of the curb (USDOJ, 2010). Given that curb width varies depending upon a number of factors (AASHTO, 2018), as well as the fact that we were unable to discern curb width via planimetric data, the sidewalks widths we focus on in this paper include the curb width.

To measure the average sidewalk width, we divided the area measurements for each sidewalk polygon by the associated centerline length, as depicted on the right side of Figure 9. We identified and reviewed anomalies in sidewalk measurements of less than one foot (0.31 meters) and greater than 30 feet (9.14 meters) width measurements. The manual review of sidewalks less than one foot (0.31 meters) typically led us to residual narrow areas of private sidewalk polygons resulting from clipping these polygons at the parcel boundary. The review of sidewalks greater than 30 feet (9.14 meters) tended to identify plazas or squares. For the sake of our study on sidewalk infrastructure, we removed both sidewalk polygons one foot (0.31 meters) wide or narrower as well as those 30 feet (9.14 meters) wide or greater.



Note: Figure is not to scale

Figure 9. Sidewalk Availability and Average Width

Chapter 9. Results and Discussion

This paper proposes a data-driven prioritization method for pedestrian infrastructure using origin-destination average-daily trip volume data. To accomplish this, we evaluated Streetlight's big data for short-vehicle trips (less than one mile) as well as for all pedestrian trips in the city of Denver, CO. We evaluated 476 of Denver's 479 TAZs, excluding three TAZs in the far northeastern section of the city with the Denver International Airport and airport parking lots. From the trip data, we developed a prioritization methodology based on the following four questions:

- Question 1: Which TAZs have the most short-vehicle or pedestrian trips?
- Question 2: Is sidewalk infrastructure design an issue in the selected TAZs?"
- Question 3: Is sidewalk infrastructure maintenance an issue in the remaining TAZs?
- Question 4: If sidewalk infrastructure does not seem to be the problem, what else could it be?

Question 1: Which TAZs have the Most Short-Vehicle or Pedestrian Trips?

First, we aim to identify the trip origin TAZs with the most short-vehicle or pedestrian trips. This means looking for the highest number of average-daily trips for each of our four origin-destination trip data sets:

1) Vehicle (V): trip volume - raw data;
2) Vehicle normalized (VN): trip volume - normalized by population;
3) Pedestrian (P): trip volume - raw data; and
4) Pedestrian normalized (PN): trip volume - normalized by population.

These are displayed at the top of Figure 10 in the four processes identified in the center of the "Question 1" box.

To answer where we have the most short-vehicle or pedestrian trips, we first sorted each of the four trip data sets in descending order to identify trips with the highest average-daily volume. Each data set included three attributes for each trip: origin TAZ, destination TAZ, and average-daily volume. An origin TAZ may appear more than once with multiple destinations. For example, if the top two average daily trip volumes consist of origin TAZ_A and destination TAZ_B as well as origin TAZ_A and destination TAZ_C, there is only one unique origin – TAZ_A.

The number of origin TAZs that we evaluated was based on thresholds of approximately 2000 or greater short-vehicle average-daily trips and 100 or greater pedestrian average-daily trips. This resulted in ten origin TAZs for each data set. In turn, we also selected the top ten origin TAZs for the short-vehicle and pedestrian average-daily trip volumes normalized by population. The initial result included 40 origin TAZs. However, some origin TAZs appeared in more than one group. Therefore, the end result included 32 unique origin TAZs, which are displayed in Figure 11 with an identification number (ID) that will be used to help identify TAZs throughout the methods section.

Question 2: Is Sidewalk Infrastructure Design an Issue in the Selected TAZs?

Question 1 identified 32 TAZs with high levels of short-vehicle and/or pedestrian trips. However, we do not know anything about the pedestrian infrastructure and whether any issues exist. This leads to our next question: is sidewalk infrastructure design an issue in the selected TAZs? Prioritizing the TAZs in Denver based on potential modal shift (short-vehicle trips) and greatest pedestrian average-daily trip volume provides a start. However, we still do not know anything about the pedestrian infrastructure in these TAZs. Accordingly, we next aim to use Denver's planimetric data to calculate sidewalk availability and sidewalk width metrics for each TAZ found with Question 1.

This effort required estimating a threshold for what constitutes a sidewalk infrastructure design issue. We are evaluating two infrastructure design characteristics independently: sidewalk availability and sidewalk average width. For both sidewalk characteristics, a TAZ with 100% sidewalk availability or a TAZ with 100% of the sidewalk polygons with a three-feet average width or greater would be ideal. However, all spatial data has a level of error, which should be taken into consideration. In addition, our sidewalk average width is as the title states, an average. If a sidewalk polygon has a four foot (1.22 meters) average width, for example, it may contain sections within that polygon that are less than three-foot, which would be non-compliant with the ADA standard. Therefore, we wanted to set the threshold below 100% to account for data discrepancies. Yet, setting the threshold too low may overlook TAZs with sidewalk infrastructure design issues. In turn, we used a reasonable threshold of 80% for both sidewalk availability and sidewalk average width as a TAZ with an infrastructure design issue. This number could change depending on the city in question and should increase over time as a city continues to improve their sidewalk infrastructure situation.

The data inputs, output, and processes for our methods in Question 2 are displayed at the bottom of Figure 10 in the "Question 2" box. The 21 ranked TAZs of the 32 TAZs identified in Question 1 are presented in Figure 12. The TAZ ID label in the Figure 7 map corresponds to the TAZ ID in the Figure 12 table.

Question 3: Is Sidewalk Infrastructure Maintenance an Issue in the Remaining TAZs?

We have 11 remaining TAZs after Question 2 that do not seem to have sidewalk infrastructure design issues. Of these 11 TAZs, six TAZs have a high volume of short-vehicle trips, two TAZs have a high volume of pedestrian trips, and three TAZs have a high volume of both. This leads to our next question: is sidewalk infrastructure maintenance an issue in the remaining TAZs? In other words, information on sidewalk availability and sidewalk width identify infrastructure design characteristics, but it does not include information about sidewalk quality such as gaps, heaving, or steep slope. In addition, we still do not know anything about the availability or quality of sidewalk-related infrastructure such as curb ramps and crossings, which provide accessibility and connectivity to the pedestrian network. To obtain this information, we next conducted field assessments to identify if sidewalk infrastructure maintenance is an issue in the TAZs remaining from Question 2.

The intent of our field visits is to collect a general assessment of sidewalk condition data as well as ramp and crossing infrastructure availability and condition data for each TAZ. At this point, the objective was not to document each and every deficiency for the entire TAZ; rather, we seek to understand which types of sidewalk infrastructure maintenance issues exist in order to help determine where to prioritize efforts and resources.

We conducted a field assessment of the 11 TAZs remaining after Question 2. Our field assessments depended on the size of the TAZ and the uniformity of the infrastructure but averaged approximately one hour per TAZ. For instance, TAZ ID 32 in the Central Business District consists of one city block, or approximately 0.006 miles^2 (0.02 kilometers^2), which took considerably less time than TAZ ID 7 in the Central Park neighborhood, which is approximately 1.2 miles^2 (1.93 kilometers^2). Before conducting the field assessments, we reviewed the 11 TAZ areas in GIS with background maps such as Google Maps. This allowed us to document any differences or uniformity in land use (e.g. residential, commercial, or industrial areas) as well as infrastructure design (e.g. block size). TAZ ID 8, for instance included approximately a 0.5 miles (0.80 kilometers) stretch of roadway in an industrial area. By conducting a review in GIS first, we were able document such issues and increase our focus on to the northern section of the TAZ with commercial businesses. As another example, TAZs 10 and 11 consisted of residential and commercial land use with similar block sizes, infrastructure design, and condition. Therefore, we walked one full block of the residential area and one full block of the commercial area for this initial sidewalk infrastructure maintenance assessment.

Next, we visited each of the 11 TAZs and walked the noted section(s) from our initial GIS assessment to collect sidewalk, curb, and crossing data. Walking allowed us to photograph, measure, and note sidewalk, ramp, and crossing quality, as well as ramp presence or absence. To accomplish this, we made use of a standard tape measure and an electronic level to measure and document gaps, cracks, elevation change (often due to heaving), and/or running or cross slope. The ADA provides legal standards for the sidewalk running and cross slope, which are 1:20 and 1:48 respectively (USDOJ, 2010). The sidewalk vertical elevation change should not exceed 0.25 inches (0.64 centimeters). The curb ramp running and cross slope should not exceed 1:12 and 1:48 respectively. In addition, the ramp landing should exist at the top and bottom of the ramp and it should be a minimum of 60 inches (1.52 meters). The ADA includes crossings (parking aprons, alley crossings, and road crossings) in the description of the "path of travel", which is a continuous pedestrian path (USDOJ, 2010). However, it does not provide specific standards for these infrastructure components. We used the ADA ramp standards for the ramps connecting the crossings, and we used the sidewalk standards for the parking apron, alley, and road connected to the ramps. Lastly, we reviewed of our photos, measurements, or notes to identify any areas to revisit for additional data.

Conducting a field assessment can be accomplished with paper maps and notation or through mobile applications, such as Google Maps or ArcGIS Collector. We opted to use ArcGIS Collector, displayed in Figure 13. With this application, we were able to load our TAZ boundaries and sidewalk data for navigation and reference. In addition, we used this to collect the location, notation, and photos of the pedestrian infrastructure, which is the "Assessment Note" shown in Figure 13. The eight ranked TAZs from our assessments of the 11 remaining TAZs from Question 2 are presented in Figure 14.

Question 4: If Sidewalk Infrastructure Does Not Seem to Be the Problem, What Else Could it be?

We have three remaining TAZs after Question 3 that do not seem to have sidewalk infrastructure design or sidewalk maintenance issues. Of these three TAZs, one has a high volume of short-vehicle trips, one has a high volume of pedestrian trips, and one has a high volume of both, as displayed in Figure 15. This leads to our next question: if sidewalk infrastructure does not seem to be the problem, what else could it be? Pedestrian infrastructure provides a conduit for people to walk, but it is not the only factor that may affect their trip. For example, even if pedestrian infrastructure is well designed and maintained, a person may still choose to drive a short distance because they need to cross a major highway or arterial to complete a trip. In turn, this may introduce an issue such as safety (or perceived safety) that impacts a person's modal choice. Therefore, we also documented other potential issues related to pedestrian trips during our field assessment as displayed in the bottom on Figure 10 (continued).

For this final component of our methodology, we sought to identify other factors potentially impacting pedestrian trips. This provides insight to other pedestrian related design issues for a municipality to take into consideration for pedestrian planning. We identified major roadways within or bordering two origin TAZs (IDs 22 and 30) as an issue, and we also identified one TAZ (ID 32) with no apparent issues. Even though we only observed one additional potential issue, this is not the extent of possibilities. Other transportation factors such as street network types, speed limits, or traffic volumes have been researched and identified as issues related to walking (Anciaes et al., 2019; Dumbaugh & Zhang, 2013; Marshall & Garrick, 2010; Omura et al., 2019; Rifaat et al., 2012; Rosenberg et al., 2012).

In addition, other non-transportation related issues such as crime, incivilities, and scenery may be potential issues (Ball et al., 2001; Foster et al., 2016; King et al., 2000; Mason et al., 2013; Whitfield et al., 2018). Lastly, there is also the possibility that there are no existing issues, which could be the reason for a high number of average daily pedestrian trips in the first place.

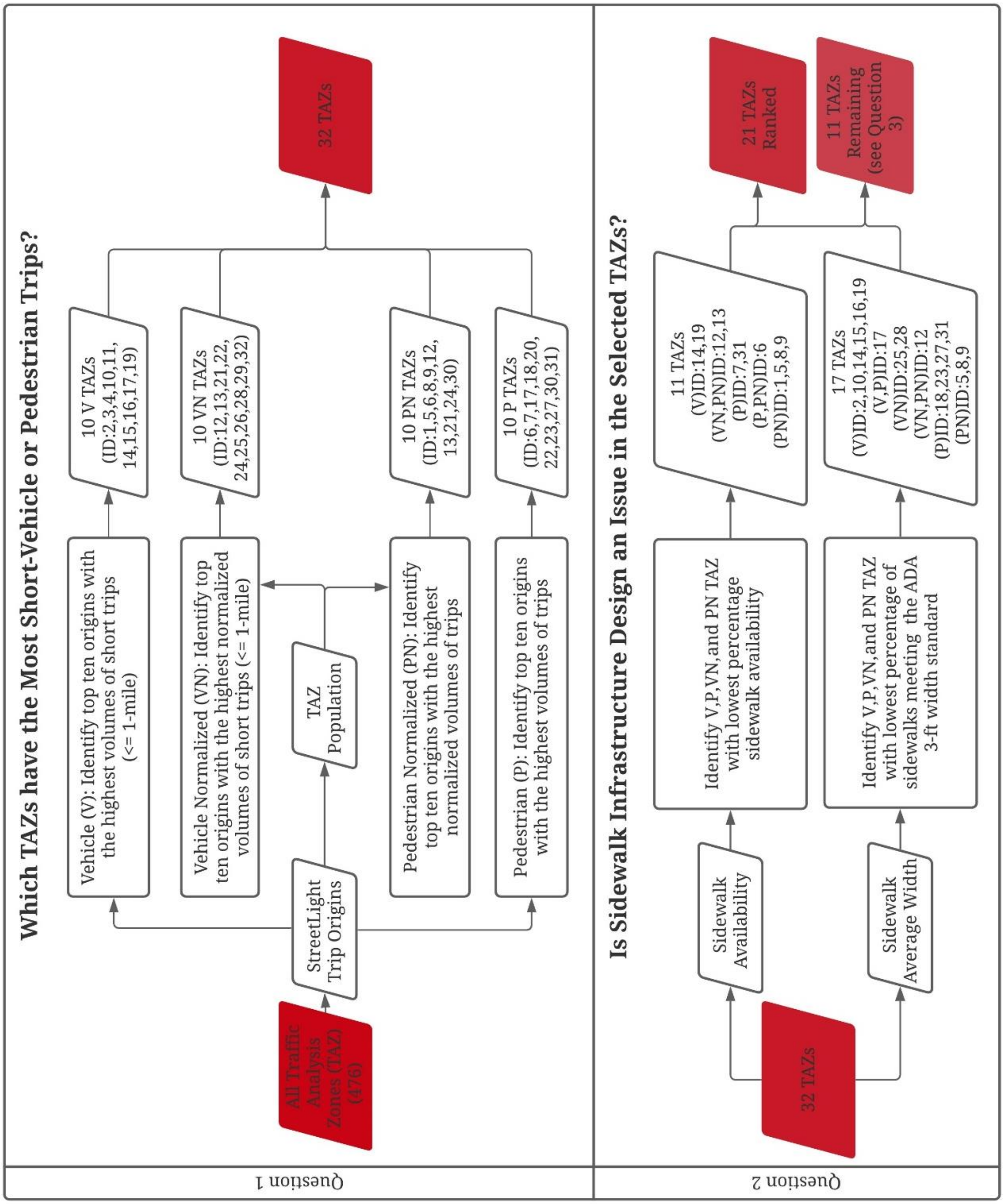


Figure 10. Prioritization Methodology (Questions 1 and 2)

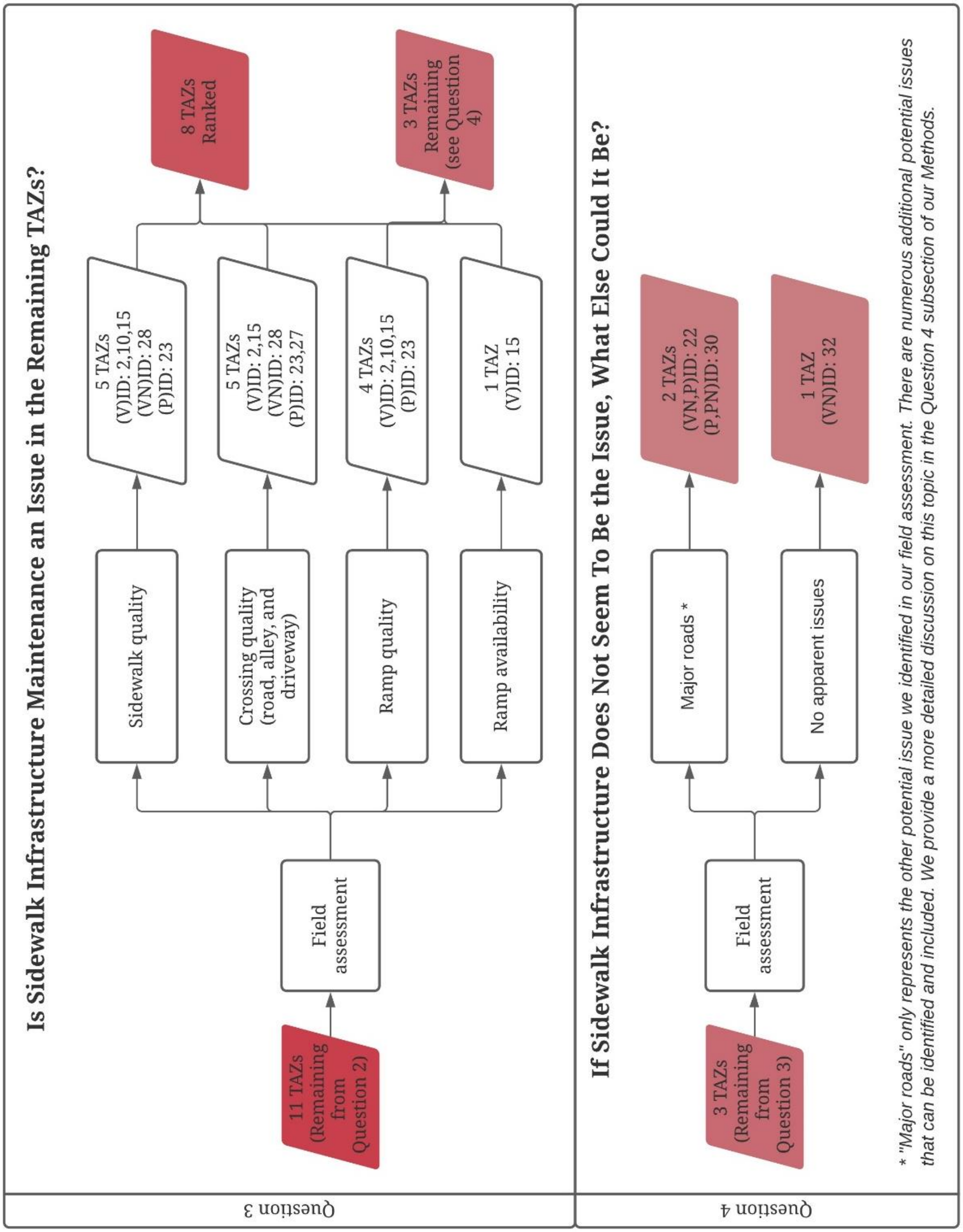
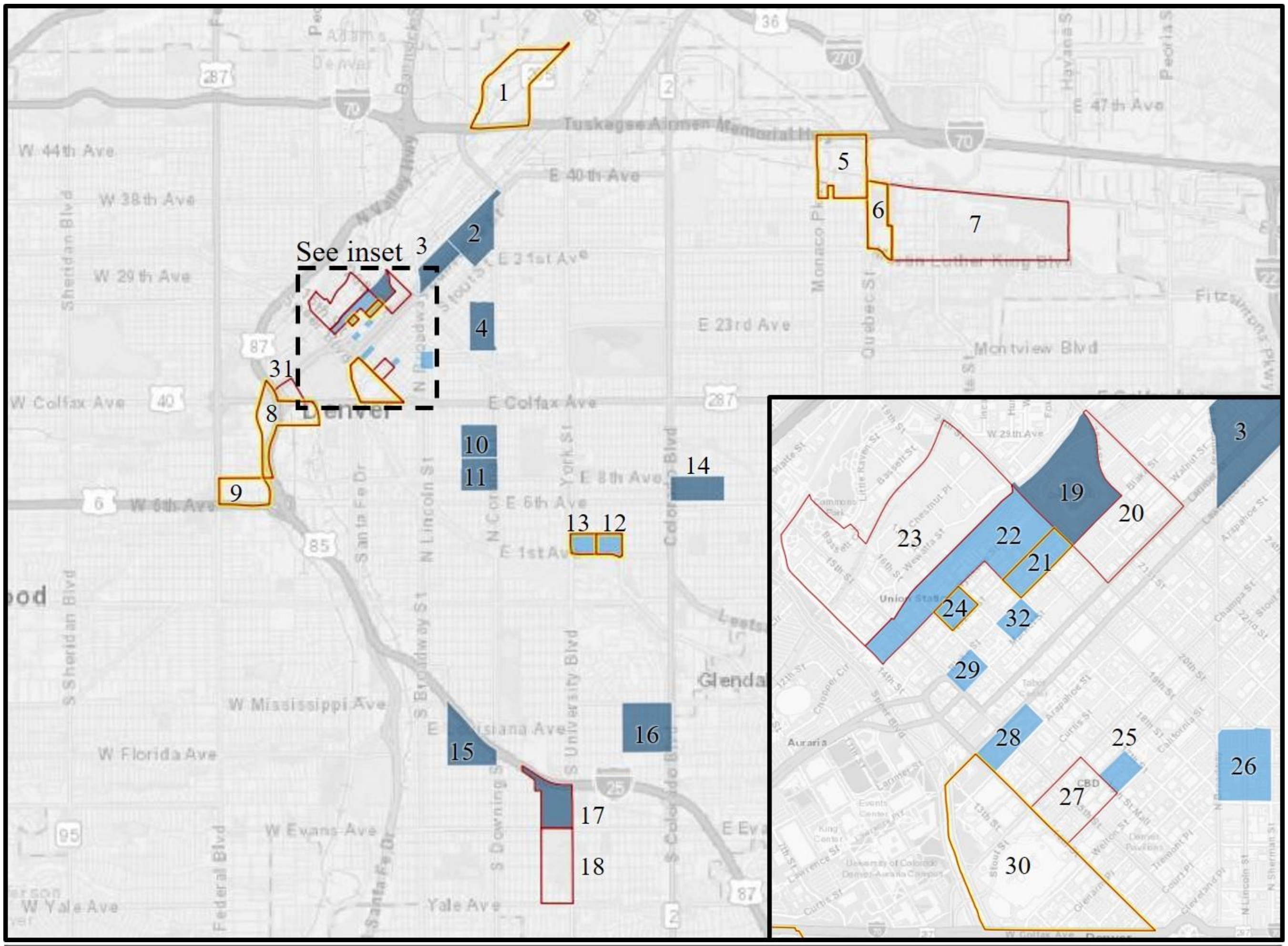
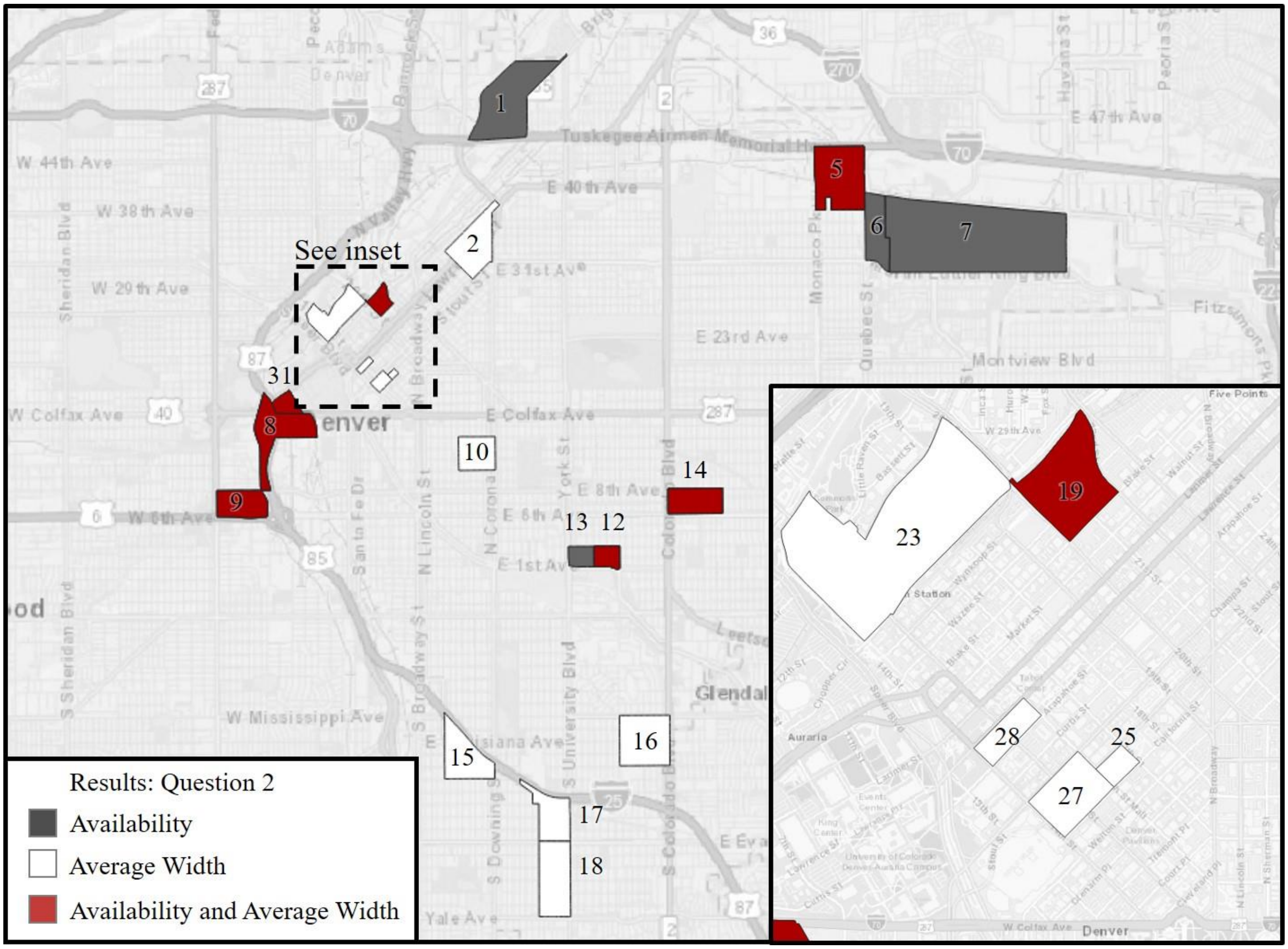


Figure 10 (continued). Prioritization Methodology (Questions 3 and 4)



Origin TAZ	Mode	Trip Volume Type	Unique Origin TAZs	Trips
	vehicle	raw data	10	10
		normalized by population		40
	pedestrian	raw data		10
		normalized by population		29

Figure 11. Top Ten Unique Origin TAZs from Four Data Sets



Sidewalk	TAZ ID																				
	1	2	5	6	7	8	9	10	12	13	14	15	16	17	18	19	23	25	27	28	31
Availability*	x		x	x	x	x	x		x	x	x					x					x
Width**		x	x			x	x	x	x		x	x	x	x	x	x	x	x	x	x	x

**TAZ with less than 80% sidewalk availability*
*** TAZ with less than 80% of sidewalks with a 3 feet average width*

Figure 12. Question 2 Results

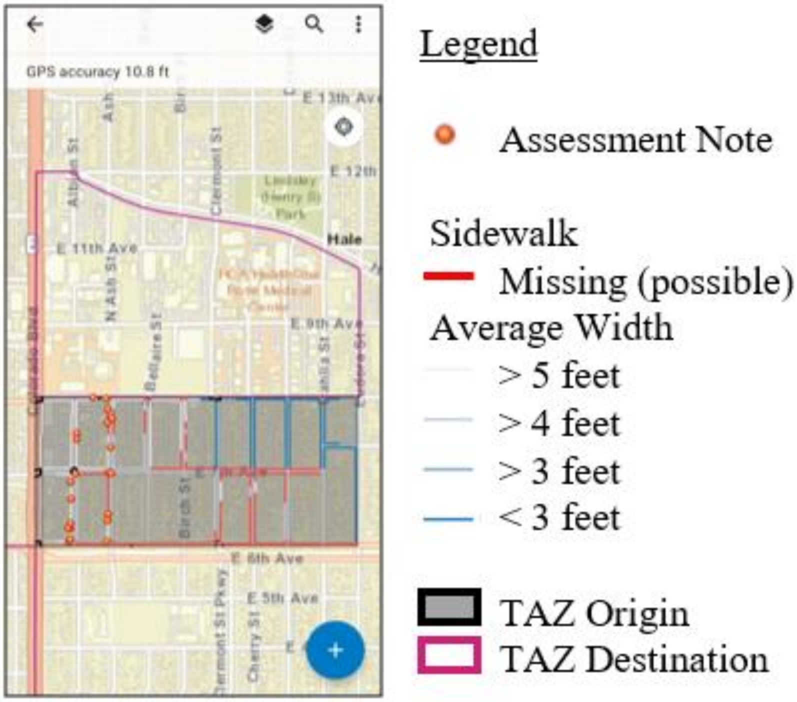
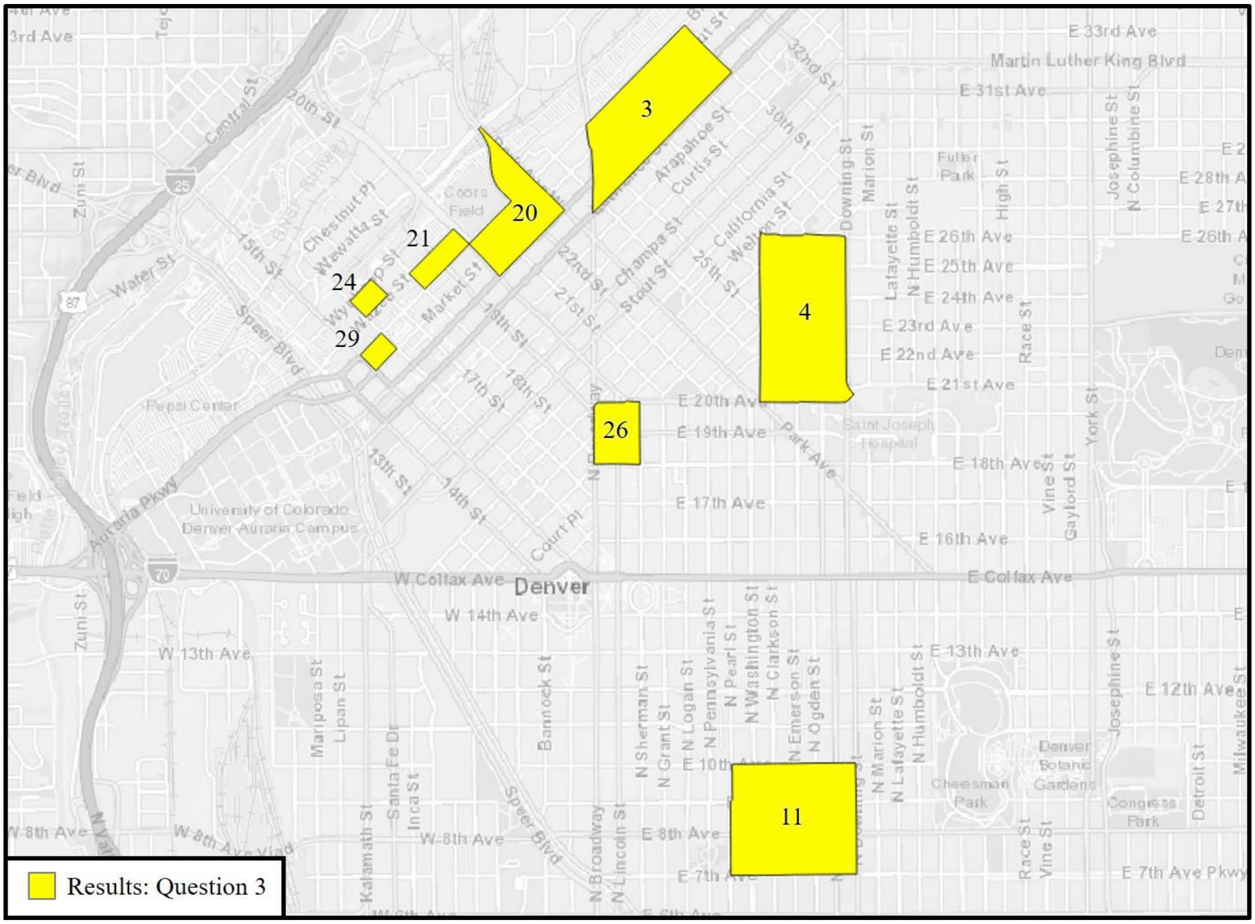
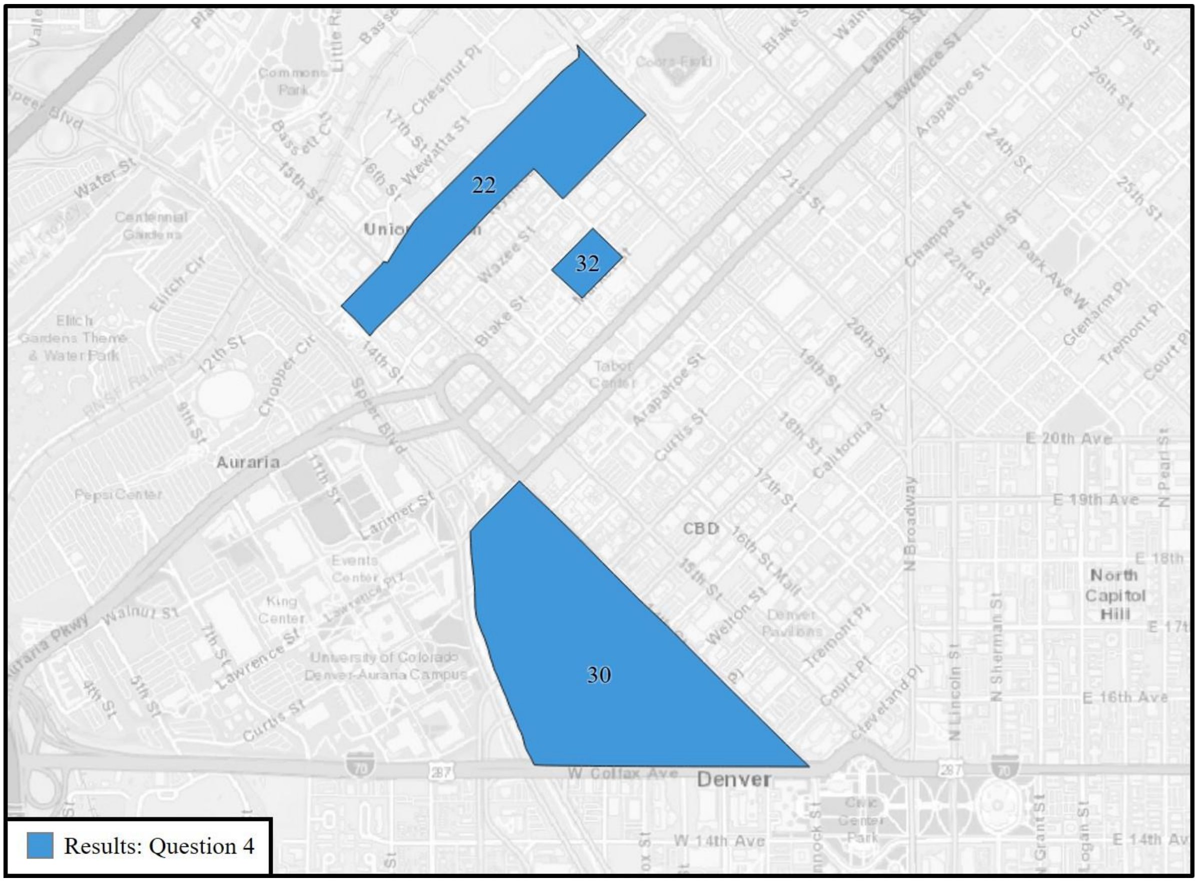


Figure 13. Screenshot: ArcGIS Collector Sidewalk Assessment Mobile Application



Issue	TAZ ID							
	3	4	11	20	21	24	26	29
Sidewalk	x	x	x	x		x		x
Crossing	x	x			x		x	x
Ramp	x	x	x		x	x		
Availability								
Ramp	x	x	x		x	x		

Figure 14. Question 3 Results



Issue	TAZ ID		
	22	30	32
Major Roads		x	x
No Apparent Reason	x		

Figure 15. Question 4 Results

Chapter 10. Summary and Conclusions

Our research presents how to use advances in big data and spatial data to assist cities in prioritizing areas needing pedestrian infrastructure attention. More specifically, we used cell-phone and vehicular GPS big data to identify areas with high volumes of average-daily short-vehicle trips that are prime for modal shift and pedestrian trips. Subsequently using sidewalk infrastructure data (planimetrics), a city can then identify which of the areas with the highest trip volumes also have sidewalk design issues. We accomplished this using planimetric data to calculate sidewalk availability and sidewalk average width, which can help cities identify where sidewalks may be missing and/or non-compliant with the ADA three foot (0.91 meters) width requirement. As a result, big data and spatial data considerably narrow the total area in a city requiring a field assessment, and thus decreases the resources needed to establish sidewalk infrastructure prioritization.

The major findings of this study are as follows:

- Big data can help cities identify areas with potential for modal shift by trip volume;
- Spatial data can help cities identify sidewalk infrastructure design issues;
- Big data and spatial data afford efficient pedestrian infrastructure prioritization methods; and
- The pedestrian infrastructure prioritization methods can be adjusted to other city focuses such as schools.

Cities often face limited resources, which can hinder their ability to tackle citywide issues such as pedestrian infrastructure. A recent report noted that only one inspector was dedicated to the sidewalk repair programs in four out of six different cities they researched (O'Brien, 2020). Our approach can help reduce the need for time-consuming, citywide field assessments. In addition, we were able to complete the field assessment work with one researcher. For a major city such as Denver – where the current city assessment program is on pace to take more than five decades – this represents a significant improvement and a data-driven methodology that can help cities get this process started.

With big data for multimodal trip volumes becoming more prevalent, cities may have additional data sources other than the StreetLight data that we used in this research. For example, Zannat and Choudhury discussed emerging big data sources beyond cell-phone and vehicular GPS data such as multimodal data from video cameras, remote sensing, and smart cards (Zannat & Choudhury, 2019). In addition, prior research by Coppola and Marshall has shown planimetric sidewalk data is available in numerous cities other than Denver, CO (Coppola & Marshall, 2019, 2020, 2021). Therefore, our methods can be easily replicated in almost any city that has access to planimetric sidewalk data.

One of the limitations of StreetLight data is that it misses trips made by people without cell phones. This is particularly an issue for children, older adults, and lower income populations. Thus, our methods could easily be adjusted to examine locations with important destinations such as schools, parks, community centers, etc. The appraised locations could also be amended to include those identified through a community engagement process. Future research may also want to account for historical inequities due to redlining or by accounting for socioeconomic and sociodemographic data. Denver, for example, has developed a "Neighborhood Equity Index" with indicators such as socioeconomics, health, and built environment data to assist in city decisions (City and County of Denver, 2021). However, the built environment indicator measures distances to grocery stores and parks without any information on pedestrian infrastructure design or quality, which our methods could provide.

A limitation of the sidewalk spatial data is the absence of static obstructions when measuring the sidewalk width. Including static obstruction has shown to provide a more accurate representation of the sidewalk clear width, which would better inform cities as to whether sidewalks are in compliance with ADA sidewalk minimum width requirements (Coppola & Marshall, 2021). Future research would also benefit from better sources of pedestrian infrastructure maintenance issues. We identified three common associated infrastructure components potentially relevant to common maintenance issues. Alleys, for example, were a frequent issue with missing ramps at the transition from the sidewalk to the alley. Another example was street trees often appearing directly next to infrastructure issues such as heaving, gaps, and cracks. In turn, researching potential sources of pedestrian infrastructure issues can help cities be proactive when building new infrastructure to prevent common issues from occurring. In addition, if cities identify common sources of maintenance issues, other data sets such as street trees, may exist to help cities further narrow their focus of where to conduct field assessment and/or maintenance.

This research presents the use of big data and spatial data as an efficient and resource saving alternative to pedestrian infrastructure prioritization, particularly with respect to identifying areas that are prime for modal shift. With some cities facing an unprecedented backlog of infrastructure deficiencies, disability rights legislation, and lawsuits in some cases, the methods in this paper provide a viable methodology to assist cities with city-wide infrastructure assessments. Our methods can help cities to become proactive and show progress towards improving pedestrian infrastructure and ADA compliance. In addition, this research helps to fill a considerable research gap on pedestrian infrastructure prioritization.

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