Connected Vehicle Pilot Deployment Program Phase 3

Mobile Accessible Pedestrian Signal System (PED-SIG) Application Test Summary and Evaluation Report – New York City

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16. Abstract

New York City is piloting connected vehicle (CV) technology to support the Vision Zero initiative and help eliminate injuries and fatalities caused by crashes. As a part of the USDOT CV Pilot Deployment Program, a Mobile Accessible Pedestrian Signal System (PED-SIG) was developed. The PED-SIG application provides audio alerts and haptic prompts to assist pedestrians with vision disabilities in safely crossing streets at instrumented intersections. This study identified four signalized intersections instrumented with CV-technologies and designed six pre-defined routes to test the developed PED-SIG application. Volunteer participants with vision disabilities were recruited to participate in the field tests where Personal Information Devices (PIDs) were given to participants. This technology supports cellular communications (4G, LTE) to receive localized Signal Phase and Timing (SPaT) and MAP messages broadcast by the local Roadside Unit (RSU) to provide information about intersection geometry and the current intersection signal status. The evaluations are based on operational data logs collected from the PIDs, observations of participants during field tests, as well as qualitative feedback provided by participants before and after the tests, through surveys conducted by the research team.

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Finally, the team wants to thank the United States Department of Transportation (USDOT) for sponsoring this project and laying the foundation for future connected vehicle deployments.

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1 Introduction

New York City (NYC) is piloting connected vehicle (CV) technology to support the Vision Zero initiative and help eliminate injuries and fatalities caused by crashes. As a part of the USDOT Connected Vehicle Pilot Deployment Program (https://www.its.dot.gov/pilots), two pedestrian oriented applications are deployed: 1) a generalized warning to vehicles of pedestrians in the roadway and 2) support for pedestrians with vision disabilities. This report describes the street crossing support application, Mobile Accessible Pedestrian Signal System (PED-SIG), which aims to advance social equity with CVs and is intended to assist pedestrians with vision disabilities in safely crossing the streets at instrumented intersections.

The study equips volunteer pedestrians with a Personal Information Device (PID), a small battery powered electronic apparatus, that can receive localized signal, phase, and timing (SPaT) and map data message (MAP) messages broadcast at specially equipped locations to provide intersection geometry and the status of the intersection signal phase. The PID supports 4G/LTE cellular communications.

The general operation uses MAP and SPaT information received by the PID to orient the pedestrian, confirm their location (street and cross street), and provide audio information regarding the signal state to improve their ability to safely cross the street. The PID uses MAP message and smartphone features to determine pedestrian's location and orientation. The SPaT message communicates the signal state information of the intended route to the pedestrian. Originally, the PID/PED-SIG application deployment included ten (10) portable personal devices to be used by 24 pedestrians with vision disabilities during the field tests. However, due to the difficulties in developing the application for two (2) platforms (iOS and Android), PED-SIG application development was limited to only iOS platform in the final scope. Therefore, five (5) PID devices operating on the iOS system were used during the field tests. The log data collected from PID was obfuscated, encrypted, and transmitted to secure servers to protect participants' privacy. Pre- and post-experiment surveys were administrated to gather the participants' user experiences and safety perception through the CV-equipped intersections.

1.1 Purpose of the Report

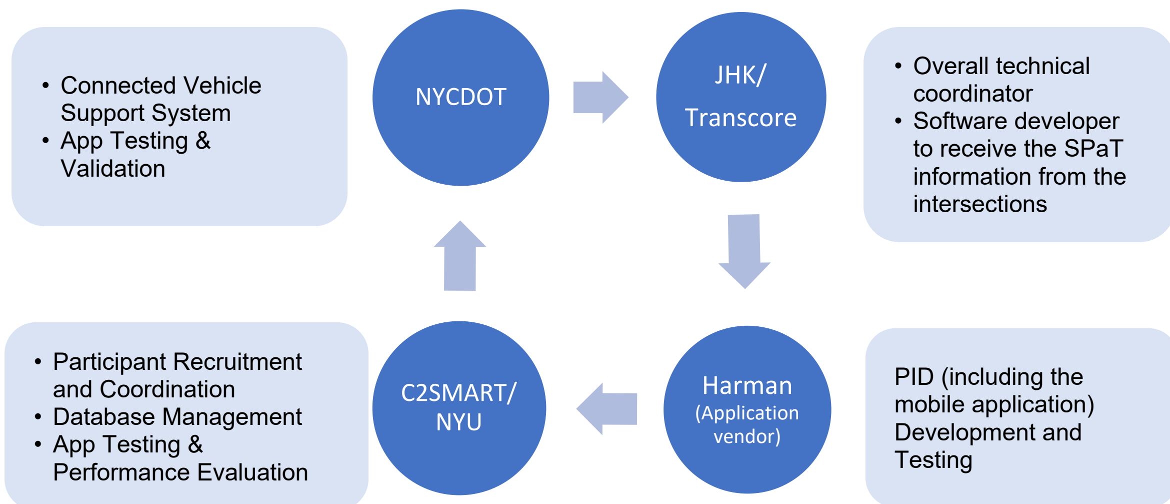
This document describes the development of the PED-SIG application for the people with vision disabilities and performance evaluation of the field tests conducted between October 29, 2021, to November 18, 2021. The report documents the system design and database management, including data collection, obfuscation and encryption, application functionality and its use cases, experiment design, and the results of the field tests. It also summarizes various lessons learned to provide insights on accessible solutions for the people with vision disabilities to navigate signalized intersections and improve their mobility and independence in using the transportation system.

1.2 Organization of the Report

The report is organized according to the following sections. Section 1 presents an overview of the Mobile Accessible Pedestrian Signal System and the role of this report in the project. Section 2 introduces the system design and database management, including the system architecture and security protocol to ensure the privacy of the PED-SIG users. Section 3 presents the smartphone application functionality and use cases, as well as the operation log data generated by the application. Section 4 describes the experiment design and performance measures, and Section 5 presents the test and system validation. Section 6 highlights the performance evaluation results from the field tests. Finally, section 7 summarizes the lessons learned during application development, project management, participant recruitment and the field test and evaluation and concludes the report.

2 System Design and Database Management

The development of PED-SIG system involves collaborative efforts between agency (NYCDOT), industry (JHK/TransCore and Harman) and academia (C2SMART University Transportation Center led by New York University (NYU). The roles of the team members are illustrated in Figure 1. The PID used for PED-SIG system is a portable information “smart device” which uses 4G/LTE wireless communication to access back-office servers to assist pedestrians with vision disabilities to cross the street at signalized intersections. The PED-SIG system consists of the hardware, software, positioning augmentation accessories, applicable enrollment certificates and firmware code.

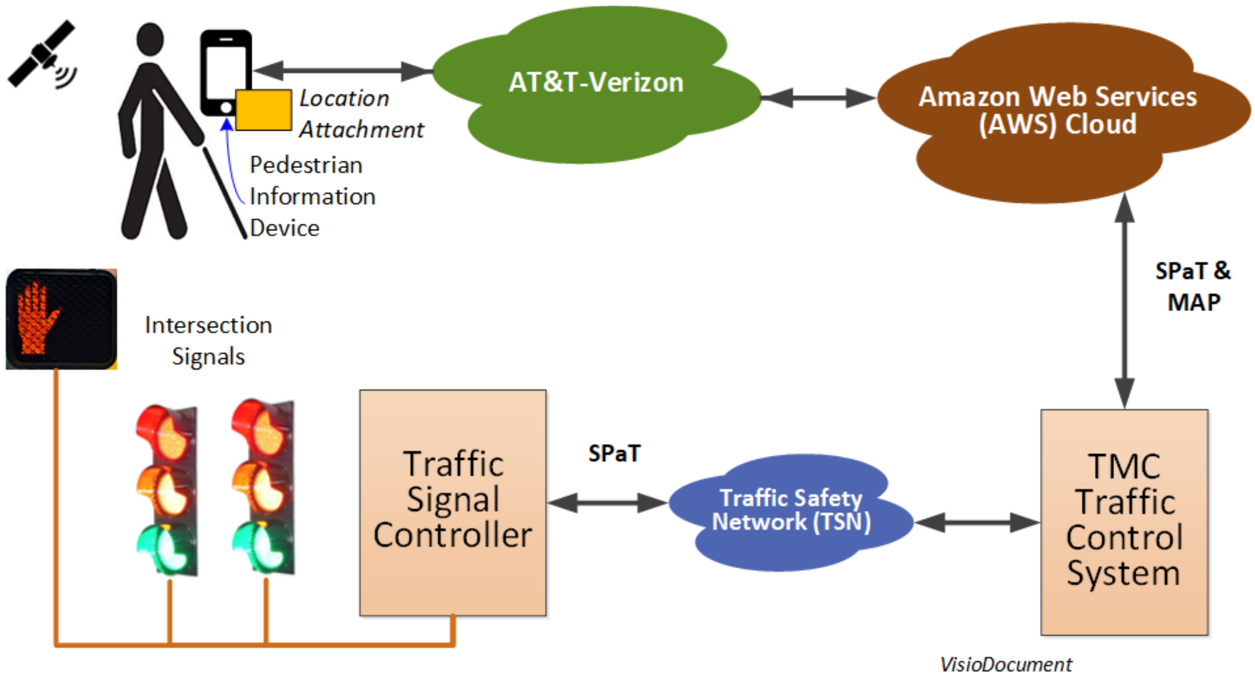


(Source: NYU C2SMART Center)

Figure 1. Agency-Industry-Academic Collaboration

The requirements for the PID include the collection of data to indicate how the application is working, reliability, and pedestrian acceptance of the information/interface. The data generated by the PID also includes selected portions of the MAP and SPaT messages and the location and time of the observation by the PID. The PID includes a mobile data communications capability which is used to download and manage the application and for the application to upload the collected data to the secure data server. The application vendor receives the SPaT and MAP messages from NYCDOTs Transportation Management Center (TMC) for the signalized intersection.

The application on the PID encrypts the collected data and transmits the encrypted data to a configured internet protocol (IP) address through the broad-band carrier service. This data is the general form of encrypted blocks which contains the device serial number, the location of the pedestrian, and the activities of the pedestrian within the vicinity of a signalized intersection which supports the CV technology. The overall PID system architecture is shown in Figure 2 below.



(Source: NYCDOT, NYU C2SMART Center)

Figure 2. PED-SIG Support Application System Architecture

The advanced solid-state traffic controllers (ASTC) were modified to transmit SPaT information to the TMC for processing in preparation for use by the PID applications. This data is transmitted to the TMC from the ASTC "on change" (i.e., when the values in the SPaT message changed). At the TMC, the information is time corrected to use Coordinated Universal Time (UTC) and sent to the Amazon Web Services (AWS) cloud along with the MAP message content. The AWS cloud is provided with duplicate data and the PID "SmartCross" application that was developed by Harman processes this information and provides it to the PID for intersection navigation assistance.

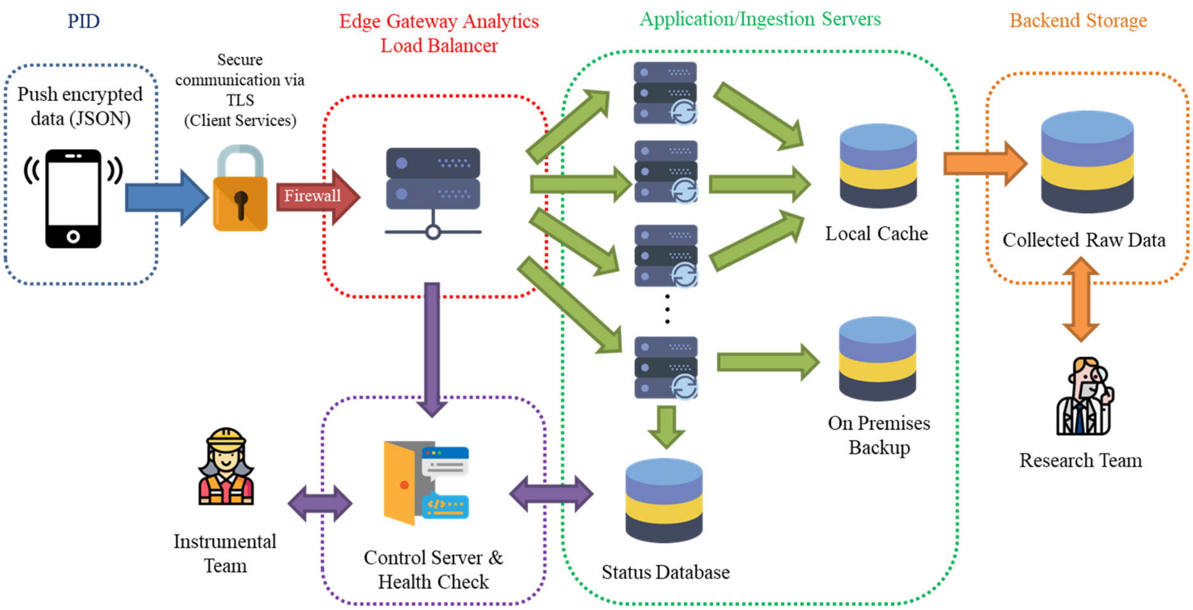
The MAP message contents were developed by TransCore using the United States Department of Transportation (USDOT) tool, updated with sidewalk descriptions, and augmented with Cyclomedia's high resolution image database to improve the accuracy of the location information for the crosswalks and landing zones. It should also be noted that the MAP message used by the PIDs is not size constrained in the same manner as the MAP message transmitted by the RSU such that the TMC sends more detailed information to the AWS cloud than is transmitted by the RSU. The TMC exports the MAP and SPaT information to the AWS cloud where it is used by the SmartCross application.

Harman developed a "Location Augmentation Device" to improve the accuracy of the location information to support the SmartCross application. The location accuracy of a smartphone in an urban environment can be inadequate, therefore a Location Augmentation Device is paired to a smartphone via Bluetooth. The SmartCross application combines the smartphone location and compass data with location information from the augmentation device to improve the accuracy for users.

When the SmartCross application is active, evaluation data is collected and sent to NYU servers where it is used for the performance evaluation for the PID program. NYU's role included acquiring the smartphones, recruiting participants, obtaining consent from the testers, and then supervising the PID trials. The data collected along with survey information was evaluated to determine the overall utility, value, and issues associated with the PID and SmartCross application for the user community. The project team worked with the NYU Independent Review Board (IRB) to ensure the safety and privacy of the participants.

2.1 Data Collection, Storage and Backup

Figure 3 illustrates the server architecture for PID data collection and storage. The security authentication uses signed certificates to establish a secure connection. Each phone must have a signed certificate to be able to connect with NYU servers. The encrypted data stored on mobile phones is pushed to the provided IP address in JavaScript Object Notation (JSON) format. The application protects against attacks by using the signed security certificate that verifies the device is secure and trusted on the response handling.



(Source: NYU C2SMART Center)

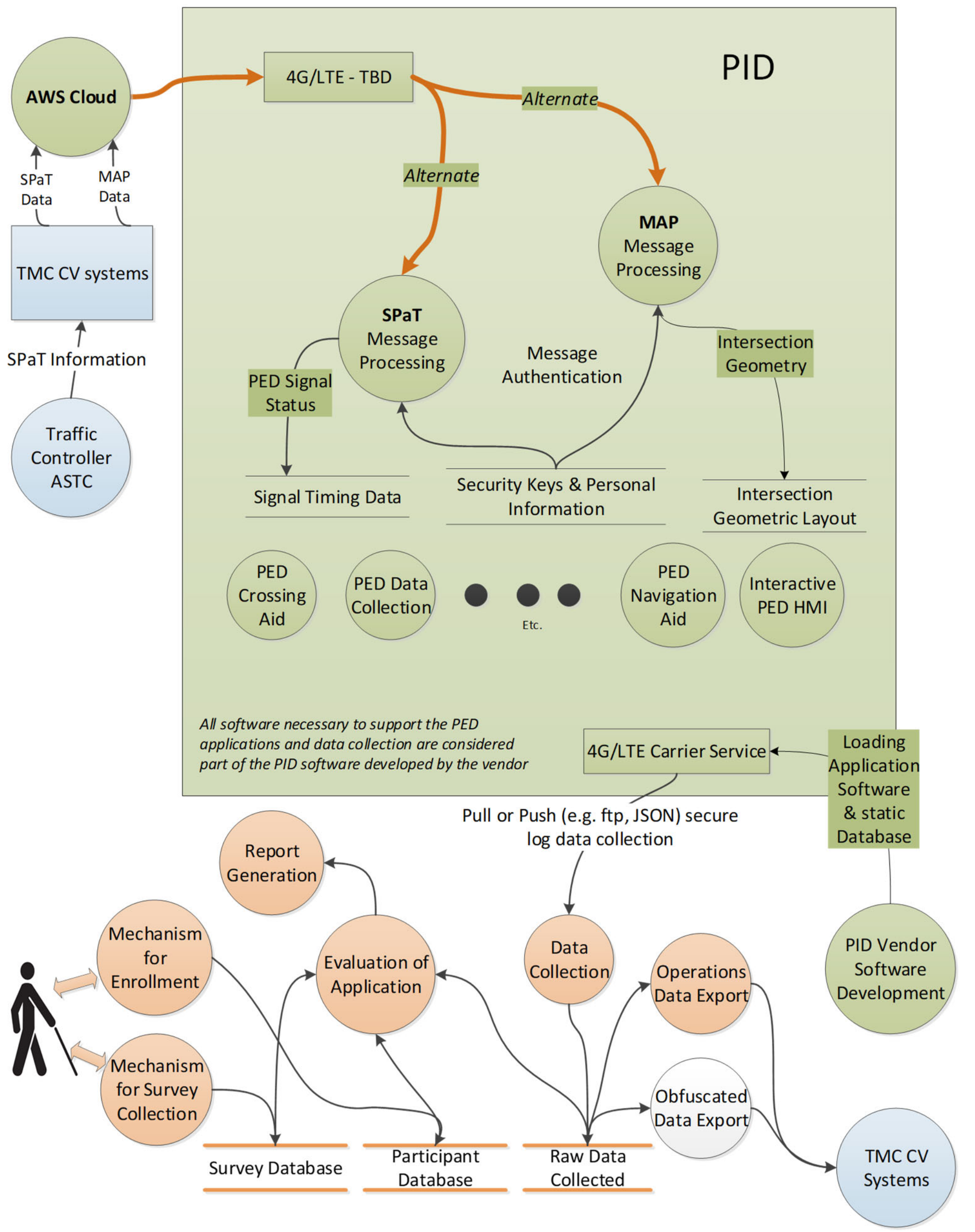
Figure 3. Data Collection/Storage Process and Server Architecture

The Application Programming Interface (API) endpoint of the server is governed by a high-performance load balancer and a web server (nginx). This server is also used as a reverse proxy; that is, it can retrieve sources on behalf of a client, a mobile phone in this case. At this gate it is possible to check the data status and the health of incoming transfers. Depending on the volume, the load balancer will distribute the data to individual ingestion server instances (i.e., Tornado web server). These individual server instances are scalable, non-blocking web servers and web application frameworks written in Python. An open-source message broker software is applied here to remove the possibility of data loss. The ingestion servers first store the data at a local cache (MongoDB) which is then replicated to the main storage server.

Collected data are also backed up on the premises at NYU. With the use of a load balancer, it is possible to direct all the received data from phones to multiple databases using ingestion servers. The secondary database shown in Figure 3 with the name “On Premises Backup” aims to independently store every data point that the main server receives.

2.2 Report Generation and Data Flows

Figure 4 illustrates how data is generated from PID, as well as participant feedback and surveys. PID Raw data, survey and participant databases are only accessible to the IRB certified research team. Algorithms were built to obfuscate/sanitize raw data and convert it to a format that can be shared with other parties.



(Source: NYCDOT)

Figure 4. General Reporting and Data Share Processes

2.3 System Security (SSL Certification Implementation)

The system security for transmitting the PID data utilizes Secure Sockets Layer (SSL) certification. SSL is a cryptographic protocol designed to keep communication safe over the Internet. An SSL certificate is a digitally signed file issued for a particular domain name(s). Besides the domain name, the certificate also contains records for the issuer signature, serial number, expiration date, and other data. Once the SSL installation is completed, users can securely access service via HTTPS or any other SSL protocols including FTPS, IMAPS, POP3S, SMTPS, NNTPS, and LDAPS. The sample data table used during testing and production phases is shown in Table 1 below.

Table 1. Sample Posted Data Table

Security Mechanism	Testing phases	Production phase
Connect server via https protocol	True	True
Connection is private and safe	True	True
Issue client-side certificate	True	True
Visiting via domain	False	True
Website verified by trusted Authority	False	True

With the implementation of the SSL, all sensitive information is encrypted through communication. Only server and client can decrypt the data. The SSL prevents any intruders from tampering with the data. In addition, the server can register all the trusted devices and can issue them their own certificates. Before each POST data transaction (send data (i.e., JSON or xml) to the server and server can digest it), trusted devices are required to provide their certificates, reducing the possibility of attacks originating from unknown devices by network intruders. The implementation was completed in two phases: 1) testing phase and 2) production phase.

2.3.1 Testing Phase

A certificate authority (CA) root certificate needs to be created in the main server and generates an intermediate CA certificate, which is used for the server and client certificates to ensure security. A root certificate is a public key certificate that identifies a root certificate authority. For the web server, the CA is used to “sign” the other intermediate certificates to ensure the all the data are encrypted by a trusted certificate during communication between app and server. Intermediate certificates are used as a proxy to keep the root certificate behind various layers of security and ensure that the master key is inaccessible. Using an intermediate CA certificate provides a higher level of security because the root CA is not located anywhere on the server. This approach keeps the root CA secure and creates the chain of trust. It is worth noting that since this server certificate is generated under the self-sign CA root certificate, it is marked unsafe by the browser when users try to connect to the server. This is the server-side SSL certification, which we need to change in the production phase.

2.3.2 Production Phase

For the production phase, NYU registered the domain (www.tandoncsmart.com) for the application server and enabled HTTPS by getting the certificate from Let’s Encrypt, the nonprofit CA providing TLS certificates to 260 million websites. By replacing the self-sign CA root certificate, the web server security was enhanced and any requests without authentication were blocked.

2.3.3 Data Obfuscation and Encryption

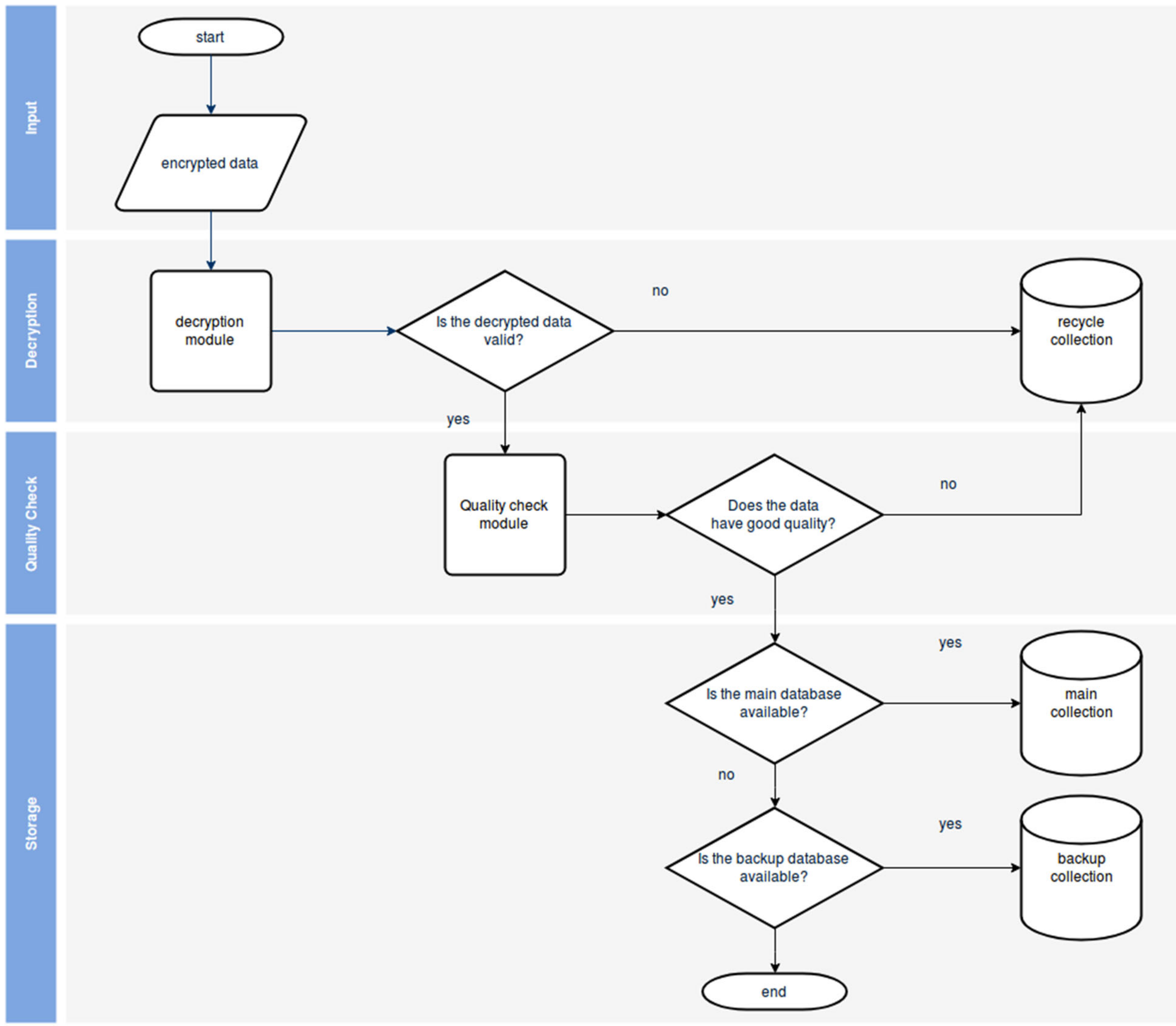
The advanced encryption standard (AES) is implemented as the encryption algorithm and cipher block chaining (CBC) mode with a random initialization vector (IV) is adopted for encrypting the raw data. To protect the privacy of all participants, a hybrid obfuscation method was designed to process the raw data. Firstly, the identity of the participant's device was removed including device information, application version and part of the SPaT/Map data. In addition, time obfuscation was applied to the data. A randomized timestamp was created to replace the start time of each test. All the other timestamps kept the same intervals as the raw data to keep the data consistency.

2.4 Data Quality and Error Checking

The data quality check includes three components: key attribute check, attribute type check, and attribute range check. Any transmissions of the data that fail the checking process are stored in the recycled collection. However, if the administrators determine that the recycled data is helpful for data analysis and should not be removed, then the recycled data may be fixed. For example, the wrong date format may be converted back to its original format.

- Key Attribute Check: The received data must have all key attributes embedded inside. For instance, if the required "date" data field is not a key in the decrypted JSON data, the exception should be raised, and the data log should be recycled.
- Attribute Type Check: The attribute type must follow the pre-defined types, which means it should not be changed or converted during the data transmission. For example, if the "date" format changes from datetime to epoch, it should be converted back to its original formatting.
- Attribute Range Check: The attribute range must be within the given range. Any attribute that does not meet the defined criteria should be recycled. For example, if the "date" shows that the data is sent from a future date, the data log should be recycled.

Moreover, two error checking functions were developed. The first one is API argument error checking. This process checks if the PID posts the data based on the NYC PID Data Collection Data Structure provided by Harman (Harman Feb 4, 2019). If the PID posts an inconsistent argument or posts a log containing no information, the error will be raised. The second error checking is the decryption error checking. This process measures whether the raw data can be decrypted to the required data format. If the decryption process fails, the data will be recycled to another table and not be parsed. The flowchart of decryption and data quality check is shown in Figure 5 below.



(Source: NYU C2SMART Center)

Figure 5. Flowchart of Decryption and Data Quality Check

3 Mobile Application

The SmartCross mobile application is an iPhone operating system (iOS) application that does the following:

- Provides the pedestrian with the current signal status of the crosswalk that he/she is facing.
- Provides the remaining time available to cross the street if the pedestrian is in the crosswalk.
- Provides situational information to the user based on the location such as street name or corner of the intersection.

The mobile application provides an audio output to help establish which corner of what intersection the pedestrians are approaching and indicates through audio and haptic prompts whether the pedestrian signal displays the 'WALK', flashing 'DON'T WALK' (FDW), or steady 'DON'T WALK' (DW) indications for each crosswalk (or crosswalk segment). The proposed feedback mechanism is shown in Table 2. It is important to note that the original intent was to support both Android and iOS; however, the prototypes delivered only work on the iOS.

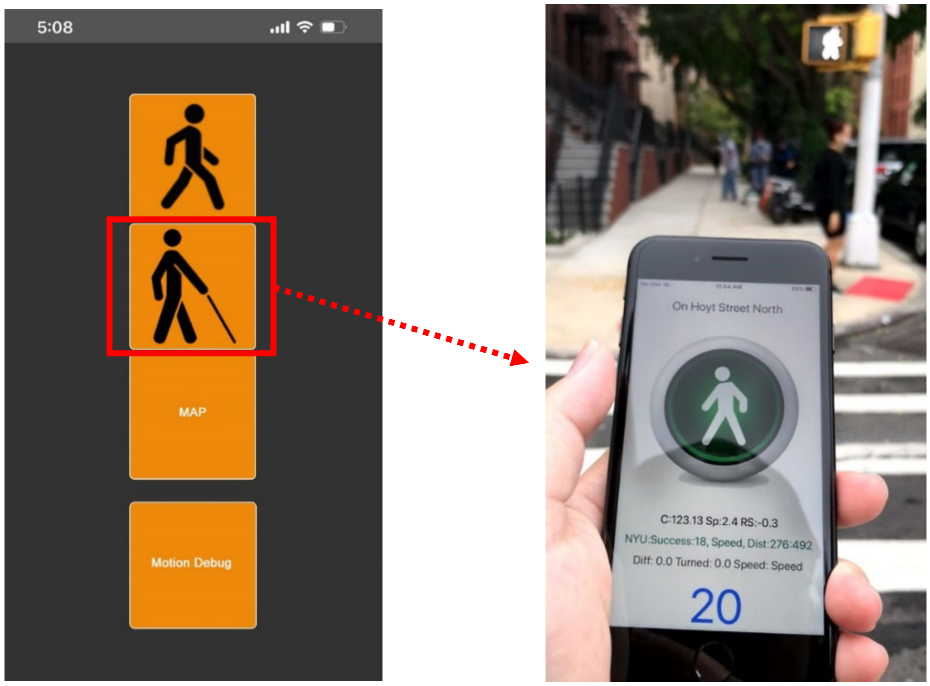
Table 2. PED-SIG Mobile Phone Application Feedback Mechanism

State	Description	Moving into Crosswalk?	Pedestrian Signal Head Status	Audio Alert (Automatic)	Audio Alert (When user tap the screen)	Haptic Alert
1	Pedestrian is approaching an intersection	-	All states	'Approaching (Street Name A) and (Street Name B) (Corner name)'; No audio alerts are given about the signal status	-	-
2	Pedestrian is at the curb	No	Walk	'Walk Sign Is On For (Crossing Street Name) + (Which Crosswalk)'	'Walk'	-
3	Pedestrian is at the curb	No	Flashing Don't Walk	'(Time Remaining) to cross (Crossing Street Name) + (Which Crosswalk).' or just countdown on the time remaining.	'Do Not Walk'	-
4	Pedestrian is at the curb	No	Do Not Walk	'Wait to Cross (Crossing Street Name) (Which Crosswalk)'	'Do Not Walk'	-

5	Pedestrian is at the curb – Traffic Controller is in conflict flash	No	-	“Traffic controller in Conflict”’	'Service Not Available' Traffic light malfunction - exercise caution	-
6	Pedestrian is at the curb	Yes	Walk	'Walk Sign Is On For (Crossing Street Name) + (Which Crosswalk)'	‘Walk’	-
7	Pedestrian is at the curb	Yes	Flashing Don’t Walk	'(Time Remaining) to cross (Crossing Street Name) + (Which Crosswalk).'	-	-
8	Pedestrian is at the curb	Yes	Do Not Walk	‘Wait to Cross (Crossing Street Name) (Which Crosswalk)'	'Do Not Walk'	Long Vibration for 500ms with 2s gap
9	Pedestrian is on the crosswalk	-	Walk	'Walk On (Crossing Street Name) + (Which Crosswalk)'	‘Walk’	-
10	Pedestrian is on the crosswalk	-	Flashing Don’t Walk	'(Time Remaining) to cross (Crossing Street Name) + (Which Crosswalk).' or just count down on the time remaining.	'Do Not Walk'	-
11	Pedestrian is on the crosswalk	-	Do Not Walk	'On (Crossing Street Name) + (Which Crosswalk)'	'Do Not Walk'	Long Vibration for 500ms with 5s gap
12	Pedestrian reaches the other end of crosswalk	-	All states	'Reaching the End of Crosswalk'	All alerts stop	All alerts stop

3.1 User Interface

The user interface for SmartCross is shown in Figure 6 below. The interface consists of three modules. (1) The main module that provides audio and haptic alerts, (2) A map module that shows the location of the user and (3) A module for the trial version for motion debug. Double tapping the screen will open a setting menu that allows the user to turn on and off some of the functions such as turn off the debugging mode.

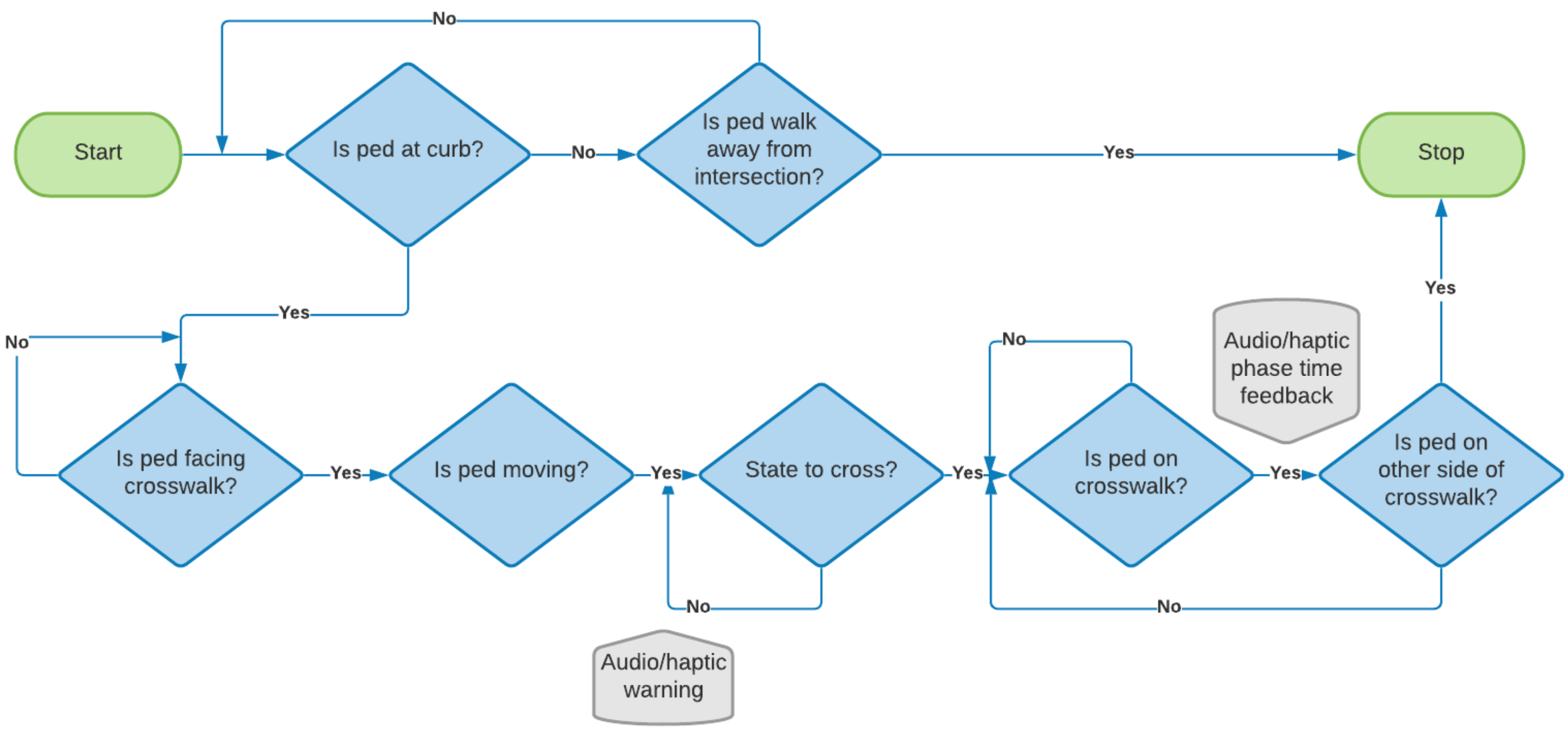


(Source: Harman)

Figure 6. User Interface for the PED-SIG Mobile Phone Application

3.2 User Scenarios

The SmartCross mobile accessible application is designed to support six (6) different use scenarios, and the user interactions, as shown in Figure 7.

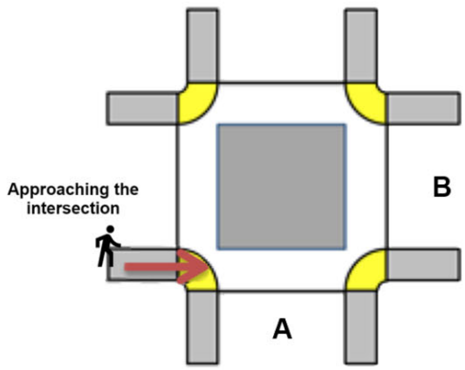


(Source: Harman)

Figure 7. SmartCross User Interaction (Harman 2019)

3.2.1 Scenario1: Pedestrian approaching the intersection

When the pedestrian is far away from the intersection, the application is silent. This is to prevent alerts when the user does not need them. The application provides alerts only when the user approaches the corner of an intersection (Figure 8). Although alerts about the signals are not activated in this scenario, an audio message is provided to inform the pedestrian that he/she is getting close to the intersection (e.g., "Approaching Street A and Street B, Southwest Corner"). Based on field observations, the audio message is activated at about 20 ft from the curb.

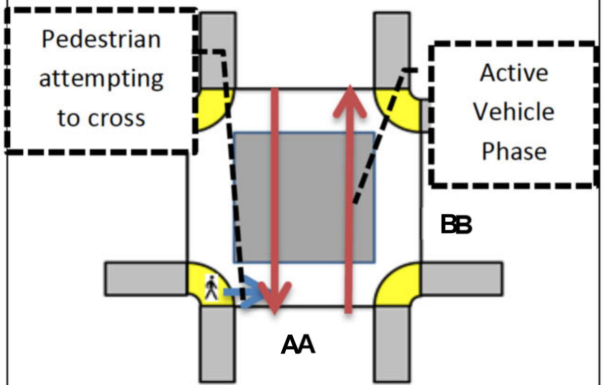
INTERSECTION	PEDESTRIAN SIGNAL HEAD	SMARTCROSS GUI
	All States	Voice Alert 'APPROACHING (STREET NAME A) and (STREET NAME B) (CORNER NAME)'

(Source: Harman)

Figure 8. PED-SIG App Use Scenario 1: Pedestrian approaching the intersection

3.2.2 Scenario 2: Pedestrian attempts to walk on DON'T WALK

In this scenario, the pedestrian is violating the pedestrian signal and attempts to cross the road when it is not safe to do so. For example, in the scenario presented in Figure 9, the SmartCross application detects this movement and alerts the pedestrian by providing a Voice Alert saying, 'WAIT TO CROSS STREET A SOUTH' with a LONG vibration and displays a DW sign on the screen. A Voice Alert saying 'DO NOT WALK' is heard when the pedestrian taps the screen.

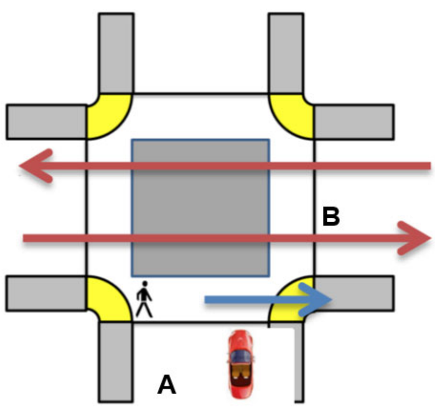
INTERSECTION	PEDESTRIAN SIGNAL HEAD	SMARTCROSS GUI
	DON'T WALK	DON'T WALK with Voice Alert ('WAIT TO CROSS (CROSSING STREET NAME) (WHICH CROSSWALK)') and Vibration (LONG)

(Source: Harman)

Figure 9. PED-SIG App Use Scenario 2: Pedestrian attempts to walk on DON'T WALK

3.2.3 Scenario 3: Pedestrian walking on WALK/FLASHING DON'T WALK

In this scenario shown in Figure 10, the pedestrian starts and completes the crossing when the pedestrian signal is either in WALK or FDW state. The SmartCross screen displays WALK and FDW in synchronization with the pedestrian signal head. It also provides audio and haptic alerts to the pedestrian.

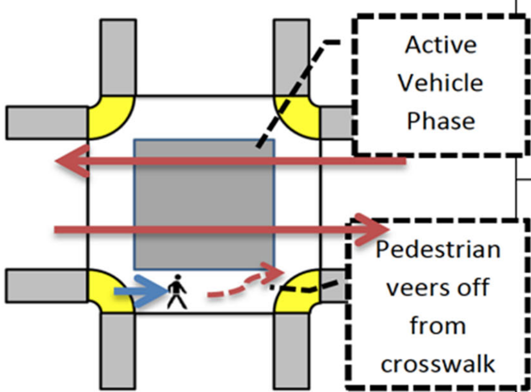
INTERSECTION	PEDESTRIAN SIGNAL HEAD	SMARTCROSS GUI
	WALK	Voice Alert 'WALK ON (CROSSING STREET NAME) + (WHICH CROSSWALK)'
	FLASHING DON'T WALK	FLASHING DON'T WALK with Voice Alert for Time Remaining

(Source: Harman)

Figure 10. PED-SIG App Use Scenario 3: Pedestrian walking on WALK/FDW

3.2.4 Scenario 4: Pedestrian veers off from crosswalk

In this scenario shown in Figure 11, the pedestrian does not violate the pedestrian signal but veers away from the marked crosswalk and potentially into the path of oncoming vehicles. When the SmartCross application detects such scenario, the application displays a DW sign along with a ‘DO NOT WALK’ voice alert. It also provides haptic feedback in the form of a long vibration. This only occurs while the pedestrian is heading in the wrong direction and reverts to the original state once the pedestrian is back on track. It is important to note that although this scenario was designed and tested in the early stage, due to the resource limitations, it was not fully implemented in the final version of the application and was not available for testing.

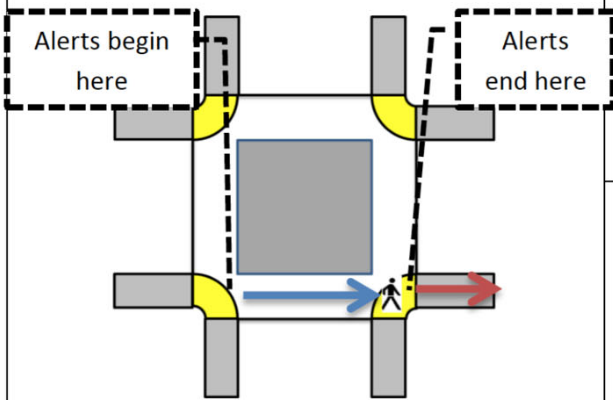
INTERSECTION	PEDESTRIAN SIGNAL HEAD	SMARTCROSS GUI
	**WALK**	**DON’T WALK with Voice Alert(‘Do Not Walk’) and Vibration(LONG)**
	FLASHING DON’T WALK	**DON’T WALK with Voice Alert(‘Do Not Walk’) and Vibration(LONG)**

(Source: Harman)

Figure 11. PED-SIG App Use Scenario 4: Pedestrian veers off from crosswalk

3.2.5 Scenario 5: Pedestrian reaching the end of crosswalk

In this scenario shown in Figure 12, the pedestrian reaches the opposite sidewalk after crossing the road and receives an audio alert “REACHING THE END OF THE CROSSWALK.” All other alerts stop as soon as the pedestrian reaches the curb at the other end of the crosswalk.

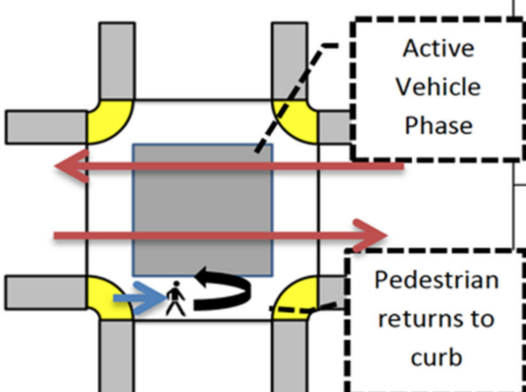
INTERSECTION	PEDESTRIAN SIGNAL HEAD	SMARTCROSS GUI
	WALK	Voice Alert "REACHING THE END OF THE CROSSWALK"
	FLASHING DON'T WALK	Voice Alert "REACHING THE END OF THE CROSSWALK"

(Source: Harman)

Figure 12: PED-SIG App Use Scenario 5: Pedestrian reaching the end of crosswalk

3.2.6 Scenario 6: Pedestrian enters crosswalk and returns to curb

In this scenario shown in Figure 13, the pedestrian does not violate the pedestrian signal upon entering the crosswalk path and returns to the curb. When the SmartCross application detects such a scenario, the application continues displaying the WALK sign along with a voice alert 'Walk on (crossing street name) and (which crosswalk)'. It also provides haptic feedback in the form of a long vibration if the phase is either FDW or DW.

INTERSECTION	PEDESTRIAN SIGNAL HEAD	SMARTCROSS GUI
	WALK	WALK with Voice Alert 'WALK ON (CROSSING STREET NAME) + (WHICH CROSSWALK)'
	FLASHING DON'T WALK/DON'T WALK	DON'T WALK with Time Remaining and Vibration (LONG)

(Source: Harman)

Figure 13. PED-SIG App Use Scenario 6: Pedestrian enters crosswalk and returns to curb

3.3 Location Augmentation Devices

Because the default accuracy provided by most smartphones does not meet the PED-SIG requirements, NYCDOT required the vendor to enhance the location with an augmentation device. Shown in Figure 14 below, the location augmentation device is connected to the smartphone via Bluetooth and provides improved accuracy for the pedestrian application. This device is a prototype and was created for this pilot. The communication interface between the mobile phone and the accessory is Bluetooth Low Energy (BLE) or classic Bluetooth depending on the smartphone used. Key features of the augmentation device are the following:

- The positioning solution is derived from uBlox F9P dual frequency, multi constellation chip
- Battery power to last up to 6 hours on a single charge
- Ruggedized enclosure
- Clip-on form factor to attach to backpacks/luggage.

In the absence of this accessory, or in the event of connection failure with the accessory, the SmartCross application will use the location provided by the smartphone's internal Global Navigation Satellite System (GNSS) chip and will notify the user appropriately. Figure 14 displays the augmentation device and the antenna position when it is used.

(Source: NYCDOT)

Figure 14. Augmentation Device and Antenna Position

4 Experiment Design

The experiment of the PID devices was conducted under specifically defined test conditions, albeit in the real-world operating environment of NYC city streets. Based on NYCDOT guidance from testing prototype PID devices, the study recruited volunteer participants with vision disabilities to participate in the field tests where PIDs were given to participants to be used, accompanied by at least one IRB-certified NYC CVPD team member to ensure their safety.

4.1 Participant Recruitment and Coordination

To ensure that the PED-SIG Application provided appropriate functionalities with an intuitive and accessible design, the PID was tested by 24 pedestrians with limited vision in real-world scenarios. We sought a wide range of potential users with diverse travel habits, mobility needs, and independence levels, including the following:

- A range of vision ability, from low vision to totally blind
- A variety of mobility assistance mechanisms, from companions, guide dogs, and long canes to vision aids and global positioning system (GPS) navigation or other assistive phone apps
- Pedestrians who were born with a vision disability as well as those who had lost their sight over time or later in life
- Pedestrians with co-existing disabilities, such as deafness

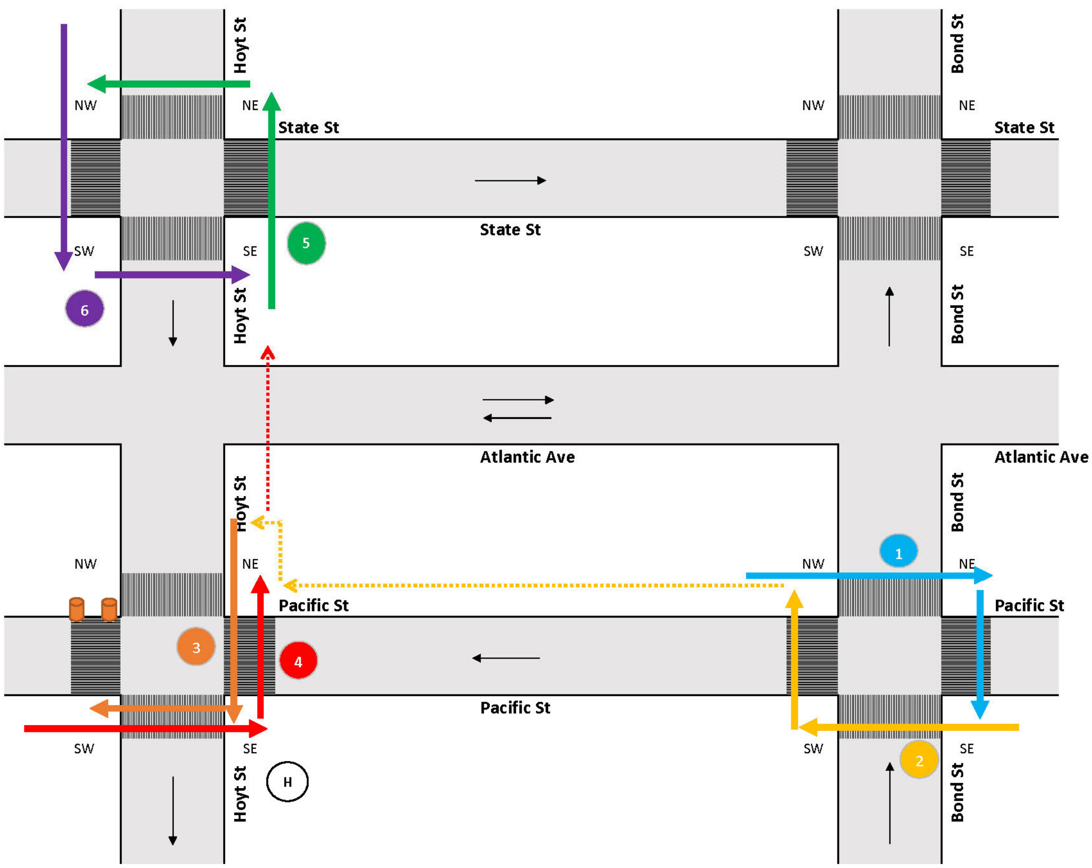
The process involved two levels of recruitment. First, working closely with NYCDOT, we contacted both local and national organizations working with blind communities. In the New York City area, we contacted the Helen Keller Services for the Blind, the Brooklyn Center for Independence of the Disabled, the Mayor’s Office for People with Disabilities, Access VR, the Lighthouse Guild, the MTA Accessibility Office, Helping Hands for the Disabled of NYC, the New York State Commission for the Blind, and Visions/Services for the Blind and Visually Impaired. We also reached out to universities, including the CUNY Coalition for Students with Disabilities, the NYU Accessibility Project, and the NYU Office of Disability and Inclusion. On a broader level, we contacted the National Federation of the Blind, Achilles International, Family Health International, the American Council of the Blind, the American Foundation for the Blind, the Center for Assistive Technology, and National Industries for the Blind. This first contact involved explaining to each organization the purpose of the study, the shape of the field test, and the goals of the CV Pilot. The second part of the recruitment process involved one-on-one conversations with each volunteer to provide an in-depth explanation of what the app does and what the field tests would entail, as well as answering any of their questions. The final 24 participants were recruited with the help from the following 14 local and national organizations:

  - Helen Keller Services for the Blind
  - Brooklyn Center for Independence of the Disabled
  - NYC Mayor's Office for People with Disabilities (MOPD)
  - CUNY Coalition for Students with Disabilities
  - Access VR
  - Achilles International
  - Lighthouse Guild

- MTA, The Systemwide Accessibility Team
- NYU Accessibility Project Team
- Helping Hands for the Disabled of NYC
- American Council of the Blind
- CAST (Center for Assistive Technology)
- NYU Disability & Inclusion
- Visions/Services for the Blind and Visually Impaired

4.2 Test Sites and Routes

Six (6) predefined routes, each made up of two (2) crosswalks, were chosen to test the utility, accuracy, and connectivity of the PID and gauge the participants' experiences through multiple CV-equipped intersections. From these six (6) predefined routes, six (6) semi-protected intersections (with an overall low traffic volume and no or low vehicle turning movements) were chosen. And four (4) of these intersections were selected for the field tests with participants: (1) Pacific Street / Bond Streets, (2) Pacific Street / Hoyt Street, (3) State Street / Hoyt Street, and ((4) State Street / Bond Street) as a backup location. All these locations are in Downtown Brooklyn. The backup intersection served to supplement the field tests when any of the three designated intersections were not available due to road construction, emergencies, or events. The predefined routes and study area are illustrated in Figure 15.



(Source: NYU C2SMART Center)

Figure 15. Predefined Routes for PID Field Tests

In the original plan, ten (10) PIDs were to be used. However, due to the difficulties in developing the application for two (2) platforms (iOS and Android), PED-SIG application development was limited to only iOS platform in the final scope. Therefore, the five (5) PID devices operating on the iOS system were used during the field tests. Each participant was asked to carry and engage with one PID and one GPS augmentation device connected with the PID via Bluetooth. The purpose of the augmentation device is to enhance the GPS accuracy of the PID. In addition, each participant was asked to answer a pre-experiment and post-experiment survey to provide user feedback on the PID. Due to COVID-19 and in-person activity restrictions put in place by the IRB panel overseeing the PID deployment, the actual field tests were not conducted until the end of October 2021.

Operation data logs were collected from the PID units during participant use as well as observations from the field test and qualitative participant feedback surveys. These measures were used to evaluate the performance of the PED-SIG application. All raw PID log data were securely transmitted from the PID cell phone units to the secure IRB approved servers in NYU and can only be accessed by IRB approved researchers. All personally identifiable information will be removed if data is shared outside of the IRB.

4.3 Management of IRB Procedures

IRB approval of the research protocol is necessary before human subjects can participate in field-testing apps developed as part of the federally funded CV Pilot research. The project thus follows the Common Rule, a rule of ethics regarding research with human subjects adopted by USDOT that is codified in U.S. Code of Federal Regulations, 49 CFR Part 11. Among other provisions, the Common Rule warrants an IRB to have oversight of the treatment of human subjects. The IRB is the administrative body established to protect the rights and welfare of human research subjects recruited to participate in research activities conducted (New York University 2020).

The NYU team administrated the preparation, application, renewal, and revision of the IRB for PED-SIG application throughout the entire project. The IRB submission (NYU IRB-FY2016-662) was initially approved on August 28, 2017, and renewed on July 13, 2018 and July 24, 2019, and the final revision was approved on September 14, 2021. The NYU team managed the following information in the IRB application:

- Project Information
- Participants & Recruitment (including a recruitment letter)
- Consent & Privacy (including a consent form)
- Data Confidentiality & Risks and Benefits

Besides the application, the NYU team also trained researchers on human subject social & behavioral research and inclusive events. Only trained and IRB-certified researchers were involved in the management, collection and analysis of data, and field tests of PED-SIG application.

4.4 Performance Measures

To measure the effectiveness of application, the following metrics are measured:

- Qualitative Operator Feedback
- Pedestrian Crossing Speed and Crossing Travel Time
- Times Out of Crosswalk
- Waiting time at intersection for crossing

4.4.1 Qualitative Operator Feedback

To collect qualitative user feedback from the participants on the effectiveness of the PED-SIG application deployed during the CV Pilot, pre-experiment and post-experiment surveys were administrated during the field tests. Individual interviews were conducted with the participants, with the questions read aloud and spoken responses recorded by the surveyors.

A. The pre-experiment survey is designed to establish baseline conditions for study participants. The questionnaire in the pre-experiment survey includes a few key demographic questions, self-ratings of mobility and travel proficiency, and questions about assistive technology usage in navigating city streets.
B. The post-experiment survey aims to collect useful feedback on participants' perceptions and experiences with the PED-SIG application during the field test and suggestions for improving the application. It includes an additional set of questions on attitudes, perceived impact on participants' safety and mobility, institutional issues (e.g., privacy), and other relevant topics.

All pedestrian surveys are used to measure the changes in users' experiences with PED-SIG application, their satisfaction with the technology, and its perceived impact on their safety and mobility. It is noted that, while the user feedback is important, it is not sufficient to conduct robust statistical analyses due to the small sample size of the survey.

Descriptive analysis is used to evaluate qualitative user feedback collected from pre-experiment and post-experiment surveys as the sample size of target group is small. This analysis focuses on the evaluation of PID ease-of-use, user experience (familiarity, confidence, reliability), application functionality (sufficient audio/haptic assistance, alert accuracy, etc.), and user perception of safety.

4.4.2 Operational Data Logs and Field Observations

To support the evaluation of the PID units, data logs are collected from the PID units when being used by pedestrians with vision disabilities to cross the selected crosswalks. These log files record time using series-based metrics of the location and movement of the pedestrian, SPaT and MAP messages from the relevant intersection, and system information about the device and its operation (including the messages delivered by and any user interactions with the PID application). The log data are exported in JSON format. From this raw log data, performance metrics regarding the use of the PID application are generated and produced (Table 3). Both aggregated and disaggregated user-based performance measures are computed and all the PII information is removed.

Most performance measures focus on the PID log files with LogType: *"MOVEMENT"*. Observations of the participants in the field test are also collected and used as supplemental information for certain performance measures, such as times out of crosswalk (number of times participants veered out of the crosswalk), that need visual field observation and manual data extraction.

It is important to note that PIDs only collect log data while the application is actively being used. No participants were asked to navigate without a PID or with the PID unit operating in silent mode.

Table 3. Operational Data Log Based Performance Measures

Measure	Description	Data Log Source Messages
Pedestrian Crossing Speed and Crossing Travel Time	These performance measures report the average crossing speed and travel time of all users.	*Required Messages* • Position.PED_IN_CROSSWALK_START • Position.PED_IN_CROSSWALK_END • Location.mLatitude • Location.mLongitude *Substitute Messages (in case of GPS errors)* • Movement.STEPS
Pedestrian Crossing Waiting Time	This performance measure reports the average crossing waiting time of all users. The crossing waiting time will be calculated using the time interval between these messages.	*Required Messages* • Position.PED_ENTERING_CROSSWALK • Position.PED_IN_CROSSWALK_START
Times Out of Crosswalk	This performance measure reports the total number of times the user steps out of the crosswalk when crossing the intersection.	*Required Messages* • Location.mLatitude • Location.mLongitude • ALERT.EVENT

5 Test and System Validation

To validate the location and signal accuracy of the PID, several system validation tests were performed prior to conducting the field experiments involving the participants. These tests were performed using the same application build, test phones and at the same intersections as the designed field experiment (see Section 6).

5.1 Pedestrian Signal Latency

The SmartCross application advises the pedestrians with vision disabilities of the signal status (WALK / DON'T WALK) so that they can determine when to enter the crosswalk. To measure the pedestrian signal latency when using PID, we used a stopwatch to record the elapsed time between the pedestrian phase transition on the pedestrian signal head and when audio alert is received from the PID. Two pedestrian phase transitions are used in the validation: 1) Transition between 'Walk' and 'Don't Walk' phase; 2) Transition between 'Flashing Don't Walk' and 'Steady Don't Walk' phase. We conducted a total of 40 tests (10 x per intersection at the four test intersections). The results are shown in the Table 4.

The average pedestrian signal latency is 1.75 seconds with a standard deviation of 0.23 second. The observed maximum latency is 2.36 seconds, and the minimum latency is 1.36 second. This latency could be due to the data transmission between the PID, the cloud service, TMC, and the ASTC.

Table 4. SmartCross Pedestrian Application Signal Latency (sec) Test Results

Test Number	STATE@HOYT	STATE@BOND	PACIFIC@BOND	PACIFIC@HOYT
1	1.73	2.36	1.66	1.39
2	1.50	1.87	1.45	1.52
3	1.83	1.73	1.88	1.88
4	1.48	1.92	1.42	1.86
5	2.05	1.95	1.72	1.76
6	1.82	1.65	1.70	1.66
7	1.90	2.05	1.92	2.10
8	1.47	1.82	1.62	1.58
9	1.36	1.46	1.79	1.59
10	2.15	1.85	1.55	1.88
MEAN	1.73	1.87	1.67	1.72
S.D.	0.25	0.23	0.16	0.20

5.2 Location Accuracy and Service Reliability

The PID uses the pedestrian's orientation and location to determine which crosswalk is of interest after which it continues to update the pedestrian as they cross the street. Utilizing multiple test cases (47 runs at four (4) intersections), the location accuracy tests of the PID were conducted using a measuring tape

(Table 5). The average distance error is 5.33 feet with a standard deviation of 3.64 feet. The observed maximum distance error is about 13.50 feet, and the minimum distance error is 0.17 feet.

Table 5. SmartCross Pedestrian Application Distance Error (ft) Test Results for Location Accuracy

Test Number	STATE@HOYT	STATE@BOND	PACIFIC@BOND	PACIFIC@HOYT
1	0.42	13.50	11.50	4.42
2	4.67	6.33	6.25	0.17
3	5.33	9.42	1.83	4.08
4	0.50	6.42	9.17	9.75
5	2.67	10.25	5.92	2.08
6	7.58	1.42	1.67	4.42
7	11.58	2.08	1.08	3.75
8	4.33	11.67	6.42	2.42
9	6.17	2.42	2.42	2.17
10	12.50	8.50	3.08	6.42
11	11.75	5.75	5.42	2.25
12	3.42	N/A	2.42	6.75
MEAN	5.91	7.07	4.49	4.06
S.D.	4.01	3.83	3.15	2.49

Besides the location accuracy, the application did not work as intended or remained silent during approximately 11% of the test runs. This reduced the reliability of the services, and sometimes provided inaccurate or incorrect alerts that led to a negative impact on the user experiences. The application had to be restarted or moved in a different direction to make it recognize / calculate the location before being functional again. Possible causes may have been the GPS coordinates drifting to areas outside the testing intersection, connection failure between AWS to TMC, connection failure between the augmentation device and mobile phone, and other environmental impacts that may affected either phone compass or GPS. Moreover, both the “in hand” and hands-free (“in pocket”) mode for the PIDs were tested for system validation. However, based on the user experience, the “in pocket” mode was found to require further development and testing. Thus, only the “in hand” mode was determined to be used in the field experiment with participants.

6 Field Experiment and Evaluation

Field tests were conducted between October 29, 2021 and November 18, 2021. During each field test, a project introduction, consent form, and pre-experiment survey questionnaire were read to the participant, followed by training for how to use the SmartCross application. The PID and GPS augmentation device were then handed to the participants. Each participant was led along the pre-determined routes (described in Section 4.2) by the team members. After the field test was completed, a post-experiment survey was read to the participants. Each field test took approximately 1-2 hours. The pre-experiment and post-experiment survey responses were collected from all 24 participants; survey questions can be found in Appendix A.

Approximately 170 runs, each made up of two (2) crosswalk crossings, were completed by the participants during the field tests. Application, hardware, devices, and test locations are as follows:

- SmartCross Demo version 1.2.6, build v105
- Location augmentation device
- iPhone 7 with iOS version 13.3
- ASTC controller software version 1007
- Test locations: Pacific Street and Bond Streets, Pacific Street and Hoyt Street, and State Street and Hoyt Street, and State Street and Bond Street in Brooklyn, NY.

As a back-up location, State Street/Bond Street intersection was used in some of the field tests when one of the three (3) designated intersections was not available for testing due to temporal road construction, emergencies, or unplanned events.

6.1 Pre-experiment Survey

The purpose of the pre-experiment survey is to understand the baseline conditions for study participants. The respondents of the survey ranged a diverse age group, vision ability, mobility assistance mechanisms, and frequency in daily signalized intersection crossing. The breakdown of each demographic and background factor is presented in Table 6 below. All participants used smartphones, with 22 (92%) using iOS phones and two (2) using Android phones daily. 80% of the participants have used GPS to navigate the city streets.

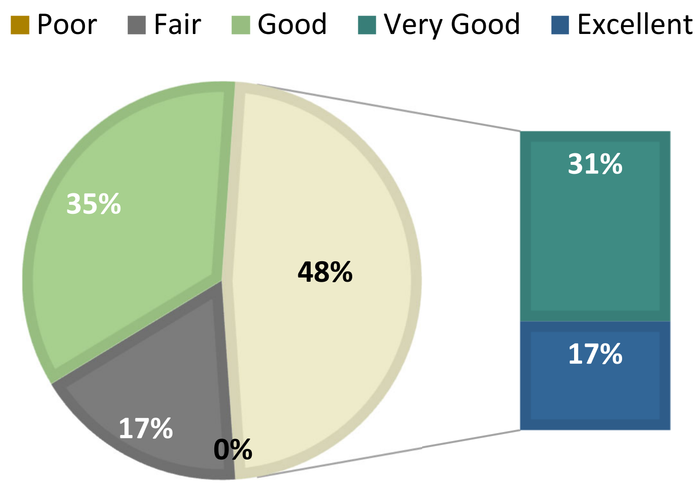
Table 6. Demographic and Background Information of the Surveyed Participants

Factors	Groups	Participants (N=24)
Age group (%)	18-24	0%
	25-44	58%
	45-64	25%
	Older than 65	17%
Vision ability (%)	Partially-sighted or low vision	29%
	Blind	29%

Factors	Groups	Participants (N=24)
	Totally blind	42%
Signalized intersection crossing frequency (%)	6 or more intersections a day	50%
	4 or 5 intersections a day	29%
	2 or 3 intersections a day	21%
	Less than 2 intersections a day	0%
Mobility assistance mechanisms (%)	Long or white cane	58%
	Guide dog	21%
	Electronic travel aid (e.g., laser cane)	0%
	Personal navigation device / GPS on the phone	0%
	Asking other pedestrians I pass	8%
Proficiency in Signalized street crossings (%)	Well above average	13%
	Above average	37%
	Average	33%
	Below Average	17%
	Well below average	0%

6.2 Post-experiment Survey

The post-experiment interview aimed to collect useful feedback on participants' perceptions and experiences with the PED-SIG application after the field test was done. The first five questions asked about the overall user experience. Figure 16 below shows that about 83% of the participants gave positive feedback ('Good', 'Very Good' or 'Excellent') when rating the overall impression for the PED-SIG application.



(Source: NYU C2SMART Center)

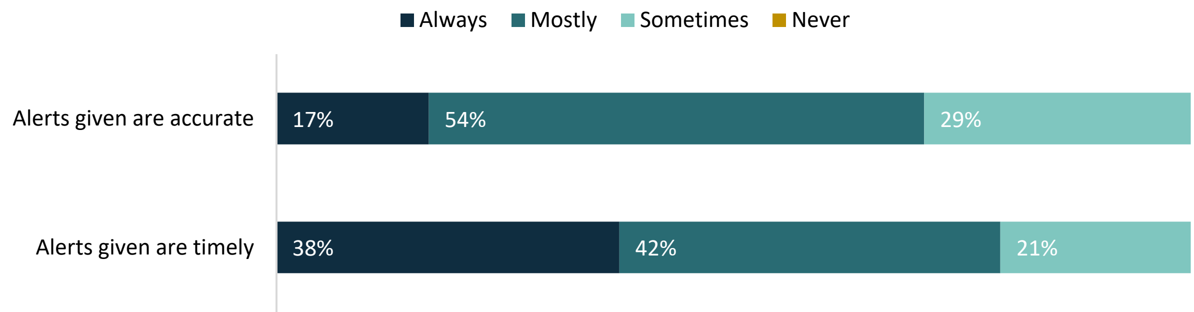
Figure 16. Overall PED-SIG Application Rating

The main problems experienced when using the PED-SIG application were as follows:

(1) The location information provided was not accurate (75%).
(2) There were slow responses (25%).
(3) The orientation was not accurate (21%).

96% of the participants felt that they were given sufficient time to cross the intersection, and 63% of them felt that they stayed oriented on the crosswalk when using the PED-SIG application. Most of the participants (92%) thought the application was easy to use. 71% of the participants strongly or somewhat agreed that they felt more confident in their ability to cross a signalized intersection with the application than with other assistive technologies they have used before. And about 25% of them kept a neutral opinion while one participant (4%) expressed some form of disagreement.

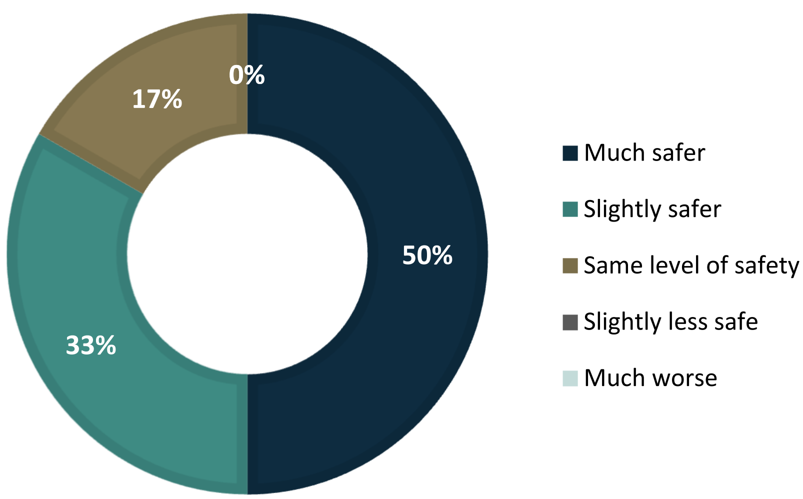
The second part of the post-experiment survey asked questions about the PED-SIG application performance. All participants (100%) agreed that the application provided sufficient information through audio to assist in their intersection crossing. However, the perception of the vibration function was mixed, with about 13% of the participants thinking that vibration information was not sufficient and about half of the participants (46%) claiming that they did not know or notice the haptic feedback. Approximately 80% of the participants received timely alerts/information from the application either always or most of the time. However, this rate dropped to 71% when asking if the alerts given were accurate (Figure 17). All the participants agreed that the information provided by the PED-SIG application was helpful, with 67% strongly agreeing and 33% somewhat agreeing.



(Source: NYU C2SMART Center)

Figure 17. PED-SIG Application Alerts Were Accurate/Timely

As the primary goal of NYC CVPD is to improve safety, Assessing and measuring the user's perception of the application's impact on safety are critical. Based on the survey results shown in Figure 18, 50% of the participants felt much safer when using the PED-SIG application compared to not using it, 33% felt slightly safer, and the remaining 17% of the participants retained the same level of perceived safety. All the participants anticipated that pedestrians would benefit from using the PED-SIG application, especially pedestrians with vision disabilities.



(Source: NYU C2SMART Center)

Figure 18. PED-SIG Application Safety Perception

Open-ended survey responses are useful in gaining insight about the issues that are not fully covered by multi-choice and Likert scale questions. The participants' suggestions to improve the current PED-SIG application and main takeaways from their responses are as follows:

- Participants wanted to test this application at more intersections, especially at the ones with complex geometry (5-leg intersections, pedestrian island etc.) and locations with leading pedestrian interval (LPI) signals.
- Use the PID without an additional device and integrate the PED-SIG application with other existing accessible or navigation applications without having to launch multiple applications.

Integration with a wearable device, such as armband or smartwatch, were also mentioned by a few participants.

- Add more information about the streets; for example, if it is a one-way or two-way street, unsignalized intersection, how many lanes, crosswalk width, orientation of intersections (4-way vs 5-way).
- Enable options for experienced users to choose what information they get (e.g., frequency of the alerts, enable or limit haptic feedback).
- Participants want to be alerted when they are veering off the crosswalk.
- Concern about needing to have the phone "in hand", especially when the participants were already using cane or guide dog. The application should also be compatible with screen reader (a form of assistive technology that renders text and image content as speech or braille output).

6.3 PED-SIG Operational Data Logs

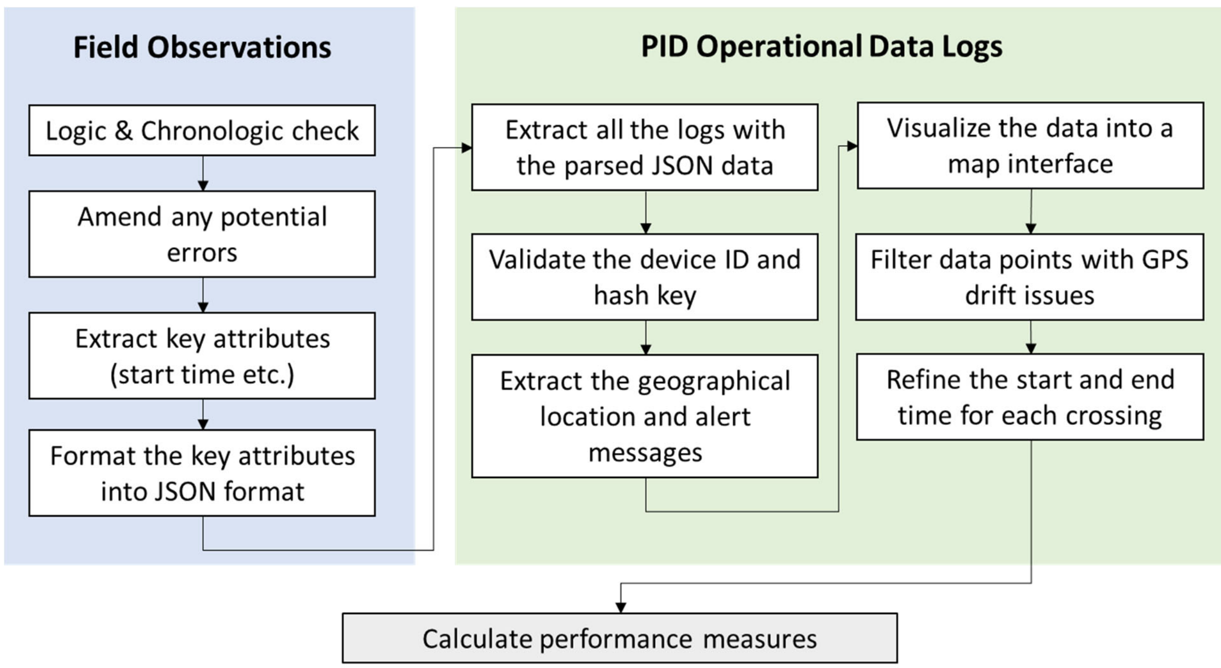
Approximately 170 runs, each made up of two (2) crosswalk crossings, were completed by the 24 participants during the field tests. Pedestrian crossing speed and travel time, waiting time at the intersection for crossing, and times out of crosswalk were evaluated using data extracted from PID operation data logs, supplemented by field observations. A visualization of the PED-SIG application operational data logs is shown in Figure 19.

(Source: NYU C2SMART Center)

Figure 19. Visualization of the PED-SIG Application Data Logs

6.3.1 Data Cleaning, Filtering and Post-processing

GPS drift issues were found during some of the field tests. Therefore, a hybrid method was designed by the NYU researchers to parse the collected data. The key attributes such as crossing start time, crossing end time were recorded using the field test note to minimize the margin of error. A map-based visualization is adopted to further filter out timestamps with GPS drifting by comparing the data points with the satellite map layer. Field observations were used to ensure data points when the participants veer off the crosswalk were not filtered by this process. In addition, the dwelling time at the corner other than waiting for the signals (e.g., time spent to answer participant questions between two runs during the test) were filtered when calculating the crossing speed. A detailed data cleaning, filtering and post-processing flow chart is provided in Figure 20.



(Source: NYU C2SMART Center)

Figure 20. Data Cleaning, Filtering and Post-processing

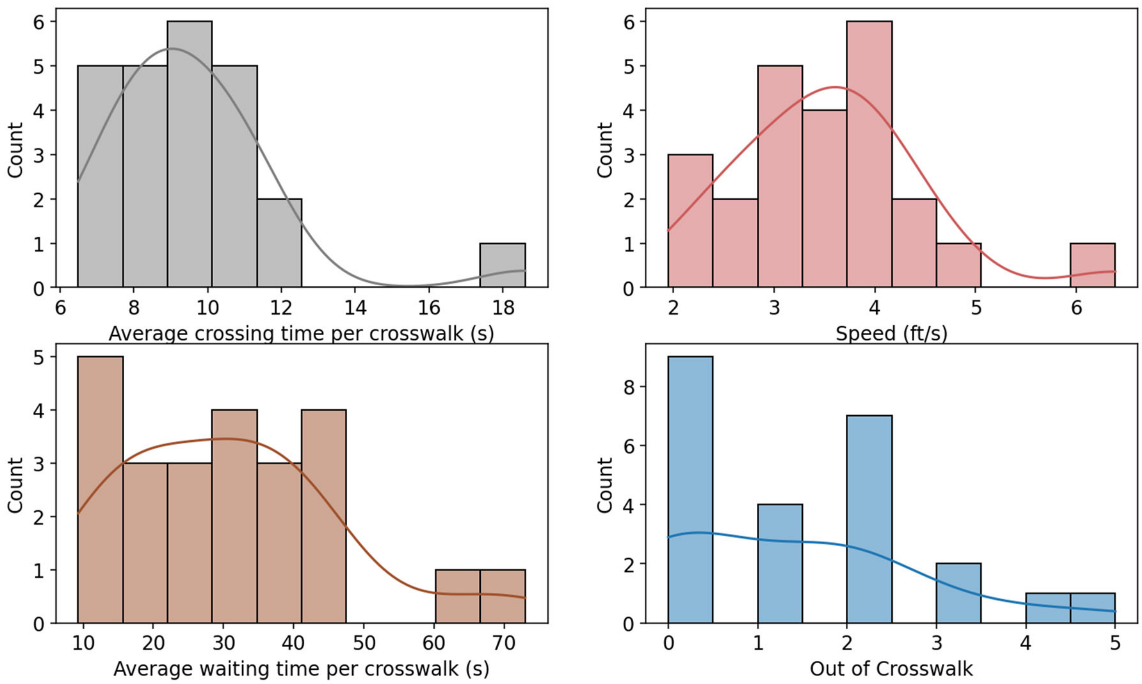
6.3.2 Evaluation Results

Based on the extracted information, both aggregated performance measures (for all participants) and disaggregated information (distributions of individual data) were generated. Table 7 shows the aggregated performance measures for all participants, and Figure 21 illustrates the distribution of disaggregated performance measures.

Table 7. Aggregated performance measures of the participants

	Crossing speed (m/s) (ft/s in the parentheses)	Average crossing time per crosswalk (s)	Average waiting time per crosswalk (s)	Out of Crosswalk (Average number of times)
Mean	1.1 (3.6)	9.6	31.0	1.4

	Crossing speed (m/s) (ft/s in the parentheses)	Average crossing time per crosswalk (s)	Average waiting time per crosswalk (s)	Out of Crosswalk (Average number of times)
Std	0.3 (0.9)	2.4	15.9	1.4
15th /85th Percentile	[0.8, 1.3] ([2.6, 4.2])	[7.7, 11.0]	[14.9, 43.0]	[0.0, 2.3]



(Source: NYU C2SMART Center)

Figure 21. Distribution of Pedestrian Crossing Speed and Crossing Travel Time, Waiting Time at Intersection for Crossing, and Number of Times Participants Stepped out of Crosswalk

The waiting time per crosswalk varies among different participants, with some of them started crossing the street right after receiving the “Walk signal is on” audio message from the application. A few of them waited for a red light and one participant always waited multiple signal cycles to ensure she can safely cross the street after receiving the notification from the PED-SIG application. In addition, 63% of the participants veered off the crosswalk at least once during the field tests. Based on field observations, 54% of the pedestrian participants crossed the streets at speeds faster than the pedestrian walk design speed of 3.5 feet/sec, which is suggested by Manual on Uniform Traffic Control Device (MUTCD) and used by many jurisdictions for calculating pedestrian phase signal timing.

7 Lessons Learned

Several valuable lessons were learned during the application development, project management, recruitment process, field tests, and performance evaluation.

During the development of the application and project management:

- Performing the application development on both Android and iOS proved to be very difficult since the two different operating systems have two different sets of utilities (e.g., libraries) and environments. This required two different implementation approaches, which required the doubling the effort for development, testing, debugging, updating, and improving the app. For a trial-version of a similar application, selecting a single platform is highly recommended.
- The initial plan had requested the pedestrian application to be a “hands free” solution to avoid interference with other commonly used assistive devices such as canes. This means the application should work when the phone is placed in the user’s pocket (vertical position). Unfortunately, due to the time limit and the changed scope, although both “in pocket” and “in hand” modes were tested by the research team, only the “in hand” mode in horizontal position oriented toward the intersection was used in the final field experiments with participants. Some participants of the pilot, especially cane users and participants with guide dogs expressed the desire to use the application while having the phone “in pocket”. Future deployment should consider continuing the development of the “hands free” solution.
- Implementation of some proposed functions/requirements were found to be infeasible during the development stage, such as logging the exact number of steps taken. Although this information could be very beneficial, not even the leading step-counting technologies (Fitbit, Apple, etc.) are able to achieve this when GPS information is not accurate. One finding from the NYC CVPD is that location accuracy remains a challenge in the urban canyon environment like NYC. Urban location accuracy requires more than GPS.
- Although a data structure document was provided at an early stage of the project, the final data format contains several changes made during the application tests and debugging by the application vendor. This created issues on receiving data from the server as some data logs did not pass the check process that was initially designed to check the data format consistency and used for automatic performance measures generation. It is recommended that an updated and detailed data structure document should be finalized prior to the field experiment with participants and the data sent by the application should follow the pre-defined format in the data structure documentation to avoid issues on the receiving data server. Application developers should always notify the team members about any changes they make to the data structure.
- Some application functionalities that were initially considered important may not be a high priority of the target users. For example, “reaching the end of the crosswalk” alert may not always be necessary as many participants, especially cane users, always knew that they reached the end of the crosswalk by touching the curb using their canes. It is suggested that during a future application development phase, proposed functionalities of an application should be well discussed with the target community to understand their usefulness.

- Docker, which packages software into standardized units (e.g., containers), is highly recommended for scalability, backup, migration, and data recovery purposes and can save time by obviating the need for manually configuring the environment of the server.

During the recruitment process:

- It is vital that organizations and agencies requesting time and travel from volunteers with any type of disability arrange transportation to and from the test site for volunteers. Travel throughout the City is significantly more difficult for individuals with limited vision, and for those unable to use public transportation, it can be expensive (when taking a taxi) or difficult to schedule.
- Many of the tools that researchers are used to using for scheduling and communication may not be accessible to volunteers with disabilities, and it is important to have a variety of options for individuals. For example, Google scheduling calendars are not accessible to screen readers. Some volunteers prefer talking on the phone to using email; others may prefer email to talking on the phone. Researchers ought to proactively determine volunteers' preferred methods of communication and adapt to them.
- It is important that any research concerning specific communities involves the input of those communities from conception. Every aspect of the research, from project design to final product, should be co-designed with the intended userbase. There will be many aspects of life about which individuals without disabilities have no or limited understanding, and these experiences will shape how the end user interacts with the research and its outputs. For this reason, projects like this one should continually solicit and iterate based off feedback from and involvement of the community it seeks to aid.

During the field tests and data analysis:

- GPS accuracy remains a major challenge. Even with a dual band GNSS, the urban environment is still difficult to get consistently accurate GNSS. A potential solution could involve Real-Time Kinematic (RTK) positioning or another location correction software. However, RTK or other location correction software is not available natively on iOS or Android and there can be an additional cost for this type of service (usually a monthly subscription or something similar). An external GNSS device will still be needed in the short-term.
- Any location correction service must be thoroughly tested before deployment – there may be locations/time periods with better or worse performance.
- All the proposed application functionality and use scenarios should be well documented, tested, and validated, especially if the functionality is demanded by the user group. For example, although the "veering off the crosswalk" audio message is included in the application functions, it was not heard in any of the pre-tests and actual field tests. Based on the post-experiment survey, this is a functionality that the participants are interested in.
- It is important to be aware of potential compass issues over the mobile phones. It was found that even using the same phone model, compass information can vary on different phones (Figure 22). In addition, environmental factors can have an impact on the compass. During the field test, the test phone compass was consistently rotated at an angle at one street corner that was near a hospital, which potentially may be due to magnet applications in medical equipment. It is suggested to also calibrate the GPS on the phone, as a slight improvement on some phones was seen after calibration.
- Additional factors that were out of control of the smartphone application (positioning, data streams from the TMC, cellular connectivity) negatively affected the User Experience (UX). Many of these factors need to be communicated with multiple stakeholders. For future deployment,

real-time monitoring of data stream connection (e.g., SPaT) and cellular/Bluetooth connection of the phone is needed. It is recommended to also add notifications alerting users when the connection is lost, or the data transmission fails.

- GPS inaccuracy and how the current application collects the data also brought challenges in computing the performance measures. For example, an “reaching the end of the crosswalk” alert may be triggered after a participant has reached the sidewalk curb for a certain distance (usually 2-10 feet) due to GPS issues. If the participant already knew he/she has reached the curb and stopped walking, this alert will not be triggered and logged into the data. The team had to use algorithms, map visualization, and field observation notes together (e.g., crossing start times and end times) to filter and compensate for the actual position of the data points. This issue needs to be considered for future large-scale testing and deployment as field observation data may not be available/feasible.
- The experience of the vibration function was found to be slightly affected by cold weather as a few participants wore thick cloths and gloves during the field tests. The field tests conducted in this study were not started until October 2021 due to COVID-19 impacts on in-person research activities. But if similar applications are to be tested in the future, it is suggested to plan the field tests in warmer weather if the project timeline allows. In addition, the 500ms vibration with a 2s/5s gap is less noticeable compared with audio alerts in a real-world test as users are distracted by many environmental factors, a longer or more frequent vibration is recommended in the application design.

(Source: NYU C2SMART Center)

Figure 22. Compass on the test phones showing different information (iPhone 13 Pro on the left; four test iPhone 7 in the middle; a military compass on the right).

8 Conclusion

This section summarizes the research scope and experiment of the NYC CVPD PED-SIG application. Additional discussion on the limitations and lessons learned during the application development, project management, participant recruitment, and performance evaluation are also summarized.

As part of the NYC CV pilot deployment, a Mobile Accessible Pedestrian Signal System (PED-SIG) was designed and tested to provide intersection navigation assistance to pedestrians with vision disabilities. This technology provides audio output and haptic prompts to assist pedestrians with visual disabilities in crossing the street.

The initial stages of PID/PED-SIG application program included deployment of ten (10) portable personal devices and recruitment of 24 participants with vision disabilities to participate in the field pilot test. However, due to the difficulties in developing the application for two (2) platforms (iOS and Android), PED-SIG application development was limited to only iOS platform in the final scope. Therefore, five (5) PID devices operating on the iOS system were used during the field tests. These portable personal devices were assigned to participants to be used while being accompanied by an NYU/C2SMART research team member. Six (6) predefined routes were designed to test the PID and the participants' experiences through four of the CV-equipped intersections. The PIDs have the capability of receiving localized SPaT and MAP messages broadcast by the intersection through cellular communications (4G, LTE) to provide the intersection geometrics and signal status of the intersection displays.

The evaluation of this CV technology was based on operational data logs collected from the portable personal devices, observations of the participants in response to the issued alerts during the field tests as well as through qualitative feedback surveys with the participants. Based on the evaluation, all the participants anticipated that pedestrians would benefit from the use of PED-SIG technologies, especially pedestrians with vision disabilities. Major findings from the survey and operational data logs are summarized as follows:

- Based on the survey results, overall, about 83% of the participants gave positive feedback ('Good', 'Very Good' or 'Excellent') when rating the overall impression for the PED-SIG application.
- 83% of the participants felt much safer or slightly safer when using the PED-SIG application in comparison to not using it.
- 96% of the participants felt they were provided sufficient time to cross the intersection and 63% felt they stayed oriented on the crosswalk when using the PED-SIG application. The majority of participants (92%) thought the application is easy to use.
- While 71% of the participants strongly or somewhat agreed they felt more confident in their ability to cross a signalized intersection with the application when compared with other assistive technologies they have used before, about 25% of them had a neutral opinion and one participant (4%) felt less confident utilizing the device.
- All participants (100%) agreed that the application provided sufficient information through audio to assist their intersection crossing. However, the perception of the vibration function was mixed, with about half of the participants stating that they did not know or did not notice the vibrations.
- Approximately 80% of the participants received timely alerts/information from the application always or most of the time. This rate drops to 71% when asking if the alerts given were accurate.

- The main problem experienced when using the PED-SIG application was inaccurate location information (75%), followed by slow responses (25%), and inaccurate orientation (21%).
- The waiting time per crosswalk varies among different participants. 63% of the participants veered off the crosswalk at least once during the field tests.
- Based on field observations, 54% of the pedestrian participants crossed the streets at speeds faster than the pedestrian walk design speed of 3.5 feet/sec, which is suggested by Manual on Uniform Traffic Control Device (MUTCD) and used by many jurisdictions for calculating pedestrian phase signal timing.

As summarized in Section 7, this report has captured numerous lessons learned and directions for future development efforts for agencies and practitioners. Several aspects including, but not limited to, application development, project management, recruitment process, field testing, and performance evaluation should be considered when designing and testing a similar mobile accessible application. The findings from this study highlighted key technical and non-technical barriers to deploying applications such as the PED-SIG application. Technical barriers include limitations in achieving location accuracy and reliability of the application. More validation tests on emerging GPS augmentation technologies and reliability of the application should be considered in a future deployment. Non-technical barriers consist of outreach and recruitment to a broad user group and maintaining a schedule from start to finish. Due to COVID-19 and in-person activity restrictions set by the IRB panel overseeing the PID deployment, the actual field tests were not conducted until the end of October 2021.

The PED-SIG application for NYC CV Pilot showcased how travel accessibility and mobility for people with vision disabilities could be facilitated. However, using such application alone does not address the need for a completely accessible door-to-door trip. Future deployers could consider an all-in-one application that integrates street crossings, surrounding information, transit accessibility, paratransit services, and similar use cases.

9 References

Table 8 below lists the references used for this report.

Table 8. References

#	Document (Title, source, version, date, location)
1	Harman. 2019. "System Overview and Functional Specifications, SmartCross Pedestrian Safety Enhancement System, Version 1.1."
2	Harman. Feb 4, 2019. "NYC PID Data Collection Data Structure, Document Version 2.0."
3	New York University. 2020. "New York University Institutional Review Board Standard Operating Procedures."

10 Acronyms

Table 9 below provides a list of the acronyms used in this document.

Table 9. Acronym List

Acronym/Abbreviation	Definition
AES	Advanced Encryption Standard
AO	Agreement Officer
AOR	Agreement Officer Representative
API	Application Programming Interface
ASTC	Advanced Solid-state Traffic Controller
AWS	Amazon Web Service
BLE	Bluetooth Low Energy
CA	Certificate Authority
CAST	Center for Assistive Technology
CBC	Cipher Block Chaining
CV	Connected Vehicle
CVPD	Connected Vehicle Pilot Deployment
DSRC	Dedicated Short Range Communications
DW	Don’t Walk
FDW	Flashing Don’t Walk
FHWA	Federal Highway Administration
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
iOS	iPhone Operating System
IP	Internet Protocol
IRB	Independent Review Board
IV	Initialization Vector
ITS	Intelligent Transportation System
JSON	JavaScript Object Notation

LPI	Leading Pedestrian Interval
MOPD	Mayor's Office for People with Disabilities
MTA	Metropolitan Transportation Authority
MUTCD	Manual on Uniform Traffic Control Device
NYC	New York City
NYCDOT	New York City Department of Transportation
NYU	New York University
PED	Pedestrian
PED-SIG	Mobile Accessible Pedestrian Signal System
PID	Pedestrian Information Device
RSU	Roadside Unit
RTK	Real-Time Kinematic
SPaT	Signal Phase and Timing
SSL	Secure Sockets Layer
TIM	Traveler Information Message
TIS	Traveler Information System
TMC	Traffic Management Center
UTC	Coordinated Universal Time
VRU	Vulnerable Road User
USDOT	United States Department of Transportation
UX	User Experience

Appendix A: Survey Questionnaire

I. Pre-Experiment Interview Protocol

The purpose of this pre-experiment interview is to understand the baseline conditions for study participants.

Demographic Information

1. Name: ___________________________________

2. What is your age:
   - 18-24
   - 25-44
   - 45-64
   - Older than 65

3. Which borough do you reside in?
   - Manhattan
   - Bronx
   - Brooklyn
   - Queens
   - Staten Island

4. Which of the following best describes your vision disability?
   - Partially-sighted or low vision
   - Blind
   - Totally blind

5. At what age did you develop a vision disability or become blind?
   - ________ years old
   - __ visually impaired since birth

6. On average, how often do you cross a signalized intersection per day?
   - 6 or more intersections a day
   - 4 or 5 intersections a day
   - 2 or 3 intersections a day
   - Less than 2 intersections a day

Self-ratings: Technology

7. Have you participated in any orientation and mobility training?
   - Yes
   - No

8. Do you currently use a mobile phone?
   - Yes: IOS or Android

- No

9. Do you currently use a mobile navigation assistant / Global Positioning System (GPS)?
   - Yes
   - No

10. Have you experienced an Accessible Pedestrian Signal before? These signals give you audio or tactile information about the state of the light at the intersection or the location of the crosswalks in addition to a light signal.
   - Yes
   - No

Navigation & Mobility

11. What is your preferred method of assistance while navigating to a destination (select only one)?
   - Long or white cane
   - Guide dog
   - Electronic travel aid (e.g., laser cane)
   - Personal navigation device / GPS on the phone
   - Asking other pedestrians I pass
   - Other (please specify____________)

12. How often do you use each of the following methods of assistance while navigating to a destination?
   A. Many times per day B. Few times per day C. Few times per week D. Less weekly E. Never

   - Long or white cane: _______
   - Guide dog: _______
   - Electronic travel aid (e.g., laser cane): _______
   - Personal navigation device / GPS on phone: _______
   - Asking other pedestrians I pass: _______
   - Other (please specify: ___________): _______

13. In general, how safe do you feel when you cross a signalized intersection?
   - Extremely Safe
   - Very safe
   - Moderately safe
   - Slightly safe
   - Not at all safe

14. How would you rate your proficiency in each of these travel skills? Are you well below average, below average, average, above average, or well above average? *[INTERVIEWER: REPEAT RESPONSE CATEGORIES AS NEEDED]*

	Well below average	Below average	Average	Above average	Well above average
General sense of direction					
Independent travel					
Signalized street crossings					

II. Post-Experiment Interview Protocol

The post-experiment interview aims to collect useful feedback on participants' perceptions and experiences with the Ped App after the field test is done. It includes an additional set of questions on attitudes, safety, and other relevant topics.

User Experience:

1. How do you rate the Ped App overall?
   - Poor
   - Fair
   - Good
   - Very good
   - Excellent

2. Did you experience any of the following problems in using the Ped App? Select all that apply.
   - Slow response
   - Location information provided not accurate
   - Type of advisory provided (i.e., signal timing) not useful
   - Other. Please specify. ____

3. When using the Ped App, do you feel you have sufficient time to cross the intersection or not?
   - Yes
   - No
   - Don't know

4. When using the Ped App, do you feel you stay oriented within the crosswalk?
   - Yes
   - No
   - Do not know

5. For each of the following statements, please tell me whether you strongly disagree, somewhat disagree, neither agree nor disagree, somewhat agree, or strongly agree. *[INTERVIEWER SHOULD REPEAT RESPONSE CATEGORIES AS NEEDED]*

   a. The operation of the Ped App is easy to use.

Strongly Disagree	Somewhat Disagree	Neither agree nor disagree	Somewhat Agree	Strongly Agree
○	○	○	○	○

   b. I am more confident in my ability to cross a signalized intersection with the CVP pedestrian application compared to other assistive technologies I have used before.

Strongly Disagree	Somewhat Disagree	Neither agree nor disagree	Somewhat Agree	Strongly Agree
○	○	○	○	○

6. Does the Ped App provide sufficient information through AUDIO to assist your intersection crossing?
   - Yes
   - No
   - Do not know

7. Does the Ped App provide sufficient information through VIBRATION to assist your intersection crossing?
   - Yes
   - No
   - Don’t know

8. For each of the following statements, please select the answer that apply. *[INTERVIEWER SHOULD READ AND REPEAT RESPONSE CATEGORIES AS NEEDED]*

   a. Alerts given by the Ped App are timely.

Always	Mostly	Sometimes	Never
○	○	○	○

   b. Alerts given by the Ped App are accurate.

Always	Mostly	Sometimes	Never
○	○	○	○

   c. Type of alerts (i.e., signal information) given by the Ped App are helpful.

Strongly Disagree	Somewhat Disagree	Neither agree nor disagree	Somewhat Agree	Strongly Agree
○	○	○	○	○

9. In general, how safe do you feel when using the Ped App in comparison with not using it?
   - Much Safer
   - Slightly Safer
   - Same level of safety
   - Slightly less safe
   - Much worse

10. How would you rate your ability to easily navigate the pedestrian crosswalk when using the Ped App?
    - Excellent
    - Very Good
    - Good
    - Fair
    - Poor
    - Very Poor

11. Do you anticipate that pedestrians will benefit from the use of Ped App technologies?
    - Yes
    - No

12. Do you have any of the following concerns about the Ped App technologies? Check all that apply.
    - Safety
    - Privacy
    - Trust in the technology
    - Too many alerts or warnings
    - False alerts or warnings (i.e., when there is no real danger)
    - Distraction (i.e., the system will be distracting)
    - Don't know enough about the technology
    - Other (please specify: ______________________________)
    - No concerns

13. Do you have any suggestions for improving the Ped App?

    ____

14. Would you recommend the Ped App to other prospective users? Please specify why or why not.
    - Yes
    - No

    ____

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