Connecting Pedestrians with Disabilities to Adaptive Signal Control for Safe Intersection Crossing and Enhanced Mobility

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16. Abstract

This report summarizes work performed under contract #DTFH6117C0001 toward the development of *PedPal*, a prototype mobile (smartphone) app designed to assist pedestrians with disabilities when crossing the street at signalized intersections. *PedPal* interacts directly with the traffic signal system controlling the intersection to communicate both crossing intent (eliminating the need to seek out and push a pedestrian call button) and personalized crossing constraints (ensuring sufficient time is allocated for the pedestrian to cross). Future versions of *PedPal* will incorporate the ability to monitor crossing progress and to dynamically extend the crossing time in situations where more time is needed to safely get across, as well as provide enhanced capabilities aimed at improving crossing efficiency and general mobility.

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Table of Contents

Chapter 1 Overview **1**
1.1 System Engineering Approach 1
1.2 System Overview – Year 1 2
1.3 System Overview – Year 2 3
1.4 Report Structure 5
Chapter 2 System Specification **6**
2.1 Stakeholder Engagement & Concept of Operations 6
2.2 System Requirements 10
2.3 System Design 11
Chapter 3 System Development **12**
3.1 Intersection Infrastructure Subsystem 12
3.1.1 SURTRAC Adaptive Traffic Signal Control System 13
3.1.2 Traffic Signal Controller 14
3.1.3 DSRC Roadside Unit 14
3.1.4 3G/4G Wireless Communication Unit 14
3.1.5 Traditional Intersection Infrastructure 15
3.1.6 Intersection Localization Infrastructure 15
3.2 Pedestrian Device Subsystem 15
3.2.1 *PedPal* Mobile App (Year 1) 18
3.2.2 *PedPal* Mobile App (Year 2) 20
Chapter 4 System Evaluation **27**
4.1 Field Test Protocol 27
4.2 Field Test Location 28
4.3 Participants 30
4.3.1 Demographics 31
4.3.2 Intersection Crossing Tendencies 32
4.3.3 Smartphone experience 32
4.3.4 Crossing challenges 33
4.3.5 Desired features in a street crossing app 34
4.4 Results 35
4.4.1 Qualitative Assessment and User Experience 35

4.4.2 Intersection Crossing Performance in the Field ... 41
4.4.3 *PedPal* Robustness and Limitations ... 42
4.5 Data Management ... 43
Chapter 5 Next Steps ... 44
5.1 Additional Prototype Refinement and Hardening ... 44
5.2 Technology Deployment ... 46
Chapter 6 References ... 48
Appendix A. System Requirements ... 49
Appendix B. Requirements to Use Case Mapping ... 64
Appendix C. *PedPal* User Manual ... 73

List of Figures

Figure 1-1: Safe Intersection Crossing System - Phased Approach 2
Figure 2-1: Physical Architecture of the Safe Intersection Crossing System 11
Figure 3-1: Physical Architecture of the Intersection Infrastructure 12
Figure 3-2: Intersection Infrastructure Equipment 13
Figure 3-3: Physical Architecture of the Pedestrian Device Subsystem 17
Figure 3-4: PDS Device Type 1 17
Figure 3-5: PDS Device Type 2 18
Figure 3-6: *PedPal* Mobile App UI Screens – User Settings... 19
Figure 3-7: *PedPal* Mobile App UI Screens – Street Crossing Process (Year 1) 20
Figure 3-8: *PedPal* Mobile App UI Screens – Street Crossing Process (Year 2) 22
Figure 3-9: Algorithm for SURTRAC response to an SRM……………………………..……24
Figure 3-10: *PedPal* Mobile App UI Screens – Route Following…………………..…………..25
Figure 4-1: The Intersection of Centre Avenue and Cypress Avenue……………………..…....29
Figure 4-2: A Representative intersection crossing tour at test location……..…………………30
Figure 4-3: *PedPal* impact on vision-impaired pedestrians……………………………………...41
Figure 4-4: Crossing Performance by Disability Type…………………………….…………42

List of Tables

Table 2-1: Desired Changes / User Needs 7
Table 2-2: List of Use Cases 9
Table 4-1: Participant Demographics.. 31
Table 4-2: User Street Crossing Practices and Tendencies 32
Table 4-3: User Familiarity with the iPhone 33
Table 4-4: Most useful *PedPal* features……………………………………………………...…36
Table 4-5: Improvements over Last Year….…………………………………………………37
Table 4-6: User rating of *PedPal*'s effectiveness………………………………………………37
Table 4-7: Types of safety issues that required intervention……………………………………43
Table 6-1: Requirements Traceability Matrix 49

Chapter 1 Overview

In this report, we detail the progress that has been made during the two years of the Department of Transportation (DOT) Accessible Transportation Technology Research Initiative (ATTRI) project # DTFH6117C00014 titled *Connecting Pedestrians with Disabilities with Adaptive Signal Control for Safe and Efficient Intersection Crossing*. This project has aimed to develop a mobile app that enables pedestrians with disabilities to more safely and more efficiently cross signalized intersections. The technology concept under investigation is a smartphone app capable of interacting directly with the traffic signal control system at the intersection, to allow the pedestrian to communicate crossing intent and issue requests for sufficient crossing time, to receive an extended crossing phase duration, to receive feedback if movement outside of the crosswalk is detected during crossing, and to dynamically extend the crossing phase duration if slower than expected crossing progress is observed during crossing.

To provide this last capability, along with other more advanced capabilities aimed at increasing mobility such as anticipating the pedestrian's arrival at the intersection and factoring it into real-time traffic control decisions and utilizing real-time bus information to better synchronize pedestrian arrival times at destination near-side bus stops, the technical approach includes integration of the mobile app with SURTRAC, a real-time adaptive traffic signal system designed specifically for multi-modal urban road networks [10,11,12]. To maximize accessibility to and use of real-time vehicle information, a uniform approach to connectivity based on (Year 1) Dedicated Short-Range Communication (DSRC) and (Year 2) 3G/4G wireless communications has been taken. A universal design approach has been taken to the mobile app's user interface, and our broad goal has been to aid individuals across a spectrum of disabilities, including visually-impaired users, wheelchair users, deaf users, users with other mobility difficulties and (ultimately) individuals with cognitive disabilities.

1.1 System Engineering Approach

Each year of the two-year system engineering project was structured into three phases as depicted in Figure 1-1 below: (1) system specification, (2) system development and testing, and (3) system evaluation. In the subsequent sections of this chapter, we summarize the approach, work activities and outputs of the systems specification phase.

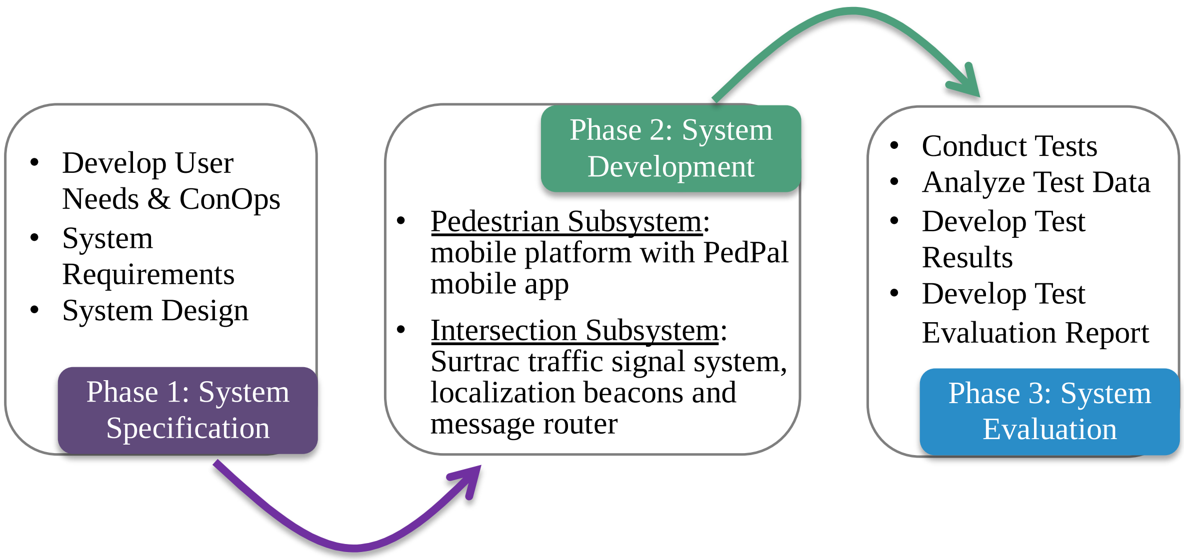

Figure 1-1: Safe Intersection Crossing System - Phased Approach

1.2 System Overview – Year 1

During the first year of the project, research focused on identification and analysis of user requirements, design and development of basic safe intersection crossing capabilities, and initial user testing of the prototype *PedPal* mobile app that was produced in Year 1. To jumpstart the development of user requirements, a workshop was held in October 2017 with 20+ members of the local disability community to describe the proposed project, present initial design ideas and solicit inputs from attendees on what features and capabilities would be most valuable in the target mobile app. These inputs were subsequently used to shape the Year 1 Concept of Operations specification [1] and eventually transformed into a System Requirements Matrix. This matrix, along with the supporting System Requirements specification [2], was then used to inform the detailed system design, which was specified in the project's System Design [3].

The project's Year 1 development efforts resulted in an initial prototype mobile app for safe intersection crossing called "*PedPal*". The initial *PedPal* mobile app was implemented on a hardware platform that consisted of an iPhone8 coupled with an Arada Locomate ME DSRC radio sleeve. It provided basic assistance to pedestrians with disabilities when crossing the street. Upon approach to the intersection, the *PedPal* mobile app received both Map Data (MAP) and Signal Phase and Timing (SPaT) messages from the intersection, which provided the app with the information necessary to present crossing options and timing information to the User. Upon selection of a crossing direction, the *PedPal* mobile app issued a crossing request to the intersection (thereby eliminating the need to locate and push a pedestrian call button if one existed), along with a personalized crossing duration that was sufficient to ensure safe crossing for the User. If the request was for a future crossing phase, the extended duration was guaranteed to be enforced on the next crossing cycle; if the request was for the current crossing phase, then the signal system determined whether the request was granted or was received too late in the crossing phase, in which case the user would have to wait for the next crossing cycle. This functionality was, and still is, provided through both a visual display and via voice over for visually impaired, and the *PedPal* mobile app takes advantage of all native accessibility features provided by the iPhone8. We anticipate that a third haptic modality will be introduced in a future version to accommodate individuals who are both deaf and blind.

To evaluate the potential of the *PedPal* mobile app and to obtain feedback for refinement and extension, a series of user field tests were conducted at the intersection of Centre Avenue and Cypress Avenue in the east end of Pittsburgh PA. This intersection is part of the Pittsburgh deployment of the SURTRAC traffic control system and has a DSRC Road Side Unit (RSU) installed, and served as the site for capability demonstrations during the *PedPal* mobile app development process. For the Year 1 field evaluation, 12 individuals from the local disability community were recruited, and this set of participants included visually impaired users, wheelchair users, elderly individuals and a deaf individual. Each was asked to carry out a series of street crossing tours around the intersection with and without the assistance of the *PedPaI* mobile app, after undergoing training with the app. Each participant was asked to complete two surveys, one before the field test to understand specific user needs and challenges for purposes of customizing the training, and one afterwards to get the participant's feedback on the app's utility and suggestions for improvement. Information was also recorded for each crossing and a log of events (including messages sent and received) was collected for further analysis. Overwhelmingly, the responses from participants were enthusiastic about the app and its potential, even though it was clear that the app would be much more useful to individuals with visual and mobility disabilities than it would be for deaf individuals or individuals using powered wheelchairs. Several great suggestions for improving the *PedPal* mobile app were provided[1], which became one focus of continued development in Year 2 of the project, along with expansion of the app's current capabilities.

1.3 System Overview – Year 2

The second year of the project focused on adding several planned features, incorporating feedback from participants, and addressing technical challenges encountered during the Year 1 field evaluation. The Year 1 system engineering specifications [1,2,3,4] were used to shape the project's Year 2 Concept of Operations specification [6], which in turn provided the foundation for the Year 2 System Requirements Matrix. This matrix, as detailed in the System Requirements specification [8], was then used to inform the specification of the project's System Design [9].

The Year 2 development plan targeted four broad objectives: (1) addressing technical difficulties encountered with use of the DSRC sleeve communication technology in the Year 1 field test experiments, (2) simplification and improvement of the *PedPal* user interaction experience, (3)

1 These suggestions are documented in the Year 1 Annual Report [6].

to improve the app's localization accuracy to enable corner identification, progress monitoring, and detection of user veering outside of the crosswalk, and (4) expansion of *PedPal* to include capabilities such as use of user route information to enhance mobility.

With regard to *PedPal* communication with the intersection, a second option to DSRC communication was implemented that leverages IP-based data exchange over 3G/4G cellular communication networks. This IP-based communication was indirectly established between the pedestrian device's *PedPal* mobile app and the SURTRAC adaptive traffic signal control system through a remote cloud-based server, which relayed messages to and from the SURTRAC process running at the target intersection via its backhaul communication link. The appropriate SURTRAC process for the data exchange was determined by the server, based on the location information provided by the Pedestrian Device. In addition to providing the establishment and management of the communication bridges between the two communications sessions, the cloud-based server provided any required translation or formatting changes needed to ensure end-to-end connectivity between the *PedPal* mobile app and the SURTRAC signal control system. To the fullest extent possible, both message dialogs and the message structures, formats and content mirrored those used for DSRC communications.

With respect to enhanced mobility, the PedPal mobile app was expanded to enable importing and use of pedestrian route information. Specifically, through communication of expected arrival time information at the intersection in advance of arrival, the SURTRAC process running at the intersection can factor this information into the signal timing plans that are generated so as to streamline pedestrian wait times at the intersection. An API similar to the route exporting format provided by BlindSquare (a popular existing navigation app for vision impaired individuals that could be one source of pedestrian routes in the future) was developed for importing a route into *PedPal*, and necessary extensions to SURTRAC were made to integrate arrival time information about the approaching pedestrian into SURTRAC's predictive model. The Year 2 development plan also included (as a stretch goal) communication of a pedestrian's destination bus stop and bus route to allow the traffic signal system to adjust timing plans to facilitate real-time synchronization with approaching buses. However, although this capability was designed, its implementation remains an objective for future research.

To address the accuracy of the smartphone's native localization service (e.g. GPS, or augmented GPS), Year 2 development included use of additional infrastructure at the intersection, specifically communication with Bluetooth beacons that are positioned at each corner of the intersection. Testing has shown this additional infrastructure to be sufficient to allow accurate corner identification when a user arrives at the intersection, as well as the ability to detect when the user starts and completes a given crossing, and these capabilities have allowed us to greatly simplify user interaction with the *PedPal* mobile app. Further extensions to use triangularization of corner beacons to enable progress monitoring and veer detection will be investigated in future work.

Much like the Year 1 system evaluation, a Year 2 user field test was held to assess the utility and potential of the Year 2 *PedPal* prototype. For this field test, 14 participants were recruited from the local disability community, comprised predominantly of low vision or blind individuals and secondarily of wheel chair users and older mobility-impaired individuals. 9 of these individuals were returning participants from the Year 1 user test, and thus able to also judge improvement over the Year 1 *PedPal* prototype. Crossing trials were conducted at 4 intersections in the vicinity of the same Centre Avenue and Cypress Avenue intersection that was used in Year 1.. Testing was performed using the cellular communication option and with a “Wizard of Oz” simulation of automatic corner identification (which has subsequently been implemented). As in year 1, feedback from users was overwhelmingly positive. Returning users remarked on the simpler user interaction requirements (making it much more usable), very much liked elimination of the extra communication device (the sleeve), and commented on how much smoother and error free use of the mobile app was. Quantitative results were obtained showing the benefits of using the app to reduce total crossing time (through reduction in the number of phase cycles it took to prepare for crossing), and characterizing the robustness of the *PedPal* mobile app’s operation over the entire set of user tests.

1.4 Report Structure

The remainder of this report is organized as follows.

- Chapter 2 summarizes the work performed during the system specification phase of the project.
- Chapter 3 summarizes the Safe Intersection Crossing system development effort, with focus on the development of the *PedPal* mobile app prototype.
- Chapter 4 summarizes the two years of testing and evaluation conducted to assess the *PedPal* mobile app prototype’s efficacy in the field, highlighting the results that were obtained.
- Chapter 5 describes the data management process and procedures used during the project.
- Chapter 6 covers lessons learned and outlines the next steps for the evolution of the Safe Intersection Crossing system and in particular, the *PedPal* mobile app prototype.

Chapter 2 System Specification

2.1 Stakeholder Engagement & Concept of Operations

The process of requirements analysis started with stakeholder engagement and Concept of Operations (ConOps) development and continued with User Requirements analysis and System Design. On October 24, 2017, a workshop was held with members of the local Pittsburgh disability community to introduce the project, present initial design ideas and solicit feedback and requirements from prospective users. The workshop included individuals from several local Pittsburgh organizations in addition to members of the Safe Intersection Crossing project team, including:

- Blind and Vision Rehabilitation Services of Pittsburgh (BVRS)
- Golden Triangle Council of the Blind
- Disability training and technology experts from the University of Pittsburgh
- The Pittsburgh Cultural Trust
- The Western Pennsylvania School for Blind Children (WPSBC)
- The Western Pennsylvania School for the Deaf (WPSD)
- Goodwill Industries

We also subsequently consulted with several additional organizations who were not able to attend the October workshop, including:

- PathVU – PathVU is another recipient of a 2017 ATTRI award for helping to develop ATTRI's wheelchair-based technology.
- University of Pittsburgh Human Engineering Laboratories – The major focus of these laboratories is on technology and services for disabled veterans.
- CMU's Osher Lifelong Learning Institute – to involve the interests of older adults
- The Port Authority of Allegheny County – Since the Port Authority provides a major mode of transportation around the city for individuals with disabilities and is actively exploring the use of DSRC-based communication with SURTRAC controlled intersections, their inputs into the Phase 1 design process were also important.

Based on the feedback received from various stakeholders, a list of user needs was developed and prioritized. These user needs, which were envisioned as features of the proposed system, are given in Table 2-1: Desired Changes / User Needs, along with an indication of the project year in which each feature was introduced. The effectiveness of some of these features ultimately depended on the accuracy of the *PedPal* mobile app localization capability and the data it provided. Based on the Year 1 User test and evaluation activities, enhancements to the baseline localization capability of the smart phone were planned for Year 2. However, due to vendor issues, the equipment to enable these planned enhancements was not received in time for the Year 2 User test and evaluation. As mentioned earlier, however, the ability to automatically identify corners, as well as crossing start and end times, has since been achieved with the use of Estimote BlueTooth beacons installed at the intersection and has been incorporated into the *PedPal* mobile app. Work is ongoing toward extending use of this added infrastructure to effectively monitor crossing progress and veering outside of the crosswalk events. User needs #5 (Positioning and Orienting) and #12 (Incorporating Transit Bus Arrivals) remain as challenges for future research.

Table 2-1: Desired Changes / User Needs

#	Desired Change / User Need	Y1	Y2
1	**Interacting with the Traffic Signal Control System:** Address pedestrians' interface with traffic signals, vehicles, nomadic devices, and automated intersection crossing assistance	X	
2	**Obtaining Real-Time Information about the Intersection:** Information about the intersection, street names, number of streets, and other data that better help the pedestrian visualize and prepare would be very helpful.	X	
3	**Assisting Crossing the Intersection:** Provide guidance, notifications and alerts to assist pedestrians and all users of the transportation system in navigating safely through intersections	X	
4	**Locating and Recognizing the Intersection:** Provide contextual information, including information on which corner, the presence and type of curb cuts at this corner, bus stop locations at the intersection, and presence of traffic islands.		X
5	**Positioning and Orienting:** We expect the above contextual information about the current corner to help pedestrians (especially those with visual disabilities) position and orient themselves for the subsequent crossing.		X
6	**Confirming**: Regular confirmation is very important for people with blindness when crossing the street to ensure the path that's taken is correct, facing correct direction, and not making unsafe mistakes.		X
7	**Customizable Assistance:** Provide flexibility in any assisting tools developed for intersection crossing. For example, if one is traveling a route every day, he/she may not need the same level of details for those intersections as would be needed for less familiar ones. Fewer details could be provided for old routes and more detail for new routes. Similarly, countdown information should be configurable to be presented with varying frequency. Pedestrians with different types of disabilities will prefer different interaction modalities (e.g., voice-over versus visual display) and aspects of each modality choice	X	X

#	Desired Change / User Need	Y1	Y2
	(e.g., voice-over speed, font-size) should also be configurable to specific individual's preferences.		
8	**Supporting Hands-Free Option:** Design the user interaction with the phone so it does not require holding it out constantly. With some of the current apps, if the phone is in someone's bag, the direction he/she gets could differ. There may be a need for a remote to communicate with the app/phone remotely instead of holding it in hand.		X
9	**Interacting with other mobile apps:** it would be very helpful to minimize the number of mobile apps that people with disabilities need to use to navigate to their final destinations safely. If this proposed *PedPal* mobile app could interact with or be integrated with other mobile apps that pedestrians already use, for example BlindSquare or another navigation app providing pre-planned routing, it would make it easier for them to navigate.		X
10	**Supporting Audio Communication:** For blind individuals, this is a critical option to be able to follow directions. Audio communication should be clear, especially for streets that have similar names. Moreover, the communication should be repeatable in case the user misses a step.	X	
11	**Integrating a Pre-planned Itinerary:** It would be additionally helpful to utilize a pre-planned itinerary to minimize the user's time spent assessing navigation routes, and subsequently entering data into the *PedPal* mobile app while in transit.		X
12	**Incorporating Transit Bus Arrivals:** For pedestrians planning to navigate to a transit bus stop and to board a transit vehicle operating on a specific route, it would be helpful if the *PedPal* mobile app could communicate this information to traffic signal control system. The traffic signal control system could then determine (using DSRC based messaging) if the transit route of an arriving transit vehicle matches the pedestrian's desired route, and if needed, adjust the signal phase length(s) to increase the pedestrian's likeliness of boarding the arriving transit vehicle.		X

The primary objective of the ConOps is to communicate with the end user of the system during the early specification stages to ensure that operational needs are clearly understood and the rationale for performance requirements is incorporated into the decision mechanism for later inclusion in the system and lower level specifications. Other objectives are to:

1. Provide traceability between operational needs and the captured source requirements
2. Establish a basis for requirements to support the system over its life
3. Establish a basis for verification planning and system-level verification requirements

4. Generate operational analysis models to test the validity of external interfaces between the system and its environment, including interactions with external systems
5. Provide the basis for computation of system capacity, behavior under/overload, and mission-effectiveness calculations
6. Validate requirements at all levels and to discover implicit requirements overlooked from other sources.

Based on stakeholder feedback, a set of 14 use cases were developed to highlight the features necessary for the prototype and used to shape the project's ConOps specification. They are listed in Table 2-2 below, and readers are encouraged to refer to the project's Year 2 ConOps specification [4] for detailed steps on the 14 use-cases identified for this system. The ConOps also delineates two major subsystems within the Safe Intersection Crossing system, the Intersection Infrastructure Subsystem (IIS), and the Pedestrian Device Subsystem (PDS) which are described later in this report.

Table 2-2: List of Use Cases

UC #	Use Case Title
1	Intersection Crossing – Signal Control is Red
2	Intersection Crossing – Signal Control is Green (Enough Time)
3	Intersection Crossing – Signal Control is Green (Not Enough Time)
4	Intersection Crossing – Multiple Pedestrians -Signal Control is Green
5	Intersection Crossing – System Communications Failure
6	Intersection Crossing – Unsafe Trajectory Detected
7	Intersection Crossing – Unexpected User Delay
8	Intersection Crossing -- Dual Crosswalk During All Pedestrian Walk Phase
9	Pre-Crossing – Notifying Pedestrian that Upcoming Traffic Signal is Red
10	Pre-Crossing – Assisting Pedestrian to Prepare for Crossing
11	Pre-Crossing – Pedestrian Requires Replay of Instructions
12	Pre-Crossing – Pedestrian Decides Not to Cross
13	Pre-Crossing – Approach of an Emergency Vehicle
14	Pre-Crossing – Pedestrian Crossing Synchronized with Bus Arrival

2.2 System Requirements

Building upon the ConOps specification and above inputs provided by various stakeholders, a list of system requirements was identified, and categorized into four types:

1. **Functional Requirements**, which specify functions, behaviors or tasks to be performed by the System.
2. **Performance Requirements**, which specify quantifiable characteristics of the System's operations.
3. **Interface Requirements**, which specify external interfaces to the System, including the interface with the user.
4. **Data Requirements**, which specify the ingesting, storing and accessing of relevant data or information within the System. Please note that these requirements, listed below, are focused on system data. For information on data management for project activities, please refer the Data Management Plan, listed in Section 5 below.

A Requirements Traceability Matrix (RTM) was then developed to record the description and characteristics for each requirement. This RTM was included with additional rationale in the project's *System Requirements Specification* [2,8]. The status field for each requirement will have one of the following values:

- ***Satisfied*** – The requirement was met with the Year 1 prototype system and will be again for the Year 2 prototype system.
- ***Partially Satisfied*** – The requirement was partially met for the Year 1 prototype system and should be completed in the Year 2 prototype system.
- ***Not Done*** – The requirement was not addressed in Year 1 will be met with the Year 2 prototype system.
- ***Defer*** – The requirement, while valid, has been deferred until after Year 2, due to technical limitations, or other feasibility considerations.
- ***Remove*** – The requirement has been removed for the reason listed in the Notes field.

A total of 108 requirements were specified in the RTM, most of which have been addressed over the two years of the project. The RTM, together with an indication of the current status of each requirement is presented in Appendix A of this Final Report. Readers are also encouraged to refer to the project's Year 2 ConOps [4] specification for detailed steps on the 14 use-cases identified for this system. A mapping of the system requirements to the use cases is provided in Appendix B of this Final Report.

2.3 System Design

The final product of the initial design phase of the project was the *System Architecture Design* specifications [3,9]. The *PedPal* mobile app user interface design based on universal design principles was specified and the system requirements specified in the SyRS [2,8] were used to drive the design of target functional capabilities. Figure 2-1 illustrates the physical architecture of the Safe Intersection System.

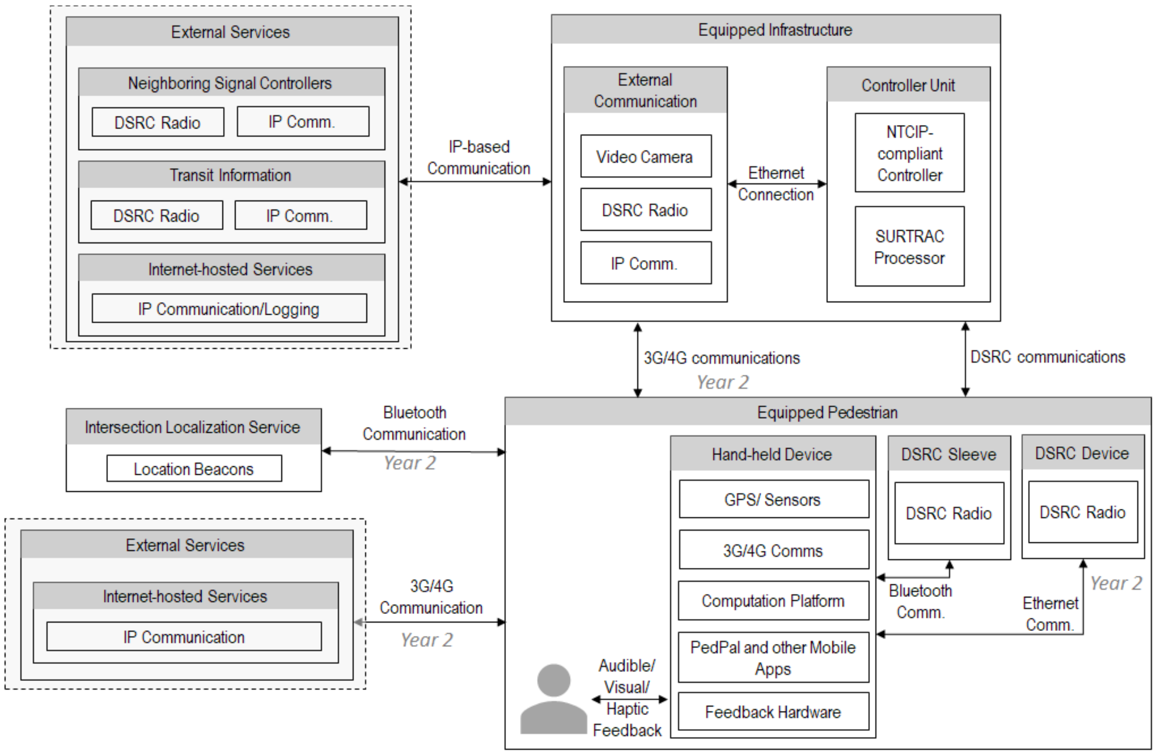

Figure 2-1: Physical Architecture of the Safe Intersection Crossing System

Chapter 3 System Development

There are two major subsystems in the Safe Intersection Crossing system, the Intersection Infrastructure Subsystem (IIS), and the Pedestrian Device Subsystem (PDS) which are described below.

3.1 Intersection Infrastructure Subsystem

Figure 3-1 depicts the physical architecture of the IIS.

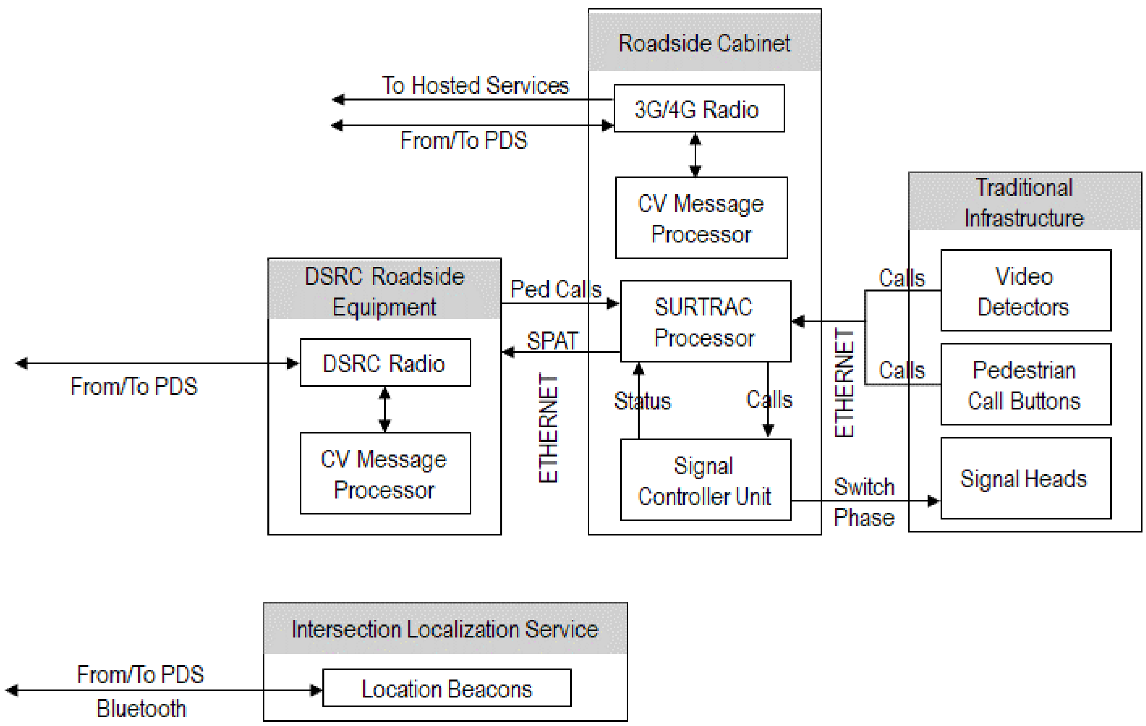

Figure 3-1: Physical Architecture of the Intersection Infrastructure

The pedestrian device communicates to a suite of infrastructure-based components via Dedicated Short-Range Communication or IP-based 3G/4G cellular communications. As shown, the infrastructure components consist of three systems - (a) A DSRC Roadside Equipment (RSE) unit, (b) the Roadside Cabinet containing the SURTRAC processor with a 3G/4G cellular radio and (c) traditional Infrastructure (hardware controller and traffic signals). Communication between the three systems is based on wired Ethernet.

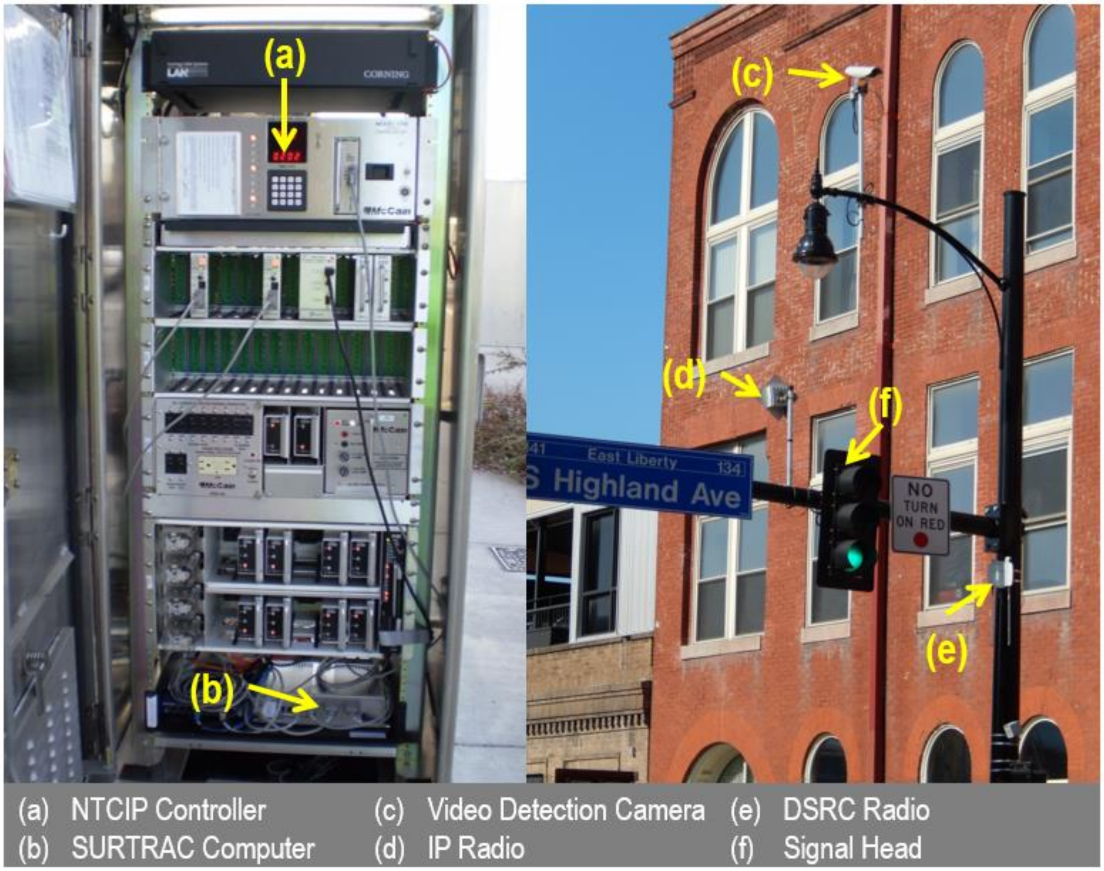

Figure 3-2: Intersection Infrastructure Equipment

Figure 3-2 shows a schematic of the physical hardware at an equipped intersection. The six components shown are: (a) Traffic Signal Controller, (b) SURTRAC computer, (c) Video Detection Camera, (d) IP Radio for communicating with other signal controllers if fiber optic cable connections do not exist, (e) DSRC RSE radio and (f) Signal Head. In the case of the 3G/4G cellular communication option, the *PedPal* app's device communicates with a cloud-based server which in turn uses SURTRAC's internal communication network together with its Wifi back hall connection to connect the *PedPal* app with the appropriate SURTRAC processor.

3.1.1 SURTRAC Adaptive Traffic Signal Control System

SURTRAC is a real-time adaptive traffic signal system designed specifically for optimization of traffic flows in complex urban road networks, where there are competing dominant flows that change significantly through the day. Architecturally, the SURTRAC component is organized internally and interacts with intersection infrastructure and neighboring intersections. Within the intersection cabinet, the SURTRAC processor realizes an iterative planning cycle wherein it (1) accepts detector data (from cameras, pedestrian call buttons, and other sensors at the intersection), (2) generates (in real-time) a timing plan for moving currently sensed traffic through the intersection efficiently, (3) issues commands to the Signal Controller (the device that actually drives the signal heads), and (4) communicates predicted outflows to downstream intersections. SURTRAC uses the current timing plan at any point to generate SPaT messages.

The embedded computer running the SURTRAC system interfaces directly with the hardware controller at the intersection, utilizing either the National Transportation Communications for Intelligent Transportation Systems Protocol (NTCIP) 1202 standard for North Electrical Manufacturers Association (NEMA) controllers, or more controller-specific protocols in the case of non-NEMA controllers such as the 170 Controllers used by the City of Pittsburgh. At the beginning of every planning cycle (which is invoked every second), the SURTRAC system accepts standardized traffic detection inputs representing traffic counts, location and heading information that are produced by commercially available vehicle detection technology (e.g., video cameras, radar, induction loops). Using this information, SURTRAC generates a prediction of stop-line arrivals in all directions. This predictive model is then used to generate, in real-time, a timing plan for moving the traffic that has been sensed through the intersection in an optimized fashion (currently minimizing cumulative wait time). Commands (calls) corresponding to the first step of the plan are then communicated to the signal controller for implementation. The SURTRAC intersection scheduler also communicates projected vehicle outflows to its downstream neighbors. The SURTRAC agent resident at each downstream intersection integrates this expected traffic with the traffic it is sensing through its local detectors to generate its own local timing plan, which allows plans to be developed over a longer future horizon.

3.1.2 Traffic Signal Controller

This device controls the state of the traffic signal heads, and as it is already integrated with the SURTRAC system, it will require no changes for the proposed system. The design of the traffic signal controller is outside of the scope of this project, and therefore this report.

3.1.3 DSRC Roadside Unit

The SURTRAC components deployed at the selected intersections have been equipped with DSRC radios. These radios have been used to establish basic vehicle-to-infrastructure (V2I) communications with DSRC enabled vehicles, including transit vehicles and emergency vehicles. The *PedPal* SURTRAC system does not require changes to the DSRC Roadside Unit, which already provides several relevant functions – (a) to receive Basic Safety Messages (BSM) from Connected Vehicles and Signal Request Messages (SRM) from pedestrians for integration into SURTRAC's predictive models of approaching traffic, (b) to broadcast SPaT and MAP messages continuously, and optionally (c) to send a Signal Status Message(SSM) to acknowledge receipt of SRM and to indicate whether the request was granted or denied.

3.1.4 3G/4G Wireless Communication Unit

Data exchange between the pedestrian device's *PedPal* mobile app and the SURTRAC can also be enabled through IP-based communications. In this case, a cloud-based server manages the communication between the pedestrian and the appropriate intersection computer running the SURTRAC component.

3.1.5 Traditional Intersection Infrastructure

The selected intersections are already equipped with the necessary traditional intersection infrastructure components – i.e., traffic signal heads and hardware controller, vehicle detection (video or radar), and (for some intersections) pedestrian call buttons, auditory cues and/or pedestrian signal heads. If pedestrian signal heads are present, they are synchronized to provide the same walk/don't walk and countdown information that provided to the user through the pedestrian device subsystem (i.e., the pedestrian signal heads are dynamically updated to reflect the extended walk time when it is granted).

3.1.6 Intersection Localization Infrastructure

One beacon is installed at each corner of the intersection (4 total per intersection) to support more accurate localization. Our current implementation is using relatively inexpensive Estimote beacons (https://estimote.com/).

3.2 Pedestrian Device Subsystem

The Pedestrian Device Subsystem (PDS) consists of the *PedPal* mobile app and a smartphone for hosting the *PedPal* mobile app. The smartphone should have accurate localization services, native 3G/4G communication capability, and an extension for DSRC communication capability. Additionally, the PDS' computational platform must support the configurable feedback options (audible, visual or tactile) required for the user interface.

For both years of the project , the PDS consists of the *PedPal* mobile app hosted on an Apple iPhone which in addition to offering localization services, and 3G/4G communications capability, also supports communication via an external mobile, DSRC-enabled OnBoard Unit (OBU) device. This device provides full DSRC/WAVE capabilities with native applications for integration with smartphones to facilitate the user-interface.

The physical architecture of this device is presented in Figure 3-3 and example hardware units are shown in Figure 3-4 and Figure 3-5. The physical hardware consists of a smartphone and an optional DSRC device connected via Bluetooth. At a high-level, the PDS works as follows:

1. Equipped pedestrian configures the device with the type of feedback (audible, visual or tactile) and the average crossing speed at intersections. Speed is adjustable, by the pedestrian in the device settings, to fit current conditions (e.g., high heels versus running shoes, inclement weather), and in the future, the *PedPal* mobile app could include machine learning processes that refine crossing speed through accumulated crossing experience.

2. Pedestrian device consists of a computation platform (i.e., a smartphone) for hosting and running the *PedPal* mobile app and optionally either an attached DSRC device, or a sleeve with a DSRC radio to which the smartphone attaches (for communication to the infrastructure). Devices that are not DSRC-enabled, will communicate with the intersection using 3G/4G communications through a dedicated cloud service, while those that are so enabled can use 3G/4G communications as an alternative. A software toggle is provided and initially used to facilitate prototype testing that allows for configuration in deployments that support either, but not both, DSRC and 3G/4G cellular communications.

3. As the pedestrian approaches the intersection, the *PedPal* mobile app receives both MAP and SPaT messages that are being broadcast by the infrastructure.

4. This information is used by the *PedPal* mobile app to provide the pedestrian with street crossing options.

5. Upon selection of a street to cross by the pedestrian, the *PedPal* mobile app issues an SRM to the infrastructure, requesting a crossing duration that is consistent with the pedestrian's speed.

6. The *PedPal* mobile app will use incoming SPaT messages to convey remaining crossing time to the pedestrian.

Readers are encouraged to refer to the project's Year 2 Concept of Operations [4] specification for detailed steps on the 14 use cases identified for this system.

Figure 3-3 below depicts the subsystem architecture of the PDS. If DSRC is used, then the MAP and SPaT, and SSM messages are both received by the DSRC radio, and then communicated to the smartphone via Bluetooth (sleeved radio) or Ethernet (cabled radio). SRMs are sent from the *PedPal* mobile app to the connected DSRC radio via Bluetooth or Ethernet, and then communicated via DSRC radio to the intersection. Alternatively, 3G/4G cellular communications can be used in lieu of DSRC communications, for both SPaT/MAP/SSM message reception and SRM message transmission.

The smartphone's native localization capability (a function of its GPS sensor, accelerometer, etc.) is used in combination with landmark beacons installed at the intersection to provide a basis for tracking the progress of the user during crossing, and for issuing a request to dynamically extend the green time if the user has encountered some difficulty and is moving slower than expected.

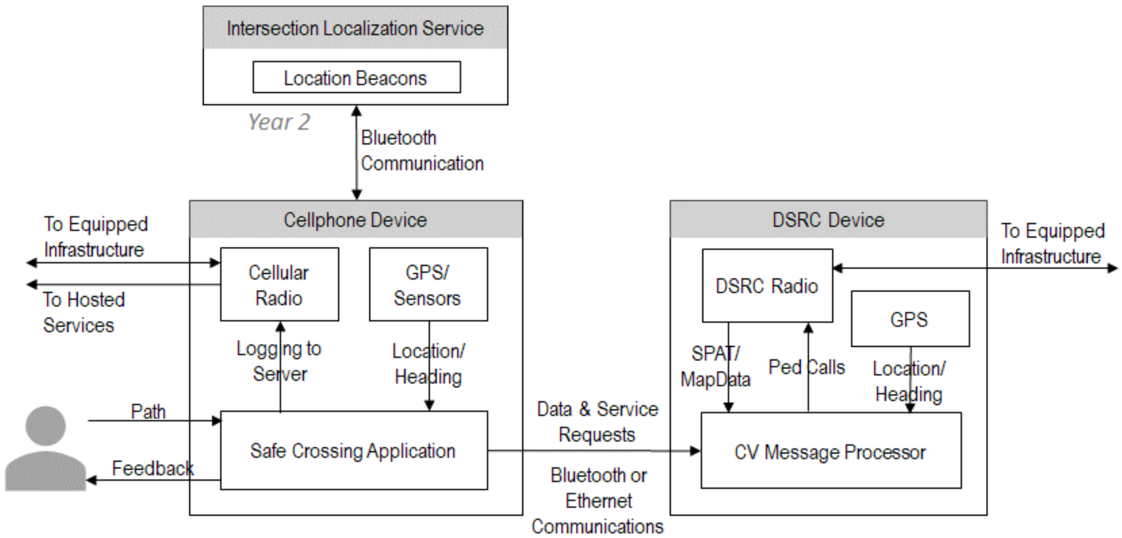

Figure 3-3: Physical Architecture of the Pedestrian Device Subsystem

If configured for DSRC based communications, there are two supported options for incorporating DSRC radios into the PDS, described below, which were developed as part of the proposed system

<u>*PDS Device Type 1*</u>: The first pedestrian device type coupled an iPhone to a mobile Arada DSRC/WAVE-capable device sleeve using a wired connection to enable end-to-end connectivity between the *PedPal* mobile app and the SURTRAC signal control system. Scripts were developed to enable the programmable DSRC sleeve unit to translate messages between the *PedPal* mobile app and the sleeve's DSRC radio. Figure 3-4 shows an example of PDS Device Type 1, consisting of an iPhone running the iPhone Operating System (iOS) coupled with a Lear Locomate ME DSRC-enabled sleeve, which will communicate with the iPhone via a Bluetooth connection to allow the device to communicate with the SURTRAC signal control system.

Figure 3-4: PDS Device Type 1

PDS Device Type 2: Figure 3-5 depicts a second pedestrian device type that could be coupled to an iPhone to support DSRC communications: a small portable Cohda DSRC on board unit (OBU), Connectivity in this case is made using a Bluetooth (or WIFI) dongle connection to enable end-to-end connectivity between the *PedPal* mobile app and the SURTRAC signal control system. It is assumed that this device would be placed somewhere on the user's person (e.g., in a backpack). It is proposed as an alternative, since Lear is currently providing minimal support for the legacy Arada Locomate ME and is offering no DSRC sleeve alternative.

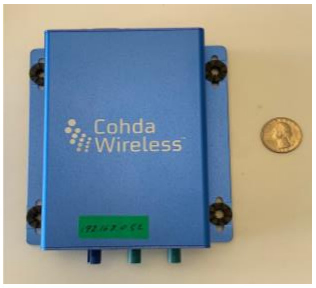

Figure 3-5: PDS Device Type 2

3.2.1 *PedPal* Mobile App (Year 1)

In Year 1, the *PedPal* mobile app prototype provides basic assistance to the user in crossing the intersection. The *PedPal* mobile app is customizable to each user and knows the user's personalized crossing constraints. It allows the user to communicate crossing intent (eliminating the need for a pedestrian call button) along with the time that the individual user requires for safe crossing. If the request is made in advance of the green in the crossing direction, then an extension to crossing time will always be granted by the traffic control system. If the request is made when the signal is already green in the crossing direction, the traffic control system will determine whether there is enough time remaining to permit crossing and grant a time extension or if the pedestrian should wait until the next green cycle.

As shown in Figure 3-6, configuration of the app currently includes specification of several settings, including:

- Traveler Type – white cane user, guide dog user, wheelchair users, deaf, etc. This setting implies a default baseline crossing speed
- Street Crossing Speed – crossing speed can be further tuned relative to the default speed using this setting.
- Show Diagonal Crossings – specifies whether diagonal crossings should be considered.
- Re-Sort Corners After Crossing – impacts user preference when using two crossings to accomplish a diagonal crossing
- Countdown Frequency (V0) – When operating with voice over on, this setting controls the verbosity of the spoken countdown.

- Device Orientation – fixed or dynamic

Figure 3-6: *PedPal* Mobile App UI Screens – User Settings

The *PedPal* mobile app supports all the native accessibility features of the iPhone, including voice-over, zoom, font enlarging, etc. These features are configured from the iPhone's Settings control. The app supports all the accessibility features native to the iPhone, including voice-over, zoom, font enlarging, etc. These features are configured from the iPhone's Settings interface.

Figure 3-7 illustrates the basic use case for crossing an intersection: Upon arrival at the intersection, the user selects which street to cross, which in turn triggers the Signal Request Message (SRM) to allocate sufficient crossing time to the next green phase in the selected crossing direction. Receipt of MapData (MAP) and Signal Phase and Time (SPaT) messages enable generation of the screen on the left, and once the user selects the street to cross, an SRM is sent to the intersection. Once the crossing duration is set by the traffic signal control system, it is reflected in the time remaining count shown on the screen. When the user is about to start to cross, he/she taps "start crossing" and when the user has completed crossing, the "crossing completed" button is tapped.

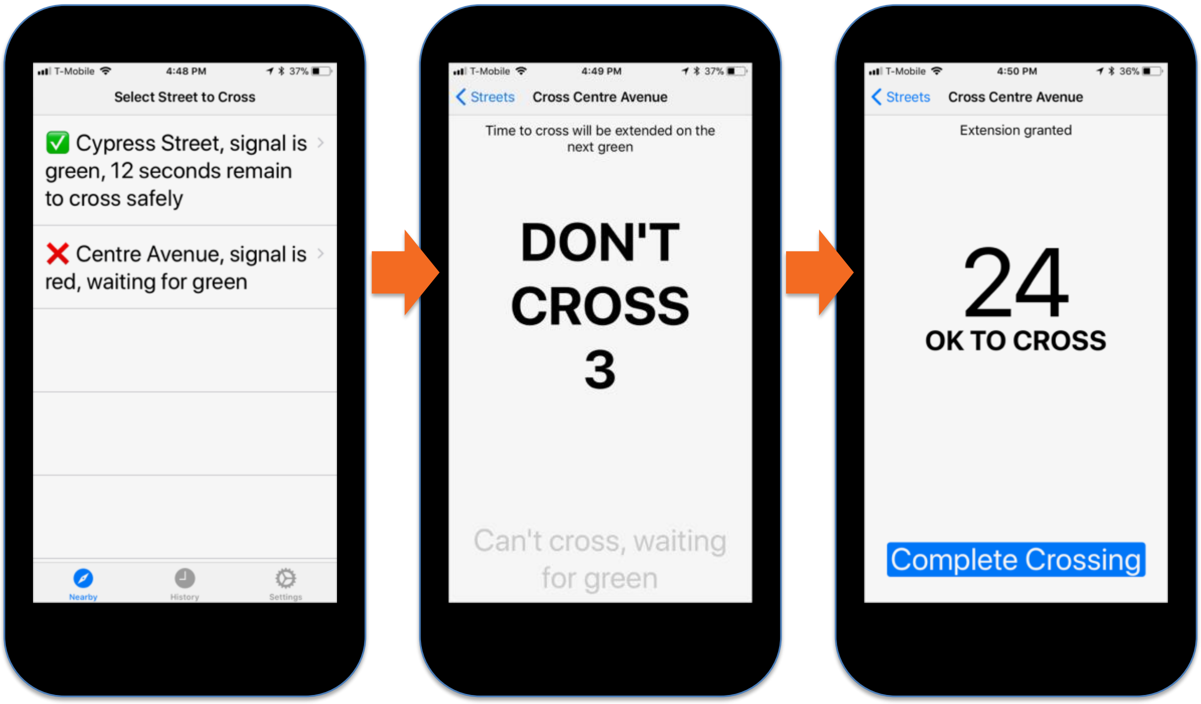

Figure 3-7: *PedPal* Mobile App UI Screens – Street Crossing Process (Year 1)

3.2.2 *PedPal* Mobile App (Year 2)

Several enhancements were made to the Year 1 the *PedPal* mobile app's UI both to enable additional features and to address feedback from users in Year 1 of this project. A list of the major changes are as follows:

1. Elimination of start/end crossing button
2. Elimination of history tab
3. Access to additional information about the corner at the current intersection
4. Localization and tracking
5. Addition of interface to routing app

These changes are described in greater detail below. The design of capabilities to anticipate pedestrian arrival at intersections using route information, to synchronize getting pedestrians to desired bus routes with real-time bus arrival information, and to support navigation of the user to and through the crosswalk at an intersection based on information about the built environment, are addressed in this section. The design of additional advanced user interface capabilities is also addressed at this time.

3.2.2.1 Elimination of Start/End Crossing Button

The Start/End Crossing button was intended to be a temporary measure for the Year 1 version of the *PedPal* mobile app's user interface, to compensate for the Year 1 prototype's inability to automatically detect crossing start and end events. Anticipating the ability to use the aforementioned Bluetooth beacons to boost the mobile app's localization capability to provide this capability (as well as the ability to identify which corner the user is standing at), these user input buttons were eliminated in the Year 2 prototype. In reducing the number of screen-taps the user is required to make when using the *PedPal* mobile app, this change significantly simplifies its operation. And as mentioned below, the capability to automatically identify corners and detect crossing start and end events has now been fully integrated into the *PedPal* mobile app.

3.2.2.2 Elimination of History Tab

The History tab was originally introduced to provide a means of collecting user data on crossing over time, for purposes of refining travel speed estimates. However, given the fact that automatic refinement of user travel speeds is outside of the scope of the project and that users did not indicate a strong interest in using this information themselves during Year 1 system evaluation, the history was eliminated in the Year 2 version of the *PedPal* mobile app to further simplify the app's user interface.

3.2.2.3 Access to Corner Information

For vision impaired individuals, additional information about the current intersection corner can provide at least some basis for self-orienting and self-positioning in preparation for crossing. Several Year 1 test participants suggested the value of knowing information such as the presence of and location of curb cuts (e.g., single curb cut at the corner or separate curb cuts aligned with the crosswalks), the presence of a traffic island midway, the presence of a left turn signal in the crossing direction, and so on, especially when faced with an unfamiliar intersection.

To make provisions for incorporating such information an API was developed for importing such information from a third party data base, and providing the user with a selectable option for seeing this information. Specifically, when the user selects which street to cross, PedPal provides a button on the crossing screen that allows the user to get more information about the corner and the crossing (if it exists). If the user presses the button, the information will be shown in a drop-down text box and a second tap will collapse the box back into its button format. (Incidentally, this button occupies the same location as the previously eliminated start and end crossing buttons.)

Figure 3-8 illustrates the extended basic use case for crossing an intersection in the Year 2 *PedPal* prototype.

Figure 3-8: *PedPal* Mobile App UI Screens – Street Crossing Process (Year 2)

3.2.2.4 Localization and Tracking

Extensions that utilize Bluetooth beacons placed at intersection to identify which corner the user is standing at have been integrated into the Year 2 *PedPal* mobile app, albeit after the Year 2 user field tests were completed. This capability relies on Proximity readings that are received from an Estimote beacon placed on a pole at the corner. The PedPal mobile app then uses a predefined "near" geo-fence together with a mapping of beacons to corners to determine the corner of interest. The same technique is used to determine both start crossing events (i.e., when the app moves outside of the “near” geo-fence) and complete crossing events (when the app moves inside the “near” geo-fence of the destination corner). Ongoing work is currently investigating the viability of associating a second, “far” geo-fence with each corner beacon, and using the combination to track crossing progress from one corner to the next. The third step will then be to triangulate additional beacons to detect crosswalk veering.

3.2.2.5 Extensions to Monitor Crossing Progress

In addition to the above work on localization, several other steps were also taken toward the development of a capability for monitoring crossing progress and reacting to slower than anticipated progress within the *PedPal* mobile app. First, the *PedPal* mobile app itself was extended to implement the process of monitoring and responding to crossing process (assuming that localization is sufficiently accurate), i.e.,

1. To periodically request the current location from a localization source (currently the native localization functionality on the iPhone8 is used but this scheme will soon be adapted to use geo-fence events),
2. To compute the user’s rate of progress,
3. To determine whether the user has sufficient time remaining to reach the other side of the intersection, and if it is determined that there is not then
4. To automatically issue an SRM (Signal Request Message) to the intersection to dynamically extend the current (green) phase.

Second, the SURTRAC subsystem for processing SRMs and issuing SSMs (Signal Status Messages) in response was generalized to incorporate both real-time, green phase extensions and multiple simultaneous requests from different users. Figure 3-9 shows the generalized algorithm that was implemented. This functionality has been demonstrated in simulation (where sensing uncertainty can be factored out), using an intersection simulator that was developed in-house for testing and debugging of the *PedPal* mobile app’s functionality during development.

3.2.2.6 Route Information

Another major extension to the *PedPal* mobile app in Year 2 provides the capability to import a route that has been pre-planned by the user and use it to improve the user’s overall travel time through a series of intersections. If a pedestrian chooses to inform the *PedPal* mobile app of its route (e.g., if the user is moving through one or more intersections to get to a specific bus stop), then SURTRAC can anticipate the user’s arrival at each intersection along the route, and take this expected arrival information into account when generating the traffic signal’s upcoming phase timing plan. The net result should be a streamlining of waiting time at each intersection for the user.

At the same time, it does not make sense to develop navigation planning capabilities within PedPal since such capabilities are either already well developed in other apps (e.g., BlindSquare), or are being developed to provide unique new navigation capabilities (e.g., PathVu’s wheelchair-friendly routing system). Consequently, our assumption is that we will import route information from such third party apps. To that end, we have defined an API and used it to demonstrated the developed *PedPal* route following capability. The route is imported as a sequence of latitude/longitude "waypoints", with each successive pair of waypoints corresponding to the start corner and the end corner of the next SURTRAC -equipped intersection along the route.

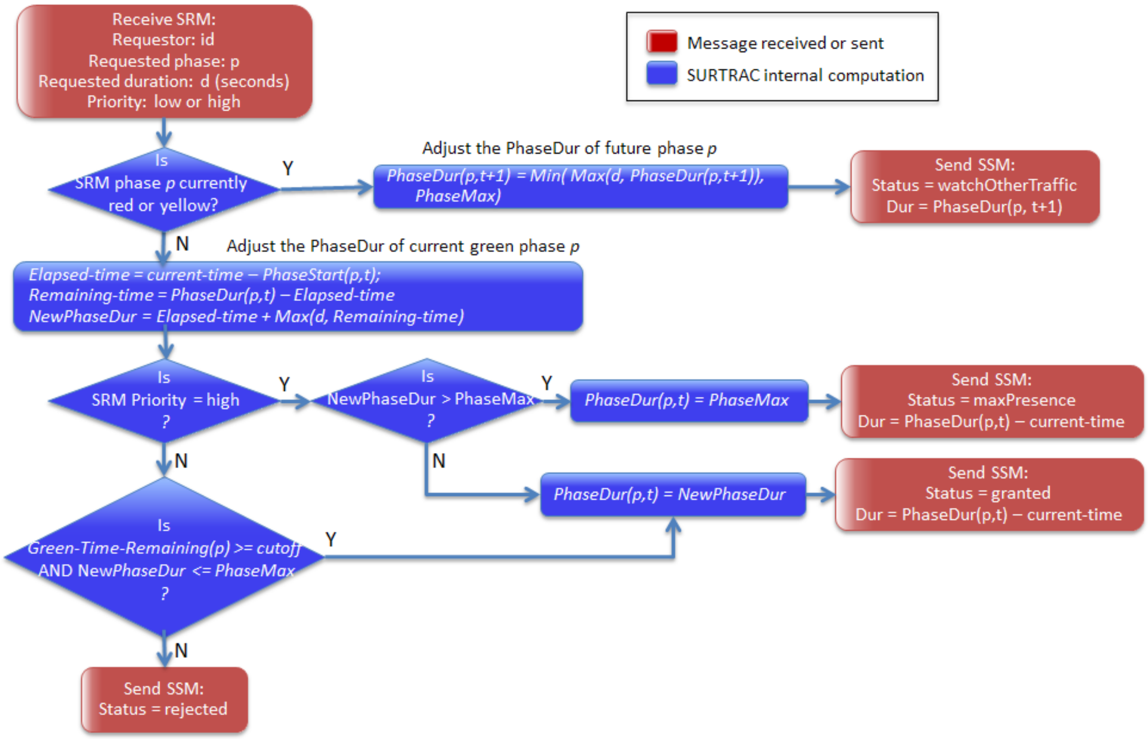

Figure 3-9: Algorithm for SURTRAC response to an SRM – General case of multiple simultaneous requests

When the *PedPal* mobile app receives such a route, it alerts the user that a route has been received and that the *PedPal* mobile app is transitioning into "route following" mode. The user then has an option to acknowledge/dismiss this alert. Once the alert is acknowledged, the user will only have access to a button to cancel the route and exit from the route following mode, and the button to learn more details about the specific corner as described in the relevant subsection above. While in route following mode, the *PedPal* mobile app automatically handles generation and communication of all crossing requests and selections in the background. At the appropriate mid-block distance to the upcoming intersection, an SRM is generated, along with an expected arrival time at the start corner. *PedPal* uses its knowledge of the user's speed to compute expected arrival time. Upon receipt of the SRM, SURTRAC will update its predictive model of approaching traffic to include the user (with appropriate weight relative to vehicle traffic) and then use this updated model generate subsequent signal timing plans (or phase schedules). At the user interface level, the *PedPal* mobile app simply alerts the user about upcoming crossings and presents the usual countdown information needed to cross the intersections safely.

The user is also alerted any time that route following mode is exited and informed as to whether the route was canceled or completed when this happens. This alert needs to be acknowledged/dismissed by the user. For purposes of demonstration in Year 2 system evaluation, the *PedPal* mobile app will read a route (sequence of waypoints) from a file, such as would be generated by the export capability of a third-party mobile app such as BlindSquare). Figure 3-10 gives the system design conceptualization of this capability within the PedPal app. See the User Manual in Appendix C below for further details on its realization in the Year 2 prototype.

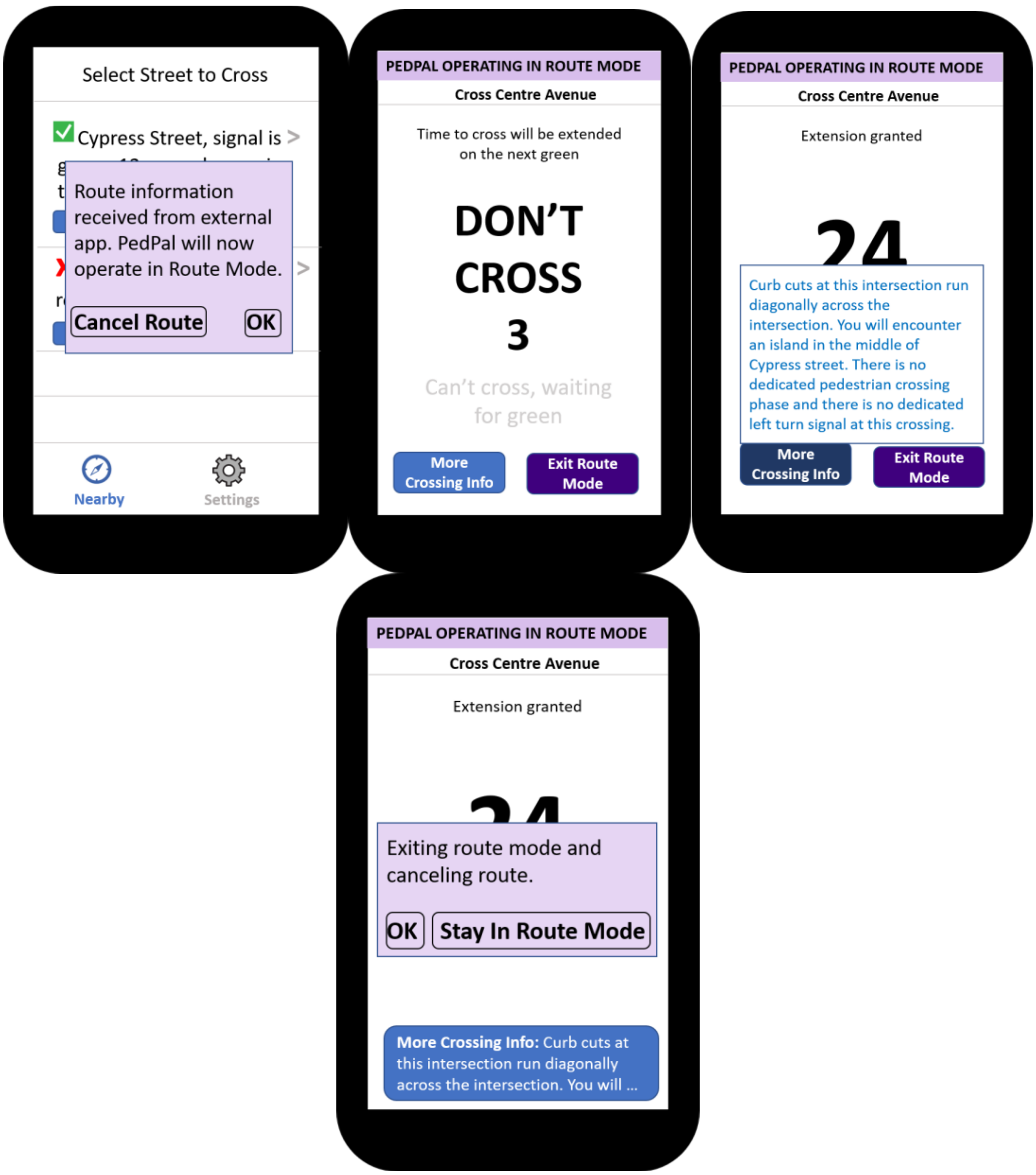

Figure 3-10: *PedPal* Mobile App UI Screens – Route Following

3.2.2.7 Bus Information

The final feature designed for introduction into the Year 2 version of the *PedPal* mobile app was the ability for users to inform the *PedPal* mobile app that he/she wishes to catch a specific bus at an intersection where *PedPal* is operational. The concept is to give SURTRAC the opportunity to combine this information with other real-time information being received independently from approaching buses, and if possible to align the signal phases so as to maximize the user's chances of catching the bus (e.g., by holding it at the light for some extra time to allow the user to get across the street and over to it for boarding). In fact, other considerations, including the fact that the Port Authority of Allegheny County has been slow to equip sufficient buses that move through the SURTRAC controlled corridors that contain our *PedPal* test intersections with DSRC OBUs to allow real-time vehicle-to-infrastructure (V2I) communication, have let us to defer implementation of this capability for future research. Nonetheless, we include a summary description of the designed capability for completeness.

As with the route following capability, we assume that the user will specify bus route (number) and bus stop via a third-party mobile app (e.g., Transit), and this app will export the information into the *PedPal* mobile app. Once this information has been received by the *PedPal* mobile app, it will be incorporated into each subsequent intersection crossing request that is sent by the app. When the user selects the street to cross at a given intersection, an SRM that includes this additional information will be sent to the intersection. In response, SURTRAC will first determine if the target bus stop is at this intersection, and if so, will determine the predicted arrival time of the next bus that is running the desired bus route. If the predicted arrival time is sufficiently close relative to SURTRAC's current prediction of when the user will complete the crossing and arrive at the bus stop, then SURTRAC will adjust the current timing plan to extend the relevant phase and hold the bus for an additional fixed amount of time. The only user interface change that this feature will manifest is that the *PedPal* mobile app will pop up an alert when bus information is received, and this alert will need to be acknowledged/dismissed by the user.

Chapter 4 System Evaluation

During the period from August 16, 2019 through September 11, 2019, an evaluation of the Year 2 *PedPal* mobile app was carried out. During this evaluation, 14 volunteers from the local Pittsburgh disability community conducted a series of intersection crossing trials with and without the use of the *PedPal* technology, at 4 intersections in the Pittsburgh SURTRAC deployment in the East Liberty section of Pittsburgh PA. These recruited participants included individuals with a range of disabilities spanning visually impaired people (most prevalent), wheelchair users, and elderly persons with mobility issues. The experimental protocol followed that of initial field test evaluation conducted in Year 1, where each user first underwent a pre-test training session, then proceeded to carry out the crossing trials in the field, and then provided feedback in a post-test session.

In the subsections below, we first summarize the user test protocol and field test environment, next we describe the user test participants and then we describe the results obtained. For details of the initial Year 1 user field test, please see [5].

4.1 Field Test Protocol

Each participant was individually engaged with members of the *Safe Intersection Crossing* project team for a 90 minute to 2-hour session. As in Year 1, the test protocol carried out consisted of three phases:

1. Pre-Test Phase – First, during the Pre-Test Phase, the participant was asked to complete an information gathering pre-test survey and then was introduced to the *PedPal* mobile app running with a simple intersection traffic signal simulator. This first Phase was carried out at Carnegie Mellon University (CMU), due to its relative proximity to the field test site and the availability of conference rooms and training area.

2. Test Phase - Once training was complete, the user was transported to the field test location, and a series of intersection crossings were performed both with and without the assistance of the *PedPal* mobile app.

3. Post-Test Phase - After completing the test activities, the participant was transported back to CMU and asked to fill out a post-test survey. All data that was collected in the field was then downloaded to a secure server.

All test activities and data handling were carried out in compliance with procedures and protocols approved by the Carnegie Mellon University (CMU) Institutional Review Board (IRB).

4.2 Field Test Location

The target location for the Year 2 field test consisted of a set of four intersections in the vicinity of University of Pittsburg Medical Center's (UPMC) Shadyside Hospital and Henry Hillman Cancer Center complex in the East End of Pittsburgh PA. More specifically, testing will involve crossing some subset of the following 4 intersections:

1. *Centre Avenue and Cypress Street* is a basic four-way intersection that consists of one travel lane in both the east/west and north/south travel directions. It is a simple two-phase intersection (i.e., no dedicated left turn phases) with the signal just cycling between east/west and north/south phases. The intersection design has a single curb cut at each corner rather than curb cuts directly interfacing with the crosswalks and, although there are pedestrian countdown signals, there are no audible pedestrian signals nor pedestrian push buttons available. The lack of audibles, corner curb cut design, and the changing amount of green time in a given direction over time, make this an extremely challenging intersection to cross for blind pedestrians. This intersection was the focus of the Year 1 user field test experiments and is depicted in Figure 4-1.

2. *Baum Boulevard and Cypress Street* is a basic four-way intersection one block north of Centre/Cypress. It consists of two travel lanes in the east/west direction and a single travel lane in the north/south travel direction. Traffic in the east/west direction on Baum Boulevard is heavier than that on Centre during certain periods of the day, and that plus the width of the roadway (4 lanes) likely presents a more significant crossing challenge than does crossing Centre Avenue (2 lanes). Like the Centre/Cypress intersection, there are no audibles, no pedestrian call buttons, and curb cuts interface directly with the crosswalks.

3. *Center Avenue and Aiken Avenue* is technically also a simple 4-way intersection with 1 travel lane in the east/west direction and 2 travel lanes in the north/south direction, located one block east from Centre/Cypress. However, just past the intersection going north is a Y of sorts, where the two sets of north/south travel lanes veer northwest to become Liberty Avenue, and a third one-way travel lane veers northeast and continues Aiken Avenue. Hence in some crossing directions the pedestrian must navigate more than one crossing in the same direction. Like the Centre/Cypress intersection, there are no audibles, no pedestrian call buttons, and curb cuts interface directly with the crosswalks.

4. *Centre Avenue and Highland Avenue* is a 4-way intersection crossing that is disconnected from the other three intersections. It is included because it is an irregularly shaped 4-way intersection that presents unique crossing challenges. Crossing the intersection from different corners involves traveling different distances and takes differing amounts of time. East-west traffic has dedicated left turn lanes in both directions. North-south traffic has one lane in each direction.

Figure 4-1: Intersection at Centre Avenue and Cypress Avenue

These intersections were chosen for the following combination of reasons: (1) because the SURTRAC adaptive signal control system and a DSRC message processing capability are installed and operational at each of these intersections, (2) because of the relatively large volume of pedestrian traffic crossing these intersections, and (3) because of the intention to test users' ability to travel routes through sequences of consecutive intersections instead of just conducting tours around a single intersection as in Year 1. Since these intersections are controlled by the SURTRAC adaptive signal control system, the green phase in any direction can (and will) vary from cycle to cycle, depending on the actual vehicle traffic on the road at any given moment.

For each participant, a series of crossing tours at a subset of these intersections was performed, both *with* the assistance of the *PedPal* mobile app and *without* it (as the individual would normally cross the street). Figure 4.2 shows a typical sequence of crossing trials carried out by a participant while using the app, where a tour is first taken around an initial intersection and then the itinerary is expanded to an adjacent intersection and back again. Comparative crossing trials performed without the assistance of the PedPal mobile app, alternatively, were restricted to the initial intersection, and the order in which *with app* and *without app* trials were performed was varied from participant to participant. During these crossing tours, data and observations were collected on crossing times, cycles required to cross, safety interventions, technical interventions and other notable events.

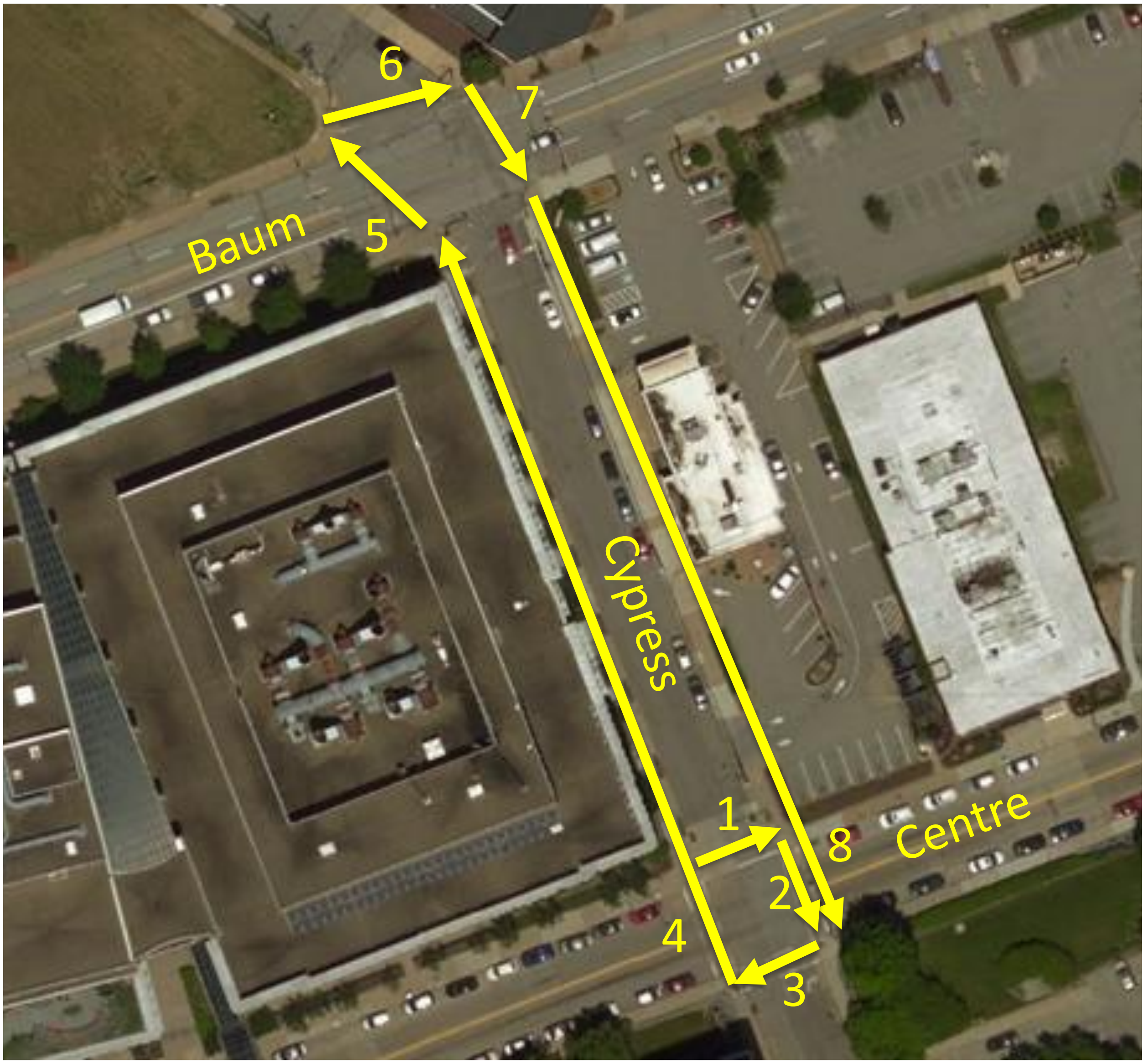

Figure 4-2: Representative intersection crossing tour at test location

4.3 Participants

As indicated above, 14 individuals participated in the Year 2 round of user tests of the *PedPal* mobile app. In the following subsections we characterize the demographics of these 14 individuals and their perspectives on needs and requirements, as aggregated from data provided through the pre-test survey.

4.3.1 Demographics

From the data collected during the pre-test survey, the demographics of the set of individuals participating in the Year 2 user test is summarized in Table 4-1.

Table 4-1: Participant Demographics

Demographic	Category 1	Category 2	Category 3
	Male	**Female**	**Prefer not to Say**
Gender	8	6	0
	Caucasian	**Hispanic**	**Prefer not to Say**
Ethnicity	12	1	1
	26-45	**46-65**	**Over 65**
Age	4	4	6
	Persons w/ disabilities	**Veterans w/ disabilities**	**Older adults**
ATTRI Target Population	13	1	9
	Vision	**Mobility**	**Hearing**
Disability Types	9	4	1

As can be seen, we achieved a reasonable amount of diversity in the types of disabilities covered by participants. For this user test, we explicitly excluded consideration of individuals with cognitive disabilities, recognizing that this is perhaps the most challenging user group. We intend to extend the scope to consider such individuals in our future research. It is also of note that there are some dimensions along which we could obviously improve our user testing pool. Our ethnic diversity, for example, is extremely low. In future experimentation we intend to take steps to recruit a more ethnically diverse set of participants.[2]

[2] In this regard, East Liberty is both a socio-economically and racially diverse neighborhood that has undergone significant transition and economic development in the past 5-10 years as high-tech companies such as Google Pittsburgh and Duolingo have moved into this area and there has been a large influx of younger engineers and professionals into this historically underprivileged and largely African-American neighborhood. Although most residents would agree that this is good for the neighborhood, there is still a significant disadvantaged community and it is common to see individuals with disabilities on the street (e.g., disabled veterans, others with severe

Our user population is also somewhat skewed toward older individuals, and we are discussing ways to attract additional younger users. Nonetheless, we believe that older individuals and individuals who are vision impaired represent two principal target user groups for *PedPal* and hence the set of individuals that participated provided a nice cross-section of potential users of the *PedPal* technology.

4.3.2 Intersection Crossing Tendencies

Another goal of the pre-test survey was to understand the intersection crossing practices and tendencies of the recruited participants, to provide a better basis for assessing the impact of *PedPal* on pedestrian crossing. Table 4-2 summaries the intersection crossing practices and tendencies indicated by the 12 participants in the pre-test survey. Notice that all participants currently cross intersections independently.

Table 4-2: User Street Crossing Practices and Tendencies

Street Crossing Characteristic	Daily	Couple Times/week	Once a Week
Crossing Frequency	9	4	1

Street Crossing Characteristic	Guide Dog	White Cane	Wheelchair (Motorized)	Walker
Assistive Tools Used	3	9	3	1

4.3.3 Smartphone experience

PedPal is currently implemented on an iPhone smartphone platform. Therefore, another relevant consideration is the participant's experience with this device. Table 4-3 summarizes the level of familiarity of participants with iPhone and features relevant to the use of *PedPal*.

mobility challenges). Some form of compensation would likely provide a fair incentive for such individuals to participate.

Table 4-3: User Familiarity with the iPhone

Skill	Most (5)	4	3	2	Least (1)	Average
iPhone Proficiency	5	5	2	2	0	3.73
Voice Over Proficiency (if relevant to the user)	5	2	2	0	0	4.20

Experience	Range	Average
Voice Over (years)	3 - 10	6.00

4.3.4 Crossing challenges

Participants were also asked what their most significant challenges were in crossing signalized intersections. A range of challenges in crossing a signalized intersection were identified, and varied according to the pedestrian's type of disability:

4.3.4.1 Blind Individuals:

1. Knowing (or learning) the characteristics of an unfamiliar intersection was identified as a big challenge. Information such as the number of different signal phases in a cycle through all vehicle approaches to the intersection, the distance across the intersection in different directions, the presence of left turns, the intersection's physical configuration (e.g., T, +, 5 way), the presence of one-way streets, and the presence of angled crosswalks are all important factors to know for safely crossing an intersection.

2. Knowing if pedestrian call buttons are present at the intersection and if so, locating them is another challenge. Further, the act of locating the call button can cause the pedestrian to lose alignment to the target crosswalk, and the time required to realign can result in the pedestrian missing the crossing phase.

3. Determining where the crosswalks are and then avoiding veering outside of them during crossings, particularly in the absence of other crossing pedestrians

4. The absence of an auditory device at an intersection that announces phase. Determination of when it is ok to cross in this case requires listening to vehicle traffic and/or learning the duration of different phases. In the case that there is sporadic traffic, quiet intersection, or inconsistent duration of green signals across cycles this problem is an even greater challenge.

5. Avoiding cars that are turning at the intersection, either in right-turn-on-red or in permissive left turn situations

6. People driving while talking on their cell phones

4.3.4.2 Mobility Impaired Individuals (e.g., Wheelchair users, Older Adults):

1. Lack of curb cuts at the intersection, as well as bad paving, poorly aligned curb cuts and curb cuts with steep descents

2. Accessibility and/or proper functioning of pedestrian call buttons at the intersection

3. Navigating around cars that are blocking the cross walk, as well as other obstacles that may be situated near the corner on the sidewalk.

4. Insufficient time allocated to make it across the intersection before the signal changes.

4.3.5 Desired features in a street crossing app

Finally, participants were asked what features they would find most important in an app that assists in safely crossing the intersection. The following features were identified as important:

1. Indication of when it is OK to cross in a given direction (accessible via voice-over)
2. Indication of how much time is left to get across the street, along with a countdown
3. The ability to provide information about the intersection, such as how far is it to get across the street in the desired direction
4. Alert capability if crossing trajectory moves outside of the crosswalk
5. Dynamic sound level control if there are loud vehicles or construction work at the intersection
6. Indication of the name of the street that the user is on, as well as the streets that could be crossed
7. Ability to control the verbosity of information provided when in voice-over mode
8. The ability to inform the intersection of crossing intention, eliminating the need for pedestrian call buttons

9. Real-time updates on curb conditions at the intersection
10. An app that requires as little handling of the phone as possible.
11. Android implementation that can be easily accessed via widgets/hot buttons for the few intersections that are frequently traversed

4.4 Results

In this section, we summarize the principal findings of the Year 2 user testing performed with the *PedPal* mobile app.[3] We start with the qualitative assessment and user experience impressions provided by the participants themselves in the Post-Test Survey that was conducted. Next we consider the supporting quantitative evidence and additional conclusions that can be drawn from the observational and log data that was collected.

4.4.1 Qualitative Assessment and User Experience

All participants in the user study were provided with an opportunity to answer questions and provide feedback about their experience using the *PedPal* prototype. IRB-certified researchers from our team asked each user about their thoughts on specific issues such as the best features of the app and enhancements they wish to see in future iterations of *PedPal*. Users were also given the opportunity to comment on anything relevant to the project, beyond answering the specific questions. The answers and comments provided by the users in these post-test interviews are summarized in the following sections.

4.4.1.1 Best features

A summary of the features mentioned by user study participants as most useful is summarized in Table 4-4. The features of the *PedPal* app that were most commonly cited as the best features of the app included *PedPal's* ability to:

1. Tell the user when it was safe to cross the intersection in a particular direction,
2. Countdown the remaining crossing time (i.e. letting the user know how much time they have left to cross),
3. Identify the intersection and possible crossing directions,
4. Extend crossing time for those who need it, and

[3] For information on the Year 1 user testing please see "Connecting Pedestrians with Disabilities to Adaptive Traffic Signal Control for Safe Intersection Crossing and Enhanced Mobility: 2018 Field Test and Evaluation Report", September, 2018.

5. *PedPal*'s intuitive and easy to use interface.

Some users also mentioned the convenience of avoiding the problems of locating and pushing the pedestrian call button as a desirable feature, and the fact that *PedPal* was able to identify the precise corner based on cardinal directions (e.g., NE corner). Users additionally noted that *PedPal* would especially be useful to visually impaired users at intersections with no audibles. Finally, one sited participant remarked on the accuracy of the app, relative to the pedestrian walk signals.

Some visually impaired users also mentioned that the feature of *PedPal* initiating vibrations on the phone when starting to cross was useful, and that the auditory output from *PedPal* was clear. One user commented that, for visually impaired pedestrians, knowing when to cross the street makes the *PedPal* app "worth its weight in gold". It should be noted that users indicated that *PedPal* is not as useful for people using powered wheelchairs or people with hearing disabilities, but that it is very useful to people who need more time to cross the street (such as people using manual wheelchairs and walkers) and people who have visual impairments.

Table 4-4: Most useful *PedPal* features.

Feature	Number of Mentions
Countdown of time remaining to cross	12
Indicating when it is time to cross	8
Identifying intersection and crossing options	5
Intuitive Use	4
Personalized extension of crossing time	3
Elimination of call button	2
Customizable crossing speed	2
Indicating cardinal direction of corner (e.g., NE)	2
Accuracy with respect to walk signals	1

Those individuals who participated in the Year 1 user test were also asked what improvements they observed in the current *PedPal* prototype over last year's edition. Table 4-5 summarizes the responses received. The most commonly cited improvements included:

- The ability to operate without an additional device (i.e., the DSRC sleeve), which was made possible by the introduction of a second, cellular communication option for interacting with the intersection and traffic signal control system. This cellular option was used exclusively during the Year 2 user tests.

- Simpler interaction with the app, due to elimination of the need for the user to tap "start crossing" and "crossing completion" buttons at the beginning and end of each cross. At present, the prototype assumes that a Bluetooth beacon is attached at each corner of the intersection, and uses proximity sensing to detect these start and end events.

- Smoother, more reliable overall operation, which has resulted from a combination of the above two improvements. One participant summed up this improvement concisely, stating that the biggest improvement this year was that "It worked."

Table 4-5: Improvements over last year

Feature	Number of Mentions
No additional device (sleeve)	5
Smoother operation	3
Simpler interaction (no start/end buttons)	3
Better connectivity	1
Greater accuracy with respect to walk signals	1
Better voice commands	1
It worked	1

4.4.1.2 User friendliness and perceived impact on safety and confidence

Table 4-6 summarizes how various participants rated the app on its user friendliness, its ability to increase crossing safety, its ability to increase crossing confidence and its ability to increase crossing efficiency. Each dimension is rated on a scale of 1 to 5, where 5 is most positive, 3 is neutral and one is most negative.

Table 4-6: User rating of *PedPal*'s effectiveness

Metric	5	4	3.5	3	2	1	Average
User Friendliness	9	5					4.64
Likelihood of Increased Safety	9	3		2			4.50
Likelihood of Increased Confidence	8	4	1	1			4.46
Likelihood of Increased Efficiency	7	5	1	1			4.39

With regard to user friendliness, all participants gave ratings between 4 and 5, and the average score was 4.62. Some participants giving a rating of 4 mentioned that they thought their user friendliness score would improve once they had more time to get used to *PedPal.* Those participants who previously participated in the Year 1 user field test were consistent in their opinions that usability of *PedPal* had improved.

With regard to perceptions of likelihood of increased safety, increased confidence, and increased efficiency, all participants gave ratings between 3 and 5, and average scores of 4.50, 4.46, and 4.39 respectively. Since advanced route following capabilities provided by *PedPal* were not emphasized during the user testing, the lower rating for likelihood of increased efficiency makes sense. Nonetheless, some vision impaired individuals did comment on the potential to reduce the number of cycles they would otherwise have to wait while listening to understand traffic flows at the intersection.

All vision impaired participants definitely agreed that *PedPal* would have significant impact on their safety and confidence at traffic intersections, and this fact was visible even during the testing by observers on the research team. When vision impaired users crossed the intersection without *PedPal* versus with *PedPal*, there was a notable difference in their level of tension and stress. Perhaps counterintuitively, vision impaired participants crossed the intersection more quickly without *PedPal* than they did when they used *PedPal.* However, this was because they seemed to rush as fast as possible across the street in a stressed state when they crossed without *PedPal* since there was always a degree of uncertainty of how much time remained for them to complete the cross without the benefit of the countdown feedback they received from *Pedpal*. When they were using *PedPa*l, they seemed visibly calmer and walked at a steady and confident pace.

Even participants who did not think they would use the app in their daily lives (for example, participants who used powered wheelchairs) rated *PedPal* highly in terms of having a positive impact on pedestrian safety and confidence when crossing traffic intersections. Some specific comments were that *PedPal* will be particularly useful in terms of safety at traffic signals that are not consistent or traffic signals that change their timing patterns through the day, and on quieter streets where signal timing patterns are not easily distinguished without the sounds of moving vehicle and, therefore, cannot be used by low vision or blind pedestrians to discern the state of the traffic signal.

4.4.1.3 Enhancements for future iterations

Several suggestions for enhancements that were provided as feedback during the Year 1 user field tests were incorporated into the Year 2 *PedPal* prototype, including:

- Providing a countdown for the red light as well as for the time remaining during the crossing phase – this capability was actually added for later participants in the Year 1 user test and as indicated above was deemed as the most popular feature of the app by Year 2 participants,

- Removing the necessity of having to tap "start crossing" and "complete crossing" buttons – the Year 2 prototype provides the ability to autonomously determine when the pedestrian starts and completes a street crossing, and thus simplifies user interaction with the *PedPal* app.
- Providing a bigger target to hit for buttons and selections on the screen – Screens have been redesigned to accommodate this suggestion.
- Adding more customization to the countdown vocalization in the app – Users can now specify the frequency at which they should be informed of remaining time (e.g., every 5 seconds, every 10 seconds, etc.).

That said, Year 2 Participants had several further suggestions for enhancements they thought would be useful in future iterations of *PedPal*. These suggested enhancements included:

- Veer detection – This capability implies monitoring for when the pedestrian veers off the crossing (perhaps simply using a tone in the relevant side of the headset to indicate recovery direction). This is a capability we are continuing to investigate with use of the Bluetooth beacons installed at each corner of the intersection.

- Voice activation - It would be great if the pedestrian could interact with the app through voice commands. In the app's current state, it can be invoked by Siri, but that is it. Unfortunately, Apple provides little detail on how to integrate with Siri, but this is nonetheless a great goal for the future.

- Orientation at the corner – Currently, PedPal provides information on the corner that the pedestrian is at, including location of curb cuts, and presence of inverted dimples. But ultimately the user must navigate to the crossing location and align with the crosswalk. Further improvement is clearly possible here.

- Additional information about the intersection – Currently, *PedPal* is capable of providing information about curb cut location at the corner, but there is additional information such as number of lanes in the crossing direction, presence of a traffic island, etc. that could be provided to support user crossing.

- iWatch interface – For mobility challenged users, one intriguing alternative to attaching the smartphone running *PedPal* to a wheelchair or walker would be to provide an iWatch interface.

- Accommodating pedestrians with cognitive disabilities – An explicit decision was made to defer consideration of the additional challenges of supporting pedestrians with cognitive disabilities, but this is an important area for future enhancement of the *PedPal* app.

- Other enhancements –

- Use a clicking noise or tone to notify the pedestrian when it is almost time to cross instead of counting

- enhancing the ability to attach the phone to something while maintaining the pedestrian's ability to touch the screen (for example, have the phone attached to the wheelchair),

- providing an indication to alert pedestrians when emergency vehicles are approaching.

Looking back more generally to the set of crossing challenges that were articulated by participants in completing their pre-test survey (see Section 4.3), we can see that the current *PedPal* prototype provides support for only a subset and leaves several challenges unaddressed. One challenge, that of monitoring for veering outside of the crosswalk, remained unaddressed at the time of the user test, but subsequently we have been experimenting with the use of Bluetooth beacons at the intersection as a means of enabling accurate veer detection. Others, such as filling in knowledge gaps and providing information on the key characteristics of an unfamiliar intersection, like crossing distance, number of signal phases, presence of left turn phases, one way streets, presence of curb cuts and whether they are angled, and presence of pedestrian call buttons, have been addressed only in providing the provision within *PedPal* to import this type of data from a third party data base. But the development and maintenance of such data sources remains an important unaddressed issue. Still other challenges, either require significant additional technology advances (such as orienting and navigating users to the cross walk or curb cuts) or are orthogonal to mobile app development (e.g., the introduction of a flashing blue light at the intersection to indicate when an emergency vehicle is approaching).

4.4.1.4 Future test interest and other optional comments

Finally, all participants were asked if they would be willing to participate in future tests of *PedPal* and were given the opportunity to comment on anything else they wished to say about the project. All participants said they would be willing to test *PedPal* again in the future if scheduling allows.

Participants also made a variety of other comments. Some commented that they enjoyed the testing and that it was fun. One participant observed that obstacles are not always a negative thing since they can help visually impaired people navigate, but if the obstacles are unexpected they can cause problems. Another participant commented that the phone app will not be a replacement for other training in orientation and mobility. Some participants suggested that *PedPal* should be integrated with a navigation app. A couple of participants talked about how it was difficult for them to cross large intersections due to the width of the intersection and the corresponding difficulty to stay on course when the pedestrian is blind. It was also suggested that it might be worth asking if users have been in accidents before since it could change how they cross intersections. One blind participant mentioned that s/he does not go out when there are fireworks because they obscure auditory cues and make it difficult to determine what is happening in their surroundings. Several participants mentioned the need to keep the app simple since sometimes new technology can be really complicated. One participant suggested that the traffic signals should have an additional light (perhaps blue) to indicate to deaf drivers and pedestrians that an emergency vehicle is approaching. All participants thought that *PedPal* was a promising development and several participants mentioned that they were really excited about *PedPal*.

4.4.2 Intersection Crossing Performance in the Field

As indicated earlier, each participant was asked to carry out a number of crossing trials at one or more of 4 designated intersections in the SURTRAC deployment in East Liberty PA. For each of these trials, a number of measurements were recorded, including (1) the amount of time the user waited upon arrival at the corner, (2) the number of traffic signal cycles that the user waited through while preparing to cross, and (3) the eventual crossing duration. In this section, we analyze this data and draw some conclusions.

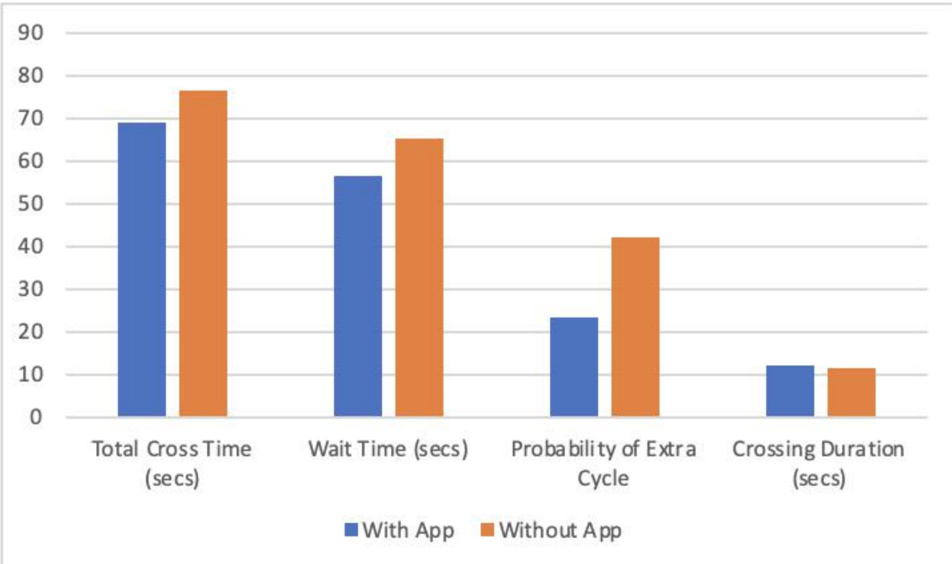

Figure 4-3: *PedPal* impact on vision-impaired pedestrians.

The Year 1 user testing experience underscored the fact that certain disability groups stand to benefit more than others from the *PedPal* intersection crossing app. Given this observation, comparative crossing trials were carried out with and without the use of the app for specific demographic groups. Figure 4-3 shows the results for vision-impaired individuals. It summarizes the observed behavior for 7 vison-impaired individuals (an 8th vision-impaired individual who participated experienced high volume traffic conditions and chose not to attempt the “without use of the app” option). As can be seen, use of the PedPal app resulted in a 8% decrease in *total crossing time,* defined as the duration from initial arrival at the corner to completion of the desired cross. This decrease is due directly to a decrease in the probability of waiting through a complete traffic signal cycle (as is often recommended to get a sense of vehicle traffic flows in different directions), from 42% (when not using the app) to 23% (when the app is being used). Note that the average actual crossing duration was observed to be 1 second shorter on average when the participant was not using *PedPal*, which corroborates our previously mentioned observation that the *PedPal* app's ability to provide a countdown of remaining crossing time allowed the user to cross with less stress and urgency.

Figure 4.4 shows the crossing performance observed when using the *PedPal* app by disability demographic and traffic condition. Vision-impaired individuals are categorized by traffic condition: free flow or highly congested. Mobility challenged individuals are partitioned into older individuals who use a walker or a cane, and individuals who are users of motorized wheelchairs. The observed results confirm prior expectations about the time required for crossing by different demographic groups. Mobility challenged individuals who are walking require the most crossing time, with vision-repaired individuals also requiring extra crossing time as a function of traffic congestion. Alternatively, motorized wheelchair users cross intersections efficiently and *PedPal* does not provide much added benefit.

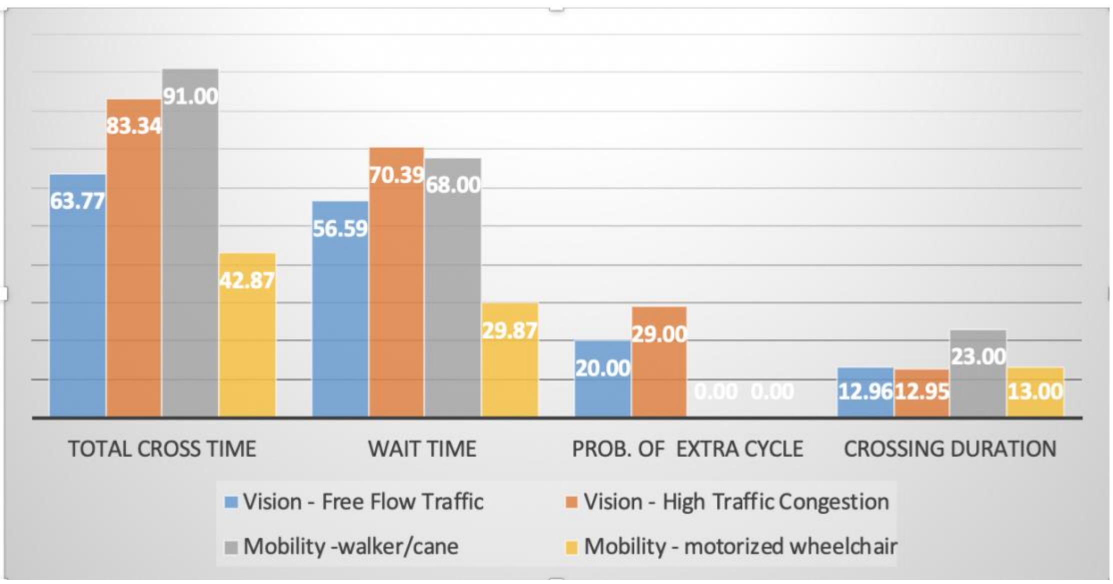

Figure 4-4: Crossing performance by disability type.

4.4.3 *PedPal* Robustness and Limitations

Two types of events were also recorded during each crossing trial: technical interventions and safety interventions. The former indicates some sort of app failure, which can be seen as indicative of the robustness of the *PedPal* app. The latter indicates some sort of circumstance where a member of the testing staff felt it necessary to intervene to protect the safety of the user. We consider each of these types of events in turn below.

With regard to technical interventions, our principal interest is in measuring the frequency of such events, to understand the relative robustness of the *PedPal* app. Overall, it was necessary to intervene to address a technical problem with the *PedPal* app on 6 of the 110 total user crossing trials that were performed using the app, giving a probability of incurring a technical problem of 5% per cross. Although there is still considerable room for improvement, this rate is at least an order of magnitude better than what was observed in the Year 1 user tests.

Finally, to underscore the fact that PedPal is not a complete solution for safe intersection crossing but rather a safety promoting tool, we also recorded the frequency and types of safety interventions that were necessary during crossing trials with the PedPal app. A total of 12 safety interventions were necessary over the course of the 110 crossing trials that were performed with the app. Hence, on about 11% of the crossing trials, there was a safety issue that required intervention. The types of safety issues that arose are given in Table 4-7 below.

Table 4-7: Types of safety issues that required intervention.

Safety Issue	Number of Occurrences
Veering outside of the crosswalk	6
Aggressive Drivers	3
Heard “cross” when the app said “don’t cross”	1
Assistance to avoid stepping in pothole	1
Unrecorded	1

4.5 Data Management

At the request of the Accessible Transportation Technology Research Initiative (ATTRI) program, the data generated during both the 2018 and 2019 user field tests will be archived and preserved for future access, use and distribution. This data will be made available in accordance with Institutional Research Board (IRB) policies and procedures, which is predicated on user consent and removal of all personal information to ensure privacy. Once the data has been properly anonymized and formatted, it will be transferred to the ITS Joint Program Office (JPO) and the ITS JPO will assume long-term responsibility for managing the data through the DOT’s ITS Data Hub located at https://www.its.dot.gov/data/. Full details of the archiving and preservation plan for data, the access policy, data redistribution, type of data archived, data structure and date use may be found in [4].

Chapter 5 Next Steps

The Year 2 user field test has provided strong evidence of the viability and potential of the *PedPal* mobile app concept for safe intersection crossing that has been developed over the course of this project. In comparison to the initial *PedPal* prototype tested in Year 1, the Year 2 prototype was found to be simpler and easier to use, and much more robust with respect to system operations. Overwhelmingly, user response was positive and enthusiastic.

At the same time, there are several additional issues that remain to be addressed to turn the *PedPal* technology into a practical tool for pedestrians with disabilities. These next steps are discussed in the subsections below.

5.1 Additional Prototype Refinement and Hardening

Perhaps the biggest technical challenge to practical application of the *PedPal* mobile app in its current form is the lack of sufficient localization accuracy in the iPhone to support corner identification, progress monitoring and veer detection. As indicated earlier in the report, we have had initial success in using signals from Bluetooth beacons deployed at each corner of the intersection to achieve reliable corner identification upon user arrival at the intersection, as well as crossing start and end events. As this report is being written, ongoing work is attempting to extend this technique to enable a basic progress monitoring capability, which would enable *PedPal*'s ability to dynamically extend the crossing signal duration if slow progress is detected. The problem of detecting when the user veers outside of the crosswalk may also be addressable with this additional sensing capability. This will require triangularization with an additional beacon not on the intersection crossing path and will be investigated in a third step.

Additional next steps relate to hardening and expansion of aspects of *PedPal*'s current feature set. These topics include the following activities:

- *Extension to exploit veering detection solution* – Assuming that the just mentioned beacon-driven approach to detecting veering outside of the crosswalk is successful, further development of the *PedPal* app will be necessary to take advantage of it. Specifically, the MAP message specification will have to be extended to include crosswalk geometry information and the app extended to properly extract this information use in detecting outside of the crosswalk veers. The PedPal user interface will also require extension to signal such events (e.g., by haptic vibration), and to properly indicate the necessary corrective direction.

- *Extension to complex intersections* – The current *PedPal* mobile app user interface makes a number of simplifying assumptions about the structure of the intersection (e.g., east-west and north-south approaches and phases only). A third focus will be to generalize user interface capabilities to relax these assumptions and enable operation in complex intersections.

- *Integration with navigation and wayfinding apps* – The current *PedPal* mobile app provides a "route following" feature that utilizes an imported user route (specified as a sequence of intersection corner waypoints) to communicate the user's expected arrival time to the next intersection in advance and allow SURTRAC to factor this information into its real-time optimization of the intersection's signal timing plan to streamline the user's wait time before crossing the intersection. To demonstrate this capability to selected participants during the user field tests, integration with a third party navigation app was simulated by loading a previously planned route into *PedPal* from a designated URL. For route following to be useful in practice, there must be more explicit integration with relevant third party navigation and wayfinding apps. This could happen in a couple of ways. One path to integration would be to establish an explicit protocol for transfer of information between apps. For example, BlindSquare currently provides the ability to export a generated route as a sequence of waypoints to an external file, which could be imported and preprocessed by PedPal in much the same fashion was simulated for the field test. A tighter integration could enable direct communication between apps (e.g., a "transfer route to *PedPal*" command within BlindSquare). A second path to integration would be to embed the *PedPal* intersection crossing functionality within a navigation or wayfinding app already being used by potential *PedPal* users. One interesting possibility in this regard could be the PathVu wheelchair navigation app currently being developed in a companion ATTRI research project. Both of these app integration paths are worthy directions for future research.

- *Real-time synchronization with bus arrivals* – As indicated earlier, our Year 2 *PedPal* system design specification included plans to use of real-time bus information obtained by SURTRAC from DSRC-equipped transit vehicles together with bus stop and bus route information received from the pedestrian to synchronize the crossing movements of bus-seeking pedestrians with their desired arriving buses. However, delays in a companion project with the Port Authority of Allegheny County to equip buses moving through the SURTRAC-controlled field test area along with more pressing *PedPal* development issues has prevented us from investigating this capability as originally planned. Extension of the current *PedPal* prototype to realize this designed capability is another obvious area for future work. It could also be interesting to explore other, simpler means of real-time coordination with buses through direct pedestrian-to-bus communication.

- *iWatch interface* – One difficulty for wheelchair users and older individuals that move with a walker is how to simultaneously cross and interact with the phone, and several user test participants expressed the need for some means for physically attaching the phone to the mobility aide or on the user's person. An interesting option in this regard that was suggested by a couple of participants was to develop an iWatch interface to the PedPal app. This would require some amount of rethinking of the interface given the smaller visual real estate to work with, but the idea of running PedPal on an iWatch makes a lot of sense for this user demographic and could broaden overall use.

- *Broadcasting pedestrian presence to approaching vehicles* – A final simple extension to *PedPal*'s current feature set that would be expected to provide increasing safety benefits as vehicles become more connected with the infrastructure over time is to simply augment the SURTRAC response to a *PedPal* signal crossing request to include a broadcast message to all approaching vehicles indicating that there is a pedestrian with a disability at the intersection waiting to cross.

5.2 Technology Deployment

In addition to refining and hardening the current *PedPal* mobile app for practical application, there are also issues relating to how to best deploy the resulting technology. We envision a couple of different (and potentially complementary) approaches to deployment:

- *Together with SURTRAC* – The SURTRAC traffic signal control system is currently marketed to municipalities by Rapid Flow Technologies, Inc., a CMU spinoff company that was founded in 2015. One baseline approach to deploying *PedPal* under consideration would be to offer it to municipalities as an extended feature that is provided free of charge as part of any purchased SURTRAC deployment. Municipalities could then offer the capability to their local disability community as a gesture of goodwill.

- *PedPal Lite* – Although this does not currently exist, it should be possible to create a version of PedPal that provides basic intersection capabilities of signaling crossing intent and receiving the amount of crossing time requested, without requiring SURTRAC as the traffic control system and instead operating with just the traffic signal controller at the intersection running a conventional fixed timing plan. Capabilities like progress monitoring and dynamic real-time extension of crossing time, and route following that depend on SURTRAC control would not be possible. But for broader use of the *PedPal* technology this might be a viable tradeoff.

In either case, there are additional important issues relating to how the *PedPal* technology is made available to prospective users. First, the fact that *PedPal* provides the ability to set the user's speed and in return get the crossing time that is implied is a feature that is appropriate for pedestrians with disabilities, but not necessarily for any pedestrian that might have access to the app. Thus, it seems unrealistic that *PedPal* should be disseminated by simply making it available at the Apple App Store (or through Android's equivalent site, once the *PedPal* technology has been ported). Instead it seems more reasonable to assume that access to *PedPal* be mediated by some sort of user registration site, where eligibility can be determined in advance of access to download it. Second, it seems necessary to provide some sort of registry of *PedPal* enabled intersections in a given municipality or geographic area where *PedPal* has been made available, since an intersection that is not enabled will have no way of communicating that information to the mobile app. Both of these practical deployment issues require development of appropriate mechanisms.

Chapter 6 References

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Appendix A. System Requirements

Table 6-1 below provides a list of all system requirements for the ATTRI Safe Intersection Crossing System along with the status, category, traceability and verification method for each requirement.

Table 6-1: Requirements Traceability Matrix

ID	Requirement Description	Status	Source (ConOps Reference)	Category	Verification Method	Subsystem
SR-001	The system shall ensure that provided information (alerts, navigation, etc.) follows universal design standards to allow accessibility for different types of disabilities.	Satisfied	SRA Discussion	Interface	Demo	PDS
SR-002	The system shall provide accessible interfaces and content that follows Web Content Accessibility Guidelines (WCAG)	Satisfied	SRA Discussion	Interface	Demo	PDS
SR-003	The system shall provide accessible interfaces and content that follows BBC Standards and Guidelines for Mobile Accessibility.	Satisfied	SRA Discussion	Interface	Demo	PDS
SR-004	The system should follow Apple's recommended advice on accessible app.	Satisfied	SRA Discussion	Interface	Demo	PDS

ID	Requirement Description	Status	Source (ConOps Reference)	Category	Verification Method	Subsystem
SR-005	The system shall have audio components to provide audible notifications and alerts.	Satisfied	ConOps/Ch6/DDF/Table1	Interface	Inspection	PDS
SR-006	The system shall have the option of slowly delivering aural (ear or hearing) information.	Satisfied	ConOps/Ch6/DDF/Table1	Interface	Inspection	PDS
SR-007	The system shall be capable of providing mono aural information.	Satisfied	ConOps/Ch6/DDF/Table1	Interface	Demo	PDS
SR-008	The system shall be capable of providing visual alerts and notifications.	Satisfied	ConOps/Ch6/DDF/Table1	Interface	Demo	PDS
SR-009	The system shall be capable of providing vibratory alerts and notifications.	Partially Satisfied	ConOps/Ch6/DDF/Table1	Interface	Demo	PDS
SR-010	The system shall have the option of delivering visual information slowly.	Satisfied	ConOps/Ch6/DDF/Table1	Interface	Inspection	PDS
SR-011	The system shall have the option of repeating visual information when needed (i.e. requested by user).	Satisfied	ConOps/Ch6/UC11	Interface	Inspection	PDS
SR-012	The system shall facilitate visual interface (reading of the instructions, etc.) in visually difficult situations (e.g. bright light, dark, etc.)	Satisfied	ConOps/Ch6/DDF/Table1	Interface	Inspection	PDS
SR-013	The system should be capable of providing the user with confirmation throughout tasks.	Partially Satisfied	ConOps/Ch6/DDF/Table1	Interface	Demo	PDS

ID	Requirement Description	Status	Source (ConOps Reference)	Category	Verification Method	Subsystem
SR-014	The system shall provide the option to the user for adjusting (i.e. reducing or increasing) the number of notifications user receives.	Partially Satisfied	ConOps/Ch6/DDF/Table1	Interface	Demo	PDS
SR-015	The system shall be able to receive commands from a user through text input.	Remove	ConOps/Ch6/UC1	Interface	Demo	PDS
SR-016	The system shall be able to receive commands from the user through voice communication	Satisfied	ConOps/Ch6/DDF/Table1	Interface	Demo	PDS
SR-017	The system shall be capable of announcing upcoming task or step.	Satisfied	ConOps/Ch6/DDF/Table1	Interface	Demo	PDS
SR-018	The system should be capable of displaying upcoming task or step with text descriptions.	Satisfied	ConOps/Ch6/DDF/Table1	Interface	Demo	PDS
SR-019	The system shall be able to adjust level of assistance based on user profile (e.g., disability type).	Satisfied	ConOps/Ch4/DCC/Table 1	Interface	Demo	PDS
SR-020	The system shall have the option of varying the level of assistance (e.g., verbosity).	Partially Satisfied	ConOps/Ch4/DCC/Table 1	Interface	Demo	PDS
SR-021	The system shall provide the user with an option to cancel receiving directions and alerts.	Satisfied	ConOps/Ch5/UC12	Functional	Demo	PDS
SR-022	The system shall have the option to be completely turned off.	Satisfied	ConOps/Ch5/UC12	Functional	Demo	PDS

ID	Requirement Description	Status	Source (ConOps Reference)	Category	Verification Method	Subsystem
SR-023	The system shall have the option of providing direction using clock position.	Defer	ConOps/Ch4/DCC/Table 1	Interface	Demo	PDS
SR-024	The system shall have the option of providing cardinal directions (e.g. East, Northwest).	Defer	ConOps/Ch6/DDF/Table1	Interface	Demo	PDS
SR-025	The system should have the option of providing relative directions (e.g. left, right, behind, in front of).	Defer	ConOps/Ch6/DDF/Table1	Interface	Demo	PDS
SR-026	The system shall be capable of recognizing when there is no connectivity with the intersection (e.g., traffic signal system).	Satisfied	ConOps/Ch5/UC5	Functional	Formal Test	IIS
SR-027	The system shall be capable of communicating "no connectivity with the intersection", with the user.	Satisfied	ConOps/Ch5/UC5	Functional	Formal Test	PDS
SR-028	The system shall have an option for the user to communicate her/his progress in case of unreliable or unavailable GPS.	Remove	ConOps/Ch7/Improvement #1	Functional	Demo	PDS
SR-029	The system shall be capable of communicating with a traffic signal system.	Satisfied	ConOps/Ch5/UC1	Interface	Formal Test	IIS
SR-030	The system shall be able to collect the signal phase and timing data from the traffic signal system.	Satisfied	ConOps/Ch5/UC1	Interface	Formal Test	PDS
SR-031	The system shall be able to interact with the traffic signal system to influence signal timing and duration.	Satisfied	ConOps/Ch5/UC1	Interface	Formal Test	IIS

ID	Requirement Description	Status	Source (ConOps Reference)	Category	Verification Method	Subsystem
SR-032	The system shall be capable of communicating with a Smart Phone device.	Satisfied		Interface	Formal Test	PDS
SR-033	The system should be able to adjust signal timing plan based on the user's speed.	Satisfied	ConOps/Ch7/Improvement #3	Functional	Formal Test	IIS
SR-034	The system should be capable of providing the user with information about the upcoming intersection (cross/don't cross signaling, how many streets crossing and crossing options, etc.)	Satisfied	ConOps/Ch5/UC9	Interface	Formal Test	PDS
SR-035	The system shall be able to recognize the intersection (e.g., intersection of Maine and 3rd).	Satisfied	ConOps/Ch5/UC10	Functional	Formal Test	PDS
SR-036	The system should be able to locate the corner of the intersection at which the user is positioned (e.g., southwest corner of Maine and 3rd).	Partially Satisfied	ConOps/Ch5/UC10	Functional	Formal Test	PDS
SR-037	The system should be able to identify where the user is standing (side walk or street).	Defer	ConOps/Ch5/UC10	Functional	Formal Test	PDS
SR-038	The system should be able to determine location of crosswalk corridor.	Defer	ConOps/Ch5/UC10	Functional	Formal Test	PDS
SR-039	The system should be able to determine location of crosswalk corridor relative to the user.	Defer	ConOps/Ch5/UC10	Functional	Formal Test	PDS

ID	Requirement Description	Status	Source (ConOps Reference)	Category	Verification Method	Subsystem
SR-040	The system shall be able to collect personalized intersection crossing constraints from the user.	Satisfied	ConOps/Ch5/Use Cases	Interface	Formal Test	PDS
SR-041	The system should be able to communicate to the user on which intersection the user is located.	Satisfied	ConOps/Ch5/UC10	Interface	Demo	PDS
SR-042	The system should be able to communicate with the user the exact corner of the intersection at which (s)he is standing.	Partially Satisfied	ConOps/Ch5/UC10	Interface	Demo	PDS
SR-043	The system should be able to communicate to the user contextual information on the built environment around an intersection.	Not Done	ConOps/Ch5/UC10	Functional	Demo	PDS
SR-044	The system should be able to provide guidance to the user in locating the crosswalk corridor (the rectangular path defined by the crosswalk pattern borders, extended onto the sidewalk it adjoins).	Defer	ConOps/Ch5/UC10	Functional	Demo	PDS
SR-045	The system should be able to provide a notification when the user locates the crosswalk corridor.	Defer	ConOps/Ch5/UC10	Functional	Demo	PDS
SR-046	The system should have the capability of providing information about the corner (e.g., presence and type of curb cuts) to users with visual impairments to help him/her orient an navigate to the crosswalk	Not Done	ConOps/Ch6/Operational Impact #5	Functional	Formal Test	PDS

ID	Requirement Description	Status	Source (ConOps Reference)	Category	Verification Method	Subsystem
SR-047	The system should have the capability to guide the user to the starting location of the crosswalk.	Remove	ConOps/Ch6/Operational Impact #5	Functional	Formal Test	PDS
SR-048	The system should be able to provide an alert when the user is not inside of crosswalk corridor.	Not Done	ConOps/Ch6/Operational Impact #5	Functional	Formal Test	PDS
SR-049	The system should be able to provide confirmation when the user is inside of crosswalk corridor.	Not Done	ConOps/Ch6/Operational Impact #5	Functional	Formal Test	PDS
SR-050	The system should inform users with intersection geometric information (e.g., curb cut locations).	Remove	ConOps/Ch6/Operational Impact #5	Interface	Formal Test	PDS
SR-051	The system should inform users with obstacle information (e.g., work zone) about the intersection	Not Done	ConOps/Ch6/Operational Impact #5	Interface	Formal Test	PDS
SR-052	The system shall be capable of alerting the user to wait when the signal indicates No Walk.	Satisfied	ConOps/Ch5/UC8	Interface	Formal Test	PDS

ID	Requirement Description	Status	Source (ConOps Reference)	Category	Verification Method	Subsystem
SR-053	The system should provide the ability to use pre-planned route and destination information (e.g., walking path)	Not Done	ConOps/Ch4/Mobile App UI	Interface	Formal Test	PDS
SR-054	The system shall be capable of alerting the user to wait when the signal indicates "Walk", but there is not enough time remaining for the user to cross.	Not Done	ConOps/Ch5/UC3	Interface	Formal Test	PDS
SR-055	The system shall be capable of notifying the user of how much time is remained of a specific signal phase (walk or no-walk)	Satisfied	ConOps/Ch4/Modes of Operation	Interface	Formal Test	PDS
SR-056	The system shall communicate with the user whether an intersection has a traffic island.	Not Done	ConOps/Ch5/UC1-5, UC6-14	Interface	Formal Test	PDS
SR-057	The system shall be able to provide guidance, notifications, and alerts in order to assist the users in crossing the intersection.	Partially Satisfied	ConOps/Ch4/DCC/Table 1	Functional	Demo	PDS
SR-058	The system shall provide the option for the user to enter crossing direction.	Satisfied	ConOps/Ch6/UC1	Interface	Demo	PDS
SR-059	The system shall provide the option for the user to indicate intent to cross.	Satisfied	ConOps/Ch6/UC1	Interface	Demo	PDS
SR-060	The system should be able to determine direction of the user relative to crossing direction.	Partially Satisfied	ConOps/Ch5/UC10	Functional	Formal Test	PDS

ID	Requirement Description	Status	Source (ConOps Reference)	Category	Verification Method	Subsystem
SR-061	If the user intends to make two consequent crosses at an intersection, the system shall provide information that enables the user to determine which cross should occur first.	Satisfied	ConOps/Ch5/UC8	Functional	Formal Test	PDS
SR-062	The system shall be able to provide real time information (signal phase, timing, etc.) about the traffic signal system.	Satisfied	ConOps/Ch6/UC1-4,6-14	Functional	Formal Test	PDS
SR-063	The system shall be able to notify the user when Walk time is extended.	Satisfied	ConOps/Ch5/UC2	Functional	Formal Test	PDS
SR-064	The system shall be capable of informing the user to cross when the signal indicates Walk and there is enough time left for the user to cross.	Satisfied	ConOps/Ch5/UC2	Interface	Formal Test	PDS
SR-065	The system should have the capability of coordinating the signal timing plans with anticipated user arrivals.	Not Done	ConOps/Ch4/Surtrac ATSC	Functional	Formal Test	IIS
SR-066	The system shall have the capability to notify the traffic signal system of the intersection crossing intention of the user.	Satisfied	ConOps/Ch6/Operational Impact #3	Functional	Formal Test	IIS
SR-067	The system should be able to determine the user speed crossing an intersection.	Not Done	ConOps/Ch5/UC7	Functional	Analysis	PDS

ID	Requirement Description	Status	Source (ConOps Reference)	Category	Verification Method	Subsystem
SR-068	The system should be capable of computing time required for a user to cross a specific intersection.	Satisfied	ConOps/Ch5/UC1	Functional	Analysis	PDS
SR-069	The system should have the capability to track the user's progress through the crosswalk (from one corner to the other).	Not Done	ConOps/Ch6/Operational Impact #4	Functional	Formal Test	PDS
SR-070	The system should be capable of identifying the user's delays in crossing an intersection.	Not Done	ConOps/Ch5/UC7	Functional	Formal Test	PDS
SR-071	The system should be capable of identifying the users' drift from the crosswalk when crossing an intersection.	Not Done	ConOps/Ch5/UC6	Functional	Formal Test	PDS
SR-072	The system should be capable of communicating with the user regarding his/her progress crossing an intersection.	Not Done	ConOps/Ch4/Mobile App UI	Functional	Formal Test	PDS
SR-073	The system shall enable the user to notify the system of his/her delay crossing an intersection.	Remove	ConOps/Ch5/UC7	Interface	Demo	PDS
SR-074	The system should be capable of communicating the user's delay to the traffic signal system in real time.	Not Done	ConOps/Ch5/UC7	Interface	Formal Test	PDS

ID	Requirement Description	Status	Source (ConOps Reference)	Category	Verification Method	Subsystem
SR-075	The system shall have the capability to allow for dynamic extension of minimum crossing time constraint if an unexpected delay is detected	Partially Satisfied	ConOps/Ch4/Surtrac ATSC	Functional	Formal Test	IIS
SR-076	The system should notify the user of her/his deviation from the crosswalk.	Not Done	ConOps/Ch5/UC6	Interface	Formal Test	PDS
SR-077	The system should provide directional guidance to help the user get back in the safe zone path in case of a drift.	Not Done	ConOps/Ch5/UC10	Interface	Formal Test	PDS
SR-078	The system should notify the user of his delay crossing an intersection.	Remove	ConOps/Ch5/UC7	Interface	Formal Test	PDS
SR-079	The system should have the capability to advise users on how to exit the crosswalk by providing guidance to the exit point (whether there is a curb or a cut-out, grade, etc.)	Defer	ConOps/Ch6/Operational Impact #2	Functional	Formal Test	PDS
SR-080	The system shall be able to provide a notification when the user successfully crosses an intersection.	Not Done	ConOps/Ch4/DCC/Table 1	Functional	Formal Test	PDS
SR-081	The system shall be capable of identifying a location (i.e. coordinates) of interest at the intersection	Partially Satisfied	ConOps/Ch5/UC6	Performance	Analysis	PDS
SR-082	The system shall correctly identify the intersection at which the user is located.	Satisfied	ConOps/Ch7/Performance Measures	Performance	Analysis	PDS

ID	Requirement Description	Status	Source (ConOps Reference)	Category	Verification Method	Subsystem
SR-083	The system shall correctly identify the intersection corner at which the user is located.	Partially Satisfied	ConOps/Ch7/Performance Measures	Performance	Analysis	PDS
SR-084	The system shall correctly determine whether a user has begun crossing an intersection and is delayed to the extent that the current GREEN phase must be extended.	Not Done	ConOps/Ch7/Performance Measures	Performance	Analysis	PDS
SR-085	The system shall correctly detect when a user veers outside of the crosswalk.	Not Done	ConOps/Ch7/Performance Measures	Performance	Analysis	PDS
SR-086	The system shall increase blind users' perceived safety crossing an intersection.	Partially Satisfied	ConOps/Ch7/Performance Measures	Performance	Analysis	PDS
SR-087	The system shall reduce the number of cycles a blind user waits to feel safe crossing the intersection.	Partially Satisfied	ConOps/Ch7/Performance Measures	Performance	Analysis	PDS
SR-088	The system shall increase the percentage of new intersections crossed by a user.	Remove	ConOps/Ch7/Performance Measures	Performance	Analysis	PDS
SR-089	The system shall decrease total time it takes for the user to cross an intersection (from arrival at the intersection to completion of the crossing) from the user's unassisted crossing time.	Partially Satisfied	ConOps/Ch7/Performance Measures	Performance	Analysis	PDS
SR-090	The system shall improve the user travel time through a sequence of intersections from the user's baseline travel time.	Partially Satisfied	ConOps/Ch7/Performance Measures	Performance	Analysis	PDS

ID	Requirement Description	Status	Source (ConOps Reference)	Category	Verification Method	Subsystem
SR-091	The system should ingest, store and access relevant information about the intersection and its corners, including presence and location of curb cuts at corners to facilitate entry into the crosswalk and presence of traffic islands in different crossing directions.	Not Done	ConOps/Ch5/UC1-5, UC6-14	Data	Inspection	PDS
SR-092	The system should be able to ingest, store, and access information on an intersection's traffic signal system.	Satisfied	ConOps/Ch5/UC1	Data	Inspection	PDS
SR-093	The system should be able to ingest, store, and access information on an intersection's traffic signal system's operational status.	Defer	ConOps/Ch5/UC5	Data	Inspection	PDS
SR-094	The system should be able to ingest, store, and access information on whether an intersection is equipped for DSRC communications	Satisfied	ConOps/Ch5/UC1	Data	Inspection	PDS
SR-095	The system shall be able to ingest, store, and access MAP message data.	Satisfied	SRA Discussion	Data	Demo	PDS
SR-096	The system shall be able to ingest, store and access SPaT message data.	Satisfied	SRA Discussion	Data	Demo	PDS
SR-097	The system should have a data validation process.	Partially Satisfied	SRA Discussion	Data	Inspection	PDS
SR-098	The system should be able to ingest, store and access data from external sources (e.g., through appropriate APIs)	Not Done	SRA Discussion	Data	Demo	PDS

ID	Requirement Description	Status	Source (ConOps Reference)	Category	Verification Method	Subsystem
SR-109	The system shall not store any PII data.	Not Done	SRA Discussion	Data	Inspection	PDS
SR-100	The system shall be able to ingest, store and access a user's travel plan,	Satisfied	ConOps/Ch5/UC14	Functional	Demo	PDS
SR-101	The system shall collect information about what kind of assistive technology or mobility aid the pedestrian is using.	Not Done	SRA Discussion	Data	Inspection	PDS
SR-102	The system shall be able to determine, prior to the user's arrival, if an upcoming intersection is adjacent to the user's bus route transfer point	Not Done	ConOps/Ch5/UC14	Functional	Demo	PDS
SR-103	The system shall be able to ingest or determine the user's embarkation bus stop and desired bus route number.	Not Done	ConOps/Ch5/UC14	Functional	Demo	PDS
SR-104	The system shall be able to determine, prior to the user's arrival, the user's expected arrival time at the intersection.	Not Done	ConOps/Ch5/UC14	Functional	Demo	PDS
SR-105	The system shall be able to determine if there is an approaching bus with the desired bus route number.	Not Done	ConOps/Ch5/UC14	Functional	Demo	IIS
SR-106	The system shall be able to estimate the time at which the bus is expected to depart from the bus stop	Not Done	ConOps/Ch5/UC14	Functional	Demo	IIS
SR-107	The system shall be able to determine if additional crossing time must be allocated to ensure that the bus remains at the bus stop until the user can embark.	Not Done	ConOps/Ch5/UC14	Functional	Demo	IIS

ID	Requirement Description	Status	Source (ConOps Reference)	Category	Verification Method	Subsystem
SR-108	The system shall be able to allocate the additional crossing time to ensure that the bus remains at the bus stop until the user can embark.	Satisfied	ConOps/Ch5/UC14	Functional	Demo	IIS

Appendix B. Requirements to Use Case Mapping

ID	Requirement Description	UC1	UC2	UC3	UC4	UC5	UC6	UC7	UC8	UC9	UC10	UC11	UC12	UC13	UC14
SR-001	The system shall ensure that provided information (alerts, navigation, etc.) follows universal design standards to allow accessibility for different types of disabilities.	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SR-002	The system shall provide accessible interfaces and content that follows Web Content Accessibility Guidelines (WCAG)	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SR-003	The system shall provide accessible interfaces and content that follows BBC Standards and Guidelines for Mobile Accessibility.	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SR-004	The system should follow Apple's recommended advice on accessible applications.	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SR-005	The system shall have audio components to provide audible notifications and alerts.	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SR-006	The system shall have the option of slowly delivering aural (ear or hearing) information.	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SR-007	The system shall be capable of providing mono aural information.	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SR-008	The system shall be capable of providing visual alerts and notifications.	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SR-009	The system shall be capable of providing vibratory alerts and notifications.	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SR-010	The system shall have the option of delivering visual information slowly.	X	X	X	X	X	X	X	X	X	X	X	X	X	X

ID	Requirement Description	UC1	UC2	UC3	UC4	UC5	UC6	UC7	UC8	UC9	UC10	UC11	UC12	UC13	UC14
SR-011	The system shall have the option of repeating visual information when needed (i.e. requested by user).											X			
SR-012	The system shall facilitate visual interface (reading of the instructions, etc.) in visually difficult situations (e.g. bright light, dark, etc.)	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SR-013	The system should be capable of providing the user with confirmation throughout tasks.	X	X	X	X			X							
SR-014	The system shall provide the option to the user for adjusting (i.e. reducing or increasing) the number of notifications user receives.	X	X	X	X	X	X	X	X						
SR-015	The system shall be able to receive commands from a user through text input.														
SR-016	The system shall be able to receive commands from the user through voice communication	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SR-017	The system shall be capable of announcing upcoming task or step.	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SR-018	The system should be capable of displaying upcoming task or step with text descriptions.	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SR-019	The system shall be able to adjust level of assistance based on user profile (e.g., disability type).	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SR-020	The system shall have the option of varying the level of assistance (e.g., verbosity).	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SR-021	The system shall provide the user with an option to cancel receiving directions and alerts.												X		
SR-022	The system shall have the option to be completely turned off.												X		
SR-023	The system shall have the option of providing direction using clock position.	X	X	X	X	X	X	X	X	X	X	X	X	X	X

ID	Requirement Description	UC1	UC2	UC3	UC4	UC5	UC6	UC7	UC8	UC9	UC10	UC11	UC12	UC13	UC14
SR-024	The system shall have the option of providing cardinal directions (e.g. East, Northwest).	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SR-025	The system should have the option of providing relative directions (e.g. left, right, behind, in front of).	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SR-026	The system shall be capable of recognizing when there is no connectivity with the intersection (e.g., traffic signal system).					X									
SR-027	The system shall be capable of communicating "no connectivity with the intersection" to the user.					X									
SR-028	The system shall have an option for the user to communicate her/his progress in case of unreliable or unavailable GPS.														
SR-029	The system shall be capable of communicating with a traffic signal system.	X													
SR-030	The system shall be able to collect the signal phase and timing data from the traffic signal system.	X													
SR-031	The system shall be able to interact with the traffic signal system to influence signal timing and duration.	X													
SR-032	The system shall be capable of communicating with a Smart Phone device.	X	X	X	X		X	X	X	X	X	X	X	X	X
SR-033	The system should be able to adjust the signal timing plan based on the user's speed.	X	X	X	X			X							
SR-034	The system should be capable of providing the user with information about the upcoming intersection (cross/don't cross signaling, how many streets crossing and crossing options, etc.)									X					
SR-035	The system shall be able to recognize the intersection (e.g., intersection of Maine and 3rd).										X				
SR-036	The system should be able to locate the corner of the intersection at which the user is positioned (e.g., southwest corner of Maine and 3rd).										X				

ID	Requirement Description	UC1	UC2	UC3	UC4	UC5	UC6	UC7	UC8	UC9	UC10	UC11	UC12	UC13	UC14
SR-037	The system should be able to identify where the user is standing (side walk or street).										X				
SR-038	The system should be able to determine location of crosswalk corridor, which is the rectangular path defined by the crosswalk pattern borders, extended onto the sidewalk it adjoins.										X				
SR-039	The system should be able to determine location of crosswalk corridor relative to the user.										X				
SR-040	The system shall be able to collect personalized intersection crossing constraints from the user.	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SR-041	The system should be able to communicate to the user on which intersection the user is located.										X				
SR-042	The system should be able to communicate with the user the exact corner of the intersection at which (s)he is standing.										X				
SR-043	The system should be able to communicate to the user contextual information on the built environment around an intersection.										X				
SR-044	The system should be able to provide guidance to the user in locating the crosswalk corridor (the rectangular path defined by the crosswalk pattern borders, extended onto the sidewalk it adjoins).										X				
SR-045	The system should be able to provide a notification when the user locates the crosswalk corridor.										X				
SR-046	The system should have the capability of providing information about the corner (e.g., presence and type of curb cuts) to users with visual impairments to help him/her orient an navigate to the crosswalk										X	X			
SR-047	The system should have the capability to guide the user to the starting location of the crosswalk.														

ID	Requirement Description	UC1	UC2	UC3	UC4	UC5	UC6	UC7	UC8	UC9	UC10	UC11	UC12	UC13	UC14
SR-048	The system should be able to provide an alert when the user is not inside of crosswalk corridor.						X								
SR-049	The system should be able to provide confirmation when the user is inside of crosswalk corridor.						X								
SR-050	The system should inform users with intersection geometric information (e.g., curb cut locations).														
SR-051	The system should inform users with obstacle information (e.g., work zone) about the intersection										X	X			
SR-052	The system shall be capable of alerting the user to wait when the signal indicates No Walk.								X						
SR-053	The system should provide the ability to use pre-planned route and destination information (e.g., walking path)									X					X
SR-054	The system shall be capable of alerting the user to wait when the signal indicates "Walk", but there is not enough time remaining for the user to cross.			X											
SR-055	The system shall be capable of notifying the user of how much time is remained of a specific signal phase (walk or no-walk)	X	X	X	X		X	X	X	X	X	X	X	X	X
SR-056	The system shall communicate with the user whether an intersection has a traffic island.	X	X	X	X		X	X	X	X	X	X	X	X	X
SR-057	The system shall be able to provide guidance, notifications, and alerts in order to assist the users in crossing the intersection.	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SR-058	The system shall allow users to enter their crossing direction.	X													
SR-059	The system shall allow users to indicate their intent to cross in the mobile application.	X													
SR-060	The system should be able to determine direction of the user relative to crossing direction.										X				

ID	Requirement Description	UC1	UC2	UC3	UC4	UC5	UC6	UC7	UC8	UC9	UC10	UC11	UC12	UC13	UC14
SR-061	If the user intends to make two consequent crosses at an intersection, the system shall provide information that enables the user to determine which cross should occur first.								X						
SR-062	The system shall be able to provide real time information (signal phase, timing, etc.) about the traffic signal system.	X	X	X	X		X	X	X	X	X	X	X	X	X
SR-063	The system shall be able to notify the user when Walk time is extended.		X												
SR-064	The system shall be capable of informing the user to cross when the signal indicates Walk and there is enough time left for the user to cross.		X												
SR-065	The system should have the capability of coordinating the signal timing plans with anticipated user arrivals.									X					
SR-066	The system shall have the capability to notify the traffic signal system of the intersection crossing intention of the user.	X	X	X	X		X	X	X	X	X	X	X	X	X
SR-067	The system should be able to determine the user speed crossing an intersection.							X							
SR-068	The system should be capable of computing time required for a user to cross a specific intersection.	X													
SR-069	The system should have the capability to track the user's progress through the crosswalk (from one corner to the other).							X							
SR-070	The system should be capable of identifying the user's delays in crossing an intersection.							X							
SR-071	The system should be capable of identifying the users' drift from the crosswalk when crossing an intersection.						X								
SR-072	The system should be capable of communicating with the user regarding his/her progress crossing an intersection.							X							
SR-073	The system shall enable the user to notify the system of his/her delay crossing an intersection.														

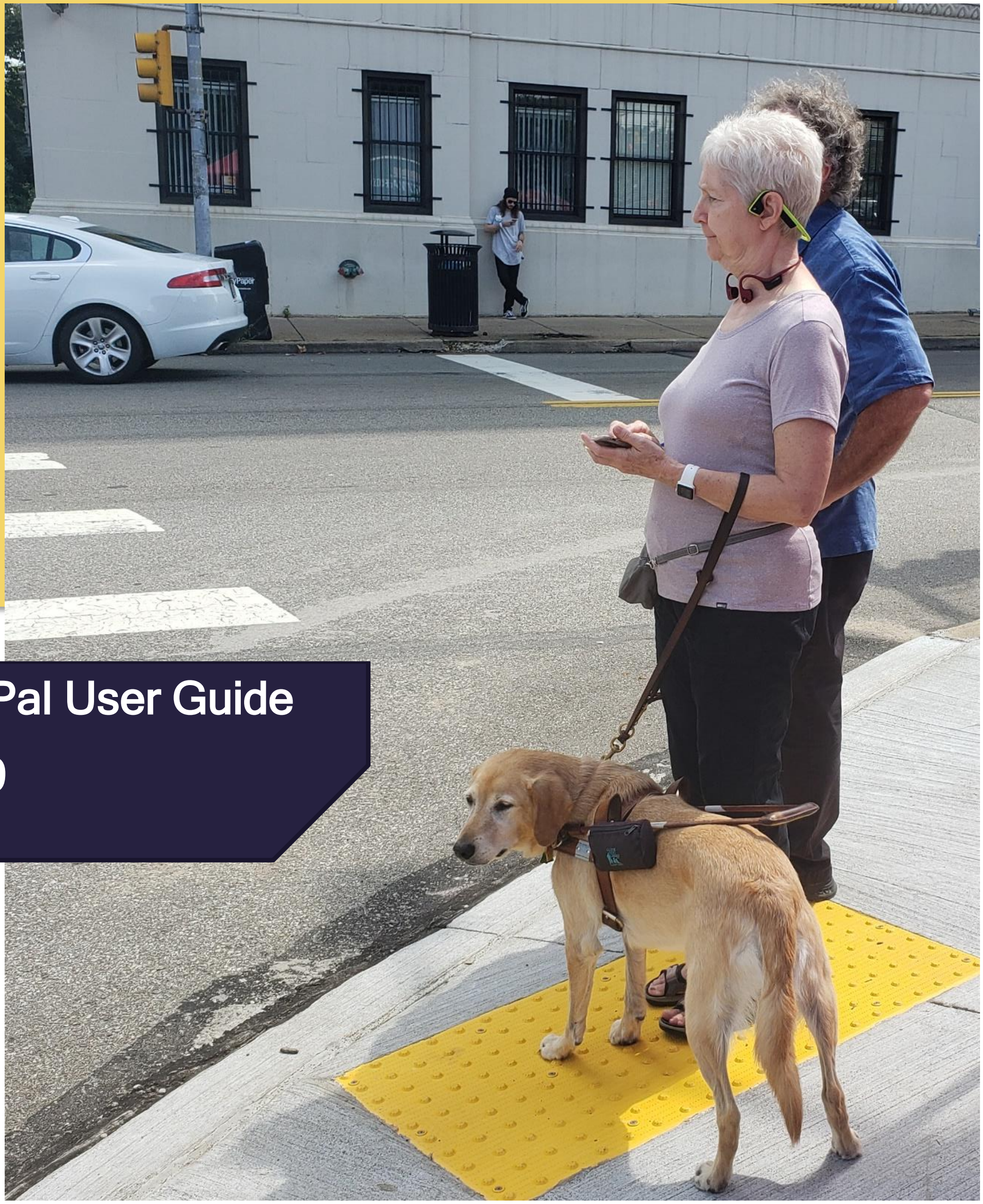
ID	Requirement Description	UC1	UC2	UC3	UC4	UC5	UC6	UC7	UC8	UC9	UC10	UC11	UC12	UC13	UC14
SR-074	The system should be capable of communicating the user's delay to the traffic signal system in real time.							X							
SR-075	The system shall have the capability to allow for dynamic extension of minimum crossing time constraint if an unexpected delay is detected							X							
SR-076	The system should notify the user of her/his deviation from the crosswalk.						X								
SR-077	The system should provide directional guidance to help the user get back in the safe zone path in case of a drift.										X				
SR-078	The system should notify the user of his delay crossing an intersection.							X							
SR-079	The system should have the capability to advise users on how to exit the crosswalk by providing guidance to the exit point (whether there is a curb or a cut-out, grade, etc.)	X	X	X	X		X	X	X	X	X	X	X	X	X
SR-080	The system shall be able to provide a notification when the user successfully crosses an intersection.	X	X	X	X		X	X	X	X	X	X	X	X	X
SR-081	The system shall be capable of identifying a location (i.e. coordinates) of interest at the intersection						X								
SR-082	The system shall correctly identify the intersection at which the user is located.	X	X	X	X						X				
SR-083	The system shall correctly identify the intersection corner at which the user is located.	X	X	X	X						X				
SR-084	The system shall correctly determine whether a user has begun crossing an intersection and is delayed to the extent that the current GREEN phase must be extended.							X							
SR-085	The system shall correctly detect when a user veers outside of the crosswalk.						X								
SR-086	The system shall increase blind users' perceived safety crossing an intersection.	X	X	X	X	X	X	X	X	X	X	X	X	X	X

ID	Requirement Description	UC1	UC2	UC3	UC4	UC5	UC6	UC7	UC8	UC9	UC10	UC11	UC12	UC13	UC14
SR-087	The system shall reduce the number of cycles a blind user waits to feel safe crossing the intersection.	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SR-088	The system shall increase the percentage of new intersections crossed by a user.														
SR-089	The system shall decrease the total time it takes for the user to cross an intersection (from arrival at the intersection to completion of the crossing) compared to the user's unassisted crossing time.	X	X	X	X	X	X	X	X	X	X	X	X	X	
SR-090	The system shall improve the user travel time through a sequence of intersections from the user's baseline travel time.	X	X	X	X	X	X	X	X	X	X	X	X	X	
SR-091	The system should ingest, store and access relevant information about the intersection and its corners, including presence and location of curb cuts at corners to facilitate entry into the crosswalk and presence of traffic islands in different crossing directions.	X	X	X	X		X	X	X	X	X	X	X	X	X
SR-092	The system should be able to ingest, store, and access information on an intersection's traffic signal system.	X													
SR-093	The system should be able to ingest, store, and access information on an intersection's traffic signal system's operational status.					X									
SR-094	The system should be able to ingest, store, and access information on whether an intersection is equipped for DSRC communications	X													
SR-095	The system shall be able to ingest, store, and access MAP message data.	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SR-096	The system shall be able to ingest, store and access SPaT message data.	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SR-097	The system should have a data validation process.	X	X	X	X	X	X	X	X	X	X	X	X	X	X

ID	Requirement Description	UC1	UC2	UC3	UC4	UC5	UC6	UC7	UC8	UC9	UC10	UC11	UC12	UC13	UC14
SR-098	The system should be able to ingest, store and access data from external sources (e.g., through appropriate APIs)									X					X
SR-099	The system shall be able to ingest, store and access a user's travel plan,									X					X
SR-100	The system shall collect information about what kind of assistive technology or mobility aid the pedestrian is using.									X	X	X		X	X
SR-101	The system shall be able to determine, prior to the user's arrival, if an upcoming intersection is adjacent to the user's bus route transfer point														X
SR-102	The system shall be able to ingest or determine the user's embarkation bus stop and desired bus route number.														X
SR-103	The system shall be able to determine, prior to the user's arrival, the user's expected arrival time at the intersection.														X
SR-104	The system shall be able to determine if there is an approaching bus with the desired bus route number.														X
SR-105	The system shall be able to estimate the time at which the bus is expected to depart from the bus stop														X
SR-106	The system shall be able to determine if additional crossing time must be allocated to ensure that the bus remains at the bus stop until the user can embark.														X
SR-107	The system shall be able to allocate the additional crossing time to ensure that the bus remains at the bus stop until the user can embark.														X
SR-108	The system shall not store any PII data.	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Appendix C. *PedPal* User Manual

Caption: A visually impaired person and their guide dog waiting to cross a signalized traffic intersection with the assistance of the PedPal smartphone app. A Bluetooth headset is worn by the person to listen to the voiceover communications of the app.



PedPal User Guide 2019

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THE ROBOTICS INSTITUTE

TABLE OF CONTENTS

INTRODUCTION ____ 3

The PedPal Smartphone App ____ 3

SETTINGS ____ 5

Primary settings options ____ 5

GENERAL USE CASE ____ 8

PedPal Interface Features ____ 8

Crossing Signalized Traffic Intersections with PedPal ____ 8

OTHER FEATURES ____ 13

Pre-planned Route Information ____ 13

Bluetooth Beacon Use ____ 14

Pre-planned Public Transit Bus Information ____ 14

TROUBLESHOOTING ____ 16

Smartphone Battery Power ____ 16

Cellular Signal Loss ____ 16

Localization Errors ____ 16

Smart Infrastructure Malfunctions ____ 17

INTRODUCTION

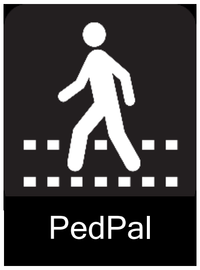

Figure 1: PedPal icon

With funding from the Department of Transportation, researchers in the Intelligent Coordination and Logistics Laboratory of the Robotics Institute at Carnegie Mellon University have developed a smartphone app called PedPal (see Figure 1 for the app icon) that enables mobility impaired pedestrians to communicate directly with the intersection, and to actively influence traffic signal control decisions, and thereby enhance the safety and efficiency of pedestrians with disabilities when crossing signalized traffic intersections.

The PedPal Smartphone App

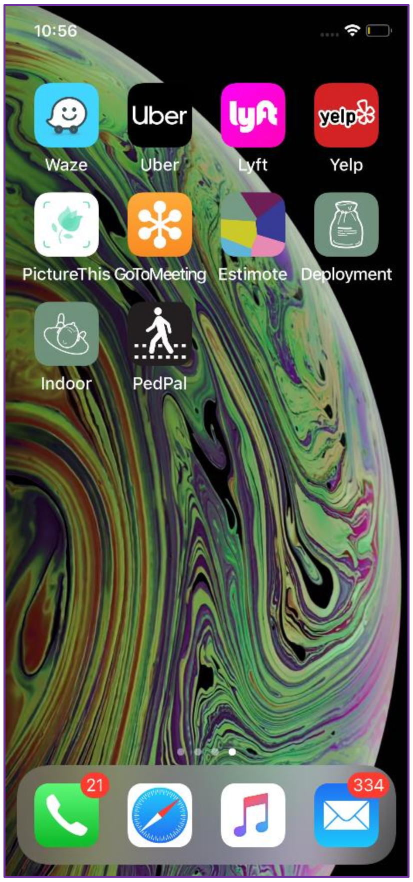

Figure 2: An image of a smartphone screen showing several app icons

Most basically, PedPal knows its user's travel speed (the user specifies this speed in the app settings) and can tell the intersection how much time the user needs to safely cross in the desired crossing direction. The smart traffic control system (SURTRAC[1]), in return, ensures that sufficient crossing time is given when the user subsequently gets the crossing signal. When a future crossing phase has been selected, PedPal counts down to the phase start and provides crosswalk information to help prepare the pedestrian to cross. The app announces that it is ok to cross at the appropriate time, and then counts down the remaining time as the user proceeds to cross. PedPal also monitors the user's progress through the intersection and if necessary, it will dynamically extend the crossing time. PedPal can also use route information provided by a 3rd party navigation app like Blindsquare to anticipate the user's arrival at each intersection and streamline overall trip travel time. Note that PedPal is not a routing app and therefore relies on an external route generator to provide route information.

[1] Smart Urban Signal Networks: Initial Application of the SURTRAC Adaptive Traffic Signal Control System, Stephen F. Smith, Gregory J. Barlow, Xiao-Feng Xie, Zachary B. Rubinstein, Proceedings 23rd International Conference on Automated Planning and Scheduling, Rome, Italy, June 2013.

SETTINGS

The PedPal smartphone app has several setting options that enable the user to customize the app performance to suit their personal preferences. Therefore, it is important to discuss the settings options in PedPal before we provide instructions for the general use case. These settings can be accessed via the settings button in the bottom right of the screen (shown below in Figure 3), and can be set one time by users who don't wish to be changing settings often, or can be changed frequently by users who prefer to fine tune the app performance for different segments of each route. The app, when downloaded, has default settings which are also indicated in the following sections.

Primary settings options

To access the settings in PedPal, launch the PedPal app and press the "Settings" button located in the bottom right of the screen. The "Settings" button is labeled and displays graphical representation of a gear as shown in Figure 3. When you select settings in the PedPal app, the primary menu presented gives you the option to select preferences for the type of traveler, the average traveler speed, and several other settings that are primarily used for technical purposes during the app development and testing phase. The only two settings that most users will need to change to accommodate their preferences are the traveler type and average speed. The options for each of these two settings are shown in the following images.

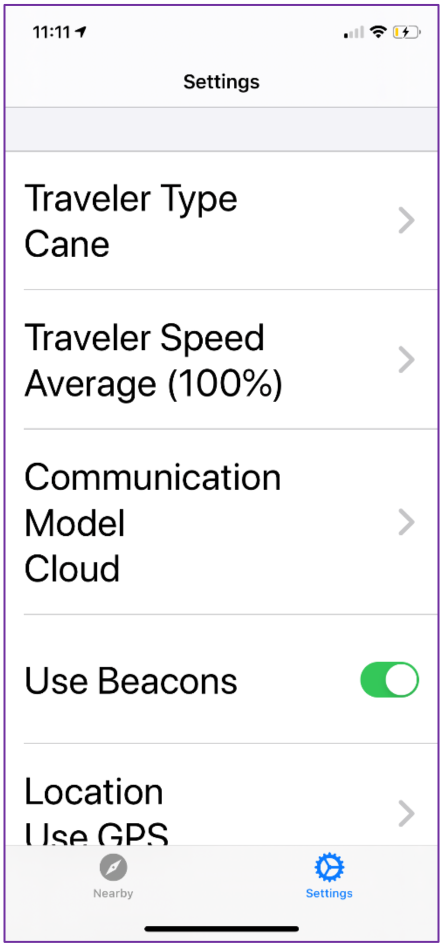

Figure 3: A screenshot of the main PedPal setting options available to users

The options for traveler type are:

- Cane
- White Cane
- Guide Dog
- Powered Wheelchair
- Unpowered Wheelchair
- Walker User
- Cognitively Impaired
- Other

The user must select one user type from this list that best fits their needs as pedestrians. The app accordingly sets relevant speeds to use in internal computations for determining how much time the user will need to cross a given intersection, and request that amount of time for the crossing phase at the signalized intersections the pedestrian chooses to cross.

The options for Traveler Speed are:

- Slowest (50%)
- Slower (75%)
- Average (100%)
- Faster (150%)
- Fastest (200%)

These settings simply provide an additional level of speed adjustment to take into account if a pedestrian is moving more slowly or quickly than average on a given day or in general. Both the "Traveler Type" setting options and the "Traveler Speed" options are shown in the screenshot figures below (see Figures 4 and 5).

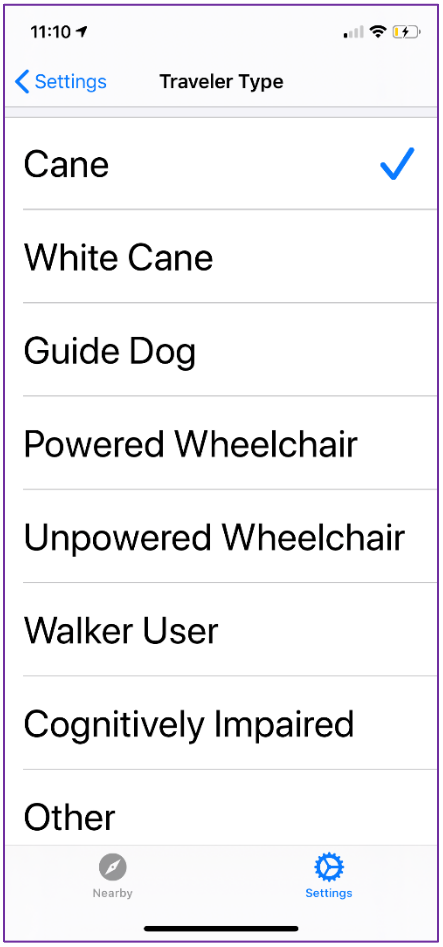

Figure 4: A screenshot of the traveler type options in the PedPal app.

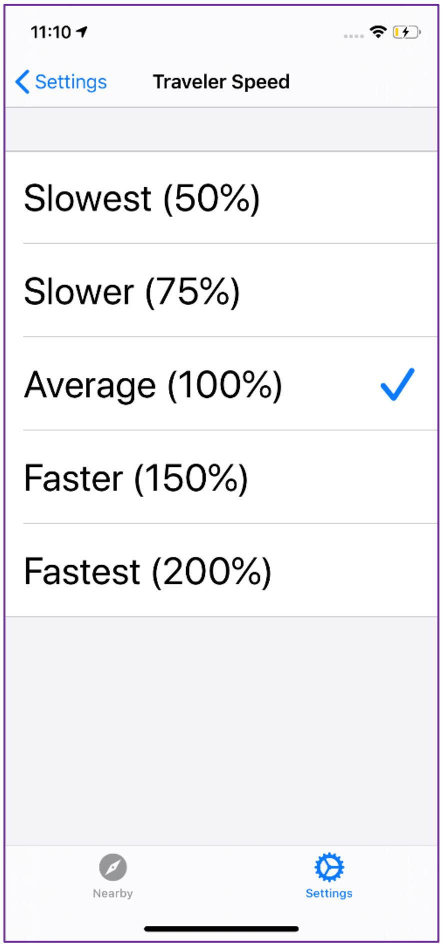

Figure 5: A screenshot of the traveler speed options in the PedPal app

The PedPal app defaults to the setting of cane user for the traveler type and average for traveler speed since this is a conservative setting that works for most users' needs. PedPal also ties into all accessibility features of the iPhones.

GENERAL USE CASE

Once the iPhone and PedPal settings are customized to reflect user preferences, the user can easily use the PedPal app to cross signalized traffic intersections with greater confidence, efficiency, and safety. This general use case is detailed next.

PedPal Interface Features

The PedPal user interface is intentionally designed to be simple and accessible. PedPal is currently only available on iPhones but will likely be available on Android phones and other devices in the future. Simplicity is maintained in the PedPal interface by minimizing the number of buttons and user interactions needed and focusing on essential information relevant to the task of safe intersection crossing for pedestrians. Accessibility is achieved in PedPal by benefitting from all of the accessibility features in the iPhone (such as voiceover, font magnification, contrast settings, etc.) and by providing a combination of textual, graphical, audio, and vibrational cues when conveying information in concise yet informative manner. The PedPal app has been tested with a variety of users with different abilities and preferences, and all user feedback has been incorporated to ensure the PedPal user interface is useful, accessible, understandable, and intuitive.

When a user first launches the PedPal app, an onboarding process will allow the user to set the relevant settings (shown above in Figures 3-5). In subsequent uses, once the PedPal app is opened, it will simply show the user nearby intersection information or inform the user that no nearby intersections are detected (shown below in Figure 6-7).

Crossing Signalized Traffic Intersections with PedPal

When the PedPal app is launched on the user's smartphone, the app displays a screen that defaults to displaying information about the intersection in the closest proximity to the user (see Figure 7 below). If no intersection is detected by the app, the message "No nearby intersection detected" is communicated to the user (see Figure 6 below). If an intersection is detected, the user is informed about the crossing options (in a list format as shown below in Figure 7) and asked to select which crossing the user wishes to execute. To assist the user in selecting a direction to cross, the app provides the following information:

- A list of streets (i.e. the names of the streets) the pedestrian can cross at the closest intersection (usually one of two streets depending on the direction in which the user wishes to travel) is displayed.
- The signal status is displayed with each street name. Signal status is indicated both graphically and in text (see Figure 7 below). This status is binary: either the pedestrian is clear to cross or it is not safe for the pedestrian to cross. If the pedestrian can cross safely, a green box containing a white checkmark is included before the name of the street that can be crossed, and the text "OK to cross" is displayed after the street name. If the signal phase

does not allow the pedestrian to cross safely, a red “x” is included before the name of the street, and the text “waiting for crossing signal” is displayed after the street name.

- The time remaining (in seconds) in the relevant signal phase is updated live for each street listed for that intersection.

Example screenshots of this street selection step in PedPal are shown below in Figure 7.

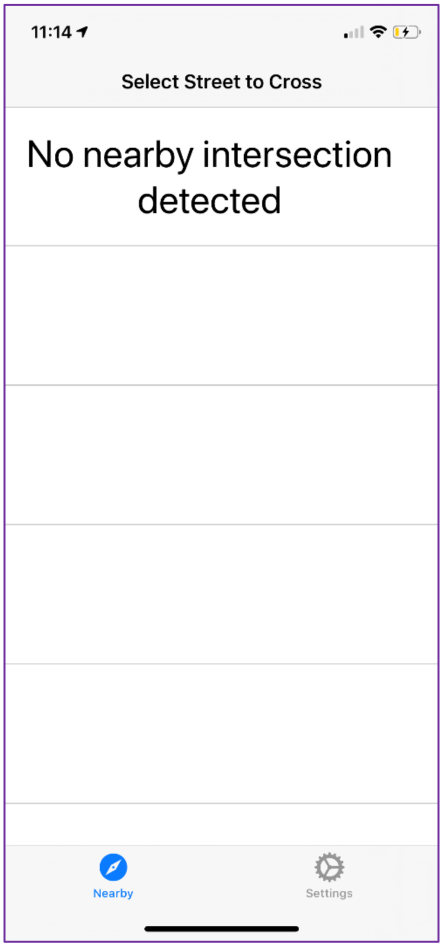

Figure 6: A screenshot of the PedPal app informing the user that no nearby intersection is detected.

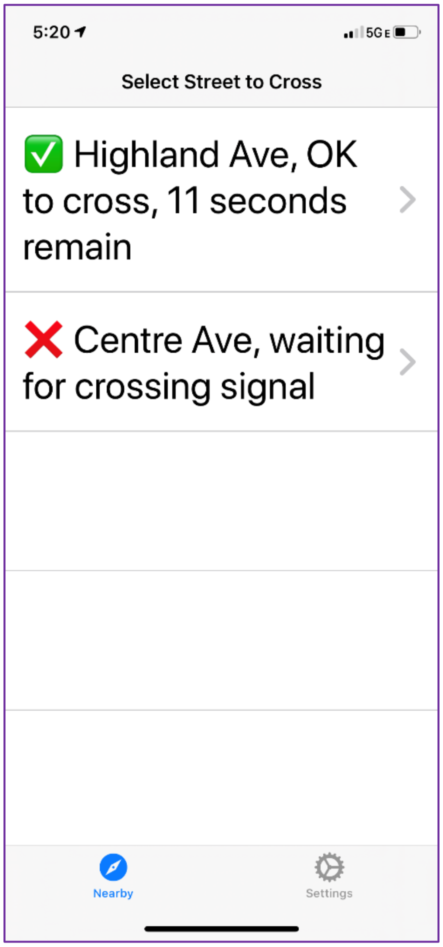

Figure 7: A screenshot of the PedPal app informing the user about the available streets to cross, along with their signal phases and how much time is remaining for those phases.

In this screen that prompts the user to select a direction for crossing, the top center of the screen displays the message “Select Street to Cross” and the bottom of the screen shows a “Nearby” button on the left displaying a graphical representation of a compass, and “Settings” button on the right displaying a graphical representation of a gear. The selected button is highlighted in blue and the button not currently selected is shown in gray.

Figure 8: A screenshot of the PedPal app informing the user that an extension was granted, it is ok to cross, and there are 41s remaining in the crossing phase for Centre Ave.

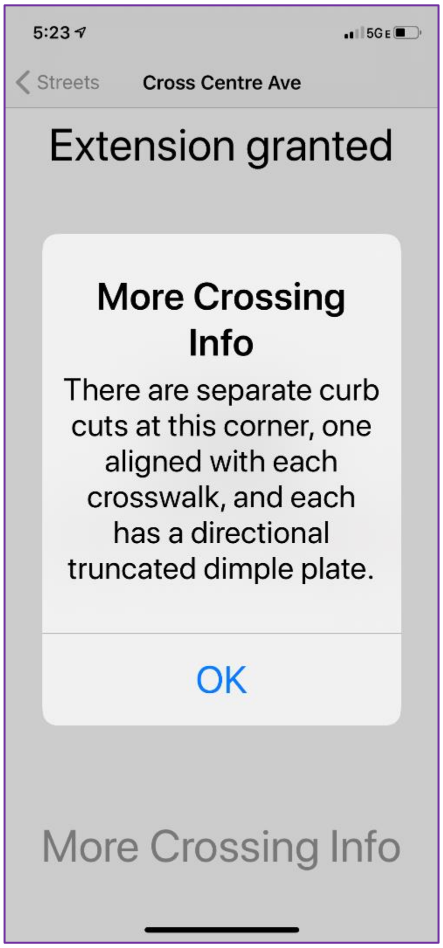

Figure 9: A screenshot of the PedPal app informing giving the user useful information about the intersection.

Figure 10: A screenshot of the PedPal app informing the user that an extension was granted, it is ok to cross, and there are 34s remaining in the crossing phase for Centre Ave.

Once the user selects a direction for crossing by tapping on the desired street to cross, the app transitions to a different screen showing the crossing status for the chosen direction. The top center of the screen now displays the name of the street chosen by the user to cross. An additional button “Streets” along with a backward pointing arrow appears on the top left of the screen to allow the user to return to the list of available streets to cross in case the user made a mistake with the current selection or changed their mind about which street they wish to cross. Below the street name, a line of text informs the user if an extension was granted or not. An extension is typically granted if the PedPal settings indicate that the user will need more time to cross than the usual pedestrian crossing phase allows at that intersection.

The user can also get additional useful information about the geography and features of the corner where the pedestrian is initiating the crossing by tapping on the only button displayed across the bottom of this screen with the text “More Crossing Info”. This button can be activated before, during, or after a crossing at the convenience of the user. The middle of the screen shows a live numerical countdown in seconds for the current signal phase followed by text indicating if it is safe to cross: “OK TO CROSS”. The three images above (see Figures 8-10) show screenshots of the case where the user chooses to cross “Centre Ave”, is granted an extension and has the signal phase allowing the user to cross. The first screen shows that the user has 41 seconds to cross, the seconds screen shows the user more information about the intersection, and the third screen shows the user that now 34 seconds remain in the crossing phase for Centre Ave.

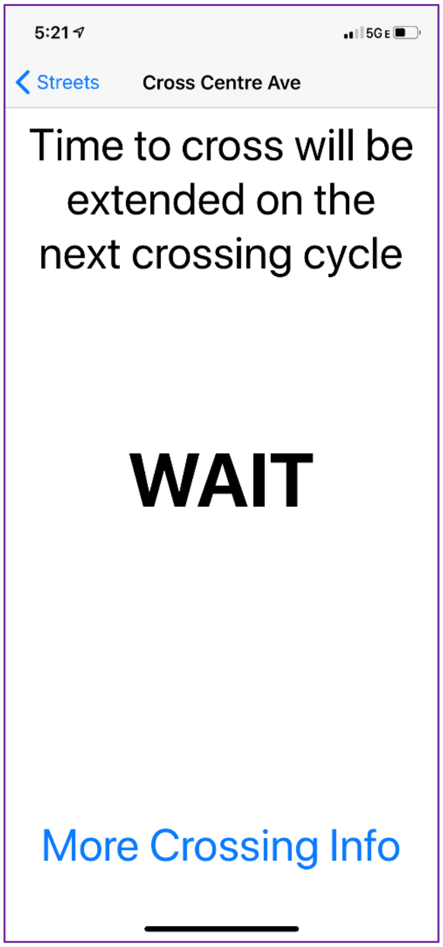

Figure 11: A screenshot of the PedPal app informing the user that an extension will be granted on the next crossing cycle and to wait to cross Centre Ave.

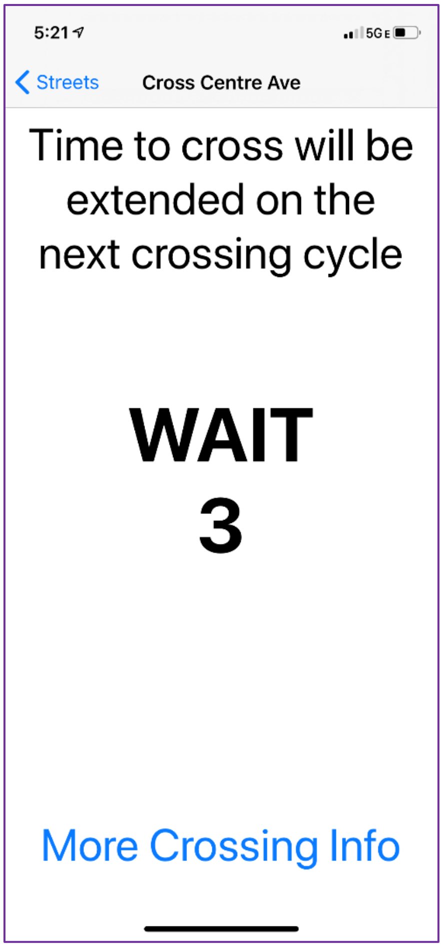

Figure 12: A screenshot of the PedPal app informing the user that an extension will be granted on the next crossing cycle and to wait 3 seconds before starting to cross Centre Ave.

An example of the additional information about an intersection available to a user is as follows: “There are separate curb cuts at this corner, one aligned with each crosswalk, and each has a directional truncated dimple plate.” Once the user has consumed this information they can exit this screen by tapping the “OK” button in the lower middle of section of the screen (at the bottom of the “More Crossing Info” text box).

If the chosen direction is currently not available for pedestrian crossing, the status “WAIT” as demonstrated in the two screenshots above (see Figures 11-12). The countdown (in seconds) to the crossing phase is displayed starting at 5 seconds to reduce verbosity of communications to the user. Information about whether the time for crossing will be extended to address user preferences is also communicated to the user at the top of the screen. The text “Time to cross will be extended on the next crossing cycle” is displayed if the extension is granted.

Once the user has completed the crossing, the app transitions back to the previous screen providing the user with options for available streets to cross or indicating that there are no nearby intersections currently detected.

OTHER FEATURES

Several additional features are being currently explored as enhancements to the general use case for PedPal. These features include providing PedPal with information about public transit buses the pedestrian wishes to catch on a given route, the ability to upload a pre-planned route to PedPal, and the use of Bluetooth beacons mounted at signalized intersections that can enhance corner identification, pedestrian progress monitoring during street crossings, and detection of pedestrian veering outside the safe crossing zone. These features are briefly described next.

Pre-planned Route Information

A feature currently being added to the PedPal app is the ability for users to inform PedPal of a pre-planned route that they wamt to follow. The route will not be planned by PedPal since PedPal is not a wayfinding or route planning app. Instead, an external app such as Google Maps might plan the route and the user can choose to export this route into PedPal. Routes can include information about buses that need to be caught at specific intersections. The route data will take the format of a list of "waypoints" where each waypoint will be associated with a smart signalized intersection. The format of each waypoint will be a pair of corners (start corner and end corner for a crossing), and an estimated arrival time for the start corner.

When PedPal receives such a route, PedPal will alert the user that a route has been received and that PedPal will be moving into "Route Following" mode. The user will then have an option to acknowledge and dismiss this alert. Once the alert is acknowledged, the user will only have access to a button to cancel the route and exit from the route following mode, and the button to learn more details about the specific corner as described in the general use case above. During the route following mode, PedPal will handle all the crossing requests and selections in the background and will only alert the user about upcoming crossings and the usual information needed to cross the intersections safely.

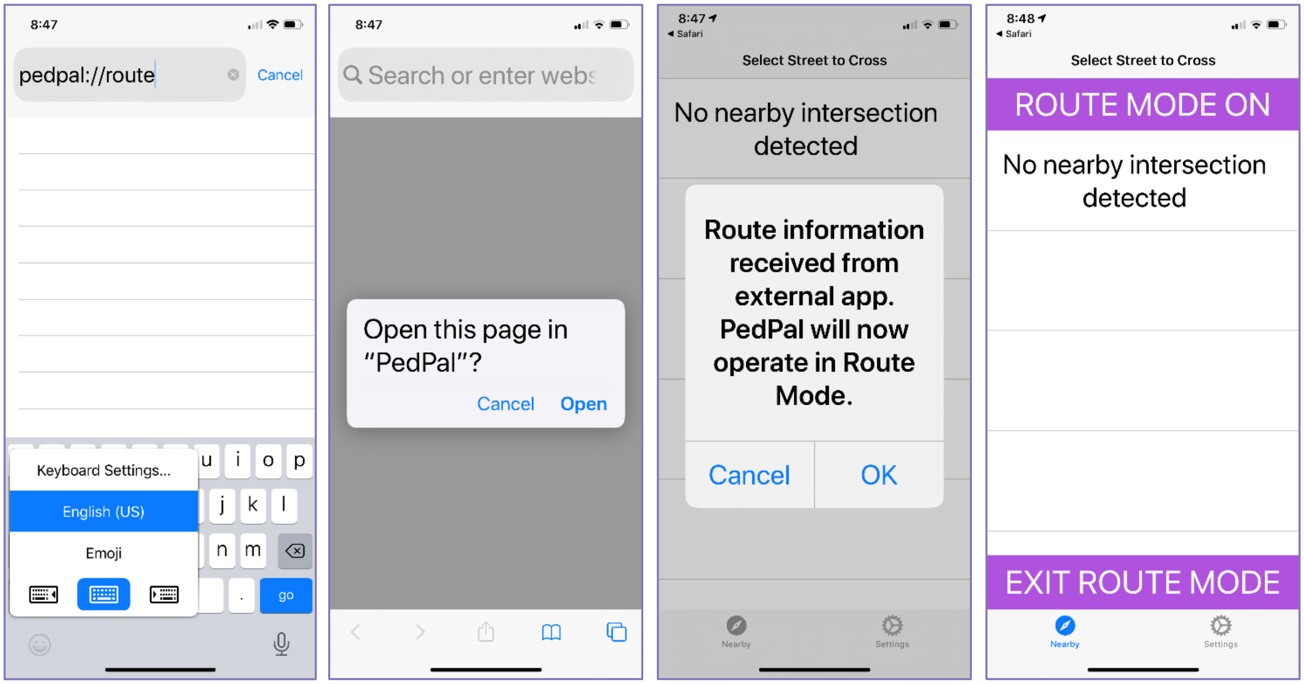

Figure 13: The sequence of screenshots a user sees when enabling route mode on the PedPal app. First, the user creates a route using an external routing app. Next, the created route is shared with the PedPal app. The third step in the sequence shows the PedPal app confirming the receipt of an externally created route and enabling the route mode. The final screenshot shows PedPal operating with route mode enabled, and providing a button that allows the user to exit route mode.

In route following mode, PedPal will operate as usual except for substituting route information for the input normally received from the user. The user will be alerted once the route following mode is exited and will also be informed whether the route was canceled or completed.

Bluetooth Beacon Use

The development team is currently exploring the use of Bluetooth beacons to enhance localization and monitoring applications to enhance the user experience of PedPal. Currently envisioned capabilities include more refined detection and identification of the street corners in the vicinity of the pedestrian, monitoring the progress of the pedestrian as they cross the street so that a green phase can potentially be extended if needed when a pedestrian is facing unexpected delays while crossing the street, and detecting situations where a pedestrian is veering out of the safe zone when crossing the street so that PedPal can alert the user to stay within the safe crossing zone.

Pre-planned Public Transit Bus Information

In the future (this is a feature still in the development stage), a pedestrian might choose to inform PedPal that they wish to catch a specific bus at an intersection where PedPal is operational. The reason for doing this is to give the smart traffic light system an opportunity to take this information into account (via the PedPal app) when scheduling the traffic light changes. For example, the pedestrian may wish to catch the Inbound 71A bus at the corner of Cypress Street and Centre Avenue after crossing Cypress. The pedestrian will be able to upload this information to PedPal. PedPal will receive this information in the format of a label, location, and time. The label will indicate which bus the pedestrian wishes to catch (for example, Inbound 71A). The location will be the location of the relevant bus stop. Finally, the time will be the estimated arrival of the time of the relevant bus at the specified bus stop. In the best case (PedPal cannot guarantee this outcome), the scheduling of the traffic lights will enable the pedestrian to cross the street and get to the bus stop in time to catch the bus.

TROUBLESHOOTING

This section provides information about some common problems that could occur leading to suboptimal performance of the PedPal app. These problems include battery power limitations of the smartphone, cellular signal loss, errors in localization, and temporary malfunctions of smart infrastructure components. These topics are briefly discussed next. This user guide will be enhanced in the future as additional troubleshooting situations are encountered.

Smartphone Battery Power

One of the most common causes of problems encountered with any smartphone app is the battery power of the smartphone running the app. Users should always make sure that their smartphone is fully charged when using PedPal or similar apps.

Cellular Signal Loss

Another common occurrence is the loss of cellular signal during urban travel. Most smartphone apps, including PedPal, will alert the user that cellular signal has been lost so that the user is not confused about why the app is not performing as expected. In the case of PedPal, a user could choose to switch to using DSRC instead of cellular communication if the user has an appropriate DSRC attachment for the smartphone. Unfortunately, no current phones have embedded DSRC capability. This could however change in the future.

Localization Errors

PedPal currently relies on the smartphone localization capabilities for guiding the user and providing relevant information to the user. However, despite tremendous progress in localization technology solutions over the past decade, smartphone technology still encounters localization errors on a regular basis either due to urban infrastructure interfering with GPS signals or for other reasons. Therefore, it is important for users to always be aware of their surroundings and independently keep track of their progress without entirely relying on their smartphone for guidance. The performance of the PedPal app is closely tied to the accuracy of the smartphone localization capability. In the future, beacon technology could give PedPal and the smartphone additional failsafe mechanisms for enhancing localization.

Smart Infrastructure Malfunctions

Finally, as with any physical or digital systems, the physical and digital smart infrastructure that PedPal relies on could have occasional malfunctions. Examples of such malfunctions can range from outdated corner information to smart traffic light outages to information servers going down for maintenance or other reasons. PedPal attempts to gracefully degrade performance in such settings and provides as much transparency as possible to keep the user informed about any problems encountered.

PedPal provides multiple interaction modalities to the user, including a visual interface, voiceover capability, and haptic signaling. User interaction can be personalized to meet each user's needs and preferences.

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