## MAT v1.1

Task 6 Multimodal and Accessible Travel (MAT) White Papers

# Multimodal and Accessible Travel White Paper on Public Right of Way

Multimodal and Accessible Travel Standards and Vulnerable Road User Cybersecurity Support Project

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# 1 Introduction

## 1.1 Problem Statement

The purpose of this white paper is to research and document previous work associated with the public right of way (PROW) as it relates to the development of multimodal and accessible travel standards for vulnerable road users. This white paper is supplemented with four additional white papers discussing (1) Reservations, Scheduling, and Dispatching (RSD); (2) Automated Eligibility, (3) Vulnerable Road Users (VRU), and (4) Cybersecurity for Vulnerable Road Users. These white papers describe downstream applications, standards, gaps in the standards and stakeholder groups who may contribute to the development or extension of existing standards.

The topic of PROW emerged as a major gap in data collection and modeling based on the Multimodal and Accessible Travel Standards Assessment (MATSA) and subsequent project review and use case development in this ITE Cybersecurity and VRU Project (Task 3.1 Multimodal and Accessible Travel Use Case Revie and Task 3.2 Multimodal and Accessible Travel Use Cases). As the focus of transportation technologies and systems shift to universal design, equity, and accessibility, understanding how public rights-of-way are managed and navigable for people, walking, cycling / wheeling, and moving across all transportation networks is a critical need. This PROW data needed is missing from our national data repositories, and inconsistent and incomplete if available.

## 1.2 Scope

The scope of this white paper is to identify the gaps in research related to data standards, specifications, and Application Programming Interfaces (APIs) focused on the public right-of-way (PROW). The paper includes a list of gaps in standards, key stakeholders and organizations developing related standards, stakeholders who are generating data, using the data, and developing tools that support the PROW data.

## 1.3 Audience

The PROW white paper is intended to inform key stakeholders contributing to the development of multimodal accessible travel (MAT) for vulnerable road users (VRU). VRUs may consist of pedestrians, cyclists, or micro-mobility device users, such as individuals riding scooters.

## 1.4 Document Organization

This white paper is organized into four sections:

- Section 1: Introduction
- Section 2: Literature Review - Summary of literature related to PROW standards, specifications, and research activities related to PROW standards and its uses. The literature search was not comprehensive; rather a selection of papers that were published in the most recent past that demonstrates the type of ongoing research and specification development currently underway. In addition, several researchers and specification developers were interviewed to understand current efforts.
- Section 3: Standards and Standard Gaps - PROW data standards and specifications, and gaps in the existing standards

- Section 4: Stakeholders - Stakeholders who inform standard development including the following:
    - Researchers
    - Applications developers needing the standard
    - Standard developers
    - Organizations collecting data

An appendix is included that contains a summary of the interviews held with key stakeholders, an annotated bibliography of research published in the last few years, and a comparison of attributes that are identified from the literature. These attributes show different results from studies that assessed the efficacy of features used by vulnerable populations.

# 2 Literature Review

## 2.1 Defining the Public Right of Way

PROW currently has no universal definition in the literature, but can be simply described as

> "(1) The safe and efficient movement of pedestrian traffic upon any sidewalk, walkway, or right-of-way upon which the public has a right to travel, or (2) any person's safe and efficient access to the entryway of any building, where such entryway abuts a sidewalk, walkway, or right-of-way upon which the public has a right to travel."[1]

An assumption underlying these definitions is that the pathway is restricted to pedestrians or active transportation modes (e.g., bicycles, skates, e-scooters, wheelchairs, scooters).

Other definitions found in the literature include the following:

FHWA[2]:

> Public right-of-way means the area across, along, beneath, in, on, over, under, upon, and within the dedicated public alleys, boulevards, courts, lanes, roads, sidewalks, spaces, streets, and ways within the City, as they now exist or hereafter will exist, and which are or will be under the permitting jurisdiction of the Department of Public Works.

District of Columbia's *Stormwater Management Guidebook*[3]:

> [PROW] may consist of bridges, highways, commercial and residential streets, alleyways, pedestrian walkways, bicycle trails, tunnels, and railway tracks. They are owned and operated by the Government. The Public Right-of-Way is defined as the surface and the air space above the surface (including air space immediately adjacent to a private structure located on Public Space or in a Public Right-of-Way), and the area below the surface of any public street, bridge, tunnel, highway, lane, path, alley, sidewalk, or boulevard, where a property line is the line delineating the boundaries of public space and private property.

District of Columbia's Department of Transportation (DDOT)[4]:

> "…paths in the public realm may "the surface, the air space above the surface (including air space immediately adjacent to a private structure located on Public Space or in a Public Right-of-Way), and the area below the surface of any public street, bridge, tunnel, highway, lane, path, alley, sidewalk, or boulevard."

Iowa State Statutes[5]:

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[1] City of Bradenton Code of Ordinances - https://library.municode.com/fl/bradenton/codes/code_of_ordinances?nodeId=PTIICOOR_CH62STSI_ARTIISI

[2] FHWA - https://www.fhwa.dot.gov/utilities/utilitycuts/manual.pdf

[3] https://dhcd.dc.gov/sites/default/files/dc/sites/ddoe/publication/attachments/ApdxBMEPforPROW.pdf

[4] DDOT Public Real Design Guide - https://ddot.dc.gov/sites/default/files/dc/sites/ddot/page_content/attachments/DDOT_Public_Space_Design_Realm_Guide_Final_updated_2019.03.15.pdf

[5] https://www.legis.iowa.gov/docs/code/2021/480A.pdf

> Public right-of-way means the area on, below, or above a public roadway, highway, street, bridge, cartway, bicycle lane, or public sidewalk in which the municipality has an interest, including other dedicated rights-of-way for travel purposes and utility easements. "Public right-of-way" does not include the airwaves above a public right-of-way with regard to cellular or other non-wire telecommunications or broadcast services or utility poles owned by a municipality or a municipal utility.

Maple Valley Code of Ordinances[6]:

> Public right-of-way means land owned, dedicated or conveyed to the public, used primarily for the movement of vehicle, wheelchair, bicycle, and pedestrian traffic, or land privately owned, used primarily for the movement of vehicle, wheelchair, bicycle, and pedestrian traffic, so long as such privately owned land has been constructed in compliance with all applicable laws and standards for a public right-of-way.

Kansas State Statutes[7]:

> Public right-of-way means only the area of real property in which the authority has a dedicated or acquired right-of-way interest in the real property. It includes the area on, below, or above present and future streets, alleys, avenues, roads, highways, parkways, or boulevards dedicated or acquired as right-of-way. "Public right-of-way" does not include any State, Federal, or interstate highway right-of-way, which generally includes the area that runs contiguous to, parallel with, and is generally equidistant from the center of that portion of the highway improved, designed, or ordinarily used for public travel.

The common theme among the definitions includes concepts related to surface space and/or space above the surface where the public is allowed to traverse that are accessible with certain restrictions or regulations.

## 2.2 Applications that Need PROW Information

### 2.2.1 Inclusive Design -- Accessibility and Equity

State and local governments as well as transit agencies are required to develop Americans with Disabilities Act (ADA) transition plans for areas requiring improvements for people with disabilities. In addition, ADA established in 1990 effectively "prohibits discrimination against people with disabilities in several areas, including employment, transportation, public accommodations, communications and access to state and local government' programs and services,[8]" which includes transit. In an effort to be compliant with ADA requirements, DOTs and departments of public works across the country are developing digital inventories and Geographic Information System (GIS) maps of their public right of way conditions to address the current gaps in pedestrian connectivity and accessibility for all roadway users, despite disability status.

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[6] https://www.codepublishing.com/WA/MapleValley/html/MapleValley18/MapleValley1850.html

[7] Extracted from http://www.kslegislature.org/li_2022/b2021_22/statute/066_000_0000_chapter/066_020_0000_article/066_020_0019_section/066_020_0019_k/

[8] U.S. DOL - https://www.dol.gov/general/topic/disability/ada

### 2.2.2 Curb Management

The edge of the roadway are expanded to include bike lanes, commercial parking with loading/unloading privileges, outdoor cafes, automated mobile robots, and more. Many of these applications rely on using a linear reference to measure location along the right of way or describing the space between the sidewalk and road. That space includes surface and above surface attributes including the sidewalk along that space.

### 2.2.3 Wayfinding and routing tools

Inclusive trip planning and modeling are critical components to effectively developing multimodal accessible travel tools for vulnerable road users. These tools use PROW data in multiple ways:

- **Routing** through pedestrian and wheeled pathways
- **Feature types** – including types of pathways, their attributes and characteristics inclusive of rules associate with their use by vehicles and travelers
- **Place locations** – location of transition points or points of interest such as doors, elevators/escalators, ramps, pedestrian crosswalks, addresses, as well as places to avoid – stairs, rough surfaces, curbs
- **Path optimization** – personalized trip plans (and rerouted trip plans) based on traveler wants and needs that include identifying costs to travel due to obstacles, preferences, or options

## 2.3 Gaps in PROW Standards

According to Wheeler et al. (2020), there are two current gaps in the development of applications for persons with disabilities. Specifically, (1) accessibility data used to identify accessible pathways for people with disabilities are not compliant with the widely agreed upon and available standards, and (2) accessibility data are not available in free and open platforms so that they can be used by developers to develop personalized wayfinding applications and services.[9]

Different methods for representing path data are proposed to support routing for trip plans. For example, Wheeler and his colleagues proposed a new extension in CityGML with accessibility data to generate pathways/routes that are all feasible based on ADA Accessibility Guidelines (ADAAG), which include the three following metrics: a) length, b) the number of turns, and c) the number of segments. Per the ADAAG, each sidewalk segment must comply with the following standards to be considered feasible for traveling by people with disabilities:

- Width should be 92 cm wide with no obstructions
- Slope should not exceed 5 percent and cross slope should not exceed 2 percent
- Should have a firm, stable, and slip resistant walking surface
- Should have a concrete, asphalt, stone, or brick surface
- Should be void of major cracks or breakage
- Should support curb ramps where applicable.

These requirements support design and construction but do not consider many other factors that drive accessibility.

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[9] Wheeler et al. (2020). https://opengeospatialdata.springeropen.com/articles/10.1186/s40965-020-00075-5

## 2.4 PROW Feature Description

While pedestrian-friendly urban environments are frequently addressed in transportation research, there is a critical gap in the literature effectively representing the pedestrian environment and accessibility in street network datasets. Researchers in Portugal developed a pedestrian network that featured formal and informal pedestrian crossings and traversable/inaccessible pathways with the purpose of establishing digitization specifications for geographic datasets to conduct pedestrian accessibility analyses.[10]

The pedestrian network developed by the researchers consisted of two (2) categories: Formal Network and Detailed Network. With the former, formal networks are "distinguishable and discernable pathways and crossing features" whereas the latter may comprise "unmarked pathways and crossing features" that are typically overlooked in most pedestrian network digitization approaches. The following fifteen (15) pedestrian network typologies were identified[11]:

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[10] Cambra, Gonvalves, and Moura (2019) - https://revistas.rcaap.pt/finisterra/article/view/16414

[11] Cambra, Gonvalves, and Moura (2019) https://revistas.rcaap.pt/finisterra/article/view/16414

**Table 1: Pedestrian Environment Network Category**

| Pedestrian Network Category | Network Type | Typologies | Description |
|---|---|---|---|
| Formal Network | Formal Pathways | Sidewalk | A sidewalk is often considered as a separate path, at a side from the road, usually paved and raised. The issue is if a sidewalk that is not raised, paved, or at the side of the street is still a sidewalk, or, if a sidewalk that is practically unsuitable for people to walk can be still considered a sidewalk. |
| | | Pedestrianized Streets | This type of street link is for exclusive pedestrian use and can be represented by a single sidewalk centerline. However, we found cases where the street is a pedestrian street by means of regulatory traffic signals — no through traffic allowed — but not in terms of its configuration, maintaining segregated sidewalks from the roadway. |
| | | Local Access Streets, Shared Space | Following the same rationale as above, we have identified local access streets, where the traffic volume is very low and people tend to walk in the roadway albeit the presence of sidewalks or, more often, given the existence of impractical sidewalks. Alternatively, with paved streets, there is no physical separation of the sidewalk from the roadway. The separation between vehicle and pedestrian space occurs by means of differentiating the pavement color or texture. Shared streets are similar to the paved streets but have no specific spatial separation. |
| | | Stairways | Stair streets are inaccessible for wheelchairs or baby strollers. Their identification is therefore crucial for accessibility analysis. However, while some sidewalks are fully composed of steps and are simple to classify, others only have steps on a small portion of its extent. |
| | Formal Crossings | Traffic Signalized Crossings (Pelican Crossings) | To minimize conflicts with other road users, pedestrian crossings are sometimes signalized by horizontal and/or vertical signs, that alerts car drivers and guides the pedestrian to a particular crossing location, to a formal crossing. |
| | | Crosswalks (e.g., Zebra Crossings) | When a pedestrian reaches the end of a sidewalk link, the pedestrian usually continues the journey either by turning to the adjacent sidewalk thus contouring the block; by crossing straightway, carrying on the same direction, or by crossing to the opposite side of the street. |
| | | Refuges, Islands | Refuge islands are portions of pavement that connect crossings. They can be used to provide a safe waiting area to crossroad sections or to guide pedestrians to crossing areas. |
| | | Overpasses | Often used to overcome a transportation infrastructure such as a railroad or a major road and often have stairs. To meet accessible design standards some overpasses and underpasses are composed of ramps or have escalators or lifts. |
| | | Underpasses | See definition for overpasses above. |
| Detailed Network | Informal Pedestrian Crossings (not suitable for streets w/ 3+ lanes) | One way or one lane streets (Type I) | We suggest informal crossings to be placed at an intersection when in presence of single lane, one-way streets, assuming relatively low traffic volume and speed, favoring a safe pedestrian crossing. |
| | | Two way or dual lane streets (Type II) | Informal crossings are suggested to be placed at an intersection when in presence of two-way streets and at a distance higher than 50m from a formal crossing (the Portuguese road regulations |

| | | | |
|---|---|---|---|
| | | | states that it is illegal for the pedestrian to cross the road if the nearest formal crossing is in a 50-meter vicinity). |
| | Unmarked Pathways | Through building lots | The representation of squares and plazas is challenging as they are in practical terms open spaces offering freedom of movement. On one hand their representation as polygons is unsuitable for network analysis and on the other hand defining only their boundaries by sidewalk links does not unveil all path possibilities. One way to overcome this issue is to delimit the square borders and set straight connections in between. |
| | | Parks | In a similar way, we opt to represent parks and open spaces with their boundaries and a set of connectors between possible access points. Some parks do have formal paths and may require a more detailed representation. |
| | | Unpaved | Roadways that are not paved. |
| | | Open Spaces (parking lots, green areas) | See definition for parks above. |

In addition to describing types of PROW nodes and edges, the list of features and attributes is also not described in enough detail to support accessibility. Table 2 lists a summary of key attributes collected for accessibility in route planning for persons with disabilities (PWD) as described by the literature.

**Table 2: Attributes Collected to Support Persons with Disabilities**

| **PROW Attribute(s) for PWD** | **Disability Type** | | | | | |
|---|---|---|---|---|---|---|
| | No disability | Hearing | Mobility | Wheelchair | Visual | Cognitive |
| Sidewalk, width | X | X | X | X | X | X |
| Sidewalk, length | X | X | X | X | X | X |
| Sidewalk, slope | | | X | X | X | |
| Sidewalk, surface type | | | X | X | X | |
| Sidewalk, surface conditions | | | | X | X | |
| Curb Ramps | | | | X | X | |
| Crosswalk | X | X | X | X | X | X |
| Crosswalks, audio feedback | | | | | X | |
| Crosswalks, visual feedback | | X | | | | |
| Crosswalks, assisted listening devices | | X | | | | |
| Elevators | | | X | X | X | |
| Accessibility Ramps | | | X | X | | |
| Steps/Stairways | | | X | X (Avoid) | X | |
| Handrails / Grab bars | | | X | X | X | |
| Lift, wheelchair | | | | X | | |
| Fences | | | X | X | X | |
| Street Furniture | | | X | X (Avoid) | | |

| PROW Attribute(s) for PWD | Disability Type | | | | | |
|---|---|---|---|---|---|---|
| | No disability | Hearing | Mobility | Wheelchair | Visual | Cognitive |
| Street Lighting | X | | | X | | |
| Traffic Noise | | | | | X | |
| Pedestrian/Cyclist Traffic | X | X | X | X | X | X |
| Vehicular Traffic | X | X | X | X | X | X |
| Transit Stops | X | X | X | X | X | X |

According to Karimi, Zhang, and Benner (2014)[12], accessibility requirements for PWD were gathered from the literature to develop a personalized accessibility map (PAM) that can produce optimal routes dependent on the user's capabilities in Pittsburgh, PA. Table 2 above outlines relevant key attributes for PWD with suggested conditions or values found in the literature available in **Appendix D: Comparison of attributes and conditions.** Persons with mobility impairments or disabilities include those that are not wheelchair bound, yet still may be an older adult, of an individual that relies on physical assistance such as a cane to get around. There is limited research available on cognitive disabilities and accessibility in the public right of way; however, advanced technologies such as Augmented Reality and other novel approaches can be leveraged to meet the needs of this community. With both visually impaired and cognitively impaired individuals often escorted (e.g., guide dog and/or caregiver) to their destinations, their accessibility requirements may not accurately describe their actual needs if a trip was conducted fully independently. Individuals with hearing impairments have the least attribute requirements yet to promote equity and accessibility, this community still requires a built environment that is adaptable to and supports assisted listening devices.

### 2.4.1 Routing Algorithms using PROW Networks with Impedance Values

Impedance value (or costs to travel) are weights applied to link and nodes used to optimize route paths. The impedance applied to the vulnerable road user journey plan weight trip alternatives based on many factors including safety, accessibility, comfort, and general preferences.[13] Identifying the best, safest, or most comfortable route may vary among people with similar or different disability types.[14] Route planning models are designed to account for costs associated with impedances along with other factors that influence time or pedestrian experience. Several routing algorithms that use specific network characteristics to customize the trip path were identified while reviewing the literature in Table 3.

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[12] Karimi, Zhang, & Benner (2014) - https://www.tandfonline.com/doi/full/10.1080/19475683.2014.904438

[13] A Personalized Trip Planner for VRUs (Park, 2021) - https://digital.library.ncat.edu/catm/8/

[14] Adaptive Personalized Routing for VRUs (2021) - https://www.researchgate.net/publication/360008073_Adaptive_personalized_routing_for_vulnerable_road_users

**Table 3: Impedance Generation Algorithms**

| Publication | Algorithm | Description |
|---|---|---|
| Route planning for blind pedestrians using OSM (2020)[15]<br>*User: Visual* | Dijsktra | In this publication, OSM is leveraged to utilize topological data structures that include the following four core elements:<br>(1) Nodes – points with a geographic position (e.g., landmarks);<br>(2) Ways – a) ordered lists of nodes that represent either a polyline (i.e., linear features, such as streets and rivers) or b) a polygon (closed shapes, such as forests, parks, parking areas, and lakes);<br>(3) Relations – relationships between existing nodes and ways (e.g., turn restrictions on roads); and<br>(4) Tags – "key-value" pairs (such as "amenity-shop") for storing metadata about map objects (e.g., type name, and physical properties).<br>A weighted network graph is created by developing sets of costs formulated as criteria that depend on the geometric and topologic attributes of each way segment and are derived from the seven central spatial and environmental elements: complexity, landmarks, accessible aids, roads, obstacles, intersections, and personal preference to optimize route planning for PWD. |
| Development of AccessPath: A pedestrian wayfinding tool tailored towards wheelchair users and individuals with visual impairment (2020) [16]<br>*User: Wheelchair, Visual* | Dijsktra | AccessPath is a project supported by USDOT's ATTRI joint program with the general purpose of developing a mobile application to support PWD navigate pedestrian pathways. The API developed by the researchers consists of three components: (1) Routing; (2) Locations; and (3) Users. The data framework includes four data quality levels:<br>(1) Sidewalk/Crosswalk Centerlines – supports both accurate path visualization for self-visualization and basic analytics for municipalities;<br>(2) Discrete Attributes -- to identify hazardous paths such as trip hazards and assist municipalities identify and prioritize sidewalk repairs;<br>(3) Connected Network of Paths – to support wayfinding and navigation around problem areas;<br>(4) Continuous Attributes – describes features such as roughness and to support wayfinding and navigation with fully accessible routes. |
| ARPA: Accessibility-focused Route Planning Assistant (2021)[17]<br>*User: Wheelchair, Visual* | A* | This doctoral dissertation explored the creation of a routing algorithm to support PWD using publicly available datasets with OSM. The researcher proposes four main components of the app's functionalities:<br>(1) Web Service – to capture user's preferences and capabilities;<br>(2) Geocoder – works with the external API calls to convert text descriptions of locations into OSM data Elements;<br>(3) Graph handler – parses the OSM data and creates a representation of the road network the user with accessibility information, also cached requests;<br>(4) Routing handler – combines the three components above into the A* algorithm on the graph with accessibility preferences of the users reflecting cost functions.<br>Each data point in OSM is represented as an Elements: Nodes (any single point in space, latitude/longitude), Ways (ordered list of nodes and describe feature of the environment), and Relations (logic between two objects such as bus stops, pedestrian areas). Tags describing accessibility can be associated to any of the elements such as characterizing nodes (e.g., curbs) with three values (e.g., "raised' curbs). |

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[15] Cohen & Daylot (2020) - https://journals.sagepub.com/doi/pdf/10.1177/2399808320933907

[16] Development of AccessPath: A pedestrian wayfinding tool tailored towards wheelchair users and individuals with visual impairments (2020). Publication Number: FHWA-JPO-21-846

[17] Ershov (2021) - https://www.scss.tcd.ie/publications/theses/diss/2021/TCD-SCSS-DISSERTATION-2021-033.pdf

| | | |
|---|---|---|
| A Personalized Trip Planner for Vulnerable Road Users (2021)[18]<br>User / Target Audience: *wheelchair/persons with disabilities* | Q-Learning & AHP (VRU Personalized Optimum Dynamic (VRUPOD) Routing) | This publication from the Center for Advanced Transportation Mobility was funded by USDOT to develop an adaptive and personalized routing model for PWD. Ultimately, the goal of their work was to identify a strategy that minimizes the total cost in a given origin-destination pair in developing routes for PWD.A weighted approach was developed to account for sidewalk accessibility factors in optimizing route planning. The authors noted OSM's limitations includes a lack of real-time information on sidewalk conditions. In this paper, cost functions are developed by accounting for the preferences of the user changing due to time and interactions with the built environment. Nodes represent sidewalk intersection and edges represent sidewalk segments in this pedestrian network graph. |
| User-Specific Route Planning for People with Motor Disabilities: A Fuzzy Approach[19]<br>*Target audience: wheelchair/persons with motor disabilities (PWMD)* | Dijkstra, Fuzzy Logic Model | This research proposes a four-step approach based on the foundations of the fuzzy theory for the evaluation of the accessibility levels:<br>(1) Identification, Fuzzification, and Rating of the Accessibility Criteria – prioritize sidewalk criteria based on PWD perceptions and preferences before fuzzifying the criteria based on existing sidewalk standards for PWD;<br>(2) Constructing the Normalized Fuzzy Vector Based on the User Confidence Levels – the purpose of this step is to transform the criteria values to scores between 0 to 1. (3) Quantifying an Accessibility Index(ces) (AI – this value is based on the PWD's capabilities and ranges from 0 to 1 with 1 implying the most favorable accessibility conditions.<br>(4): Optimal Routing Computation - representing the cost of each segment and computing the optimal routes. |
| Towards routine, city-scale accessibility metrics: Graph theoretic interpretations of pedestrian access using PPNA (2021) [20]<br>*Target audience: wheelchair, no physical disability* | n/a | UW researchers used OpenSidewalks (OS) to retrieve pedestrian and street network data on OSM with GeoPandas or plotnine Python libraries and QGIS for visualization to create the Personalized Pedestrian Network Analysis (PPNA). PPNA can be leveraged to better calculate walkshed which is more accurate than using traditional street networks. Additionally, two other scoring metrics of accessibility were developed; graph connectivity and centrality. Pedestrian mobility profiles (PMPs) can also be integrated to PPNAs and it is where an individual (or a subpopulation) may be represented as a vector of cost parameters determining composite internal costs of travel through particular environments. The profiles are used as a parametric expression of factors and weights of factors that impact route choice and traversal through pedestrian paths. Future work includes adapting the PPNA to evaluate the implementation of Complete Streets specifications. |

| **Publication** | **Algorithm** | **Description** |
|---|---|---|
| Route planning for blind pedestrians using OSM (2020)[21]<br>*User: Visual* | Dijsktra | In this publication, OSM is leveraged to utilize topological data structures that include the following four core elements:<br>(1) Nodes – points with a geographic position (e.g., landmarks);<br>(2) Ways – a) ordered lists of nodes that represent either a polyline (i.e., linear features, such as streets and rivers) or b) a polygon (closed shapes, such as forests, parks, parking areas, and lakes);<br>(3) Relations – relationships between existing nodes and ways (e.g., turn restrictions on roads); and<br>(4) Tags – "key-value" pairs (such as "amenity-shop") for storing metadata about map objects (e.g., type name, and physical properties).<br>A weighted network graph is created by developing sets of costs formulated as criteria that depend on the geometric and topologic attributes of each way segment and are derived from the seven central spatial and environmental elements: complexity, landmarks, accessible aids, roads, obstacles, intersections, and personal preference to optimize route planning for PWD. |

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[18] Park et al. (2021) - https://digital.library.ncat.edu/catm/8/

[19] (2021) User-Specific Route Planning for People with Motor Disabilities: A Fuzzy Approach (mdpi.com)

[20] Bolten & Caspi (2021) https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0248399#sec003

[21] Cohen & Daylot (2020) - https://journals.sagepub.com/doi/pdf/10.1177/2399808320933907

## 2.5 Summary of Findings

The studies listed in **Table 3** provide insight into the elements that require standardization related to the functions provided by trip planners and that are currently missing from most maps and geospatial models. The following identify some of the gaps.

**Routing:** The **routing function** requires a typologically connected graph that describes the PROW and its association with other modal graphs (e.g., road and public transportation networks). The paths may extend beyond sidewalks adjacent to road networks. While pedestrian-friendly urban environments are frequently addressed in transportation research, there is a critical gap in the literature effectively representing the pedestrian environment and accessibility in street network datasets. Cambra, Gonvalves, and Moura (2019) developed a pedestrian network that features formal and informal pedestrian crossings and pathways with the purpose of establishing digitization specifications for geographic datasets to conduct pedestrian accessibility analyses.[22] The classifications also relate to wheeled pathways. For example, the formal network includes the following:

- Pathways (e.g., sidewalks, pedestrian streets, shared spaces, pedestrian bridges, cycle tracks, bike lanes, bike trails)
- Crossings (e.g., signalized crosswalks, pedestrian islands, overpass/underpass, bike crossings)

These formal PROW network elements are typically represented as attributes of road networks since they border the road network. However, there are informal paths that are unmarked paths, open spaces such as parks and plazas, pathways through buildings, parking, and stations.

**Feature Types: Feature types** require a complete and consistent set of terms and definitions used to describe the characteristics of the network including edge or node types, objects in the PROW network, and rules associated with its use. The feature list also includes a consistent and repeatable measurement system for ranking condition of the features. For example, surface type roughness or compliance with ADAAG provisions.

**Place Location:** The **location of features and places** requires that a set of objects be associated with the road network although many places only describe the sidewalk. For example, sidewalks include curbs (heights), curb cuts, stairs, (accessible) doors to buildings, ramps, widths that accommodate people, packages, wheelchairs, transit stops (basic points and with shelters), and more. They also include rough and bumpy surfaces due to tree roots, uneven pavement, poles obstructing passage, protrusions from buildings, and gradients. Furthermore, the routing algorithm should precisely locate the feature to direct and orient the traveler to the precise location – directly to the accessible door, directly through the entrance to the pedestrian shortcut.

**Path optimization:** Path optimization is based on assigning impedances to the PROW at node and edge of the PROW graph where the cost to travel differs. This may require the following:

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[22] Cambra, Gonvalves, and Moura (2019) - https://revistas.rcaap.pt/finisterra/article/view/16414

- Formal and informal pathways and crossing that describe the connected PROW network including type and rules that describe edges and nodes where impedances to travel may differ (based on traveler, and user preferences and capabilities)
- Complete and consistent set of attributes that describe features and their conditions
- Consistent and repeatable measures to rate feature conditions
- Association of impedances related to PROW nodes and edges to accommodate travel for persons with similar and different preferences and capabilities
    - The impedances will differ for different vulnerable populations for example, people with visual disabilities or people with mobility disabilities including use of walkers, and manual or motorized wheelchairs.
- Links with public transportation and other modes (e.g., airports, water ports).

These findings will help inform a work program for standards development and enhancement to support PROW data collection, storage, use, and distribution.

# 3 Standards and Standard Gaps

Standards typically are packaged with interconnected specifications. For example, a data model may be encoding using Extended Markup Language (XML) or JavaScript Object Notation (JSON). The underlying reference model is the same, but the encoding differs. Additionally, the Open Systems Interconnection (OSI) model shows us how to modularize communications standards so that they can work using different physical implementations. Mapping standards differentiate similar standard layers. The Open Geodata Consortium (OGC) defines several transfer layers for map, map tile, and features services. This section describes types of mapping standards and gaps for PROW that exist.

For the most part, sidewalks and bike paths (lanes, cycle tracks, etc.) are defined as attributes of street networks (centerline) or faces of plot boundaries. Some accessibility features such as curb cuts and ramps are rendered as a point that may or not be associated with a curb, intersection, or even a road network. Many "informal" pathways are not represented or have no object models in navigation maps (Cambra). In addition, three-dimensional models such as CityGML (OGC/TC 211) may have multiple ways to transform the solid/surface model to a navigable model that can be used to generate trip plans. Although some standards or methods are under development for describing accessible pathways and integrating pedestrian/active mode networks with vehicle mode networks, there is no consistent approach nor one that is recognized across the industry.

## 3.1 Accessibility Specifications

There are several policy guidelines that drive specifications for people with disabilities. The most significant guideline is the following:

> **ADAAG** -- part of the Americans with Disabilities Act (Appendix A: Accessibility Guidelines for Buildings and Facilities) which describes sets of requirements related to the following:
>
> - Accessibility routes
> - Transit facilities design
> - General site and building elements
> - Recreational facilities
> - And more
>
> The specification does not provide the capability to encode the infrastructure into a digital twin that can be represented, visualized, or processed (e.g., generate routes). Many standards and specifications (developed in the US) use these guidelines to assess compliance with ADA requirements.

**Linked Data for Accessibility Group**[23] — Linked Data for Accessibility Group is a coordinated effort by the World Wide Web Consortium (W3C) to standardize accessibility information about buildings, services, and routes by "(1) by creating an open standard vocabulary for accessibility and (2) by

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[23] The Future of Urban Accessibility for People with Disabilities: Data Collection, Analytics, Policy, and Tools - Froehlich (2022)

providing a central place for the web community to discuss issues around physical accessibility data."[24]

## 3.2 Curb Management

There are several standards that represent curbs and their attributes in the public domain. They include the following:

**Curb Data Specification:** An Open Mobility Foundation (OMF) specification that "covers the supply component of the curb but incorporates a demand component by having both an events and metrics API."[25]

**CurbLR:** "A specification developed by SharedStreets…It was designed to capture the complex structure of curb regulations in a robust, priority driven design with locations based off of the SharedStreets [linear] referencing system."[26]

**CityGML** -- Open Geodata Consortium (OGC)'s CityGML defines "a conceptual model and exchange format for the representation, storage, and exchange of virtual 3D city models. It facilitates the integration of urban geodata for a variety of applications for Smart Cities and Urban Digital Twins, including urban and landscape planning, Building Information Modeling (BIM), mobile telecommunication, disaster management, 3D cadastre, tourism, vehicle and pedestrian navigation, autonomous driving and driving assistance, facility management, and energy, traffic, and environmental simulations."[27]

## 3.3 Wayfinding and Routing

**OpenSidewalks**[28] – OpenSidewalks is a coordinated effort by the University of Washington Tasker Center for Accessible Technology. OpenSidewalks was designed for creating an open-source pedestrian map layer that standardizes "transportation network-focused methods for gathering detailed information such as sidewalks, curb cuts, crossings, and street furniture."[29]

**GTFS-Pathways -** A proposed extension to the General Transit Feed Specification (GTFS) that describes transit stations pathways including entrances and interiors including elevator, escalator, and stairs, platforms, bus bays, and fare gates. [30]

**CityGML –** (see description in Section 3.2)

**OSM** – OpenStreetMap, open specifications, visualizations, and interfaces that represent geographic data including "physical features on the ground (e.g., roads or buildings) using tags attached to its

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[24] World Wide Web Consortium (W3C) - Linked Data for Accessibility Community Group (w3.org)
[25] Extracted from CurbIQ (https://curbiq.io/blog/using-data-standards-for-curb-management/) (3/15/2023)
[26] Ibid.
[27] Extracted from OGC (3/15/2023) https://www.ogc.org/standard/citygml/
[28] Tradeoffs for Data-Intensive Technology Development - Tanweer 2022
[29] Extracted from https://tcat.cs.washington.edu/opensidewalks-2/ (3/15/2023)
[30] GTFS Pathways Overview - https://gtfs.org/schedule/examples/pathways/

basic data structures (its nodes, ways, and relations). Each tag describes a geographic attribute of the feature being shown by that specific node, way, or relation."[31] Features include the following:

- Public transportation modes (aerialway railways, transit)
- Barriers
- Boundaries
- Buildings
- Places of interest
- Highways (all roads)
- Land use
- Routes including bicycle, public transportation, detours, foot, hiking
- Natural features and landmarks
- Waterways

### 3.4 Types of Standards

Most of the aforementioned standards provide a digital twin of the infrastructure that includes modeling the infrastructure. Some of these standards apply to other standards/protocols that are typically used to access, transmit, or describe the information. Most use the Open Systems Interconnection (OSI) or Internet model. Both the models include higher level layers for encoding and application data that is transmitted from one system to another. Key protocols related to data transfer including the following:

- Encoding standards such as GML, JSON/GeoJSON, REST, XML, Delimited files

- Application protocols such as HTTP or OpenAPI

- Feed or exchange specifications that describe the semantics and their structure of information including shapefiles (ESRI format), map and feature services (OGC), General Transit Feed Specification

Some of the specifications include metadata descriptions, data dictionaries or semantic specifications, and testing/compliance protocols.

The following types of standards may be needed to create a complement of standards for PROW data.

- **Network modeling** – this includes how the PROW is related to other transportation networks. This includes the graph and linear referencing models that describe paths through accessible features (e.g., edges and nodes).

- **Attributes / semantic ontologies** – that describe the meaning of similar PROW attributes across different domains.

- **Metadata** – information about the data (in a feed), its content (coverage and attributes), source, lineage, processing, quality, and other information that describes how to discover, access, and

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[31] Extracted from Map Features (3/15/2023) https://wiki.openstreetmap.org/wiki/Map_features

use the data. This includes the minimum set of attributes and their quality to support accessibility for different VRU communities.

- **Compliance tests** -- to measure the quality. Quality factors might include accuracy, precision, resolution, consistency, currency. Completeness is based on a different set of criteria based on the usage and end-users of the data. For example, the minimum set of attribute information needed to generate cost functions for travel for people using manual vs. motorized wheelchairs differs, as does the set minimum set of requirements for transition plans versus curb management versus trip planning (point vs. linear vs. topologically connected graphs models).

- **Performance descriptions and tests** – to measure the metrics (enumerated values) assigned to an attribute. For example, a measure for the surface may include values from rough to smooth. A major challenge for any standard is to provide guidelines or rules to quantify these values. The performance description and test provide a rubric or algorithm for each qualitative value. Performance tests are one approach for building consistency.

# 4 Stakeholders

The stakeholders who participate in developing, collecting, and using PROW standards include the following categories:

- Standard or specification development organizations
- Data collectors and repository managers
- Users of PROW data

Specific organizations that fall under each category are listed below.

## 4.1 Standards Development Organizations and Community Based Specification Development Organizations

- Open Mobility Foundation
- MobilityData
- Open Geospatial Consortium / ISO Technical Committee 211
- ISO Technical Committee 204
- SharedStreets
- OpenStreetMap
- University of Washington Taskar Center
- SDOs involved in Smart Intersection and Work Zones standards

## 4.2 PROW Data Collection and Repository Managers

- Public jurisdictions including cities, counties, local planning organizations, and states
- USDOT Federal Geographic Data Committees (FGDC)
- OpenStreetMap / OpenStreetMap Foundation (OSMF)

## 4.3 Users of PROW data

**Application Developers who use PROW**

- Curb management tools
- Trip planning/511 tools, e.g., OpenTripPlan
- Transportation planning models
- Transportation management tools

**Users who promote applications or data**

- ADA transition planners
- Crowdsourcing using data collection tools like OpenStreetMap
- VRU communities
- Public agencies (IOOs) including 511 and trip planning services

**Infrastructure Owners / Operators who collect and provide data to applications**

- State, local, territorial, or tribal governments

- Regional authorities, including transit agencies, open-space /parkland managers, etc.
- Building and private park owners
- Private IOOs such as parking, hospitals, mall and other publicly accessible facilities

# 5 Summary

The gaps in standards for PROW is a major hole in describing and representing all transportation networks. As priorities for active and human-powered transportation networks, their expansion, connectivity, and accessibility increase, distribution about those public right of ways are limited different feature definitions, typologies, attributes and quality measures. This paper expands on the gaps from the Task 3 study and provides more insight into the gap for the Task 4 MAT Coordination Plan.

# 6 Appendices

## 6.1 Appendix A: Acronyms

| Acronym | Description |
|---|---|
| ADA | Americans with Disability Act |
| ADAAG | Americans with Disability Act Accessibility Guidelines |
| AI | Artificial Intelligence |
| API | Application programming interface |
| BIM | Building Information Modeling |
| DDOT | District of Columbian Department of Transportation |
| EAR | Exploratory Advanced Research |
| FGDC | Federal Geographic Data Committee |
| FHWA | Federal Highway Administration |
| GTFS | General Transit Feed Specifications |
| IOO | Infrastructure and Operations Operators |
| JSON | JavaScript Object Notation |
| LiDAR | Laser Imaging, Detection, and Ranging |
| MAT | Multimodal and Accessible Travel |
| MATSA | Multimodal and Accessible Travel Standards Assessments |
| OGC | Open Geodata Consortium |
| OMF | Opem Mobility Foundation |
| OS | OpenSidewalks |
| OSI | Open Systems Interconnection |
| OSM | OpenStreetMaps |
| OSMF | OSM Foundation |
| PAM | Personalized Accessibility Map |
| PMP | Pedestrian Mobility Profiles |
| POI | Point of Interest |
| PPNA | Personalized Pedestrian Network Analysis |
| PROW | Public Right-of-Way |
| PWD | Persons with Disabilities |
| PWMD | Persons with Motor Disabilities |
| RSD | Reservations, Scheduling, and Dispatch |
| SDO | Standard Development Organization |
| SME | Subject Matter Experts |
| TCAT | Taskar Center for Accessibility Technology |
| USDOT | United States Department of Transportation |
| USGS | United States Geological Survey |
| UW | University of Washington |
| VRU | Vulnerable Roadway Users |
| VRUSI | VRU Safety Index |

| | |
|---|---|
| W3C | World Wide Web Consortium |
| XML | eXtensible Markup Language |

## 6.2 Appendix B: Summary of Interviews with Stakeholders

### 6.2.1 Open Mobility Foundation

Two members of the Open Mobility Foundation (OMF) were interviewed to learn more about the organization’s future efforts, transitioning needs, and opportunities to advance the Mobility Data Specification (MDS) as a formal standard. The group recognizes that Curb Data Specifications (CDS) is going to be a critical component of shared streets concepts and the deployment of micromobilitysuch as dockless electric scooters. OMF is primarily focusing on establishing communication channels between the public agencies and the operators with standardized data that provides information related to mobility conditions occurring on the public rights-of-way.

Currently, OMF is not essentially designed as a public-facing standard but rather focuses on device operators and those who create policy impacting device operators and data scientists. MDS 2.0 is expected to be released soon and includes four modes total: 1) micromobility, 2) passenger services, 3) car-share, and 4) delivery robots. In lessons learned with the deployment of TNCs, if data is not collected at the start, the data may never be retrieved. Therefore, many public agencies nationwide are hoping to promote Curb Data Specification (CDS) and other data specifications earlier in the deployment process in the future.

Since vendors often have proprietary data, it makes it difficult for integration among public agencies. As a result, MnDOT, for example, is exploring the possibility of leveraging procurement processes to require vendors to use specific data specifications for interoperability and integration purposes. This would encourage the transit and micromobility vendors to share data with one another. It was also suggested that the federal government (e.g., USDOT) could assist by requiring or advising as a best practice for recipients to have its vendors adopt standards in their procurement processes. Additionally, specification working groups could benefit from grant funding to continue to develop these data tools and specifications.

### 6.2.2 OpenSideswalks (University of Washington)

The Taskar Center for Accessibility Technology (TCAT) at the University of Washington developed OpenSidewalks (OS) to close the existing gaps in data related to key roadway attributes associated with sidewalks. Specifically, OS seeks to establish standards for essential transportation network components such as sidewalks, curbs, crossings, and street furniture. In an interview conducted with UW, several topics were discussed including the background, characteristics, downstream applications, deployment sites, success stores, existing gaps, and next steps related to the continued advancement and development of OS.

TCAT’s interest in developing AccessMaps, a tool designed to help persons with disabilities navigate the urban environment by providing customized accessible pedestrian routes while accounting for physical mobility limitations, was to develop a trip planning tool that can reflect various personal preferences and abilities such as wheelchair users compared to a visually impaired person. TCAT researchers determined that there are inadequate existing data collection methods related to pedestrian mobility. Namely, the lack of existing data standards exacerbates the widespread issue surrounding existing data collection efforts associated with sidewalks and the public right-of-way being incompatible and/or insufficient for maximizing trip planning tools’ ability to better support pedestrians and persons with disabilities equitably.

In TCAT's experiences, stakeholders are not willing to invest into public right-of-way data collection which leads to crowdsourcing and volunteer efforts being the key drivers in obtaining this data in present time.

TCAT described OS functionalities to be based on the core requirements for pedestrian mobility targeting specific subpopulations (e.g., persons with disabilities) and differential routing for users. Additionally, establishing a definitive network (rather than extrapolating from geospatial data) on sidewalk connectivity and using physical attributes that can be independently verified (rather than crowdsourcing) with sidewalk assessment tools and technologies such as LiDAR. OS is unique in that it is designed to allow stakeholders and users with limited knowledge or subject matter expertise to the public right-of-way or built environment to contribute to the data collection process in a standardized manner. UW's data schema mitigates subjective reasoning by posing specific binary prompts for data collection instead of questions such as "is this route passable?"

Currently, there is no best path forward in the OSM community in a direction to association roadway and sidewalk attributes at a large scale. Another issue impacting downstream applications of OS is the fact that most cities lack consistency in their built environments and land planning, including the construction of sidewalks and other PROW assets. As a result, the coinciding lack of standardizations associated with Complete Streets, Vision Zero, and other similar concepts continues to be an existing gap in advancing the OS application. TCAT is still working collectively to improve the reliability of associating the sidewalk conditions for various use cases and supporting the user's transitions from urban environments to indoor settings.

Successful pilots of data collection with OS includes King County Metro Transit with WSDOT expecting to soon deploy OS statewide. Regarding SDOs, OS seeks to continue to work with curb management specification/standards as it continues to make OS more robust.

### 6.2.3 Bureau of Transportation Statistics / USGS Transportation Theme Lead

In an interview with the BTS USGS Transportation Theme Lead, several topics were discussed including defining public right-of-way and sidewalk data, related specifications and standards, PROW data attributes, associating PROW layers with road networks, applications of PROW data, and stakeholders of PROW datasets. PROW was described as a jargony terminology and preferred to use the common phrase of "sidewalks" and argues that pathways may be more accurate as it captures pedestrian travel along plazas, alleyways, etc. At the time the interview was conducted, the project was only about 6 months into the process of gathering research and developing an approach. Currently, the project team is still learning and establishing partnerships. While there is no differentiation between pathways along plazas versus sidewalks, this is expected to change overtime.

The lead noted that CurbLR, GTFS-Flex's Pathways component and OSM are notable standards for sidewalk data. In particular, CurbLR is effective for shared streets while GTFS is the most recommended due to its affordability, efficacy, and current interoperability. The ultimate vision of the department is to adopt ISO standards whenever possible in hopes of providing wayfinding navigation support to persons from bed to desk. The latter, indoor navigation is especially challenging to establish to create the connected network. Due to the varying project purposes and organizational missions, PROW and sidewalk data attributes have varied greatly in previous efforts.

Unfortunately, limited resources have constrained the BTS from pursuing, collecting, and modeling sidewalk attributes. Currently, they plan to create a working group of stakeholders because top-down efforts to develop standards are not as successful as community-driven efforts such as GTFS or the Work Zone Data Exchange. Other USDOT programs working in parallel with the collection of PROW datasets includes Complete Streets, the cycling network, and ADA compliance. A metadata draft consisting of measures on attributes and datasets was shared by the lead.

### 6.2.4 FHWA Exploratory Advanced Research (EAR) Program

The efforts of the Exploratory Advanced Research group begun around 2008 with initial projects focusing on the cost efficacy, localization, and positioning of connected vehicles when researchers were inquiring on leveraging the technology for pedestrians. By 2014, the organization had three projects exploring assistive wayfinding technologies with vision impaired individuals at the forefront. In 2019, EAR funded several projects to follow up on mapping gaps, which included advanced technology for pedestrian mapping, airport facility navigation in the interests of the FAA, and securing funding. Key stakeholders and uses for standards identified by EAR includes public facilities (e.g., hospitals, government facilities, airports), vulnerable communities, and SW vendors (e.g., map makers and tools to generate floor plans and constructions (facilities and sidewalks).

EAR recognizes several existing approaches for collecting and storing sidewalk data but cost and scalability continues to be two critical limitations due to a lack of automation to increase the production of data collection, data cleaning and analysis, and transformation of the data from latitude/longitudinal and DOT linear referencing systems.

Currently, there are no next steps because there is a lack of investment and therefore no business case to support advancement. It was suggested to look into other USDOT related work, including digital infrastructure with John Corbin (FHWA) and Volpe, as well as civil rights and professionals assisting or reviewing ADA transition plans.

- List of presenters that we considered for the workshop:
  - Presented at workshop
    - Municipalities we considered to provide local perspective:
      - Medford, MA (here and here)
      - *Austin, TX Sidewalk Program (here, Justin Norvell and John Eastman, john.eastman@austintexas.gov, justin.norvell@austintexas.gov)
      - Lebanon, TN – not super flashy, but might be interesting to have a smaller community? (here, here, and here).
      - Cambridge, MA (Melissa Miguel, mmiguel@cambridgema.gov)
      - Durham, NC (sidewalk inventory)
    - Academics
      - Hao Tang at City College of New York, who received a related NSF award, NSF; Award Search: Award # 2131186 - CISE-MSI: DP: HCC: Training a Virtual Guide Dog for Visually Impaired People to Learn Safe Routes Using Crowdsourcing Multimodal Data.

- *Wesley Marshall, UC Denver, https://www.mountainplains.org/research/details.php?id=476
- *Yochai Eisenberg, University of Illinois at Chicago

## 6.3 Appendix C: Annotated Bibliography of Recent Research on PROW

- Chang, Carlos M., Marketa Vavrova, and Syeda Lamiya Mahnaz. "Integrating Vulnerable Road User Safety Criteria into Transportation Asset Management to Prioritize Budget Allocation at the Network Level." *Sustainability* 14.14 (2022): 8317. - https://www.mdpi.com/2071-1050/14/14/8317#B16-sustainability-14-08317

There are several safety indices developed by governmental associations, researchers, and transportation agencies to assess VRU safety. The Vulnerable Road User Safety Index (VRUSI) is adopted as part of the methodology. VRU expresses the need for road user safety and considers the level of comfort, traffic stress, and risk of facilities. VRUSI was developed to identify high risk safety areas for pedestrians at intersections. The higher the VRUSI, the higher the risk for pedestrians.

Equation (1) calculates the VRUS: VRUSI =Σ (PLOC + PLTS + Ped ISI) where:

- VRUSI—Vulnerable Road User Safety Index;
- PLOC—Pedestrian Level of Comfort;
- PLTS—Pedestrian Level of Traffic Stress;
- Ped ISI—Pedestrian Intersection Safety Index.

- Darvishy, Alireza, Hans-Peter Hutter, and Roland Mosimann. "Towards personalized accessible routing for people with mobility impairments." Computers Helping People with Special Needs: 18th International Conference, ICCHP-AAATE 2022, Lecco, Italy, July 11–15, 2022, Proceedings, Part I. Cham: Springer International Publishing, 2022.

This paper describes a methodology for collecting PROW data using a combination of automated, semi-automated, crowd-based, and field-based methods for OSM applications.

- Darko, Justice, et al. "Adaptive personalized routing for vulnerable road users." *IET Intelligent Transport Systems* 16.8 (2022): 1011-1025. (https://www.researchgate.net/publication/360008073_Adaptive_personalized_routing_for_vulnerable_road_users?sequence=3)

Discusses the sidewalk accessibility factor selection and related algorithms used for VRUs. This research presents an adaptive and personalized routing model that enables individuals with mobility impairments to save their route preferences to a mobility assistant platform. The proactive approach based on anticipated user need accommodates vulnerable road users' personalized optimum dynamic routing rather than a reactive approach passively awaiting input. Most currently available trip planners target the general public's use of simpler route options prioritized based on static road characteristics. In this study, the vulnerable road user mobility problem is modeled by accommodating personalized preferences changing by time, sidewalk segment traversability, and the interaction between sidewalk factors and weather conditions for each segment contributing to a path choice. The developed reinforcement learning solution presents a lower average cost of personalized, accessible, and optimal path choices in various trip scenarios and superior to traditional shortest path algorithms (e.g., Dijkstra) with static and dynamic extensions.

- Ershov, Igor. "ARPA: Accessibility-focused Route Planning Assistant." (2021). - (https://www.scss.tcd.ie/publications/theses/diss/2021/TCD-SCSS-DISSERTATION-2021-033.pdf)

Building upon this established research, this dissertation aims to find out to what extent is it possible to create a routing algorithm that can provide routing to walking impaired persons, taking into account their specific needs, showing them the accessibility information for each step of the route while also letting them have control of the final route, using publicly available datasets for accessibility information. To achieve this, a customizable walking-focused routing algorithm that provides an individualized route that addresses their needs is presented. The accessibility information is gathered from the OpenStreetMap project. Users are prompted with questions about their needs, and the answers will then be used as weights for the A* algorithm used when creating the route. When making a route, all the accessibility information used will be shown to the user to account for missing or unreliable information. Based on this additional information, the user can veto specific road parts they do not feel comfortable taking and get offered alternative solutions until a satisfactory route is found. ***Appendix B – Contains constants and values used in the routing function***.

- Freemark, Yonah, Peace Gwam, and Eleanor Noble. "Redefining Walkability: Examining Equity and Creating Safer Streets for All in DC." (2022). (https://www.urban.org/sites/default/files/2022-04/Redefining%20Walkability.pdf)

Research suggests examining overall crashes, driver fatality score, pedestrian injury score, bicyclist injury score, high traffic score, high speeds score, road exposure score in the PROW in addition to:

i. ***Access –*** Job Scores, Schools Score, Bus Transit Score, Metro Transit Score, Parks Score, Libraries Score, Hospitals Score, Farmer's Market Score
ii. ***Environment –*** Air quality score, Heat score, Vegetation Score, Noise Score
iii. ***Policing –*** Police stop score, Nonviolent nontraffic Police Stop Score,
iv. Infrastructure – Neighborhood Sidewalk Accessibility Score, Illegal Dumping Score, Sidewalk Repairs Score, Street light coverage score
v. ***Safety –*** Overall crashes score, Driver Fatality Score, Pedestrian Injury Score, Bicyclist Injury Score, High Traffic Score, High Speeds Score, Road Exposure
vi. ***Equity*** – Income, Race, PwD

- Gharebaghi, Amin, et al. "User-specific route planning for people with motor disabilities: A fuzzy approach." *ISPRS International Journal of Geo-Information* 10.2 (2021): 65. (https://www.academia.edu/73361897/User_Specific_Route_Planning_for_People_with_Motor_Disabilities_A_Fuzzy_Approach)

Routes should consider PWMD's personal capabilities as well as sidewalk-network conditions. In this paper, we propose a novel approach for computing a user-specific route for PWMD. Such a route is personalized based on the user's confidence to deal with obstacles such as slopes, uneven pavement, etc. We show how user-reported confidence levels could be used to aggregate sidewalk conditions in a routing model to offer user-specific routes. The proposed methodology was developed using a fuzzy approach and is evaluated by manual wheelchair users in Quebec City.

- Gieschen, Antonia & Roumpani, Flora. *The Alan Turing Institute. Data Study Group Final Report: CityMaaS.* The Alan Turing Institute, 2021. (https://www.turing.ac.uk/sites/default/files/2022-07/the_alan_turing_institute_data_study_group_final_report_-_citymaas.pdf)

Developed a proof of concept for personalized route-planning with accessibility and POIs. For routing, we created a POC for a routing algorithm (”routing engine”) that attempts to avoid obstacles in the form of steep route sections, busy areas, and that can be set to attempt to minimize overall distance or up/down elevation change, and maximize number of accessible POIs nearby to the route. For this purpose, we incorporated the open-source routing engine OSMnx with LIDAR data (point elevation data) for detecting elevation changes as well as the provided OSM POI data which contain information on obstacles. We developed an algorithm for creating several different wheelchair/walking routes between any two locations and assigning scores on four different metrics to these. End-users could then choose from the routes according to their own needs by comparing the values along the different metrics.

- Hosseini, Maryam, et al. "Towards Global-Scale Crowd+ AI Techniques to Map and Assess Sidewalks for People with Disabilities." *arXiv preprint arXiv:2206.13677* (2022). (https://arxiv.org/pdf/2206.13677.pdf)

This paper describes a four-phase approach to creating a sidewalk visualization of topology, surface materials, and accessibility. The first phase requires the extraction of pedestrian pathways from orthorectified satellite image tiles. The next phase converts the auto-labeled sidewalk, footpath, and crosswalk rasters into georeferenced polygons and centerlines. In the final two phases, an accessibility score is calculated based on inferences on the surface material and with crowdsourced accessibility information, respectively speaking.

- Karimi, Hassan A., Lei Zhang, and Jessica G. Benner. "Personalized accessibility map (PAM): A novel assisted wayfinding approach for people with disabilities." *Annals of GIS* 20.2 (2014): 99-108.

A precursor to the research done for AccessPath listed above. Dr. Karimi with the University of Pittsburgh identified routing criteria for people with disabilities and other data requirements (See Tables 3 and 4 on page 6).

- Luaces, Miguel R., et al. "Accessible routes integrating data from multiple sources." *ISPRS International Journal of Geo-Information* 10.1 (2020): 7(***https://www.mdpi.com/2220-9964/10/1/7***)

The article describes the processes of building a network of pedestrian infrastructures from the OpenStreetMap information (i.e., sidewalks and pedestrian crossings), improving the network with information extracted obtained from mobile-sensed LiDAR data (i.e., ramps, steps, and pedestrian crossings), detecting obstacles using volunteered information collected from the hardware sensors of the mobile devices of the citizens (i.e., ramps and steps), and detecting accessibility problems with software sensors in social networks (i.e., Twitter). The information system is validated through its application in a case study in the city of Vigo (Spain).

- Ntakolia, Charis, George Dimas, and Dimitris K. Iakovidis. "User-centered system design for assisted navigation of visually impaired individuals in outdoor cultural environments." *Universal*

*Access in the Information Society* (2022): 126.(https://link.springer.com/content/pdf/10.1007/s10209-020-00764-1.pdf)

In this paper, we present a novel system for VIIs and its design considerations, which follow a UCD approach to determine a set of operational, functional, ergonomic, environmental, and optional requirements of the system. Both VIIs and non-VIIs took part in a series of interviews and questionnaires, from which data were analyzed to form the requirements of the system for both the on-site and remote use. The final requirements are tested by trials and their evaluation and results are presented. The experimental investigations gave significant feedback for the development of the system, throughout the design process. The most important contribution of this study is the derivation of requirements applicable not only to the specific system under investigation, but also to other relevant SASs for VIIs. Table 11 present a summary of the (216) requirements that have been identified in the literature review regarding smart assistive systems for visual impaired individuals.

- Nunes, Ana Sofia Pereira. *Healthy Track: healthy route recommendation*. Diss. 2022. (https://repositorio.ul.pt/bitstream/10451/53512/1/TM_Ana_Nunes.pdf)

An interesting document that highlights the development of a route recommendation algorithm that incorporates air quality and proximity to green spaces.

- Park, Hyoshin, et al. *A Personalized Trip Planner for Vulnerable Road Users*. No. CATM-2021-R1-NCAT. North Carolina A&T State University. Transportation Institute. Center For Advanced Transportation Mobility, 2021.). https://trid.trb.org/view/1884859

This research presents an adaptive and personalized routing model that enables individuals with disabilities to save their route preferences to a mobility assistant platform in Boston. The proactive approach based on anticipated user need accommodates vulnerable road users' personalized optimum dynamic routing rather than a reactive approach passively awaiting input. Most of the currently available trip planners target the general public's use of simpler route options prioritized based on static road characteristics. These static normative approaches are only satisfactory when conditions of intermediate intersections in the network are consistent, a constant rate of change occurs per each change of the segment condition, and the same fixed routes are valid every day regardless of the user preference. In this study, we model the vulnerable road user mobility problem by accommodating personalized preferences changing by time, sidewalk segment traversability, and the interaction between sidewalk factors and weather conditions for each segment contributing to a path choice. The developed reinforcement learning solution presents a lower average cost of personalized, accessible, and optimal path choices in various trip scenarios and superior to traditional shortest path algorithms (e.g., Dijkstra) with static and dynamic extensions.

- Sinagra, Eric, and Pathway Accessibility Solutions. *Development of AccessPath: A pedestrian wayfinding tool tailored towards wheelchair users and individuals with visual impairments; Phase 1 Final Report*. No. FHWA-JPO-21-846. United States. Department of Transportation. Federal Highway Administration, 2020. (https://rosap.ntl.bts.gov/view/dot/55240/dot_55240_DS1.pdf)

The overall goal of this project was to develop a mobile app that provides pedestrian navigation and directions to people with disabilities based on their abilities to navigate sidewalks and pedestrian pathways. Typical travel apps neither focus on pathway quality nor consider the user's comfort navigate those routes. To that end, AccessPath provides real-time step-by-step directions customized to a user's comfort settings. Each pedestrian has unique abilities and disabilities, and so their routes must be customized to their individualized needs. The app provides the ability to submit reports about hazards, construction, accessible entrances, and the level of accessibility indoors. This enables people with disabilities to contribute data to help others as well as understand important accessibility features about points of interest. The app provides other important features such as favorites, alerts, recent paths, What's Around Me, and VoiceOver/TalkBack compatibility. ***Chapter 2 – Contains Algorithm Development for the App. Chapter 3 – Contains Data Collection and Implementation Methods (Pathway Attributes).***

- Zimmermann-Janschitz, Susanne, et al. "Independent mobility for persons with VIB using GIS." *Journal of Enabling Technologies* 15.3 (2021): 159-174. (https://www.emerald.com/insight/content/doi/10.1108/JET-03-2020-0014/full/html)

In this paper, special attention is given to intersections, corners, and public open space (Bentzen et al., 2017; Coughlan and Shen, 2013). This is necessary to give detailed turn-by-turn directions at crucial parts of a route. Intersections differ in their infrastructure, like the existence of zebra crossings, traffic lights, tactile pavement, or auditory and tactile signals. The infrastructure of intersections is represented both in linear features (crossing) of the intersection as well as in point features (lights and pavement). The equipment is added as attributes to the crossings in the database. After modeling zebra crossings with linear features from point-based information and assigning street names to crossings using the spatial join tool in ArcGIS, the different settings of intersections are examined. If, e.g., an intersection has a traffic light, a tactile pavement but no auditory signal, the text in the directions will be "traffic light with tactile pavement." In suburban areas, indicated crossings are missing due to a dispersed and more rural settlement. In this case, additional non-corner crossings were defined in the database to reduce walking distance. These are modeled based on availability and distance of crossings, respectively, intersections and speed limit. The final network data set, which serves as basis for the routing algorithm, consists of the following: sidewalks attributed with names of adjoining streets, usage type of streets and surface of the sidewalk/street, crossings attributed with name of street to be crossed, and additional equipment of the crossing.

### 6.4 Appendix D: Comparison of attributes and conditions

The following information provides information on the attributes and conditions (metrics) identified by different research sources.

| **Source** | **Requirement** | **Description** | **Reference Value** |
|---|---|---|---|
| Accessible Path Finding for Historic Urban Environments: Feature Extraction and Vectorization | Width | Assuming that the sidewalk width is uniform along the analyzed segment, and that the sidewalk is parallel to the roadway line, width was computed by exploiting the difference between the further and closer point of the sidewalk respect the roadway line (taking care | ≥ 0.90 m |

| | | | |
|---|---|---|---|
| From Point Clouds (Treccani, Diaz-Vilarino, Adami, 2022)[32] | | of eventual noisy points); the value was then rounded to the closer 5 centimeters. | |
| | Sidewalk-road Relative Elevation: | If present, relative elevation was computed by exploiting the difference between the average Z-coordinate value of sidewalk points and road points in the proximity of sidewalks. | ≤ 1% |
| | Transverse and Longitudinal Slopes: | After having computed the Principal Component Analysis (PCA) of sidewalk points, the slopes of the longer eigenvectors represented the slope of the sidewalk itself. | ≤ 5% |
| | Paving Surface Material | Implementing a machine learning tool, it was possible to predict the paving material; the case study tested the pavings and they were only of two types: bricks or stone | ≤ 0.025 m |

| **Source** | **Requirement** | **Description** | **Recommended value** | **User Weights Value** |
|---|---|---|---|---|
| ARPA: Accessibility-Focused Route Planning Assistant (2021)[33] | Sidewalk | Presence of a dedicated footpath | Pedestrian-only | |
| | Surface | | | *.75* |
| | (Sidewalk) Inclines | Gradient incline of sidewalk/road segments and ramps | <3-6% (user defined, maxIncline = 6) | *.5* |
| | (Sidewalk) Width | Width of the sidewalk/road | Comfortably wide (user defined, minWidth = 1) | .5 |
| | Curbs | Height of the curb with respect to the road level | <3cm | .25 |
| | Noise | Level of noise along the sidewalk/road | Low | |
| | Steps | Presence of steps without an access ramp | None, user defined | 1 |
| | Handrails | Availability of handrails at a ramp | At every ramp | |
| | Street crossings | Type of street crossing | Supervised (Traffic lights) | 0 |

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[32] Treccani, Diaz-Vilarino, Adami (2022) isprs-archives-XLVI-2-W1-2022-199-2022_opt.pdf (polimi.it)
[33] ARPA (2021) https://www.scss.tcd.ie/publications/theses/diss/2021/TCD-SCSS-DISSERTATION-2021-033.pdf

| | | | | |
|---|---|---|---|---|
| | Car traffic | Amount of car traffic on the adjacent road | Low | |
| | Amenities | Presence of amenities such as accessible parking and toilets | Frequent | |
| | Street furniture | Presence of street furniture such as benches | Frequent | |
| | Street lighting | Presence of lighting on the sidewalk/road | Well lit | 0 |

| **AccessPath Attributes**[34] | **Field** | **Description** | **Units/ Data Range** |
|---|---|---|---|
| Pathway Attributes | FID | Unique ID for pathway | None |
| | Picture_Di | Image distance from the beginning of the run | Feet |
| | Max_Roughn | Maximum roughness for that segment | mm/m |
| | Max_Runnin | Maximum running slope for that segment | Degrees |
| | Max_Cross_ | Maximum cross slope for that segment | Degrees |
| | Max_Trips_ | Maximum tripping hazard over 0.25 inches for that segment | Inches |
| | Num_Trips | Number of tripping hazards greater than or equal to 0.25 inches | None |
| | Max_Dep_in | Maximum depression over 0.25 inches for that segment | inches |
| | Num_Dep | Number of depressions over 0.25 inches for that segment | None |
| | Overall_Le | Total length of a particular run (same file name) | Feet |
| | Segment_RA | Route Accessibility Index (RAI) of that segment | None |
| | Run_RAI | Average RAI of all the segments of a particular run | None |
| | Width | Width of particular segment | Inches |
| | Image_URL | URL for image | None |
| | File Name | File name of a particular run | None |
| | Picture Name | Unique ID for image | None |
| | Flags | Subjective hazards flagged during data collection | None |
| | PictureFile | HTML to make image appear in popup window | None |
| | Type | Segment type (sidewalk, crosswalk, construction, etc.) | None |

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[34] Development of AccessPath: A pedestrian wayfinding tool tailored towards wheelchair users and individuals with visual impairments (2020)- https://rosap.ntl.bts.gov/view/dot/55240/dot_55240_DS1.pdf

| | | | |
|---|---|---|---|
| | Street Name | Name of corresponding street parallel to segment | None |
| | Length | Length of segment | Feet |
| Curb Ramp Attributes | FID | Unique ID for each curb ramp | N/A |
| | Latitude | Latitude of curb ramp point | Decimal degrees |
| | Longitude | Longitude of curb ramp point | Decimal degrees |
| | Detectable Warning | Does it have detectable warning | Yes/No |
| | Lippage (1-Poor, 3-Good) | Quality of transition from street to curb ramp or curb ramp to sidewalk | 1-3 |
| | Width (1-Poor,3-Good) | Quality of width of curb ramp | 1-3 |
| | Slope (1-Poor,3-Good) | Quality of running or cross slope of curb ramp | 1-3 |
| | Obstructions | Are there obstructions on or near the curb ramp | Yes/No |
| | Overall Condition (1-Poor,3Good) | Overall quality of curb ramp | 1-3 |
| | CreationDate | Creation date of this curb ramp | Date |
| | Creator | Creator of this curb ramp on map | N/A |
| | EditDate | Date data was last edited | Date |
| | Editor | User who last edited data | N/A |
| | ImageURL | URL to access image | N/A |
| | Passability | Is the curb ramp passable or not | Passable/Not Passable |
| Transit Attributes | FID | Unique ID for each transit stop | |
| | Latitude | Latitude of transit stop | |
| | Longitude | Longitude of transit stop | |
| | StopID | Unique ID given by port authority for each transit stop | |
| | Stop_Name | Name/Location of stop | |
| | CleverID | Unsure (taken from port authority) | |
| | Direction | Direction into or out of downtown | |
| | Route_coun | Unsure (taken from port authority) | |
| | Timepoint | Unsure (taken from port authority) | |
| | Routes | Transit routes that stop at this location | |
| | PatternSeq | Unsure (taken from port authority) | |
| | Mode | Mode of transportation this stop supports | |
| | Shelter | Type of shelter | |

| | | | |
|---|---|---|---|
| | Stop_type | Type of transit stop | |
| | On_avwk_CY | Unknown (taken from port authority) | |
| | Off_avwk_C | Unknown (taken from port authority) | |